Biomechanical investigations of coordination during initial acceleration in highly trained to world class sprinters

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September 2023

A thesis submitted in publication format for the degree of

Doctor of Philosophy

in

Sport Science (Biomechanics)

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
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Declaration

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I, **Byron John Donaldson** (student number: 05038601), declare that:

I understand and am aware of what plagiarism is, and am familiar with the university policy and implications with regard to plagiarism.

I declare that this thesis is my own original work. Any and all work of others that has been included in this thesis has been appropriately noted and referenced in accordance with the requirements of the department.

I submit this thesis for the degree of Doctor of Philosophy in Biomechanics at the University of Pretoria, and declare that it has not been previously submitted for any degree or examination, at this or any other university.

Byron Donaldson

Byron John Donaldson

28 September 2023

Acknowledgements

What they say of children is also true of graduate students: it takes a village to raise one! I am indebted to a number of people for their support, guidance and assistance during the course of this work. First and foremost, to my supervisors, Helen Bayne and Neil Bezodis. Thank you for taking on an a wayward physiologist and showing him the light of an education in biomechanics. I have learned so much from you both over the past four years and I am deeply grateful for your guidance and mentorship, your patience through some of the doldrums, the occasional cajoling and for reading all the many drafts compiled in the course of this work.

Sprint research is of course not possible without sprinters. Thank you to all of the participants who agreed to take part in this research. I am grateful to Willie de Beer, Frans de Waal, Paul Gorries, Werner Prinsloo and especially Hennie Kriel for allowing me into your sessions, tolerating all the many Whatsapp messages and teaching me so much about sprinting, especially in the midst of a pandemic.

A special thank you to Ernest Hobbs, Limbi Seyani, Bryant de Coter, Darius Sangari and the many 'Irish' for all the assistance and good humour during data collection, it is much appreciated.

I am grateful to many friends for their support, for taking me on a run when needed, for not getting too bored by discussions about sprinting, and for making sure my life never got too serious. I am especially grateful to my family: Waz, Tas, Zo, Eli, Jay and Megs as well as Ron for your belief and much needed getaways to the bush, the mountains or the Cape. And finally, I owe my biggest thanks to my parents, John and Diane, for showing me the value of both science and education, but more importantly a positive and inquisitive attitude to life. Thank you for encouraging me to pursue my own interests wherever they may lead, I've come a long way since learning to write my name in the right direction.

A final note of thanks to SEMLI and the University of Pretoria for their financial support.

Abstract

Biomechanical Investigations of Coordination During Initial Acceleration In Highly Trained to World Class Sprinters

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2023

Initial sprint acceleration is a complex and dynamic skill, requiring the application of large forces to propel the body forwards. Effective force application is achieved through the use of joint and segment rotations in an organised and inter-related manner. While many of the isolated angular kinematic features associated with effective external force profiles are established, little is currently known about the relationships that exist between the key segments during the first steps of acceleration, i.e., the coordination of movement between functionally related elements. Through a series of three studies, this thesis explores inter- and intra-limb coordination during initial acceleration in sprinters ranging from highly trained to world class level, to enhance the understanding of sprint acceleration technique and performance.

The first study provided a detailed description and quantification of inter-limb thigh-thigh, intra-limb shank-foot, and trunk-shank coordination during the first four steps of acceleration, and investigated changes in coordination between steps. Specific coordination features were identified and between-individual variation in coordination patterns in preparation for, or response to, the major transitions in the step cycle, i.e., touchdown and toe-off, were observed. Additionally, step-to-step changes in coordination and angular kinematics were identified, showing clearly differentiated coordination in step 1 compared to later steps.

The second study utilised a novel application of hierarchical cluster analysis to vector coding data in order to identify and characterise sub-groups of sprinters with similar thigh-thigh and shank-foot coordination patterns, and subsequently explored discrete kinematic and performance differences between sub-groups. Three sub-groups were identified in step 1 and two sub-groups over steps 2-4. Sub-groups tended to be differentiated by differences in thigh-thigh coordination at the beginning and end of the step, and shank-foot coordination during flight as well as during ankle dorsiflexion in early stance. Combining sub-groups from step 1 and steps 2-4 to describe entire initial acceleration strategies, cluster combinations identified coordination approaches more likely to be associated with higher level sprinters and better performance.

In the final investigation, relationships between coordination and lower body strength were evaluated in the context of dynamical systems theory, and the interaction of these two factors with regard to acceleration performance was explored. Several correlations existed between measures of lower body strength and features of thigh-thigh and shank-foot coordination, while multiple regression analysis suggested the presence of interaction effects between coordination and tests associated with lower body power in relation to performance. Thus, lower body power appeared to influence the relationships between coordination features and performance, such that the effectiveness of particular coordination patterns varied depending the lower body power of the athlete.

The work included in this thesis provides a basis for understanding coordination during initial sprint acceleration, and includes several novel and exploratory approaches to investigating these questions which provides relevant information for practitioners and coaches interested in exploring the organisation of the body and coordination of segments during initial acceleration. Moreover, this work facilitate the generation of new hypotheses and encourages new directions in future research.

Supervisors: Helen Bayne & Neil Bezodis

Contents

Appendices

List of Publications

The following research outputs have resulted from work included in this thesis:

Journal articles:

1. Donaldson BJ., Bezodis NE., Bayne H. (2022) Inter- and intra-limb coordination during initial sprint acceleration. *Biology Open* 11(10), bio059501. https://doi.org/10.1242/bio.059501
2. Donaldson BJ., Bezodis NE., Bayne H. (2024) Characterising coordination strategies during initial acceleration in highly trained to world class sprinters. *Journal of Sports Sciences.* https://doi.org/10.1080/02640414.2023.2298100
3. Donaldson BJ., Bezodis NE., Bayne H. (*In Preparation*) Relationships between coordination, strength and performance during initial sprint acceleration. *Scandinavian Journal of Medicine and Science in Sport.*

Conferences Proceedings & Presentations:

1. Donaldson B., Bezodis N., Bayne H. (2021) Within-subject repeatability and between-subject variability in posture during calibration of an inertial measurement unit system. *ISBS Proceedings Archive*, 39(1):224. https://commons.nmu.edu/isbs/vol39/iss1/58
2. Donaldson BJ., Bezodis NE., Bayne H. (2021) Step-to-step changes in foot-shank coordination during initial sprint acceleration. **In** Bayne H., Albertus Y., Cockcroft J., Kramer M. (Eds.) 1st Conference of the South African Society of Biomechanics, *South African Journal of Sports Medicine.* Vol. 34(1)p.8
3. Donaldson B., Bezodis N., Bayne H. (2022) Similarity of coordination patterns in a group of highly trained sprinters: A novel approach. *ISBS Proceedings Archive*, 40(1):155. https://commons.nmu.edu/isbs/vol40/iss1/37
4. The relationship between lower body strength and initial acceleration coordination in sprinters. 28th Annual conference of the European College of Sports Science, 2023 July 4-7; Paris, France.

List of Figures

List of Tables

Abbreviations & Symbols

Item	Explanation
θ	Angle
ω	Angular Velocity
1-RM	1-repetition maximum
AP	Anti-phase
ANOVA	Analysis of Variance
BC	Block clearance
BW	Body Weight
CA	Coupling Angle
$\mathrm{CA}_{\mathrm{Diff}}$	Coupling Angle Difference Score
$\mathrm{CA}_{\mathrm{Dist}}$	Coupling Angle Distance Score
CM	Centre of Mass
CMJ	Countermovement Jump
CRP	Continuous Relative Phase
DJ	Drop Jump
D_{RF}	Degradation in Ratio of Forces
F	Female
F_0	Theoretcial Maximum Horizontal Force
FVP	Force-Velocity-Power profile
GRF	Ground Reaction Force
HJ	Hop Jump
IMTP	Isometric Mid-Thigh Pull
IMU	Inertial Measurement Unit
IP	In-phase
ISqT	Isometric Squat
JH	Jump Height

M	Male
OMC	Optical Motion Capture
PB	Personal Best
$\mathrm{P_{Max}}$	Maximum Horizontal Power
RF	Ratio of Forces
$\mathrm{RF_{Max}}$	Maximal Ratio of Forces
RJM	Resultant Joint Moment
RSI	Reactive Strength Index
SEM	Standard Error of Measurement
SSC	Stretch Shortening Cycle
TD	Touchdown
TE	Typical Error
TO	Toe-off
$\mathrm{V_0}$	Theoretical Maximal Velocity

Chapter 1

Introduction

1.1 Background

> *There is about world-class athletes*
> *carving out exemptions from physical*
> *laws a transcendent beauty that*
> *makes manifest God in man*
> ***David Foster Wallace***

The sprint is the foundational act in athletic competition. It was the sole event - a 180 m run called the *stadion* - in the first Olympic games in 776 BC (Kyle, 2013; Pleket, 2004), and has captured the attention of athletes and spectators ever since. The appeal is dual: in the first instance, sprinting is a simple and pure pursuit of the extremes of human capabilities, and in the second, as noted by Wallace in the caption above, it is undeniably beautiful. A raw expression of force and speed somehow elegant, a delicate balance of poise and power. While the task in a sprint may be simple, it is not easy. Sprinting is a complex movement requiring expert use of muscle contractions in concert with effectively coordinated joint and segment rotations to impart large forces to the ground and propel the body forward (Davids et al., 2003; Glazier, 2017; Morin et al., 2015). These are the factors that draw in the scientist and the coach: to discover the physical, technical and mechanical features that govern effective sprinting, and translate that into practice.

Sprinters at the top level can achieve peak velocities in excess of 12 m.s^{-1} and regularly achieve average velocities upwards of 10 m.s^{-1} over 100 m - indeed they must to run under the famous 10 second mark (Healy et al., 2022; Krzysztof and Mero, 2013; Slawinski et al., 2017b). However, for a given top speed, the ability to raise the average velocity depends on an effective acceleration from a stationary start in the blocks, with performance both in the start and during acceleration therefore strongly associated with 100 m time (Bezodis et al., 2015; Healy et al., 2022; Slawinski et al., 2017a). A key feature of the challenge of acceleration, in contrast to maximal velocity sprinting, is changing demands as it progresses (Colyer et al., 2018; Nagahara et al., 2014; Slawinski et al., 2017a; von Lieres und Wilkau et al., 2020). Consequently, acceleration and maximal velocity have long been considered separate phases of the sprint with differing technical features that relate to performance in each phase (Healy et al., 2022; Krzysztof and Mero, 2013; Nagahara et al., 2014; Slawinski et al., 2017a). However, kinematic and kinetic changes are not uniform across acceleration, leading to a further subdivision of acceleration into sub-phases determined primarily by changes in centre of mass (CM) height and the magnitude and rate of kinematic and kinetic changes during the phase (Colyer et al., 2018; Nagahara et al., 2014; von Lieres und Wilkau et al., 2020). The first sub-phase is termed initial acceleration, characterised by a rapid raising and acceleration of the CM in the initial steps after exiting the blocks, as well as greater magnitudes of step-to-step changes in joint angular kinematics compared to the subsequent transition phase (Nagahara et al., 2014; Slawinski et al., 2010; von Lieres und Wilkau et al., 2020). Consequently, owing to its occurrence immediately following block exit and association with the specific technical challenges of raising and accelerating the CM, initial acceleration is a key phase in sprinting and therefore of considerable interest to researchers and coaches.

The bulk of existing angular kinematic research into initial acceleration has relied either on discrete joint and segment angles at key events in the step cycle such as touchdown and toe-off (e.g. Bezodis et al. (2015); Slawinski et al. (2010); von Lieres und Wilkau et al. (2020); Walker et al. (2021)) or on time series from isolated joints or segments over the movement (e.g. Debaere et al. (2013); Kugler and Janshen (2010); Nagahara et al. (2014); Schache et al. (2019)). This literature has established numerous important technical features of acceleration and substantially enhanced our understanding of how sprinters accelerate their CM in the initial steps of the sprint. However, the body is a linked segment system in which different components are functionally related such that for a more complete understanding of technique, knowledge of the relationships between components is required (Davids et al., 2003; Glazier, 2017). In the dynamical systems theory of motor control, complex movements arise from self-organisation of the linked segment system within interacting constraints imposed on and by the biological system, the task and the environment (Davids et al., 2003; Glazier, 2017; Kimura et al., 2021; Newell, 1986). Within this paradigm, biomechanical investigations of coordination typically quantify the relationships between functionally related joints or segments to enhance understanding of emergent movement patterns and gross movement organisation (Hamill et al., 1999; Kimura et al., 2021; Sparrow et al., 1987). Such approaches can provide valuable insight into the higher-level organisation of movement between key events, the potential influence of one component of the system on another, and the influence of particular constraints on the relationships between components. Moreover, these approaches suggest the potential to classify and characterise different acceleration strategies through analysing coordination in key segments and joints. Although there have been some preliminary studies (Bayne et al., 2020; Bezodis et al., 2019a), a comprehensive quantification and characterisation of coordination during initial acceleration has not yet been achieved.

Given the importance of effective force application to acceleration (Bezodis et al., 2019b; Kugler and Janshen, 2010; Morin et al., 2012; Rabita et al., 2015) and the ubiquity of additional resistance training in sprint training programmes (Bolger et al., 2016; Burnie et al., 2018; Moir et al., 2018), lower body strength in sprinters has long been of wide interest. Existing studies have for the most part either reported comparisons of strength variables between sprinters of different levels or associations between strength variables and broad sprint performance measures (i.e. personal best and/or sprint time) (e.g. Brady et al. (2020); Healy et al. (2019); Loturco et al. (2015); Young (1995a)). Despite the established mechanical properties of effective acceleration and direct theoretical links with lower body strength, investigations of relationships between strength and acceleration performance have so far been somewhat equivocal (Brady et al., 2020; Healy et al., 2019; Moir et al., 2018; Young, 1995a). One recognition of dynamical systems theory is that the technique an athlete adopts is not independent of their physical qualities, which are necessarily an important component of organismic constraints (Davids et al., 2003; Newell, 1986). Thus, emergent coordination strategies may be influenced by an athlete's strength characteristics, and particular strength characteristics may be associated with particular coordination strategies and technical features of acceleration. As such, there is a need to explore the relationships between physical characteristics like strength and technical features like coordination, as well as the potential interactions between physical and technical features in relation to performance. To date, there is a paucity of studies considering these questions, especially in sprinters.

1.2 Motivation & purpose

Initial acceleration is a key phase of sprint running, with unique demands imposed on athletes due to block exit and the need to rapidly accelerate the CM over a small number of steps. This phase has been associated with distinct technical features compared to later phases, resulting in considerable specific attention from both researchers and coaches despite representing only a relatively small subset of total steps in a race (Bezodis et al., 2019b; Colyer et al., 2018; Nagahara et al., 2014; von Lieres und Wilkau et al., 2020). Despite a wealth of literature devoted to understanding this phase, there remains little published data regarding the interrelations of the components of the linked segment system of the body, and no attempts to provide a comprehensive characterisation of the emergent coordination patterns in initial acceleration. To move toward a more complete understanding of acceleration technique, there is a need to go beyond isolated joint and segment analyses and discrete observations towards more integrated approaches that facilitate a holistic understanding of technique (Glazier, 2017). Moreover, given the increased adoption of dynamical systems theory based approaches to movement and training (Burnie et al., 2018; Davids et al., 2015), analyses of coordination can enhance the broader understanding of movement patterns in sprinting and the training approaches associated with them.

An additional factor to consider is the interaction between physical qualities and coordination patterns. From the theoretical perspective, it appears clear that the physical capacities of an athlete will constrain the emergent coordination strategies they can adopt during complex movement tasks. An individual who is insufficiently strong or flexible, or with specific anatomical features, may be unable to adopt certain coordination patterns, but may be able to achieve similar performance outcomes with different coordination patterns within their own constraints. Given the established mechanical demands of acceleration and the ubiquity of strength training as an auxiliary to sprint training programmes, as well as the substantial attention given to understanding the association between lower body strength and sprint performance, within context strength may be considered one of the most prominent organismic constraints to consider and it is important to understand the relationships between coordination patterns and strength capacities. In addition to the general paucity of coordination studies in sprinting, there is a distinct lack of research exploring interactions between coordination and strength characteristics. Determining the primary coordination patterns exhibited by trained sprinters and the interactions with lower body strength and acceleration performance will provide novel information to researchers and coaches seeking a holistic understanding of acceleration technique, and aid coaches in identifying and understanding the factors influencing the movement patterns of their athletes in an individualised training context.

1.3 Aim

The aim of this thesis was to develop a comprehensive empirical understanding of coordination during initial acceleration in highly trained to world class sprinters and assess the relationships between coordination, lower body strength and acceleration performance.

1.4 Objectives

Six specific objectives were developed in order to fulfill the aim of this research programme:

1. Describe and quantify inter- and intra-limb coordination patterns exhibited by sprinters during initial acceleration.
2. Assess step-to-step changes in coordination during initial acceleration.
3. Identify different initial acceleration coordination strategies used by sprinters and characterise the typical features of these patterns.
4. Explore the associations between the coordination strategies exhibited by sprinters and their performance during acceleration.
5. Assess the relationship between initial acceleration coordination patterns and strength characteristics in sprinters.
6. Explore potential interactions between coordination and strength characteristics in relation to acceleration performance in sprinters.

1.5 Context & methodology

The research objectives for this thesis are addressed in a sequence of three cross-sectional studies performed with the same convenience sample of sprinters at the University of Pretoria. The

University of Pretoria provides a unique setting in the South African context as a hub for top level South African and visiting international sprint training groups, based at the Tuks Athletics Stadium. Data collection for this research formed part of applied biomechanics support available to these sprint groups, resulting in a study sample of experienced male and female sprinters ranging from highly trained to world class, and including Olympic and World Championship finalists. Inertial measurement units (IMUs) were utilised as a field based tool to collect three-dimensional (3D) kinematic data, which allowed for data collection to be incorporated into regular training sessions, at the minimal inconvenience for athletes, which also included the collection of velocity-time profiles using a radar gun. Secondary data collection included laboratory strength tests conducted as part of the routine biomechanical support, performed using embedded force plates and a selection of other proprietary tools in the SEMLI Biomechanics Lab at the University of Pretoria. These assessments resulted in three distinct data sets: one for acceleration performance, one for 3D kinematics and one for lower body strength. These data sets were analysed and combined across the three studies in order to meet the specific research objectives of this thesis.

1.6 Outline & structure

1.6.1 Chapter 2

The basis of chapter 2 is a review of literature pertinent to the work included in this thesis, providing a comprehensive background and context for the subsequent chapters. This chapter defines the initial acceleration phase, before discussing relevant literature relating to the external kinetics, kinematics and internal kinetics associated with initial acceleration. Moreover, this chapter provides background on coordination analysis, the underlying dynamical systems theory and relevant discussion of the methodological considerations in quantifying coordination before examining the existing studies of coordination in sprinting. Finally, the chapter details the relevance of lower body strength in the context of acceleration and discusses the empirical findings of lower body strength in sprinters as well as the known relationships between strength and acceleration performance.

1.6.2 Chapter 3

Focusing on the first four steps after block exit, chapter 3 examines inter- and intra-limb coordination during initial acceleration. Using a vector coding approach, this chapter details a comprehensive description of individual and group coordination profiles for thigh-thigh, trunk-shank and shank-foot segment couplings, addressing objective 1 of this thesis. Additionally, differences in coordination between steps are assessed in the context of step-to-step changes in kinematics, thereby addressing objective 2.

1.6.3 Chapter 4

Building on the initial analysis in chapter 3, this chapter applies hierarchical cluster analysis to thigh-thigh and shank-foot coordination in step 1 and steps 2-4 to identify sub-groups of sprinters with similar coordination patterns. The characteristic features of each cluster are described and differences in touchdown and toe-off kinematics between clusters are evaluated, in accordance with objective 3. Finally, the combinations of step 1 and steps 2-4 clusters are considered and acceleration performance between clusters and cluster combinations compared, addressing objective 4.

1.6.4 Chapter 5

Having comprehensively analysed coordination in chapter 3 and examined different strategies in the context of performance in chapter 4, this chapter considers the relationships between coordination and lower body strength. The associations between a range of lower body strength capacities and features of step 1 and steps 2-4 coordination are explored in accordance with objective 5, and subsequently interactions between strength and coordination in relation to acceleration performance are explored to address objective 6.

1.6.5 Chapter 6

In the final chapter, an overview of the thesis is provided and the initial research objectives are addressed in the context of each of the investigations presented in the preceding chapters. The results of chapters 3 to 5 are synthesised and discussed in the context of the broader literature, highlighting the novel contributions to the field. The strengths and limitations of the research are then discussed. Finally, consideration is given to the practical implications of this research for sprint coaches and those interested in improving sprint performance.

References

Bayne, H., Donaldson, B. and Bezodis, N. (2020), ‘Inter-limb Coordination During Sprint Acceleration’, *ISBS Proceedings Archive* **38**(1), 448–451.

Bezodis, I. N., Brazil, A., von Lieres und Wilkau, H. C., Wood, M. A., Paradisis, G. P., Hanley, B., Tucker, C. B., Pollitt, L., Merlino, S., Vazel, P.-J., Walker, J. and Bissas, A. (2019a), ‘World-Class Male Sprinters and High Hurdlers Have Similar Start and Initial Acceleration Techniques’, *Frontiers in Sports and Active Living* **1**, 23.

Bezodis, N. E., Salo, A. I. T. and Trewartha, G. (2015), ‘Relationships between lower-limb kinematics and block phase performance in a cross section of sprinters’, *European Journal of Sport Science* **15**(2), 118–124.

Bezodis, N. E., Willwacher, S. and Salo, A. I. T. (2019b), ‘The Biomechanics of the Track and Field Sprint Start: A Narrative Review’, *Sports Medicine* **49**(9), 1345–1364.

Bolger, R., Lyons, M., Harrison, A. and Kenny, I. (2016), ‘Coaching sprinting: Expert coaches’ perception of resistance-based training’, *International Journal of Sports Science & Coaching* **11**(5), 746–754.

Brady, C. J., Harrison, A. J., Flanagan, E. P., Haff, G. G. and Comyns, T. M. (2020), ‘The Relationship Between Isometric Strength and Sprint Acceleration in Sprinters’, *International Journal of Sports Physiology and Performance* **15**(1), 38–45.

Burnie, L., Barratt, P., Davids, K., Stone, J., Worsfold, P. and Wheat, J. (2018), ‘Coaches’ philosophies on the transfer of strength training to elite sports performance’, *International Journal of Sports Science & Coaching* **13**(5), 729–736.

Colyer, S. L., Nagahara, R. and Salo, A. I. T. (2018), ‘Kinetic demands of sprinting shift across the acceleration phase: Novel analysis of entire force waveforms’, *Scandinavian Journal of Medicine & Science in Sports* **28**(7), 1784–1792.

Davids, K., Araujo, D., Seifert, L. and Orth, D. (2015), ‘Expert performance in sport: An ecological dynamics perspective’, *Handbook of sport expertise* pp. 273–303.

Davids, K., Glazier, P., Araujo, D. and Bartlett, R. (2003), ‘Movement Systems as Dynamical Systems: The Functional Role of Variability and its Implications for Sports Medicine’, *Sports Medicine* **33**(4), 245–260.

Debaere, S., Delecluse, C., Aerenhouts, D., Hagman, F. and Jonkers, I. (2013), 'From block clearance to sprint running: Characteristics underlying an effective transition', *Journal of Sports Sciences* **31**(2), 137–149.

Glazier, P. S. (2017), 'Towards a Grand Unified Theory of sports performance', *Human Movement Science* **56**, 139–156.

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

Healy, R., Kenny, I. C. and Harrison, A. J. (2022), 'Profiling elite male 100-m sprint performance: The role of maximum velocity and relative acceleration', *Journal of Sport and Health Science* **11**(1), 75–84.

Healy, R., Smyth, C., Kenny, I. C. and Harrison, A. J. (2019), 'Influence of Reactive and Maximum Strength Indicators on Sprint Performance', *The Journal of Strength & Conditioning Research* **33**(11), 3039–3048.

Kimura, A., Yokozawa, T. and Ozaki, H. (2021), 'Clarifying the Biomechanical Concept of Coordination Through Comparison With Coordination in Motor Control', *Frontiers in Sports and Active Living* **3**, 290.

Krzysztof, M. and Mero, A. (2013), 'A Kinematics Analysis Of Three Best 100 M Performances Ever', *Journal of Human Kinetics* **36**(1), 149–160.

Kugler, F. and Janshen, L. (2010), 'Body position determines propulsive forces in accelerated running', *Journal of Biomechanics* **43**(2), 343–348.

Kyle, D. G. (2013), Greek Athletic Competitions, *in* 'A Companion to Sport and Spectacle in Greek and Roman Antiquity', John Wiley & Sons, Ltd, pp. 17–35.

Loturco, I., Pereira, L. A., Cal Abad, C. C., D'Angelo, R. A., Fernandes, V., Kitamura, K., Kobal, R. and Nakamura, F. Y. (2015), 'Vertical and Horizontal Jump Tests Are Strongly Associated With Competitive Performance in 100-m Dash Events', *Journal of Strength and Conditioning Research* **29**(7), 1966–1971.

Moir, G. L., Brimmer, S. M., Snyder, B. W., Connaboy, C. and Lamont, H. S. (2018), 'Mechanical Limitations to Sprinting and Biomechanical Solutions: A Constraints-Led Framework for the Incorporation of Resistance Training to Develop Sprinting Speed', *Strength and Conditioning Journal* **40**(1), 47–67.

Morin, J.-B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P. and Lacour, J.-R. (2012), 'Mechanical determinants of 100-m sprint running performance', *European Journal of Applied Physiology* **112**(11), 3921–3930.

Morin, J.-B., Slawinski, J., Dorel, S., de villareal, E. S., Couturier, A., Samozino, P., Brughelli, M. and Rabita, G. (2015), 'Acceleration capability in elite sprinters and ground impulse: Push more, brake less?', *Journal of Biomechanics* **48**(12), 3149–3154.

Nagahara, R., Matsubayashi, T., Matsuo, A. and Zushi, K. (2014), 'Kinematics of transition during human accelerated sprinting', *Biology Open* **3**(8), 689–699.

Newell, K. (1986), Constraints on the development of coordination, *in* 'Motor Development in Children : Aspects of Coordination and Control', Martinus Nijhoff, pp. 341–360.

Pleket, H. W. (2004), 'The Olympic Games in antiquity', *European Review* **12**(3), 401–413.

Rabita, G., Dorel, S., Slawinski, J., Sàez-de-Villarreal, E., Couturier, A., Samozino, P. and Morin, J.-B. (2015), 'Sprint mechanics in world-class athletes: A new insight into the limits of human locomotion: Sprint mechanics in elite athletes', *Scandinavian Journal of Medicine & Science in Sports* **25**(5), 583–594.

Schache, A. G., Lai, A. K. M., Brown, N. A. T., Crossley, K. M. and Pandy, M. G. (2019), 'Lower-limb joint mechanics during maximum acceleration sprinting', *The Journal of Experimental Biology* **222**(22), jeb209460.

Slawinski, J., Bonnefoy, A., Levêque, J.-M., Ontanon, G., Riquet, A., Dumas, R. and Chèze, L. (2010), 'Kinematic and Kinetic Comparisons of Elite and Well-Trained Sprinters During Sprint Start:', *Journal of Strength and Conditioning Research* **24**(4), 896–905.

Slawinski, J., Houel, N., Bonnefoy-Mazure, A., Lissajoux, K., Bocquet, V. and Termoz, N. (2017a), 'Mechanics of standing and crouching sprint starts', *Journal of Sports Sciences* **35**(9), 858–865.

Slawinski, J., Termoz, N., Rabita, G., Guilhem, G., Dorel, S., Morin, J.-B. and Samozino, P. (2017b), 'How 100-m event analyses improve our understanding of world-class men's and women's sprint performance', *Scandinavian Journal of Medicine & Science in Sports* **27**(1), 45–54.

Sparrow, W. A., Donovan, E., van Emmerik, R. and Barry, E. B. (1987), 'Using Relative Motion Plots to Measure Changes in Intra-Limb and Inter-Limb Coordination', *Journal of Motor Behavior* **19**(1), 115–129.

von Lieres und Wilkau, H. C., Irwin, G., Bezodis, N. E., Simpson, S. and Bezodis, I. N. (2020), 'Phase analysis in maximal sprinting: An investigation of step-to-step technical changes between the initial acceleration, transition and maximal velocity phases', *Sports Biomechanics* **19**(2), 141–156.

Walker, J., Bissas, A., Paradisis, G. P., Hanley, B., Tucker, C. B., Jongerius, N., Thomas, A., von Lieres und Wilkau, H. C., Brazil, A., Wood, M. A., Merlino, S., Vazel, P.-J. and Bezodis, I. N. (2021), 'Kinematic factors associated with start performance in World-class male sprinters', *Journal of Biomechanics* **124**, 110554.

Young, W. (1995a), 'Laboratory Strength Assessments of athletes', *New Studies in Athletics* (10), 89–96.

Chapter 2

Review of the Literature

2.1 Introduction

In track and field, sprinting involves accelerating the body from a static, crouched position in the starting blocks toward maximal horizontal velocity in an upright running posture - a considerable challenge requiring effective technique and appropriate physical qualities. Consequently, the acceleration phase of sprinting receives widespread attention in the sprint literature. The following chapter will define the initial acceleration phase as it pertains to this thesis and summarise the relevant literature on the kinematics and internal and external kinetics of initial acceleration. Subsequently, existing knowledge of coordination in sprinting will be discussed, preceded by a discussion of the definitions and theoretical underpinnings of coordination analysis as well as relevant methodological considerations. The final section will address the physical qualities of sprinters and the relationships between relevant strength capacities and sprint acceleration. While this review will specifically focus on sprinters and the initial acceleration phase, references will be made to team sport athletes and other sprint phases, where relevant, to add context or to demonstrate specific points. This chapter will provide critical discussion of the literature and suitable context for the studies comprising the body of this thesis.

Studies in sprinting have been performed across a range of different populations and performance levels, from junior level athletes and physical education students to international and Olympic level competitors (e.g. Bezodis et al. (2019a); Ciacci et al. (2017); Debaere et al. (2013a); Kugler and Janshen (2010); Loturco et al. (2019); Nagahara et al. (2014a); Rabita et al. (2015); Slawinski et al. (2010, 2017a); Walker et al. (2021); Young et al. (1995b)). However, the terminology used to describe and classify the performance levels of participants across studies has not been standardised and has seldom been consistent, leading to the same terminology (such as 'elite') being used to describe athletes with substantial and meaningful differences in performance level and training history (McKay et al., 2021). A lack of standardised and clearly defined terms for classifying performance level can make comparisons between studies and critical discussions of the literature confusing, necessitating a robust set of classification criteria for study populations. Consequently, McKay et al. (2021) developed a participant classification framework in order to create a unified set of criteria for describing participants in studies where the performance level and training history are distinguishing features of the sample.

Table 2.1: Participant classification framework, as developed by McKay et al. (2021). Estimated 100 m ranges added for the context of this thesis based on percentages of world records, world leads and typical Olympic and World Championship finalist times at the time of writing.

Tier	Relevant Classification Criteria	Estimated 100 m time range*
Tier 5: World Class	- Olympic / World championship medalists - Within ∼2% of world record / lead - Top 20 in world rankings and/or Olympic/World finalist - Exceptional skill-level achieved (i.e. running biomechanics)	M ∼ < 10.00 s F ∼ < 11.00 s
Tier 4: Elite / International	- Within ∼7% of world record / lead - Competing at international level - NCAA Division I - Top 4-300 in world rankings (depending size of field) - Highly proficient in skills required to perform sport - Maximal, or nearly maximal training, with intention to compete at top-level competition	M ∼ 10.00 - 10.30 s F ∼ 11.00 - 11.50 s
Tier 3: Highly Trained / National	- ∼20% of world record / lead - Competing at national level - NCAA Division II and III - Completing structured and periodised training, developing towards maximal	M ∼ 10.30 - 11.20 s F ∼ 11.50 - 12.50 s
Tier 2: Trained / Developmental	- Competing at local level - Regular training ∼3 times per week - Training with purpose to compete	M∼ >11.20 s F∼ >12.50 s
Tier 1: Recreationally active	- Meet WHO activity guidelines At - least 150 to 300 minutes moderate intensity exercise per week - May participate in multiple sports / activities	NA
Tier 0: Sedentary	- Do not meet WHO activity guidelines	NA

*Estimated range of 100 m personal best times corresponding to criteria for classification at the time of compilation.
NCAA: National Collegiate Athletics Association; WHO : World Health Organisation.

In order to provide a clear discussion of the literature and maintain consistent use of terminology across disparate studies, this chapter will adopt the McKay et al. (2021) criteria for classifying participants when discussing various studies (Table 2.1), in place of the original terminology used by the study authors. Instances where there is insufficient participant information provided to classify participants according to McKay et al. (2021) will be appropriately noted. These criteria for participant classification will be maintained for the sprinters analysed in the remaining chapters of this thesis.

2.2 The Initial Acceleration Phase

Sprinting has long been characterised by coaches and researchers as consisting of different phases that place different demands on the athlete (Bezodis et al., 2019c; Jones et al., 2009; von Lieres und Wilkau et al., 2020a). In the most general terms, sprinters in the 100 m begin the race in the start blocks, accelerate towards maximal velocity, maintain maximal velocity and then decelerate over the last portion of the race (Jones et al., 2009). Definitions of phases have varied as to precisely which steps comprise each phase as well as the inclusion of sub-phases within the broader categories of acceleration, maximal velocity and deceleration. Further, somewhat ambiguous terms such as 'sprint start' are sometimes used, which may refer to only the block phase but can also include the first one or two steps (Bezodis et al., 2019a,c; Slawinski et al., 2010; Walker et al., 2021). Moreover, 'sprint start' may also be used in studies utilising standing, crouched or three-point starts rather than starting blocks (e.g. Slawinski et al. (2017a); Wild et al. (2018)). Regardless of the precise definition of phases, the rationale behind the divisions is that there are differences in centre of mass (CM) motion, linear and angular kinematics, and both internal and external kinetics at different periods of the sprint, and therefore different technical demands and training emphasis. Thus, from a training perspective, building a sprint performance can comprise distinct areas of focus at different times, where performance in each phase can be critical to the race outcome. For example, performance even in short phases such as the blocks can be strongly associated with overall race performance (Bezodis et al., 2015a).

Several studies have sought to define phases during accelerated sprinting and identify the breakpoints between phases. Nagahara et al. (2014a) identified three phases (and two breakpoints) during acceleration based on the CM trajectory, with corresponding differences in angular kinematics between phases. Subsequently, von Lieres und Wilkau et al. (2020a) compared breakpoint identification from CM trajectory to identification from angular kinematics, which is more typical of coaching approaches. These studies agreed on an initial acceleration phase covering the first 3-6 steps in highly trained sprinters (Tier 3), with a first breakpoint around step 4, and a subsequent transition phase lasting up to steps 13-17 (Nagahara et al., 2014a; von Lieres und Wilkau et al., 2020a). Both studies showed kinematic differences between phases; clear step-to-step changes in kinematics were evident as a feature of the initial acceleration phase before declining in later phases, and this could represent an important component of initial acceleration technique (Nagahara et al., 2014a; von Lieres und Wilkau et al., 2020a). Thus, these studies have formalised the definition of initial acceleration as the first four steps after block exit, which will be the definition adopted for the remainder of this chapter and overall thesis.

2.2.1 External Kinetics

While the mechanical limits of running speed appear to be determined by the magnitude of the ground reaction forces (GRFs) an athlete can produce during the available contact time (Weyand et al., 2010, 2000), numerous studies have now indicated that - in line with Newton's second law - net antero-posterior forces (i.e. horizontal force application) are more important than the total magnitude of the GRF for performance during acceleration (Kugler and Janshen, 2010; Morin et al., 2012, 2011; Nagahara et al., 2018; Rabita et al., 2015; von Lieres Und Wilkau et al., 2020b). Indeed, the proportion of the total GRF oriented in the horizontal direction, represented as the ratio of the horizontal GRF component to the resultant GRF and known as the ratio of forces (RF), is strongly associated with initial acceleration performance (Bezodis et al., 2019b; King et al., 2023; Morin et al., 2012, 2011; Rabita et al., 2015).
The magnitude of the net horizontal force component declines over the acceleration phase, with a concomitant increase in the vertical component, such that the resultant GRF vector has an increasingly vertical orientation (Nagahara et al., 2019; Rabita et al., 2015; von Lieres Und Wilkau et al., 2020b), and a decline in RF as the sprint progresses (Bezodis et al., 2019b; Morin et al., 2011, 2019). However, evidence suggests that in addition to a high maximal RF, a slower decline in RF (D_{RF}) is also associated with better acceleration performance, such that the ability to maintain a higher proportion of horizontal force for longer enhances acceleration performance (Rabita et al., 2015). As the acceleration phase progresses and the positive propulsive forces decline, so the negative braking forces increase; however net propulsive forces remain positively correlated with acceleration performance across the entire phase in highly trained sprinters (Tier 3) (Colyer et al., 2018a; von Lieres Und Wilkau et al., 2020b). Furthermore, some studies report mean propulsive forces to be more influential to performance than peak forces (Nagahara et al., 2019; von Lieres Und Wilkau et al., 2020b), while Colyer et al. (2018a) found the peak antero-posterior force to shift from a peak during mid to late stance in the initial steps towards a progressively earlier peak as acceleration progresses.

The results of Colyer et al. (2018a) imply acceleration performance is dependent on producing high propulsive forces during the initial steps and being able to reduce braking forces during later steps. Both treadmill and overground sprint trials indicate that high net antero-posterior forces averaged over the entire acceleration phase are associated with better sprinters and higher horizontal velocities (Morin et al., 2012, 2011; Rabita et al., 2015). In highly trained (Tier 3) female sprinters and hurdlers, Stavridis et al. (2019) reported greater horizontal force application in sprinters and higher vertical forces in hurdlers. Further, Rabita et al. (2015) found antero-posterior force output to be the main differentiator between elite international finalists (Tier 4) and highly trained (Tier 3) counterparts. Another comparison between elite to world class (Tier 4 and 5) and highly trained (Tier 3) sprinters found that while maximal theoretical velocity primarily differentiated between performance levels, theoretical maximum horizontal force differentiated between best and worst trials within elite to world class athletes (Bayne, 2018). As such, differences between good and bad trials within athletes may result from differences in force application during the start. In summary, applying large forces to the ground is pivotal to sprint performance, but during acceleration, applying those forces in a more horizontal direction in conjunction with lower braking forces is more important than the total magnitude of the GRF, provided that a sufficient magnitude is achieved and enough vertical force is applied to provide sufficient flight time to reposition the limbs (Colyer et al., 2018a; Morin et al., 2011, 2015b). In acceleration, it is the skill of applying large forces in a more antero-posterior direction that counts, which requires effective use of kinematic features to achieve desired force profiles.

2.2.2 Linear kinematics

2.2.2.1 Centre of mass motion

The primary goal of sprinting is to move the CM forward across a given distance in the shortest possible time. In initial acceleration, the CM generally shifts from a low position ahead of the point of foot contact towards a higher position above the point of foot contact as steps progress (Kugler and Janshen, 2010; Nagahara et al., 2014a; Slawinski et al., 2010; von Lieres und Wilkau et al., 2020a). Indeed, studies of both sprinters (Tier 3 and 4) (Nagahara et al., 2014a; Slawinski et al., 2010) and physical education students (Tier 1) (Kugler and Janshen, 2010) indicate that better performances are associated with further forward CM positions and that higher level athletes show a more gradual raising of the CM during initial acceleration. Kugler and Janshen (2010) showed in recreational athletes (Tier 1) that higher angles between the point of foot contact, the ground and the CM correspond to greater propulsive impulses and therefore horizontal forces. Slawinski et al. (2010) reported that elite and highly trained sprinters (Tier 3 and 4, 100 m PB: 10.27 ± 0.14 s) had a further forward CM position at block clearance, and at both touchdown and toe-off in the first two steps compared to trained sprinters (Tier 2; 11.31 ± 0.28 s). The CM position relative to the position of foot contact with the ground (touchdown distance) is also important. A negative touchdown distance, with the CM ahead of the foot at ground contact, is associated with higher RF and better performance than when the CM is directly above or behind the position of foot contact (Bezodis et al., 2015a; King et al., 2023; Kugler and Janshen, 2010). Thus, over the course of initial acceleration, the CM is raised and the touchdown distance shifts from negative to positive, with a concomitant shift toward a more vertical angle between foot and CM and a corresponding decline in propulsive forces and RF (see Section 2.2.1). Since the CM position is the result of the position of each body segment and not itself directly manipulable, advantageous CM positions result from effective use of joint and segment rotations. These rotations are discussed in detail in Sections 2.2.3.1 and 2.2.3.2.

2.2.2.2 Spatiotemporal variables

Sprint velocity is the product of step frequency and step length. Average velocity at step 1 ranges from around 3.14 $m.s^{-1}$ in highly trained sprinters (Tier 3) to greater than 5 $m.s^{-1}$ in world class sprinters and increases to in excess of 7 $m.s^{-1}$ by step 4 (Debaere et al., 2013a; Nagahara et al., 2014a; Slawinski et al., 2010; von Lieres und Wilkau et al., 2020a; Walker et al., 2021). Velocity is primarily increased through changes in step length over this period, starting from 0.9 - 1.0 m at step 1 and rising to 1.4-1.5 m at step 4 in highly trained to elite sprinters (Tier 3 and 4)(Ciacci et al., 2017; Debaere et al., 2013a; Nagahara et al., 2014a; Slawinski et al., 2010; von Lieres und Wilkau et al., 2020a). During *Diamond league* competition, elite to world class sprinters (Tier 4 and 5) exhibited longer step lengths at step 1 compared to highly trained sprinters (Tier 3), with a mean of 1.14 m and 1.07 m in male and female *Diamond League* sprinters respectively (Ciacci et al., 2017).

Step frequency, in contrast, is already close to maximal at step 1 (4 Hz), and increases only marginally through step 4 (4.5 Hz) (Debaere et al., 2013a; Nagahara et al., 2014a; Slawinski et al., 2010; von Lieres und Wilkau et al., 2020a). The relatively consistent frequencies occur due to compensatory changes in flight time and contact time over initial acceleration: flight time increases while contact time decreases (Bezodis et al., 2019c). Debaere et al. (2013a) reported mean contact times of 0.129 ± 0.007 s and mean flight times of 0.102 ± 0.010 s over the whole initial acceleration phase in highly trained sprinters (Tier 3). Ciacci et al. (2017) found flight time during the first step to be 0.045 ± 0.025 s in both male and female elite to world class *Diamond League* sprinters (Tier 4 and 5) compared to 0.064 ± 0.009 s and 0.085 ± 0.011 s in highly trained (tier 3) males and females, respectively. In these *Diamond League* sprinters, contact times during the first stance were 0.210 ± 0.035 s and 0.225 ± 0.034 s for males and females compared to 0.176 ± 0.008 s and 0.166 ± 0.017 s in their respective highly trained counterparts (Ciacci et al., 2017). Walker et al. (2021) reported contact times of 0.175 ± 0.015 s from an in-competition analysis of world class male *World Indoor Championships* sprinters (Tier 5). Although Ciacci et al. (2017) found flight times in step 2 remained similar to step 1, they reported shorter contact times in the second stance, while other studies have demonstrated progressively diminishing contact times and concomitant increases in flight time across initial acceleration (Nagahara et al., 2014a; von Lieres und Wilkau et al., 2020a). Previous results suggest that better sprinters exhibit shorter flight times and longer contact times compared to lower level sprinters during the first step and initial acceleration more generally (Bezodis et al., 2019c; Ciacci et al., 2017). However, the results of Walker et al. (2021) imply that contact times in a world class cohort may be in line with those reported for lower level competitors.

2.2.3 Angular kinematics

2.2.3.1 Segment kinematics

In human movement, CM translation results from segment and joint rotations according to interacting anatomical and geometrical constraints (van Ingen Schenau, 1989; van Ingen Schenau et al., 1987). Consequently, understanding segment and joint rotations facilitates an understanding of technique, especially in movements such as sprinting where performance is directly linked to CM motion. Moreover, given the predominantly linear nature of sprinting, major components of technique can be described by a relatively small number of sagittal plane segment and joint rotations. Both coaches and researchers, therefore, are especially interested in sagittal plane segment and joint angles. Jacobs and van Ingen Schenau (1992) provided a model for CM motion during sprinting where the body can be considered as a mass (i.e., the CM) with a support that connects the mass to the ground (i.e., the lower limb) (Figure 2.1) (Jacobs and van Ingen Schenau, 1992). Once the support has contacted the ground (i.e., during stance) the CM can be translated in the horizontal direction via two actions of the support: rotation and extension. In such a model, CM horizontal motion during ground contact is achieved by firstly rotating the mass over the base where the support contacts the ground, and subsequently through lengthening the support (i.e., extension) once rotation becomes less effective at achieving further horizontal CM translation (Figure 2.1)(Jacobs and van Ingen Schenau, 1992). This simple model provides a conceptual framework for how lower limb joint and segment rotations translate the CM forward during sprinting. The actions of relevant joint and segment rotations during initial acceleration are considered below (Note that for discussions of joint and segment rotations in this section, and for the remainder of this thesis, a convention of describing rotations from the right side view of the sprinter will be adopted).

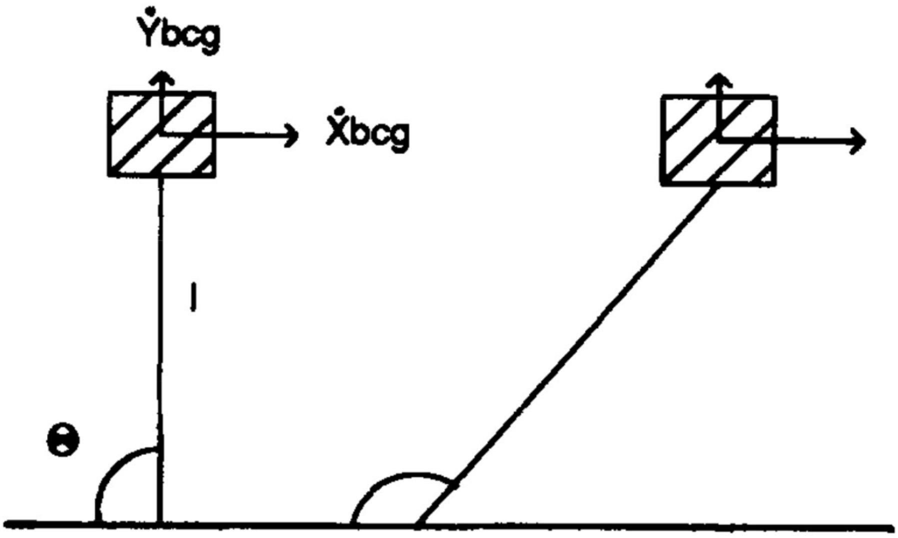

Figure 2.1: Schematic representation of the model of centre of mass movement via rotation and extension. `Xbcg` and `Ybcg` reflect the velocity of the body centre of gravity (i.e., centre of mass) in the X and Y directions respectively. Reproduced from Jacobs and van Ingen Schenau (1992).

Trunk

The CM is raised rapidly after block exit, especially during the first 3-4 steps, which results largely from an increasingly vertical trunk with assistance from changes in stance limb segment orientations (Kugler and Janshen, 2010; Nagahara et al., 2014a; von Lieres und Wilkau et al., 2020a). The trunk typically continues to become more vertical over the course of acceleration until the end of the transition phase, reaching a plateau around step 14 (Nagahara et al., 2014a; von Lieres und Wilkau et al., 2020a). However, while the net trend is to become more vertical, within an individual step, the trunk switches rotation direction between stance and flight - rotating clockwise (from the right hand view, i.e., forward) in flight and anticlockwise during stance (Donaldson et al., 2020; Nagahara et al., 2018). Evidence suggests that better performance is associated with a more gradual shift toward a vertical trunk orientation. In recreational athletes (Tier 1), faster runners maintain more horizontal trunk orientations further into acceleration than their slower counterparts (Kugler and Janshen, 2010). Furthermore, these more horizontal trunk orientations (i.e., greater forward lean) were associated with greater propulsive forces in acceleration (Kugler and Janshen, 2010), while Walker et al. (2021) reported that more horizontal trunk orientations in the first stance were associated with faster performances in world class *World Indoor Championship* finalists (Tier 5). However, there may be a limit to the benefits of greater forward lean of the trunk. Donaldson et al. (2020) found highly trained sprinters (Tier 3) to have more horizontal trunk angles than elite to world class sprinters (Tier 4 and 5) as well as greater ranges of motion within the step cycle. Thus there may be a range beyond which greater horizontal trunk lean may not be beneficial. Altogether, the trunk appears as a key segment in facilitating the forward leaning CM positions associated with superior horizontal force outputs. However, trunk movement is also dynamic during initial acceleration, with contrasting motion during flight and stance within individual steps, as well as a general shift in orientation with the progression of steps.

Thighs

Few studies have directly investigated thigh angular motion during acceleration. Generally, thigh angular motion during sprinting follows the oscillatory pattern inherent to human bipedal gait (Kiely and Collins, 2016) and can be effectively modeled with a sine wave (Clark et al., 2021). The importance of thigh motion to sprinting appears to be more related to thigh angular velocity, and the inter-relation between thighs as they oscillate, than any isolated thigh angles (Bayne et al., 2020; Clark et al., 2020; Kakehata et al., 2021; Okudaira et al., 2021; Walker et al., 2021). In maximal velocity running, Bushnell and Hunter (2007) showed that trained sprinters have shorter distances between their knees, and therefore smaller angular displacement between their thighs, than distance runners at touchdown, although Walker et al. (2021) indicated that thigh separation at touchdown was not related to performance in world class sprinters (Tier 5) in the first stance. Walker et al. (2021) did, however, find that greater thigh separation at toe-off was related to initial acceleration performance in that population. Examining the continuous relationship between thighs during acceleration, Bayne et al. (2020) found elite to world class (Tier 4 and 5) sprinters spend more time with directly opposed (anti-phase) inter-limb thigh rotation than highly trained (Tier 3) counterparts, implying more synchronous thigh flexion and extension in elite compared to highly trained sprinters (further discussion of this coordination study is provided in Section 2.3.4). Furthermore, Clark et al. (2020) reported greater thigh angular accelerations and average thigh angular velocity over the whole step in highly trained (Tier 3) sprinters compared to highly trained non-sprinters at maximal velocity, supporting an important role for rapid reversals in thigh flexion and extension for sprint performance. Overall, better acceleration performance appears to be associated with a small touchdown difference between thighs, a large separation at toe-off and rapid reversals in thigh rotation - i.e., rapidly pulling the stance leg forward after toe-off and retracting the front leg at the same time with the aim of achieving high thigh angular velocity prior to touchdown. Indeed, a high retraction angular velocity could correspond with the large extensor power generation and angular velocity at the hip observed before touchdown by Debaere et al. (2013a).

Shank

The shank is an important component of adopting the forward leaning body positions associated with acceleration performance (Alt et al., 2022; Kugler and Janshen, 2010; von Lieres Und Wilkau et al., 2020b), yet there remain few studies directly examining shank motion during acceleration. Alt et al. (2022) proposed a 'shin roll' framework for interpreting shank motion during sprinting, and acceleration in particular. This framework provides a comprehensive model of shank rotation from late flight to the end of stance, a period that would coincide with the shank's contribution to CM translation through rotation of the support in the model from Jacobs and van Ingen Schenau (1992). To that effect, in order to skillfully achieve horizontal force transfer, an athlete must first rotate over the point of contact with the ground (i.e., the stance foot) and then execute proximal to distal joint extension and energy transfer (Figure 2.2) (Bezodis et al., 2015a; Jacobs and van Ingen Schenau, 1992; van Ingen Schenau et al., 1992).

Shank range of motion during stance increases from step 1 to the following steps as part of step-to-step kinematic changes during initial acceleration, while shank angle at touchdown becomes more vertical with each step (Alt et al., 2022; Donaldson et al., 2020; Nagahara et al., 2014a; von Lieres und Wilkau et al., 2020a). In flight, the shank rotates anticlockwise toward the vertical before reaching what Alt et al. (2022) labeled ‘shin block’, the instant at which shank rotation direction reverses in late flight, rotating clockwise into ground contact (Alt et al., 2022; Debaere et al., 2013a; Donaldson et al., 2020; von Lieres und Wilkau et al., 2020a). After touchdown, shank rotation is clockwise toward a more horizontal orientation as the ankle dorsiflexes in early stance (Bezodis et al., 2014; Charalambous et al., 2012; Schache et al., 2019), exhibiting a ‘horizontal ankle rocker’ motion that denotes forward shank rotation over a relatively fixed foot (Alt et al., 2022). However, in this framework it is unclear what the implications of different foot angles and rotations might be for shank motion during this period.

As steps progress, the shank exhibits increasing anticlockwise rotation during flight, contacting the ground at more and more vertical orientations and subsequently undergoing greater and greater rotation during stance in order to achieve desired toe-off angles (Alt et al., 2022; Donaldson et al., 2020; von Lieres und Wilkau et al., 2020a). However, more horizontal mean touchdown shank angles over the first four steps have been associated with greater RF (r = -0.764) in trained to highly trained sprinters (Tier 2 and 3), suggesting it is advantageous to keep the shank as horizontal as possible at touchdown during this period in order to direct force in a more effective direction (King et al., 2023). The final stage of shin motion during stance occurs after the peak flexion of the lower limb joints, when the foot is at its most horizontal orientation (Alt et al., 2022; Bezodis et al., 2014; Charalambous et al., 2012; Schache et al., 2019). In the Alt et al. (2022) framework, the subsequent raising of the foot causes the shank to undergo a final forward rotation - called ‘shin drop’ - to reach orientations at toe-off that can facilitate horizontal CM translation through joint extension (Figure 2.2) (Bezodis et al., 2015a; Jacobs and van Ingen Schenau, 1992).

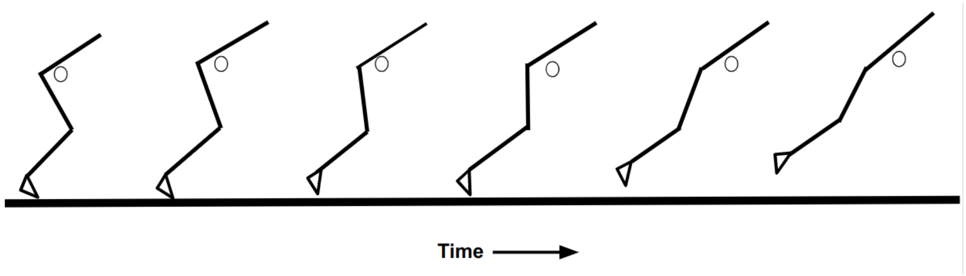

Figure 2.2: Illustration of trunk and stance leg thigh, shank and foot segments demonstrating centre of mass translation (open circle) through rotation and a proximal to distal pattern of joint extension, adapted from Jacobs and van Ingen Schenau (1992).

Ultimately, the shank undergoes a sequence of rotations through the step cycle which appear integral to the skill of applying force in the horizontal direction, while the changes in shank orientations over the course of initial acceleration appear to contribute to the changes in CM motion over the same period. However, the trunk is also a key contributor to changes in CM motion, and shank rotation occurs over the base of the foot, so understanding how shank rotation relates to rotations in these segments is an important consideration to further understanding shank rotation with respect to CM motion and horizontal force transfer.

Foot

The foot, as the interface between body and ground, must necessarily play a role in running technique and performance. Although the foot provides the base over which the shank and CM rotate during stance, it is not stationary during ground contact, but rotating - rotations that necessarily affect more proximal components of the chain (Alt et al., 2022; Jacobs and van Ingen Schenau, 1992). Owing to this interaction with the ground during contact, considerations of foot kinematics are primarily centred on the stance phase, where the foot can be most influential. In the first steps, the foot typically rotates anticlockwise - dropping the heel toward the ground - briefly in early stance, before remaining stable into mid-stance and rapidly rotating clockwise through late stance (Bezodis et al., 2019a; Jacobs and van Ingen Schenau, 1992). The stable period in mid-stance likely corresponds to the 'heel lock' position described by Alt et al. (2022), where the ankle is at its lowest position relative to the ground, prior to the heel raising with foot clockwise rotation and concomitant forward shank rotation. There is a paucity of published comparisons of foot angles between steps in initial acceleration, however observations by Bezodis et al. (2019a) point toward early stance anticlockwise rotation occurring in step 1 but little anticlockwise rotation occurring in the third stance. Bezodis et al. (2019a) also reported a lower foot range of motion in the first stance compared to the third in sprinters, which may reflect the apparently more vertical foot positions at touchdown in step 1 compared to step 3.

Touchdown foot angle may be another important consideration in directing force in the horizontal direction, and is likely intrinsically linked to touchdown distance. Given the anatomical and geometric constraints on the ankle joint (van Ingen Schenau, 1989; van Ingen Schenau et al., 1987), touchdown distance and the resulting implications for the angle of the lower limb limit the possible foot angles achievable at ground contact. For example, a very large negative touchdown distance will not be compatible with a very flat foot angle at ground contact without severely impacting the ability to sprint because of limitations in the ankle joint range of motion, and a similar effect is true with a vertical foot angle and positive touchdown distance. Thus, at least to a certain degree, foot angle and touchdown distance are likely to be linked. King et al. (2023) showed a very large association (r = -0.724) between a more vertical touchdown foot angle and ratio of forces in trained to highly trained sprinters (Tier 2 and 3), and a large association (r = -0.672) between negative touchdown distance and ratio of forces in the first four steps. Thus, a more vertical foot angle at touchdown is associated with a more favourable horizontal force profile. Within the constraints of the ankle joint, negative touchdown distances may facilitate such vertical foot angles at touchdown and thereby facilitate better force application in the forward direction (Bezodis et al., 2015b; Jacobs and van Ingen Schenau, 1992; King et al., 2023; Kugler and Janshen, 2010). However, while King et al. (2023) reported the same shift from negative to positive touchdown distance from step 1 to step 4 as has been observed before (Bezodis et al., 2017, 2015b), the reported foot angles were only the mean over all four steps. Consequently, the precise relation between foot angle, touchdown distance and horizontal force application must still be clarified. Moreover, since the ‘shin roll’ framework primarily addresses shank rotation in the context of a stable foot over which the shank rotates, the implications of vertical touchdown foot orientations and foot rotation during stance on this shank rotation framework remain to be determined.

2.2.3.2 Joint kinematics & kinetics

While segment kinematics are sometimes preferred in applied settings where they may be the most practical and easily visualised technical feature, a majority of research has focused on joint motion during acceleration (e.g. Bezodis et al. (2014); Brazil et al. (2016); Charalambous et al. (2012); Debaere et al. (2013a); Schache et al. (2019)). Most studies of joint kinematics and kinetics during initial acceleration have focused on the first step, and specifically on the stance phase. The following sections summarise the relevant literature related to sagittal plane joint motion and internal kinetics during initial acceleration.

Hip

Given the inherent oscillation of bipedal gait during running, for a given step the hips of the swing and stance limbs are generally simultaneously extending and flexing (Clark et al., 2020; Kiely and Collins, 2016). As such, starting from rear foot block exit and continuing to later steps, the swing leg hip flexes for the majority of the swing phase, typically reaching peak flexion around toe-off of the contralateral leg (i.e., stance leg) and extending thereafter into ground contact (Debaere et al., 2013a; Nagahara et al., 2014a, 2017). Meanwhile, the stance leg hip extends for the duration of stance, from foot contact to toe-off (Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013a; Schache et al., 2019). Across the initial acceleration phase, the hip angular displacement (the difference between maximum and minimum hip angles) increases with a concomitant increase in mean hip angular velocity during the stance phase (Nagahara et al., 2014a). In the first step, there is a peak flexor resultant joint moment (RJM) in early flight for the rear leg in the blocks, which shifts to a large peak extensor RJM around touchdown, with the timing of the peak extensor moment appearing to vary between athletes - occurring either before, at, or after touchdown (Bezodis et al., 2014, 2019c; Brazil et al., 2016; Charalambous et al., 2012; Schache et al., 2019). The hip RJM is once again flexor dominant in late stance, but there is substantial variation between and within studies as to the timing of the switch from extensor to flexor moment (Bezodis et al., 2014, 2019c; Brazil et al., 2016; Debaere et al., 2013a; Schache et al., 2019). For the majority of stance, the hip is a power generator with peak extensor power generation typically occurring in early stance but with mostly consistent power generation until late stance (Bezodis et al., 2014; Brazil et al., 2016; Charalambous et al., 2012; Schache et al., 2019). There is a brief peak of power absorption at the hip in late stance and hip joint power is approximately zero at toe-off (Bezodis et al., 2014; Brazil et al., 2016; Charalambous et al., 2012; Schache et al., 2019). In a comparison of different magnitudes of acceleration across sprint phases in trained sprinters (Tier 2), Schache et al. (2019) reported similar magnitudes of extensor power generation with high acceleration (acceleration = 5.30 ± 0.64 $m.s^{-2}$), medium acceleration (2.93 ± 0.14 $m.s^{-2}$) and low acceleration (1.32 ± 0.11 $m.s^{-2}$) conditions but that during high acceleration a greater proportion of stance was spent in power generation with lower peak energy absorption compared to the other two conditions. Thus, greater acceleration magnitudes are associated with less energy absorption and greater time in power generation, if not higher peak power generation, in the stance leg.

Knee

The knee typically flexes through the majority of the swing phase, before extending into ground contact, exhibiting this pattern from the first step (Debaere et al., 2013a). During the first stance the knee extends throughout ground contact (Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013a; Schache et al., 2019), but this pattern changes across the initial acceleration phase. Nagahara et al. (2014a) and Schache et al. (2019) independently reported only knee extension during stance in the first steps (steps 1-3) but knee flexion during the first half of stance in steps thereafter. This change corresponds with the first breakpoint in acceleration (steps 3-6), and therefore also corresponds to an increase in CM height across these steps (Nagahara et al., 2014a; von Lieres und Wilkau et al., 2020a). The majority of stance has a knee extensor RJM and the peak extensor RJM occurs around mid-stance (Bezodis et al., 2014, 2019c; Brazil et al., 2016; Debaere et al., 2013a; Schache et al., 2019). In later steps, while the overall shape of the joint moment curve during stance is similar to that of the first step, the peak joint moment is higher (Schache et al., 2019), and peak knee extension angular velocities during stance also rise across acceleration phases (Nagahara et al., 2014a). Moreover, the lack of knee flexion in early stance in step 1 is associated with only positive extensor power generation during this period and the knee only absorbing power in the final stages of stance (Bezodis et al., 2014; Brazil et al., 2016; Debaere et al., 2013a; Schache et al., 2019). This contrasts with later steps in acceleration and maximal velocity sprinting where the knee acts in a more spring-like fashion, absorbing power during the early stance and generating through the latter parts of stance (Bezodis et al., 2008; Schache et al., 2019).

Ankle

The ankle arrives at touchdown in step 1 in a dorsiflexed position, and typically dorsiflexes further for the majority of the first half of stance, before rapidly plantarflexing in the second half of stance (Bezodis et al., 2014, 2019c; Brazil et al., 2016; Charalambous et al., 2012; Debaere et al., 2013a; Schache et al., 2019). This contrasts to later steps in acceleration where the ankle becomes more neutral at step 5 and is in overall net plantarflexion at touchdown by maximal velocity (Miyashiro et al., 2019; Schache et al., 2019). In contrast, plantarflexion in late stance and at toe-off is similar across acceleration phases and maximal velocity (Miyashiro et al., 2019; Schache et al., 2019). The ankle has a plantarflexor RJM for the duration of stance in step

1, as it does across acceleration and maximal velocity sprinting with the peak RJM occurring in mid-stance (approx. 45-65%), around the onset of rapid plantarflexion during mid to late stance (Bezodis et al., 2008, 2014; Brazil et al., 2016; Debaere et al., 2013a; Schache et al., 2019). Reduced dorsiflexion in the first part of stance compared to later phases results in reduced power absorption at the ankle in initial acceleration, with a large amount of relative joint power generated during the subsequent plantarflexion (Bezodis et al., 2014, 2019c; Brazil et al., 2016; Charalambous et al., 2012; Schache et al., 2019). Consequently, the ankle is a net power generator in the early steps, but by later steps net power generation is reduced and by maximal velocity the ankle is a net power absorber (Bezodis et al., 2008, 2019c; Debaere et al., 2013a; Schache et al., 2019). The ankle produces more power relative to the hip and knee, and the relative contribution of the ankle to power generation appears to increase over the course of acceleration, although total combined power generation declines over this period (Bezodis et al., 2008, 2019c; Debaere et al., 2013a; Schache et al., 2019). The weight of these findings together with simulations (Bezodis et al., 2015a) suggest that reduced ankle dorsiflexion range in the first part of stance can improve performance, likely through reducing or removing negative power absorption and allowing greater net power generation at the ankle. This likely accounts, at least in part, for coaching emphasis on 'stiff' ankles at ground contact and along with alterations in body orientation contributes to associations between performance and touchdown distance (Bezodis et al., 2019c; King et al., 2023; Wild et al., 2018).

2.2.4 Section Summary

The overriding theme of segment and joint kinematics and kinetics during initial acceleration is one of change. Not only are these angles, rotations, moments and powers different from those during maximal velocity sprinting, they also transition through acceleration phases. From the crouched start position in the blocks, a sprinter reaches touchdown in step 1 with a more vertical foot and dorsiflexed ankle, a more horizontal shank and trunk and a more flexed knee than later phases, facilitating large net positive joint powers to propel the body forward. By maximal velocity they have transitioned to an upright posture with a plantarflexed ankle and near horizontal foot at touchdown, a more vertical shank and trunk and a more extended knee producing approximately net zero joint power. From a performance perspective, in the early steps, a small touchdown distance coupled with a more horizontal shank and trunk at touchdown, reduced ankle dorsiflexion in early stance and a large distance between the thighs at toe-off appear to facilitate a CM position further down the track and a greater RF.

2.3 Coordination

2.3.1 Dynamical systems theory

In sprinting, the goal is to move the CM in a forward direction over a given distance in the shortest possible time. In such complex movements, CM translation is achieved through the rotation of segments and joints constrained by the anatomical system and geometrical laws (van Ingen Schenau, 1989; van Ingen Schenau et al., 1987). Therefore, the interaction of these rotations with the intended direction of external force and the mechanically defined goals of the movement are essential considerations in effective movement (van Ingen Schenau, 1989; van Ingen Schenau et al., 1987), and consequently, segment organisation is a vital component of technique. Segment organisation during an act such as sprinting produces a series of apparently ordered states around key events, typically identifiable visually, which are frequently the focus of study as well as coaching interventions. Coordination patterns, then, refer to the relationships between functionally related segments in achieving these ordered states (Kimura et al., 2021). From a dynamical systems theory perspective, coordination patterns are emergent properties of the musculoskeletal system and therefore arise spontaneously - they are self-organising - with respect to the movement (Davids et al., 2003; Glazier, 2017; Kelso and Schöner, 1988). Self-organising coordinative structures are a way of utilising the inherent inter-connectedness of the musculoskeletal system to reduce the complexity of movement tasks, in response to what Bernstein (1967) called the ‘fundamental problem of movement’ - i.e., dealing with the large number of redundant degrees of freedom in musculoskeletal system configurations for any given task. In this dynamical systems perspective, self-organisation occurs within the confines of a set of interacting internal and external factors which restrict the possible configurations the system can adopt out of the numerous available degrees of freedom, known as constraints (Glazier, 2017; Newell, 1986; Sparrow and Newell, 1998). Constraints come in three broad categories, relating to the requirements of the movement (task constraints), the external conditions at any given time (environmental constraints) and the physical and psychological characteristics particular to the individual (organismic constraints) (Figure 2.3) (Davids et al., 2003; Glazier, 2017; Newell, 1986).

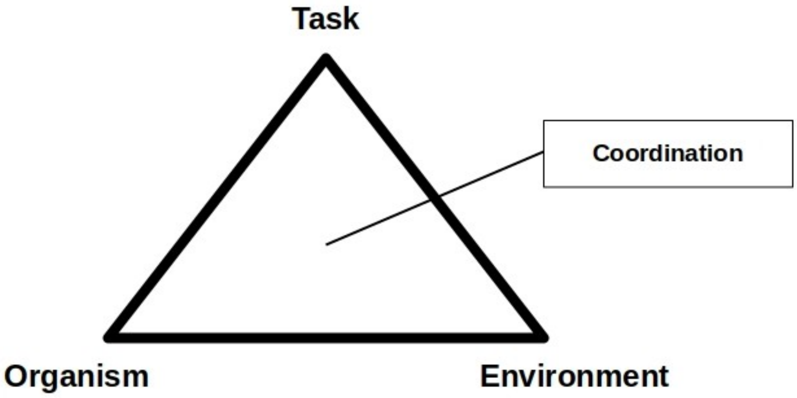

Figure 2.3: Illustration of the emergence of coordination within Newell's model of constraints. Adapted from Newell (1986) and Glazier (2017).

Under this model, individuals achieve ordered coordination patterns through self-organisation within limits defined by the specific interactions of constraints at any one moment. Moreover, coordinative behaviour must be stable in response to changing environmental and organismic conditions but also flexible to respond to environmental changes in service of preserving the functional outcome (Davids et al., 2003; Kelso and Schöner, 1988; Kimura et al., 2021). However, different strengths of constraints may result in different levels of variability associated with the task or the individual. Strong organismic constraints may yield coordination patterns very particular to individuals and high between-individual variability, while strong task constraints might enforce similar coordination and low variability between individuals (Davids et al., 2003). Environmental constraints are often standardised as much as possible between individuals in research and competition settings, but high variability in environmental conditions is likely to result in increased variability in coordination between individuals (Davids et al., 2003).

2.3.2 Biomechanical coordination

The term 'coordination' is used widely within motor control and biomechanics, but refers to different concepts in the different fields (Kimura et al., 2021). Within biomechanics, coordination is commonly used to refer to two subtly different things, stemming from the underlying dynamical systems concepts. In the first use, coordination focuses only on the description of relationships between system elements, irrespective of functional or practical considerations (Glazier, 2017; Kimura et al., 2021). In the second case, coordination is defined as the relations between elements to achieve a common task goal (Glazier, 2017; Kimura et al., 2021), and thus specifies that coordination relates only to relationships between elements that are functionally related in terms of the goals of the task. In the context of sprint acceleration, technique is typically understood and quantified in terms of segment and joint kinematics in both coaching and research contexts, such that sagittal plane angles have direct functional considerations for technique and force application (see Section 2.2.1, 2.2.3.1 and 2.2.3.2 for relevant discussion of these topics). Thus, in acceleration, there are segments that act together to achieve the task goal of moving the CM forward and therefore the study of relationships between these elements incorporates the consideration of functional outcomes. Consequently, for the purposes of the current research and in the context of this thesis, coordination will be defined as the relationship between linked segments in achieving a functional goal over the course of a movement based on the principles of self-organisation from a dynamical systems theory perspective.

2.3.3 Methodological considerations in coordination analysis

Broadly, two avenues have emerged to quantify biomechanical coordination - discrete measures which seek to derive point estimates reflecting the relative timing of key events in the movement cycle, and continuous measures which seek to represent the relative motion of elements over a whole movement (Hamill et al., 2000). Since discrete methods are limited to only evaluating differences in timing with respect to a single point in any movement cycle Hamill et al. (2000), continuous methods have become the predominant approach to understanding broader patterns within movements. Within continuous coordination analyses, two primary methods have been adopted: continuous relative phase (CRP) and vector coding. The relative merit of each class of measurements depends on the specifics of the research question being investigated. Given the scope and aims of this thesis, this section will focus primarily on continuous methods of analysis, and vector coding in particular, with a brief discussion of CRP.

2.3.3.1 Continuous Relative Phase

CRP describes the relationship between elements through the relative phase, which denotes the degree to which two elements are in-phase (same direction of rotation) or anti-phase (opposite directions) (Hamill et al., 2000; Kelso and Schöner, 1988). The relative phase of two elements is the difference between phase angles of each element, determined from a parametric phase plot (Dierks and Davis, 2007; Gittoes and Wilson, 2010; Hamill et al., 2000). The phase plot is constructed by plotting the segment or joint angle against the angular velocity, centred around the origin, such that the phase angle denotes the four quadrant arctangent angle between the right horizontal and the vector between the origin and each point on the phase plot (Dierks and Davis, 2007; Gittoes and Wilson, 2010; Hamill et al., 2000). Thus, CRP at any instant of time represents the difference in phase angle between the two elements - an angle between 0° and 360°. However, the CRP is typically constrained between 0° and 180° - where 0° is perfectly in-phase and 180° is perfectly anti-phase - since CRP values are not directional and therefore values above 180° are redundant (A CRP of 345° is equal to a CRP of 15°, and so on) (Hamill et al., 2000).

There are several limitations to the use of CRP in applied settings however. Firstly, CRP makes several assumptions around sinusoidal motion of the components which, if not addressed, can lead to problems in analysing non-sinusoidal waveforms (Hamill et al., 2000; Lamb and Stöckl, 2014; Peters et al., 2003). CRP methods thus require normalisation of the amplitudes of the underlying signals to handle both the nature of the waveform as well as potential differences in the frequency of oscillations. The choice of approach to this normalisation procedure can have a large impact on the subsequent CRP results, and especially if normalisation is ignored, which can lead to discrepancies between studies and interpretations of results (Hamill et al., 2000; Lamb and Stöckl, 2014; Peters et al., 2003). Finally, interpreting both the type and nature of the relationship described by the CRP value can be difficult for applied practitioners, which is an important consideration in both clinical and sport performance settings. Moreover, group comparisons under different conditions can be difficult or inappropriate to perform on the CRP time series, which has resulted in studies comparing only the average CRP across the entire movement between groups. This further inhibits interpretation of coordination differences across movement cycles. As such, vector coding approaches have become popular in many fields of coordination research in order to facilitate more intuitive interpretation and practical application of results, among other advantages (McErlain-Naylor and Needham, 2021; Needham et al., 2015, 2020).

2.3.3.2 Vector coding

Sparrow et al. (1987) first established vector coding approaches with the analysis of angle-angle diagrams and the calculation of the angle between adjacent points on the diagram, later termed the coupling angle (CA) by Hamill et al. (2000). The CA provides a representation of the change in each segment for each time point in an angle between 0° and 360° that can be easily related back to the original shape of the angle-angle diagram (Figure 2.4A). Modern vector coding studies have developed a 'binning' approach, dividing the 360° plane into discrete bins that describe the relationship between segments (i.e., in-phase, anti-phase) and the relative direction of movement (Figure 2.4B). Binning was introduced by Chang et al. (2008) to analyse rearfoot-forefoot coordination during walking, with the approach facilitating easy comparison of coordination between groups and individuals by comparing the relative frequency of each coordination bin across the movement. In this way, vector coding has allowed for more straightforward and interpretable comparisons of coordination patterns during the entirety of complex movements.

More recently, Needham et al. (2015, 2020) developed the use of colour coding to represent coordination over the course of a movement cycle, with an emphasis on individual profiling. However, CAs and the binning approaches common in vector coding analyses have several important considerations with regard to making comparisons and analysing data. In the first instance, CAs are a circular variable which requires the use of circular statistics to attain sample means, standard deviations and other common statistics. Further, researchers are typically interested in coordination over the course of a movement with CAs frequently represented as time series, but many standard statistical tools for analysing time series data are inappropriate to apply to circular variables. One advantage of binning approaches is to reduce some of this complexity in the underlying CAs, by providing discrete categories at each time point for which the overall frequency (i.e., the proportion of total time spent in each bin) during the movement can be determined and compared (Chang et al., 2008; Needham et al., 2014). These frequencies provide a very useful overall categorisation of the coordination for a given task and can also be analysed more appropriately with standard statistical approaches. However, bin frequencies lose temporal information contained in the time series such as the sequence, timing and regularity of bin patterns across a movement. Thus, more recent studies have utilised colour-coding and individualised profiling, in addition to bin frequency approaches, in order to show the sequence and timing of bins within the movement cycle (e.g. Bayne et al. (2020); Beitter et al. (2020); Bezodis et al. (2019a); Brazil et al. (2020); Needham et al. (2020); Okudaira et al. (2021)). Bin frequencies can therefore be easily related back to individual profiles to determine the distribution of dominant bin patterns or bins that differ between groups or individuals, while colour-coded profiles provide more intuitive interpretation of both individual and overall coordination patterns. However, the number of bins and the specific angles separating bins are essentially arbitrary. As such, greater or fewer bins can provide more or less precise information about relative motion, and two CAs separated by only a small difference in degrees can be classified into different bins while at the same time two other CAs can be separated by relatively large differences in degrees but classified in the same bin (Needham et al., 2015). The fewer bins chosen, the more relevant this issue becomes. It is therefore important to carefully consider the specific bin convention adopted as well as the use of frequencies and profiles in the context of the research goals and the movement and segments in question.

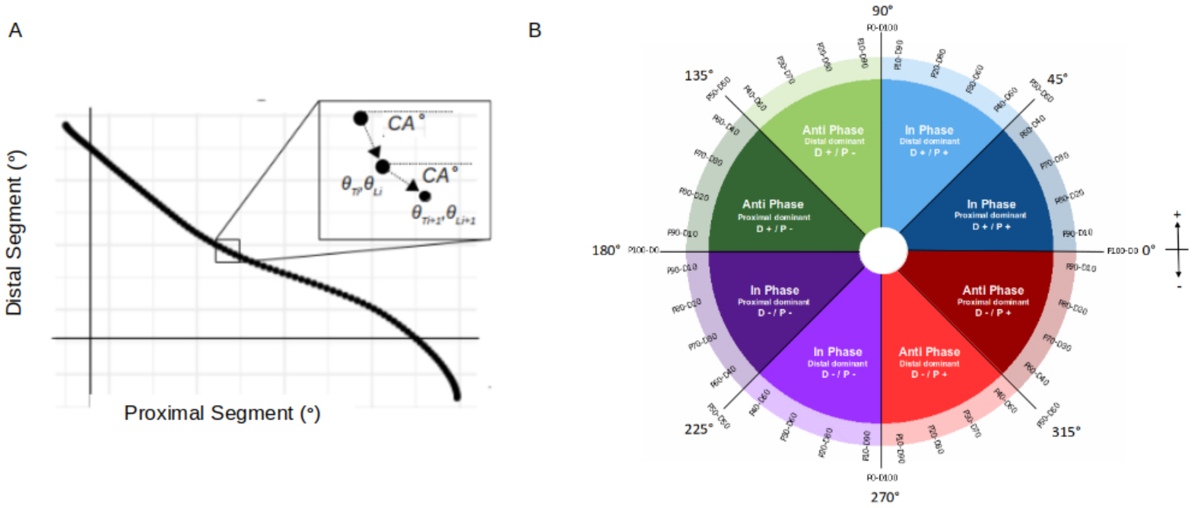

Figure 2.4: Example of coupling angle determination (A) and colour-coded coordination bins (B). P is proximal element and D is distal element. Adapted from Bezodis et al. (2019a) and Needham et al. (2020). Bin colours and conventions to be used for remainder of this thesis.

In dynamic movements, segments are rarely completely stationary. Thus, in a given movement plane, the primary relationship between two segments is almost always in-phase or anti-phase. Since segments in a particular 2D movement plane can only rotate in two directions, there are four patterns to describe this segment coordination, based on the primary relationship between the segments and the particular directions of rotation. As such, Needham et al. (2015) developed a bin convention comprised of these four primary bins. Furthermore, since two segments that undergo the exact same amount of rotation will have a CA that lies directly on the 45° line within the primary coordination quadrant, each quadrant can be divided into two to reflect which segment undergoes the greater rotation in the specified time. Needham et al. (2015) called this additional division *segment dominancy*, such that the 'dominant' segment referred to the segment undergoing the greater rotation. Consequently, with this convention there are eight bins to describe the primary coordination pattern, the relative directions of each segment's rotation and the dominant segment (Figure 2.4B). Extending the segment dominancy concept, Needham et al. (2015) recognised that the 90° quadrant could be easily converted to 100 gradians and therefore facilitated the quantification of segment dominancy within each bin as a percentage, which may be useful in indvidualised coordination profiling as well as addressing some of the information loss that occurs with other bin conventions and frequencies. A limitation to binning approaches to vector coding derives from the fact that they do not account for the distance between adjacent points (i.e., the length of the vector) and are concerned primarily with representing the directional information. As such, binning profiles do not necessarily capture the rate of change between adjacent CAs. Needham et al. (2020) and Stock et al. (2022) have each proposed methods that might be useful in this regard, however the methods of Stock et al. (2022) are primarily concerned with studies investigating coordination variability and the best methodological approach to quantify and present the rate of change in coordination studies remains to be determined.

2.3.4 Sprint coordination

Coordination studies have long been popular in swimming (e.g. Nikodelis et al. (2005); Seifert (2010)), walking and running (e.g. Chang et al. (2008); Dierks and Davis (2007); Needham et al. (2014); Seay et al. (2006)), as well as other athletic movements such as cutting, jumping and gymnastics (e.g. Irwin et al. (2021); McErlain-Naylor and Needham (2021); Weir et al. (2019)) and clinical settings (e.g. Beitter et al. (2020); Heiderscheit et al. (2002)). Yet, there are few published studies on coordination in sprinting. In one of the first studies, Gittoes and Wilson (2010) used CRP to evaluate knee-ankle and hip-knee coordination during maximal velocity running. The primary findings suggested that touchdown and early stance were associated with anti-phase coordination in both joint couplings, with knee-ankle becoming increasingly anti-phase until approximately mid-stance and then shifting to become increasingly in-phase towards toe-off, while hip-knee coordination was almost perfectly anti-phase at touchdown and gradually became more in-phase in the first half of stance before accelerating the shift to in-phase towards toe-off (Gittoes and Wilson, 2010). Thus, in maximal velocity sprinting the touchdown event was suggested to be a destabilising event in the transition from swing to stance, with lower limb joints appearing to align in more stable in-phase joint extension in the second half of stance and into toe-off. To the best of the author's knowledge, this remains the only specific investigation of coordination during maximal velocity sprinting, with a focus on joint rotations as opposed to segment rotations which have been typical in acceleration studies.

In acceleration, Bezodis et al. (2019a) compared lower limb coordination during the block phase, first and third step between world-class sprinters and hurdlers during the *World Indoor Championships*. The primary finding from that study suggested that world class hurdlers and sprinters have similar coordination patterns to each other during the start, such that - at the start at least - the additional constraint of a hurdle after the seventh step did not result in substantial differences in trunk-thigh, trunk-shank or thigh-shank coordination (Bezodis et al., 2019a). Bezodis et al. (2019a) reported that the greatest difference between groups (and between-individuals) occurred after first movement in the block phase, speculating that differences in the set position may result in coordination differences at the onset of movement. This aligns with observations from Brazil (2018) during the block phase, who found higher between-individual coordination variability in lower limb joint couplings after first movement in both rear and front legs. Bezodis et al. (2019a) reported both trunk-thigh and thigh-shank coordination to be almost exclusively characterised by thigh dominant rotation during the first and third stance in world class athletes (Tier 5), with the thigh rotating throughout stance while the trunk and shank remained relatively stable.

In contrast, Bezodis et al. (2019a) reported a trunk-shank sequence exhibiting primarily shank rotation in early stance, followed by in-phase rotation in mid stance before an anti-phase relationship in late stance. Moreover, they reported a shift in trunk-shank coordination between the first and third stance phases, with late stance in the first ground contact exhibiting coordination characterised by a stable shank and anticlockwise trunk rotation (i.e., toward a more vertical position) whilst during the third stance this period was absent, and late stance displayed an anti-phase pattern with the same trunk movement toward the vertical but greater clockwise shank rotation toward a horizontal orientation (Bezodis et al., 2019a). To the author's knowledge, this remains the only investigation of intra-limb coordination during acceleration. Donaldson et al. (2020), while not explicitly quantifying coordination, compared the relative position of the trunk and shank at key events between elite to world class (Tier 4 and 5) and highly trained (Tier 3) sprinters in the first four steps. Their data appears to agree with Bezodis et al. (2019a), with a stable shank coupled with trunk rotation in the second half of the first stance but greater shank rotation during the same period in the third stance (Donaldson et al., 2020). As such, trunk and shank rotations appear to be primarily anti-phase during acceleration, approaching more or less vertical or horizontal orientations in opposing sequences over the step cycle. Further, while coordination appeared similar under slightly different task constraints between sprinters and hurdlers, the available evidence suggests trunk-shank coordination changes from the first step to the third (Bezodis et al., 2019a; Donaldson et al., 2020).

The remaining studies of sprint coordination have focused on inter-limb thigh-thigh coordination, investigating the patterns associated with the inherent oscillation between limbs in bipedal gait (Clark et al., 2020; Kiely, 2017). Thigh motion during sprinting can be roughly modeled by a sine wave, with oscillating curves for the left and right leg as they interchange in a cyclic manner (Clark et al., 2020). As such, thigh-thigh coordination would be expected to be mostly anti-phase across the step: the thighs rotating in opposing directions as the legs cycle from one step to the next. Indeed, Bayne et al. (2020) reported the majority of the step to be anti-phase coordination throughout the first four steps of acceleration, with other patterns only emerging around the transition between steps, and some athletes exhibiting a period of stable lead leg and rotating trail leg (i.e. swing leg) during early to mid stance. Moreover, they reported that elite and world class sprinters (Tier 4 and 5) spent more of the step in anti-phase coordination than highly trained sprinters (Tier 3), such that it may be characteristic of better sprinters to exhibit more anti-phase coordination through the step and therefore more synchronous rotation during the cyclic interchange of limbs (Bayne et al., 2020; Clark et al., 2020). Okudaira et al. (2021) reported an increasing proportion of anti-phase thigh-thigh coordination with increasing incline during uphill sprint acceleration. Their results also confirmed the period of stable lead leg coordination during stance, which they further found to disappear at greater inclines which might suggest this pattern represents inefficient acceleration mechanics or, since they found it to be more present in level ground sprinting, it may be more representative of later phases of sprinting compared to acceleration. Overall inter-limb coordination patterns may reflect aspects of timing of muscle activations, especially around the reversals in thigh rotations. Kakehata et al. (2021) reported that important components of limb interchange are related to the timing of switches in activation between *rectus femoris* and *biceps femoris* both ipsilaterally and contralaterally, particularly around the reversal of thigh rotation at toe-off. Indeed, Kakehata et al. (2021) found muscle activation patterns to be associated with step frequency, and they likely represent an important factor in thigh angular accelerations and inter-limb coordination patterns. Together, these studies have begun to demonstrate the importance of thigh angular dynamics in sprint running and acceleration, however a complete understanding of the coordination during initial acceleration, the different strategies available, the potential individual constraints (see Section 2.3.1), and the implications for performance remain to be determined.

2.3.5 Section Summary

Coordination analysis in biomechanics centres around a dynamical systems approach to understanding movement. From this perspective, coordination describes the patterns of relative motion between components in a linked segment system which emerge from interacting constraints at the level of the individual, task and environment. Coordination is quantified through the relative motion of paired segments or joints, with modern approaches providing means to profile the relative organisation of the body throughout a movement. This understanding of relative organisation is an important component of a complete understanding of sprint technique, since particular positions at key events, which are known to be important features of acceleration technique (See Section 2.2.3) and are the focus of the majority of sprint biomechanics studies, could be achieved in different ways by different athletes. Furthermore, differences in relative motion between segments can be identified even when differences are not apparent between individual segment motions or key event positions. Currently, coordination in sprinting is under-explored, with only a handful of studies in the literature. These studies have observed components of inter-limb thigh coordination and intra-limb coordination during acceleration that could have important implications for training and technique analysis and warrant further investigation of coordination during acceleration to further advance the understanding of acceleration technique.

2.4 Strength and Acceleration

While the mechanical demands of sprinting shift across the acceleration phase, previous literature has established that generating high propulsive forces (Colyer et al., 2018a; Morin et al., 2015b; von Lieres Und Wilkau et al., 2020b) and effective orientation of the resultant GRF in a more horizontal direction (Kugler and Janshen, 2010; Morin et al., 2011; Rabita et al., 2015) are associated with better acceleration performance (see Section 2.2.1). Consequently, the force generating capacities of athletes and the relationships between different aspects of lower body strength and acceleration performance has been of wide interest, especially given that sprinters routinely perform resistance training programmes as part of their training (Bolger et al., 2016; Burnie et al., 2018). In addition, in the context of Newell's (1986) constraints framework (Figure 2.3), physical qualities such as strength represent a major component of organismic constraints and are therefore likely to influence the movement patterns exhibited during sprinting (see Section 2.3.1), providing further rationale for understanding different strength components in sprinters.

Force generation during movement varies depending on the speed and type of muscle contraction, as well as the plane of movement (Brazil et al., 2020; Newton and Dugan, 2002; Turner et al., 2020). As such, potential associations between strength and acceleration may vary depending on the aspect of strength tested and the specific features of acceleration. The following sections briefly summarise the literature on relevant components of strength in sprinters and their known relationships with acceleration performance.

2.4.1 Maximal Strength

Newton and Dugan (2002) defined maximal strength as the highest force capability of the neuromuscular system produced during slow eccentric, concentric, or isometric contractions. For lower body movements as related to athletic performance, maximum strength is typically measured either isometrically using tests such as the isometric mid-thigh pull (IMTP) and the isometric squat (ISqT), or dynamically through the 1-repetition maximum (1RM) of lower body exercises such as the back squat or deadlift. Isometric tests have become popular since they are less influenced by variation in factors like technique and range of motion and are less intensive and therefore more accessible than 1RM tests (Newton and Dugan, 2002). Maximal strength gives an indication of an athlete's ability to generate force, through largely removing the velocity component of the exercise. Since sprinting requires high amounts of force, the relationships between maximal strength and sprint performance is of substantial interest - especially in the context of strength training (Bolger et al., 2016; Burnie et al., 2018; Moir et al., 2018). Despite a number of studies reporting significant associations between maximal strength and sprint performance in team sport athletes as well as improvements in sprint performance with improvements in maximal strength (e.g. Delecluse (1997); Furlong et al. (2021); Lockie et al. (2012); Seitz et al. (2014)), fewer studies have investigated these relationships in sprinters, with a distinct lack of published data in elite and world class sprinters. Studies in these populations would be useful, since there are technical differences between sprinters and team sport athletes (see for e.g. Colyer et al. (2018b); Wild et al. (2018)) which may influence relationships between strength and sprint performance. In addition, relationships between physical qualities such as maximal strength and sprint performance may be different at lower and higher levels of performance. For example, low maximal strength may be a limiting factor to performance at lower performance levels such that improving strength improves sprint performance, but for sprinters at the top level maximal strength may no longer be a limiting a factor and therefore potentially have no relationship with performance in that population.

Young et al. (1995b) reported a mean ISqT maximum force of 2603 ± 575 N across trained (Tier 2) male and female junior track and field athletes with a relative maximum force of approximately 37 N.kg^{-1}. More recently, Healy et al. (2022) used IMTP tests to investigate maximum strength in male and female highly trained and elite sprinters (Tier 3 and 4), reporting 2642 ± 437 N (36.3 N.kg^{-1}) and 1913 ± 342 N (29.8 N.kg^{-1}) respectively. Brady et al. (2020) measured both IMTP and ISqT in highly trained male and female track athletes (Tier 3), finding IMTP maximal force values of 2070 ± 548 N (27.3 N.kg^{-1}) and 1420 ± 400 N (21.9 N.kg^{-1}), respectively. Maximal forces in the ISqT were 2314 ± 646 N (30.6 N.kg^{-1}) and 1884 ± 521 N (29.2 N.kg^{-1}) for males and females respectively (Brady et al., 2020). These studies by Healy et al. (2022) and Brady et al. (2020) showed conflicting results with regard to relationships with acceleration performance. Healy et al. (2022) found no significant associations between IMTP maximal force or relative maximal force with any sprint time up to 40 m while Brady et al. (2020) reported significant large negative correlations with 5 m time and both absolute and relative peak force in IMTP and ISqT ($r = -0.527$ — -0.714), although these relationships were only present in male participants. Moreover, neither study found significant relationships with distances above 10 m. Finally, the apparent sex differences observed by Brady et al. (2020) may reflect differences in these relationships between male and female sprinters, but it also could reflect differences in the composition and relative performance level of the sample, since nine of the fourteen male participants were 100 m specialists (100 m PB = 10.92 ± 0.22 s) and only two of the ten female participants were 100 m specialists (11.66 ± 0.04 s). The study by Healy et al. (2022) was the first to assess strength measures in relation to mechanical variables from the sprint start, finding a significant large correlation between IMTP maximal force and maximal horizontal power during acceleration (Pmax) ($r = 0.61$), which has been strongly associated with sprint performance (Hicks et al., 2020; Morin et al., 2012; Rabita et al., 2015). On balance, taking into account evidence from both sprint and team sport samples, higher maximal strength appears to be associated with faster early acceleration (i.e., <5 m) sprint times. However, the strength and importance of this association in trained sprinters, especially those at the highest level, is unclear while differences between sexes may also be present. Moreover, whether high maximal force transfers effectively to acceleration performance may depend on an athlete's technical efficiency and to fully understand the relationship between strength and performance there is a need to consider the kinematics and coordination in that context.

2.4.2 Explosive Strength

Since the time to apply force to the ground during sprinting is limited by the contact time, it is not only the ability to generate high forces which is of interest, but also the ability to generate and apply forces rapidly. This capacity is often termed 'explosive' by practitioners (Turner et al., 2020). The term explosive strength generally refers to tasks that require both generating high forces and short periods of time to apply those forces - movements associated with high amounts of mechanical power (Turner et al., 2020). Lower body power in this context is commonly assessed using jump tests such as the squat jump (SJ) and countermovement jump (CMJ) (e.g. Beattie et al. (2020); Čoh and Mackala (2013); Loturco et al. (2019, 2015); Young (1995a)). Tests such as the CMJ offer the added advantage of being movements utilising the stretch shortening cycle (SSC), reflecting the SSC utilisation during running. Although lower body power tests such as the CMJ are classified as slow SSC activities, with relatively longer contact times (> 250 ms) as compared to hop tests or, indeed, running (Schmidtbleicher, 1992).

Several studies have used jump tests to evaluate lower body power in sprinters. Beattie et al. (2020) reported higher jump heights in elite to world class (Tier 4 and 5) (57 ± 3 cm) compared to highly trained (Tier 3) (44 ± 1 cm) male sprinters. Meanwhile, Loturco et al. (2015) reported CMJ heights of 51 ± 4 cm for elite sprinters (Tier 4), which is between the two groups described by Beattie et al. (2020) and also appears to correspond to the performance levels (100 m PB = 10.28 s in Loturco et al. (2015) versus 10.06 s and 10.58 s for world class and highly trained in Beattie et al. (2020), respectively). However, Loturco et al. (2019) further reported CMJ heights of 47 ± 7 cm in male highly trained to elite (Tier 3 and 4) jumpers and sprinters, while Nagahara et al. (2014b) reported CMJ heights of 50 ± 5 cm in trained to highly trained male sprinters (Tier 2 and 3; 11.19 ± 0.34 s) and Čoh and Mackala (2013) found jump heights of 65 ± 6 cm in faster highly trained (Tier 3; 10.66 ± 0.18 s) and 58 ± 2 cm in slower highly trained (Tier 3; 10.96 ± 0.16 s) sprinters, similar to what Maulder et al. (2006) reported for highly trained male sprinters (Tier 3; 10.87 ± 0.36 s). Thus, while sprinters are generally reported to have high CMJ heights compared to other athletes, the association of high jump heights with performance level is equivocal. For example, while Beattie et al. (2020) found higher CMJ heights in elite and world class (Tier 4 and 5) compared to highly trained (Tier 3) sprinters and Čoh and Mackala (2013) found significantly higher jump heights in faster compared to slower highly trained sprinters, both groups in Čoh and Mackala (2013) as well as the sample of Maulder et al. (2006) had comparable or higher jump heights than the those in Beattie et al. (2020) despite being of a lower performance level.

Moderate to strong correlations have been reported between CMJ height and the fastest 10 m of a 50 m sprint (Young et al., 1995b), 60 m times (Loturco et al., 2015; Nagahara et al., 2014b) and 100 m race performances (Loturco et al., 2019) in sprinters ranging from trained (Tier 2) (Young et al., 1995b) to elite (Tier 4) (Loturco et al., 2019). However, Young et al. (1995b) found no association between CMJ height and 2.5 m time, while Nagahara et al. (2014b) reported that CMJ as well as squat jump (SJ) height were significantly associated with the magnitude of acceleration from steps 5 to 11, but not earlier steps. These studies might suggest that explosive strength, particularly when it corresponds to movements with SSC components such as the CMJ, is less associated with acceleration performance and more strongly related to later phases where contact times are shorter and SSC utilisation might be more important. This may correspond to the observations in sprinters (Loturco et al., 2019) and a mixed sample of sprinters and jumpers Loturco et al. (2018) where correlations between jump heights and 10 m time were lower compared to with 20 m, 40 m and 60 m time. It is important to note, however, that while correlation effect sizes were lower with 10 m time, they were still significant and very large ($r > 0.74$). In sum, the evidence suggests that CMJ performance is directly associated with sprint performance across a range of performance levels, with stronger relationships in later phases of the sprint compared to initial acceleration where findings may be less consistent. The prevailing literature has typically analysed lower body power in relation to either performance level or sprint time; including mechanical variables and acceleration specific performance measures such as average horizontal external power or the ratio of forces may aid in developing a full understanding of how jump tests and lower body power relate to initial acceleration performance. Moreover, these relationships may be mediated by technique, and consideration of the interactions between lower body power and acceleration technique measures is warranted.

2.4.3 Reactive Strength

While tests such as the CMJ represent capacities during slow SSC actions, even the longest contact times during acceleration are typically under 250 ms (Ciacci et al., 2017; Debaere et al., 2013a; Schmidtbleicher, 1992). The quality of reactive strength refers to effectively performing these fast SSC actions, therefore reflecting the capacity to accommodate a stretch load and transition rapidly from an eccentric to a concentric action (Blazevich, 2011; Newton and Dugan, 2002). Reactive strength is typically assessed through jump tests with a reactive or repeated nature, focusing on three relevant outcome variables: jump height, contact time and reactive strength index (RSI) - the ratio of jump height to contact time (Newton and Dugan, 2002; Pedley et al., 2017; Young et al., 1995b). While a modified RSI score can be obtained from CMJ tests, reactive strength is typically assessed using either drop jumps or repeated hop tests (e.g. Healy et al. (2019); Loturco et al. (2019, 2015); Nagahara et al. (2014b)). Drop jumps offer the advantage of assessing the athletes' reactive strength capacities at different loads by manipulating the height from which the test is performed (Loturco et al., 2019; Newton and Dugan, 2002; Pedley et al., 2017) while repeated hop tests are associated with shorter contact times and repeated jumps and therefore may be more representative of sport movements - especially those like sprinting which require repeated fast SSC actions (Harper et al., 2011; Healy et al., 2022; Nagahara et al., 2014b).

Young et al. (1995b) performed drop jumps from 30, 45, 60 and 75 cm in male and female trained sprinters (Tier 2), finding RSI values of 2.08 - 2.18. Healy et al. (2022) reported similar drop jump RSI values in highly trained to elite (Tier 3 and 4) male sprinters from 30 cm (2.06 ± 0.43) and lower values in females (1.65 ± 0.35). Healy et al. (2022) also performed a repeated hop test, reporting mean RSI values of 0.72 in both male and female sprinters. In contrast, Loturco et al. (2019) reported lower mean DJ RSI values at both 45 and 75 cm in highly trained to elite (Tier 3 and 4) males and females (1.03 - 1.17), which seems to be related to substantially longer contact times in Loturco et al. (2019) compared to Healy et al. (2022), even when taking into consideration the difference in box heights. None of Young et al.

(1995b), Healy et al. (2022) and Loturco et al. (2019) found any relationships between jump RSI and sprint times at any distance, however Loturco et al. (2019) did find significant very large correlations between DJ height and sprints times from 10 m to 60 m. Finally, Nagahara et al. (2014b) reported results for a hop test and ankle specific repeated hop test in trained to highly trained sprinters (Tier 3). Hop test RSI was substantially higher (2.63 ± 0.37) compared to Healy et al. (2022), resulting from jump heights almost four times higher in Nagahara et al. (2014b) despite similar contact times, although these differences may have been influenced by differences in protocol. Alternatively, in the ankle hop test of Nagahara et al. (2014b), jumps were isolated to be performed without knee flexion and therefore relied only on plantarflexion to generate jump height. This approach has not yet been replicated by other studies and no comparable data is thus available. Male sprinters had RSI values of 1.13 ± 0.27 for ankle hops with jump heights of 15 ± 3 cm, both of which had significant moderate correlations with 60 m sprint time (Nagahara et al., 2014b). However, when assessing the correlation between hop and ankle test results and the magnitude of acceleration at each step, Nagahara et al. (2014b) found no correlations with hop test performance, while ankle hop tests only correlated for steps 14-19, and thus had no association with performance during initial acceleration. The ankle specific test may be best utilised in relation to specific questions regarding the ankle during acceleration, but the repeated hop test may be more reflective of general reactive strength capabilities and may also be preferred to the DJ owing to the similarity in contact times between acceleration and the hop test, as well as the repeated nature of both activities.

Overall, jump and hop test RSI do not appear to be associated with sprint performance across a range of distances, although drop jump height may be associated with sprint times. Most studies have compared reactive strength measures only against overall sprint times, such that relationships during acceleration remain somewhat unclear. The existing evidence suggests reactive strength may be more likely to be associated with performance in later sprint phases when contact times are shorter and therefore faster SSC reactions are required. Moreover, the correlations between DJ height and sprint performance, but not RSI, imply that the physical qualities to produce large jump heights may be related to those required to sprint effectively, but that the ratio of jump height to contact time does not represent any physical quality relevant to sprint performance, especially during acceleration. Wild et al. (2021) have shown in rugby players that lower RSI might be associated with an initial acceleration linear kinematic strategy exhibiting long step length and low step rate combined with long contact time and short flight time, suggesting that the physical qualities associated with high or low RSI may not directly relate to higher acceleration performance but may require an athlete to adopt a particular technical strategy to be effective. Indeed, an athlete's reactive strength capacities may be an organismic constraint influencing the kinematic strategy they adopt during acceleration.

2.4.4 Hip extensor strength

Given the association between horizontal force application and performance during acceleration (see Section 2.2.1), there is additional interest in strength features which might correspond to horizontal force orientation. Morin et al. (2015a) reported a major role for the hamstrings in horizontal force application, with high *biceps femoris* activity in late flight associated with a higher horizontal GRF component and higher horizontal force also associated with greater eccentric hamstring peak torque. Further studies in sprinting have supported an important role for the hamstring muscles during the swing phase (Alt et al., 2021; Kakehata et al., 2021), and the large power generation at the hip during acceleration supports a potentially important role for hip extensor strength in acceleration performance. Indeed, Loturco et al. (2018) reported a greater association between maximal strength in a hip extensor exercise (barbell hip thrust) and 10 m time than in vertical jump tests in highly trained and elite sprinters (Tier 3 and 4). Moreover, Alt et al. (2021) found that eccentric hamstring strength training improved sprint velocity as well as increased hip and knee moments and work during the swing phase in trained (Tier 2) male sprinters.

Despite these observations, published data on hamstring strength in sprinters are lacking, and there are no published studies evaluating associations between eccentric hamstring strength and acceleration performance. To date, only a single study has reported eccentric hamstring strength (Nordic hamstring exercise) in sprinters. In that study, Giakoumis et al. (2020) reported eccentric hamstring strength for highly trained to world class (Tier 3-5) sprinters on the *British Athletics Olympic Program*. Total peak force values in males were 407 ± 67 N (4.99 $N.kg^{-1}$) and 418 ± 74 N (5.14 $N.kg^{-1}$) in the left and right leg, respectively. Females had lower total peak force values with 303 ± 63 N and 311 ± 59 N for left and right, respectively, although, these were more similar to males after accounting for body mass (4.67 and 4.80 $N.kg^{-1}$ in left and right, respectively). Given that the hamstrings may have an important role in acceleration, more studies examining strength associations with performance should include hip extensor strength measures, especially in the consideration of technique, since Morin et al.'s

(2015a) original associations were with horizontal force application and thus directly associated with the kinematics which facilitate a higher horizontal force component. Wild et al. (2021) reported in rugby players that differences in hip extensor torque, and the ratio of hip extensor torque to contact time, differed between whole body kinematic strategies even though performance did not differ between clusters. Thus, relationships between hip extensor strength and acceleration performance may be affected by the technique adopted by an athlete such that different strength profiles are associated with different technical strategies. Further investigations that can include associations between hip extensor strength and technique measures as well as performance measures are required to determine how hip extensor strength influences acceleration performance.

2.4.5 Section Summary

Despite a widely acknowledged importance of strength to sprint performance, in light of the high external force generation required during sprinting, studies in trained sprinters have produced somewhat inconsistent results. While tests reflecting lower body power have shown associations with sprint times at short to medium distances, maximal force has sporadically been associated with initial acceleration performance and reactive strength has shown no association with acceleration performance, while there are a lack of studies investigating associations with hamstring strength. There are several possible explanations for these inconsistent findings. In the first instance, differences in test protocol, performance level, sex and training history might explain why some studies have found associations while others have not. Moreover, it may be the case that above a certain level of strength, other factors such as technique primarily determine performance and that higher level sprinters have already reached that base level, above which further strength improvements will not correspond to performance. Finally, it is possible that in trained sprinters, especially those at a higher level, the relationship between strength and performance is influenced by technique, such that effective acceleration performance is possible with a range of lower body strength values but that different strength characteristics require different technical strategies in order to achieve it.

2.5 Chapter Summary

This chapter has discussed and appraised appropriate literature related to the kinetics, kinematics and coordination of the initial acceleration phase of sprinting, as well as the theoretical underpinnings of coordination analysis and relevant methodological considerations related to this approach. Finally, it discussed relevant physical capacities in sprinters and the known associations between physical capacities and acceleration performance. Thus, this chapter has provided relevant background for this thesis and linked the primary themes of the work that follows in later chapters. This review has demonstrated the substantial attention that has been dedicated to initial acceleration from a kinematic and kinetic point of view, however it has also highlighted the scarcity of considerations of the relationships between linked components of the musculoskeletal system. Adopting a dynamical systems theory approach, it is clear that a more complete understanding of sprint acceleration technique requires knowledge of inter- and intra-limb coordination. Although there have been some initial studies in this area, a comprehensive characterisation of coordination during this phase, especially in the context of performance, remains lacking. Furthermore, whilst current research has shown some associations between strength qualities and acceleration performance, reported associations have been inconsistent in sprinters and there is a clear need for further investigation with high level sprinters. Moreover, despite strength representing a key component of individual constraints, there have been no investigations into the relationships between strength capacities and kinematics or coordination, nor how these interactions potentially relate to initial acceleration performance.

The remaining chapters of this thesis will detail a sequence of investigations that have been developed to address specific objectives under the umbrella of the overall thesis aim, in order to further advance the understanding of initial acceleration technique in sprinters.

References

Alt, T., Oeppert, T. J., Zedler, M., Goldmann, J.-P., Braunstein, B. and Willwacher, S. (2022), ‘A novel guideline for the analysis of linear acceleration mechanics – outlining a conceptual framework of ‘shin roll’ motion’, *Sports Biomechanics* **0**(0), 1–18.

Alt, T., Severin, J., Komnik, I., Nodler, Y. T., Benker, R., Knicker, A. J., Brüggemann, G.-P. and Strüder, H. K. (2021), ‘Nordic Hamstring Exercise training induces improved lower-limb swing phase mechanics and sustained strength preservation in sprinters’, *Scandinavian Journal of Medicine & Science in Sports* **31**(4), 826–838.

Bayne, H. (2018), ‘Force-Velocity-Power Profiles Of Elite Sprinters: Inter-And Intra-Individual Determinants Of Performance’, *ISBS Proceedings Archive* **36**(1), 1000–1003.

Bayne, H., Donaldson, B. and Bezodis, N. (2020), ‘Inter-limb Coordination During Sprint Acceleration’, *ISBS Proceedings Archive* **38**(1), 448–451.

Beattie, K., Tawiah-Dodoo, J. and Graham-Smith, P. (2020), ‘Countermovement Jump Characteristics of World-Class Elite and Sub-Elite Male Sprinters’, *Sports Performance Science Reports* p. 4.

Beitter, J., Kwon, Y.-H. and Tulchin-Francis, K. (2020), ‘A combined method for binning coupling angles to define coordination patterns’, *Journal of Biomechanics* **103**, 109598.

Bernstein, N. A. (1967), *Co-Ordination and Regulation of Movements*, Pergamon Press.

Bezodis, I. N., Brazil, A., von Lieres und Wilkau, H. C., Wood, M. A., Paradisis, G. P., Hanley, B., Tucker, C. B., Pollitt, L., Merlino, S., Vazel, P.-J., Walker, J. and Bissas, A. (2019a), ‘World-Class Male Sprinters and High Hurdlers Have Similar Start and Initial Acceleration Techniques’, *Frontiers in Sports and Active Living* **1**, 23.

Bezodis, I. N., Kerwin, D. G. and Salo, A. I. T. (2008), ‘Lower-Limb Mechanics during the Support Phase of Maximum-Velocity Sprint Running’, *Medicine & Science in Sports & Exercise* **40**(4), 707–715.

Bezodis, N., Colyer, S., Nagahara, R., Bayne, H., Bezodis, I., Morin, B., Murata, M. and Samozino, P. (2019b), ‘Understanding Ratio of Forces Duirng Early Acceleration’, *ISBS Proceedings Archive* **37**(1), 499–502.

Bezodis, N. E., North, J. S. and Razavet, J. L. (2017), 'Alterations to the orientation of the ground reaction force vector affect sprint acceleration performance in team sports athletes', *Journal of Sports Sciences* **35**(18), 1817–1824.

Bezodis, N. E., Salo, A. I. T. and Trewartha, G. (2014), 'Lower limb joint kinetics during the first stance phase in athletics sprinting: Three elite athlete case studies', *Journal of Sports Sciences* **32**(8), 738–746.

Bezodis, N. E., Salo, A. I. T. and Trewartha, G. (2015a), 'Relationships between lower-limb kinematics and block phase performance in a cross section of sprinters', *European Journal of Sport Science* **15**(2), 118–124.

Bezodis, N. E., Trewartha, G. and Salo, A. I. T. (2015b), 'Understanding the effect of touchdown distance and ankle joint kinematics on sprint acceleration performance through computer simulation', *Sports Biomechanics* **14**(2), 232–245.

Bezodis, N. E., Willwacher, S. and Salo, A. I. T. (2019c), 'The Biomechanics of the Track and Field Sprint Start: A Narrative Review', *Sports Medicine* **49**(9), 1345–1364.

Blazevich, A. (2011), The stretch-shortening cycle (SSC), *in* 'Strength and Conditioning: Biological Principles and Practical Applications', Wiley-Blackwell, pp. 209–222.

Bolger, R., Lyons, M., Harrison, A. and Kenny, I. (2016), 'Coaching sprinting: Expert coaches' perception of resistance-based training', *International Journal of Sports Science & Coaching* **11**(5), 746–754.

Brady, C. J., Harrison, A. J., Flanagan, E. P., Haff, G. G. and Comyns, T. M. (2020), 'The Relationship Between Isometric Strength and Sprint Acceleration in Sprinters', *International Journal of Sports Physiology and Performance* **15**(1), 38–45.

Brazil, A. (2018), A Biomechanical Framework of the Training Principles to Inform Exercise Selection within Strength and Conditioning for Sprinting, Thesis.

Brazil, A., Exell, T., Wilson, C. and Irwin, G. (2020), 'A biomechanical approach to evaluate overload and specificity characteristics within physical preparation exercises', *Journal of Sports Sciences* **38**(10), 1140–1149.

Brazil, A., Exell, T., Wilson, C., Willwacher, S., Bezodis, I. and Irwin, G. (2016), ‘Lower limb joint kinetics in the starting blocks and first stance in athletic sprinting’, *Journal of Sports Sciences* **35**(16), 1629–1635.

Burnie, L., Barratt, P., Davids, K., Stone, J., Worsfold, P. and Wheat, J. (2018), ‘Coaches’ philosophies on the transfer of strength training to elite sports performance’, *International Journal of Sports Science & Coaching* **13**(5), 729–736.

Bushnell, T. and Hunter, I. (2007), ‘Differences in technique between sprinters and distance runners at equal and maximal speeds’, *Sports Biomechanics* **6**(3), 261–268.

Chang, R., Van Emmerik, R. and Hamill, J. (2008), ‘Quantifying rearfoot–forefoot coordination in human walking’, *Journal of Biomechanics* **41**(14), 3101–3105.

Charalambous, L., Irwin, G., Bezodis, I. N. and Kerwin, D. (2012), ‘Lower limb joint kinetics and ankle joint stiffness in the sprint start push-off’, *Journal of Sports Sciences* **30**(1), 1–9.

Ciacci, S., Merni, F., Bartolomei, S. and Di Michele, R. (2017), ‘Sprint start kinematics during competition in elite and world-class male and female sprinters’, *Journal of Sports Sciences* **35**(13), 1270–1278.

Clark, K. P., Meng, C. R. and Stearne, D. J. (2020), ‘“Whip from the hip”: Thigh angular motion, ground contact mechanics, and running speed’, *Biology Open* p. bio.053546.

Clark, K. P., Ryan, L. J., Meng, C. R. and Stearne, D. J. (2021), ‘Evaluation of maximum thigh angular acceleration during the swing phase of steady-speed running’, *Sports Biomechanics* pp. 1–14.

Čoh, M. and Mackala, K. (2013), ‘Differences Between the Elite and Subelite Sprinters in Kinematic and Dynamic Determinations of Countermovement Jump and Drop Jump:’, *Journal of Strength and Conditioning Research* **27**(11), 3021–3027.

Colyer, S. L., Nagahara, R. and Salo, A. I. T. (2018a), ‘Kinetic demands of sprinting shift across the acceleration phase: Novel analysis of entire force waveforms’, *Scandinavian Journal of Medicine & Science in Sports* **28**(7), 1784–1792.

Colyer, S. L., Nagahara, R., Takai, Y. and Salo, A. I. (2018b), ‘How sprinters accelerate beyond the velocity plateau of soccer players: Waveform analysis of ground reaction forces’, *Scandinavian Journal of Medicine & Science in Sports* **28**(12), 2527–2535.

Davids, K., Glazier, P., Araujo, D. and Bartlett, R. (2003), ‘Movement Systems as Dynamical Systems: The Functional Role of Variability and its Implications for Sports Medicine’, *Sports Medicine* **33**(4), 245–260.

Debaere, S., Delecluse, C., Aerenhouts, D., Hagman, F. and Jonkers, I. (2013a), ‘From block clearance to sprint running: Characteristics underlying an effective transition’, *Journal of Sports Sciences* **31**(2), 137–149.

Delecluse, C. (1997), ‘Influence of Strength Training on Sprint Running Performance: Current Findings and Implications for Training’, *Sports Medicine* **24**(3), 147–156.

Dierks, T. A. and Davis, I. (2007), ‘Discrete and continuous joint coupling relationships in uninjured recreational runners’, *Clinical Biomechanics* **22**(5), 581–591.

Donaldson, B., Bayne, H. and Bezodis, N. (2020), ‘A Comparison of Trunk and Shank Angles between Elite and Sub-elite Sprinters During Sprint Acceleration’, *ISBS Proceedings Archive* **38**(1), 744.

Furlong, L.-A. M., Harrison, A. J. and Jensen, R. L. (2021), ‘Measures of Strength and Jump Performance Can Predict 30-m Sprint Time in Rugby Union Players’, *Journal of Strength and Conditioning Research* **35**(9), 2579–2583.

Giakoumis, M., Pollock, N., Mias, E., McAleer, S., Kelly, S., Brown, F., Wootten, M. and Macdonald, B. (2020), ‘Eccentric hamstring strength in elite track and field athletes on the British Athletics world class performance program’, *Physical Therapy in Sport* **43**, 217–223.

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

Glazier, P. S. (2017), ‘Towards a Grand Unified Theory of sports performance’, *Human Movement Science* **56**, 139–156.

Hamill, J., Haddad, J. M. and McDermott, W. J. (2000), ‘Issues in Quantifying Variability from a Dynamical Systems Perspective’, *Journal of Applied Biomechanics* **16**(4), 407–418.

Harper, D., Hobbs, S. and Moore, J. (2011), The ten to five repeated jump test. A new test for evaluation of reactive strength., *in* ‘BASES Student Conference’.

Healy, R., Kenny, I. C. and Harrison, A. J. (2022), 'Profiling elite male 100-m sprint performance: The role of maximum velocity and relative acceleration', *Journal of Sport and Health Science* **11**(1), 75–84.

Healy, R., Smyth, C., Kenny, I. C. and Harrison, A. J. (2019), 'Influence of Reactive and Maximum Strength Indicators on Sprint Performance', *The Journal of Strength & Conditioning Research* **33**(11), 3039–3048.

Heiderscheit, B. C., Hamill, J. and van Emmerik, R. E. (2002), 'Variability of Stride Characteristics and Joint Coordination among Individuals with Unilateral Patellofemoral Pain', *Journal of Applied Biomechanics* **18**(2), 110–121.

Hicks, D. S., Schuster, J. G., Samozino, P. and Morin, J.-B. (2020), 'Improving Mechanical Effectiveness During Sprint Acceleration: Practical Recommendations and Guidelines', *Strength & Conditioning Journal* **42**(2), 45–62.

Irwin, G., Williams, G., Kerwin, D., von Lieres und Wilkau, H. and Newell, K. (2021), 'Learning the High Bar Longswing:I. Task Dynamics and Emergence of the Coordination Pattern', *Journal of Sports Sciences* **39**(23), 2683–2697.

Jacobs, R. and van Ingen Schenau, G. J. (1992), 'Intermuscular coordination in a sprint push-off', *Journal of Biomechanics* **25**(9), 953–965.

Jones, R., Bezodis, I. and Thompson, A. (2009), 'Coaching Sprinting: Expert Coaches' Perception of Race Phases and Technical Constructs', *International Journal of Sports Science & Coaching* **4**(3), 385–396.

Kakehata, G., Goto, Y., Iso, S. and Kanosue, K. (2021), 'Timing of Rectus Femoris and Biceps Femoris Muscle Activities in Both Legs at Maximal Running Speed', *Medicine & Science in Sports & Exercise* **53**(3), 643–652.

Kelso, J. A. S. and Schöner, G. (1988), 'Self-organization of coordinative movement patterns', *Human Movement Science* **7**(1), 27–46.

Kiely, J. (2017), 'The Robust Running Ape: Unraveling the Deep Underpinnings of Coordinated Human Running Proficiency', *Frontiers in Psychology* **8**, 892.

Kiely, J. and Collins, D. J. (2016), 'Uniqueness of Human Running Coordination: The Integration of Modern and Ancient Evolutionary Innovations', *Frontiers in Psychology* **7**, 262.

Kimura, A., Yokozawa, T. and Ozaki, H. (2021), 'Clarifying the Biomechanical Concept of Coordination Through Comparison With Coordination in Motor Control', *Frontiers in Sports and Active Living* **3**, 753062.

King, D., Burnie, L., Nagahara, R. and Bezodis, N. E. (2023), 'Relationships between kinematic characteristics and ratio of forces during initial sprint acceleration', *Journal of Sports Sciences* **40**(22), 2524–2532.

Kugler, F. and Janshen, L. (2010), 'Body position determines propulsive forces in accelerated running', *Journal of Biomechanics* **43**(2), 343–348.

Lamb, P. F. and Stöckl, M. (2014), 'On the use of continuous relative phase: Review of current approaches and outline for a new standard', *Clinical Biomechanics* **29**(5), 484–493.

Lockie, R. G., Murphy, A. J., Schultz, A. B., Knight, T. J. and Janse de Jonge, X. A. (2012), 'The Effects of Different Speed Training Protocols on Sprint Acceleration Kinematics and Muscle Strength and Power in Field Sport Athletes', *Journal of Strength and Conditioning Research* **26**(6), 1539–1550.

Loturco, I., Contreras, B., Kobal, R., Fernandes, V., Moura, N., Siqueira, F., Winckler, C., Suchomel, T. and Pereira, L. A. (2018), 'Vertically and horizontally directed muscle power exercises: Relationships with top-level sprint performance', *PLOS ONE* **13**(7), e0201475.

Loturco, I., Kobal, R., Kitamura, K., Fernandes, V., Moura, N., Siqueira, F., Cal Abad, C. C. and Pereira, L. A. (2019), 'Predictive Factors of Elite Sprint Performance: Influences of Muscle Mechanical Properties and Functional Parameters', *The Journal of Strength & Conditioning Research* **33**(4), 974–986.

Loturco, I., Pereira, L. A., Cal Abad, C. C., D'Angelo, R. A., Fernandes, V., Kitamura, K., Kobal, R. and Nakamura, F. Y. (2015), 'Vertical and Horizontal Jump Tests Are Strongly Associated With Competitive Performance in 100-m Dash Events', *Journal of Strength and Conditioning Research* **29**(7), 1966–1971.

Maulder, P. S., Bradshaw, E. J. and Keogh, J. (2006), 'Jump Kinetic Determinants of Sprint Acceleration Performance from Starting Blocks in Male Sprinters', *Journal of Sports Science & Medicine* **5**(2), 359–366.

McErlain-Naylor, S. and Needham, R. (2021), Inter-individual Variation in Coordination and Control of Countermovement Jumps, *in* 'Proceedings of the International Society of Biomechanics', Vol. 49, Stockholm.

McKay, A. K., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Goosey-Tolfrey, V. L., Sheppard, J. and Burke, L. M. (2021), 'Defining Training and Performance Caliber: A Participant Classification Framework', *International Journal of Sports Physiology and Performance* **17**(2), 317–331.

Miyashiro, K., Nagahara, R., Yamamoto, K. and Nishijima, T. (2019), 'Kinematics of Maximal Speed Sprinting With Different Running Speed, Leg Length, and Step Characteristics', *Frontiers in Sports and Active Living* **1**, 37.

Moir, G. L., Brimmer, S. M., Snyder, B. W., Connaboy, C. and Lamont, H. S. (2018), 'Mechanical Limitations to Sprinting and Biomechanical Solutions: A Constraints-Led Framework for the Incorporation of Resistance Training to Develop Sprinting Speed', *Strength and Conditioning Journal* **40**(1), 47–67.

Morin, J.-B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P. and Lacour, J.-R. (2012), 'Mechanical determinants of 100-m sprint running performance', *European Journal of Applied Physiology* **112**(11), 3921–3930.

Morin, J.-B., Edouard, P. and Samozino, P. (2011), 'Technical Ability of Force Application as a Determinant Factor of Sprint Performance', *Medicine & Science in Sports & Exercise* **43**(9), 1680–1688.

Morin, J.-B., Gimenez, P., Edouard, P., Arnal, P., Jiménez-Reyes, P., Samozino, P., Brughelli, M. and Mendiguchia, J. (2015a), 'Sprint Acceleration Mechanics: The Major Role of Hamstrings in Horizontal Force Production', *Frontiers in Physiology* **6**, 404.

Morin, J.-B., Samozino, P., Murata, M., Cross, M. R. and Nagahara, R. (2019), 'A simple method for computing sprint acceleration kinetics from running velocity data: Replication study with improved design', *Journal of Biomechanics* **94**, 82–87.

Morin, J.-B., Slawinski, J., Dorel, S., de villareal, E. S., Couturier, A., Samozino, P., Brughelli, M. and Rabita, G. (2015b), 'Acceleration capability in elite sprinters and ground impulse: Push more, brake less?', *Journal of Biomechanics* **48**(12), 3149–3154.

Nagahara, R., Kanehisa, H. and Fukunaga, T. (2019), 'Ground reaction force across the transition during sprint acceleration', *Scandinavian Journal of Medicine & Science in Sports* **30**(3), 450–461.

Nagahara, R., Matsubayashi, T., Matsuo, A. and Zushi, K. (2014a), 'Kinematics of transition during human accelerated sprinting', *Biology Open* **3**(8), 689–699.

Nagahara, R., Matsubayashi, T., Matsuo, A. and Zushi, K. (2017), 'Alteration of swing leg work and power during human accelerated sprinting', *Biology Open* **6**(5), 633–641.

Nagahara, R., Matsubayashi, T., Matsuo, A. and Zushi, K. (2018), 'Kinematics of the thorax and pelvis during accelerated sprinting', *The Journal of Sports Medicine and Physical Fitness* **58**(9), 1253–63.

Nagahara, R., Naito, H., Miyashiro, K., Morin, J. B. and Zushi, K. (2014b), 'Traditional and ankle-specific vertical jumps as strength-power indicators for maximal sprint acceleration', *The Journal of Sports Medicine and Physical Fitness* **54**(6), 691–699.

Needham, R. A., Naemi, R. and Chockalingam, N. (2015), 'A new coordination pattern classification to assess gait kinematics when utilising a modified vector coding technique', *Journal of Biomechanics* **48**(12), 3506–3511.

Needham, R. A., Naemi, R., Hamill, J. and Chockalingam, N. (2020), 'Analysing patterns of coordination and patterns of control using novel data visualisation techniques in vector coding', *The Foot* **44**, 101678.

Needham, R., Naemi, R. and Chockalingam, N. (2014), 'Quantifying lumbar–pelvis coordination during gait using a modified vector coding technique', *Journal of Biomechanics* **47**(5), 1020–1026.

Newell, K. (1986), Constraints on the development of coordination, *in* 'Motor Development in Children : Aspects of Coordination and Control', Martinus Nijhoff, pp. 341–360.

Newton, R. U. and Dugan, E. (2002), 'Application of Strength Diagnosis', *Strength and Conditioning Journal* **24**(5), 50–59.

Nikodelis, T., Kollias, I. and Hatzitaki, V. (2005), 'Bilateral inter-arm coordination in freestyle swimming: Effect of skill level and swimming speed', *Journal of Sports Sciences* **23**(7), 737–745.

Okudaira, M., Willwacher, S., Kawama, R., Ota, K. and Tanigawa, S. (2021), 'Sprinting kinematics and inter-limb coordination patterns at varying slope inclinations', *Journal of Sports Sciences* **39**(21), 2444–2453.

Pedley, J. S., Lloyd, R. S., Read, P., Moore, I. S. and Oliver, J. L. (2017), 'Drop Jump: A Technical Model for Scientific Application', *Strength and Conditioning Journal* **39**(5), 36–44.

Peters, B. T., Haddad, J. M., Heiderscheit, B. C., Van Emmerik, R. E. and Hamill, J. (2003), 'Limitations in the use and interpretation of continuous relative phase', *Journal of Biomechanics* **36**(2), 271–274.

Rabita, G., Dorel, S., Slawinski, J., Sàez-de-Villarreal, E., Couturier, A., Samozino, P. and Morin, J.-B. (2015), 'Sprint mechanics in world-class athletes: A new insight into the limits of human locomotion: Sprint mechanics in elite athletes', *Scandinavian Journal of Medicine & Science in Sports* **25**(5), 583–594.

Schache, A. G., Lai, A. K. M., Brown, N. A. T., Crossley, K. M. and Pandy, M. G. (2019), 'Lower-limb joint mechanics during maximum acceleration sprinting', *The Journal of Experimental Biology* **222**(22), jeb209460.

Schmidtbleicher, D. (1992), 'Training for power events', *Strength and power in sport* **1**, 381–395.

Seay, J. F., Haddad, J. M., van Emmerik, R. E. and Hamill, J. (2006), 'Coordination Variability around the Walk to Run Transition during Human Locomotion', *Motor Control* **10**(2), 178–196.

Seifert, L. (2010), 'Inter-limb coordination in swimming: Effect of speed and skill level', *Human Movement Science* **29**(1), 103.

Seitz, L. B., Reyes, A., Tran, T. T., de Villarreal, E. S. and Haff, G. G. (2014), 'Increases in Lower-Body Strength Transfer Positively to Sprint Performance: A Systematic Review with Meta-Analysis', *Sports Medicine* **44**(12), 1693–1702.

Slawinski, J., Bonnefoy, A., Levêque, J.-M., Ontanon, G., Riquet, A., Dumas, R. and Chèze, L. (2010), 'Kinematic and Kinetic Comparisons of Elite and Well-Trained Sprinters During Sprint Start:', *Journal of Strength and Conditioning Research* **24**(4), 896–905.

Slawinski, J., Houel, N., Bonnefoy-Mazure, A., Lissajoux, K., Bocquet, V. and Termoz, N. (2017a), 'Mechanics of standing and crouching sprint starts', *Journal of Sports Sciences* **35**(9), 858–865.

Sparrow, W. A., Donovan, E., van Emmerik, R. and Barry, E. B. (1987), 'Using Relative Motion Plots to Measure Changes in Intra-Limb and Inter-Limb Coordination', *Journal of Motor Behavior* **19**(1), 115–129.

Sparrow, W. and Newell, K. (1998), 'Metabolic energy expenditure and the regulation of movement economy', *Psychonomic Bulletin and Review* **5**(2), 173–196.

Stavridis, I., Smilios, I., Tsopanidou, A., Economou, T. and Paradisis, G. (2019), 'Differences in the Force Velocity Mechanical Profile and the Effectiveness of Force Application During Sprint-Acceleration Between Sprinters and Hurdlers', *Frontiers in Sports and Active Living* **1**, 26.

Stock, H. A., Wilson, C., van Emmerik, R. E. and Preatoni, E. (2022), 'Angular dynamics in vector coding: A new approach based on angular velocity', *Sports Biomechanics* **0**(0), 1–16.

Turner, A. N., Comfort, P., McMahon, J., Bishop, C., Chavda, S., Read, P., Mundy, P. and Lake, J. (2020), 'Developing Powerful Athletes, Part 1: Mechanical Underpinnings', *Strength and Conditioning Journal* **42**(3), 30–39.

van Ingen Schenau, G. (1989), 'From rotation to translation: Constraints on multi-joint movements and the unique action of bi-articular muscles', *Human Movement Science* **8**(4), 301–337.

van Ingen Schenau, G., Bobbert, M. and Rozendal, R. (1987), 'The unique action of bi-articular muscles in complex movements', *Journal of Anatomy* **155**, 1.

van Ingen Schenau, G., Boots, P., de Groot, G., Snackers, R. and van Woensel, W. (1992), 'The constrained control of force and position in multi-joint movements', *Neuroscience* **46**(1), 197–207.

von Lieres Und Wilkau, H. C., Bezodis, N. E., Morin, J.-B., Irwin, G., Simpson, S. and Bezodis, I. N. (2020b), 'The importance of duration and magnitude of force application to sprint performance during the initial acceleration, transition and maximal velocity phases', *Journal of Sports Sciences* **38**(20), 2359–2366.

von Lieres und Wilkau, H. C., Irwin, G., Bezodis, N. E., Simpson, S. and Bezodis, I. N. (2020a), 'Phase analysis in maximal sprinting: An investigation of step-to-step technical changes between the initial acceleration, transition and maximal velocity phases', *Sports Biomechanics* **19**(2), 141–156.

Walker, J., Bissas, A., Paradisis, G. P., Hanley, B., Tucker, C. B., Jongerius, N., Thomas, A., von Lieres und Wilkau, H. C., Brazil, A., Wood, M. A., Merlino, S., Vazel, P.-J. and Bezodis, I. N. (2021), 'Kinematic factors associated with start performance in World-class male sprinters', *Journal of Biomechanics* **124**, 110554.

Weir, G., van Emmerik, R., Jewell, C. and Hamill, J. (2019), 'Coordination and variability during anticipated and unanticipated sidestepping', *Gait & Posture* **67**, 1–8.

Weyand, P. G., Sandell, R. F., Prime, D. N. L. and Bundle, M. W. (2010), 'The biological limits to running speed are imposed from the ground up', *Journal of Applied Physiology* **108**(4), 950–961.

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

Wild, J. J., Bezodis, I. N., North, J. S. and Bezodis, N. E. (2018), 'Differences in step characteristics and linear kinematics between rugby players and sprinters during initial sprint acceleration', *European Journal of Sport Science* **18**(10), 1327–1337.

Wild, J. J., Bezodis, I. N., North, J. S. and Bezodis, N. E. (2021), 'Characterising initial sprint acceleration strategies using a whole-body kinematics approach', *Journal of Sports Sciences* **40**(2), 203–214.

Young, W. (1995a), 'Laboratory Strength Assessments of athletes', *New Studies in Athletics* (10), 89–96.

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

Chapter 3

Inter- and intra-limb coordination during initial sprint acceleration

This chapter has been published in ***Biology Open*** *as:*

Donaldson BJ., Bezodis NE., Bayne H. (2022) Inter- and intra-limb coordination during initial sprint acceleration. *Biology Open* 11(10), bio059501.

Abstract

In complex movements, centre of mass translation is achieved through effective joint and segment rotations. Understanding segment organisation and coordination is therefore paramount to understanding technique. This study sought to comprehensively describe inter- and intra-limb coordination and assess step-to-step changes and between-individual variation in coordination during initial sprint acceleration. Twenty-one highly trained to world class male (100 m PB 9.89 - 11.17 s) and female (100 m PB: 11.46 - 12.14 s) sprinters completed sprint trials of at least 20 m from which sagittal plane kinematics were obtained for the first four steps using inertial measurement units (200 Hz). Thigh-thigh, trunk-shank and shank-foot coordination was assessed using a modified vector coding and segment dominancy approach. Common coordination patterns emerged for all segment couplings across sexes and performance levels, suggesting strong task constraints. Between-individual variation in inter-limb thigh coordination was highest in early flight, while trunk-shank and shank-foot variation was highest in late flight, with a second peak in late stance for the trunk-shank coupling. There were clear step-to-step changes in coordination, with step 1 being distinctly different to subsequent steps. The results demonstrate that inter-limb coordination is primarily anti-phase and trailing leg dominant while ankle motion in flight and late stance appears to be primarily driven by the foot.

3.1 Introduction

Acceleration from a stationary block position in athletic sprinting is a complex task with important implications for race performance (Bezodis et al., 2015, 2019b; Walker et al., 2021). Initial acceleration consists of the first 3-6 steps after block exit and is distinguished from later phases by step-to-step kinematic changes (Nagahara et al., 2014; von Lieres und Wilkau et al., 2020). As such, researchers and coaches approach initial acceleration as a unique technical component of the sprint (e.g. Bezodis et al. (2019a); Debaere et al. (2013); Jones et al. (2009); Walker et al. (2021)). Effective acceleration depends more on force vector orientation than total magnitude of the resultant force generated (Kugler and Janshen, 2010; Morin et al., 2011; Rabita et al., 2015), with more horizontally directed forces corresponding to a further forward centre of mass (CM) (Kugler and Janshen, 2010; Slawinski et al., 2010). Since CM position is a function of overall musculoskeletal system organisation, a horizontal CM position, and horizontal force application, results from effectively organising the linked segment system (Kugler and Janshen, 2010; Nagahara et al., 2014; Slawinski et al., 2010; von Lieres und Wilkau et al., 2020). Whilst existing literature has quantified isolated joint and segment kinematics during initial acceleration (e.g. Debaere et al. (2013); Nagahara et al. (2014, 2018); Slawinski et al. (2010); von Lieres und Wilkau et al. (2020); Walker et al. (2021)), an evaluation of the relative movement these system components is needed to understand how sprinters coordinate the motion of their available degrees of freedom to satisfy the task constraints (Davids et al., 2003; Glazier, 2017; Newell, 1986). By quantifying this in a cohort of highly-skilled sprinters, the importance of both organismic and task constraints can be understood by assessing the aspects of emergent coordination patterns unique to individuals (organismic) and the similarity of coordination patterns between individuals (task) during maximal sprint acceleration efforts.

In linear sprinting, the vast majority of movement is in the sagittal plane, and therefore most research and coaching analyses of segment kinematics are focused on sagittal plane trunk and lower limb motion (e.g. Clark et al. (2020); Debaere et al. (2013); Nagahara et al. (2014, 2018)). During initial acceleration, there is a step-to-step raising of the CM in part due to step-to-step shifts toward more vertical shank and trunk segments (Nagahara et al., 2014; von Lieres und Wilkau et al., 2020). Better performers exhibit smaller shifts towards a vertical trunk orientation over the initial steps (Kugler and Janshen, 2010; von Lieres und Wilkau et al., 2020) while a more horizontal trunk at toe-off is associated with better performance during the first stance of world class sprinters (Walker et al., 2021). However, as a more proximal segment, trunk motion during stance could be a function of more distal (stance leg) segment orientations. The trunk typically rotates clockwise (as viewed from the right) during flight before reversing direction during stance (Donaldson et al., 2020; Nagahara et al., 2018), whilst the shank does the opposite - rotating anticlockwise toward a vertical orientation during flight and the opposite during stance, rotating back toward a horizontal orientation (Donaldson et al., 2020; Nagahara et al., 2014; von Lieres und Wilkau et al., 2020). However, the relationship between the timing and relative magnitude of these rotations is unclear. Given the coaching interest in the relationship between trunk and shank angles at key events (Donaldson et al., 2020; von Lieres und Wilkau et al., 2020) and the role both the shank and the trunk play in facilitating more forward CM positions and orienting force in the horizontal direction (Alt et al., 2022; Jacobs and van Ingen Schenau, 1992; Kugler and Janshen, 2010; von Lieres und Wilkau et al., 2020), understanding of this inter-segmental relationship is needed. In the only study to so far investigate trunk-shank coordination in sprinting, Bezodis et al. (2019a) found in-phase coordination (same rotation direction) during mid stance, suggesting timing differences in trunk and shank rotation reversals. Further understanding shank and trunk coordination may provide important insight regarding CM raising and forward translation during acceleration.

Several studies have established the importance of ankle energy absorption and power generation during acceleration (Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013; Gittoes and Wilson, 2010), while ankle stiffness has been associated with acceleration performance (Charalambous et al., 2012). However, little is known about how ankle dorsiflexion and plantarflexion are achieved by the motion of the segments which comprise the joint. Indeed, no study has investigated shank and foot coordination, with a resultant gap in understanding of the relative contributions of shank and foot rotation to ankle motion. Theoretically, the changes in shank angle across acceleration (Nagahara et al., 2014; von Lieres und Wilkau et al., 2020) suggest possible changes to geometric constraints (van Ingen Schenau et al., 1987) which could alter the relative importance of shank or foot rotation to ankle motion in different steps. Studies of shank-foot coordination are required to elucidate the roles of the shank and foot to ankle motion within a step as well as the shift in their relationship between steps and phases.

Recent studies have investigated thigh angular motion during maximal velocity (Clark et al., 2020; Kakehata et al., 2021), acceleration (Bayne et al., 2020; Walker et al., 2021) and uphill sprinting (Okudaira et al., 2021). From coaching observations, such investigations focus on 'switching' and 'scissoring', the respective points where the thighs cross over or reverse rotation (Clark et al., 2020; Kakehata et al., 2021; Okudaira et al., 2021). Clark et al. (2020) found faster sprinters had greater thigh angular accelerations and greater average thigh angular velocity over the gait cycle, suggesting the ability to rapidly transition between thigh flexion and extension is important. During acceleration, maximal velocity and uphill running, the thighs produce an oscillatory motion rotating in opposing directions, with one flexing and the other extending (Bayne et al., 2020; Clark et al., 2020; Okudaira et al., 2021), resulting from unique constraints on human bipedal gait (Kiely and Collins, 2016). Only two studies have investigated inter-limb thigh coordination. Bayne et al. (2020) found elite sprinters spent more of the step in anti-phase (opposing rotation) than sub-elite counterparts during initial acceleration while Okudaira et al. (2021) found increased anti-phase with increased incline in uphill sprinting. However, neither study found anti-phase motion at all time points, and were not able to identify why that was the case or any other characteristic features of thigh coordination. It also remains unclear whether oscillatory thigh motion is driven equally by each leg or if there is greater rotation in one leg at any given time.

To date, sprint coordination studies have primarily focused on coordination patterns between two groups over multiple steps, with less emphasis on potential differences between steps or individuals (Bayne et al., 2020; Bezodis et al., 2019a; Okudaira et al., 2021). However, previous literature suggests the first step may have unique characteristics (Bezodis et al., 2014; Charalambous et al., 2012) and key segment angles change from step-to-step during initial acceleration (Donaldson et al., 2020; Nagahara et al., 2014; von Lieres und Wilkau et al., 2020). It remains unclear whether there are concomitant differences between steps in segment coordination and what that might imply about the constraints on initial acceleration technique. Further, given the self-organising nature of coordination patterns, group based analyses could overlook between-individual variation and make it harder to identify underlying causes and constraints from which technique differences between individuals may arise.

Understanding segment organisation is essential to understanding sprint technique. Considering the coaching emphasis on kinematics, the task's technical nature and step-to-step changes during initial acceleration, a comprehensive description of whole-body coordinative strategies is warranted and can provide unique insight into both task- and individual-related aspects of technique.Therefore, this study aimed to comprehensively describe relevant intra- and inter-limb coordination couples and segment dominancy during initial acceleration in highly trained to world-class male and female sprinters, and to quantify between-individual variation and step-to-step changes in these features.

3.2 Materials and Methods

3.2.1 Participants

Fifteen male (age = 22.0 ± 3.6 yrs, stature = 1.77 ± 0.06 m, mass = 74.6 ± 9.7 kg, 100 m PB = 10.47 ± 0.42 s) and six female (age = 22.8 ± 6.5 yrs, stature = 1.62 ± 0.05 m, mass = 54.1 ± 2.2 kg, 100 m PB = 11.79 ± 0.24 s) - classified as highly trained (14), elite (5) and world class (2) according to McKay and colleagues' framework (2021) - volunteered for this study. Participants provided written informed consent after having the protocol explained to them, which was approved by the institutional research ethics committee (612/2020) and completed in accordance with the Declaration of Helsinki.

3.2.2 Protocol

Sprints were performed at an outdoor athletics stadium during routine training sessions in the competition phase of the season, where training regularly included block starts. Participants completed their habitual warm up, which included multiple sub-maximal block starts. After warm up, participants performed three maximal effort trials of at least 20 m from blocks, separated by at least five minutes rest. Participants used their own spikes and preferred block settings.

3.2.3 Data collection

Instantaneous velocity was recorded using a radar gun (47 Hz; Stalker Pro II ATS, Stalker, USA) from which split times were derived (Samozino et al., 2016). Three-dimensional (3D) kinematics were recorded using tri-axial inertial measurement units (IMU) (200 Hz, MyoMotion; Noraxon, USA), for which sagittal plane validity and reliability has previously been reported (Balasubramanian, 2013; Berner et al., 2020; Cottam et al., 2022; Yoon, 2017) and which have been used in previous sprint research (e.g. Bayne et al. (2020); Struzik et al. (2015, 2016)). Between warm up and sprint trials, participants were fitted with nine IMU sensors, affixed to the upper spine (T1), lower spine (T12) and sacrum as well as the lateral aspect of the left and right thigh, medial aspect of each shin and dorsal surface of each foot (Figure 3.1A-E). Upper spine and pelvis sensors were secured using double sided tape, after the area had been toweled dry and prepared using alcohol swabs and an adhesive spray. Adhesive tape was then applied over the sensors (Figure 3.1B). The lower spine sensor was attached using a manufacturer-supplied custom Velcro strap (Figure 3.1B), applied tightly to avoid moving or slipping due to impact or sweat, but not so tight that it restricted breathing. Thigh and shank sensors were attached using double sided tape (Figure 3.1C) and secured tightly with self-adhesive bandages (Figure 3.1D) so as to minimise movement due to soft-tissue artifact or impact. Foot sensors were attached in manufacturer provided plastic clips on the upper portion of the foot and the laces pulled tight over the sensor, through the available hooks in the clip, and tape applied over the laces. Sensors were thus securely attached and checked before each trial. Trials where a sensor came loose were excluded.

Sagittal plane video of the first four steps after block exit was recorded by a camera (120 Hz, Ninox-250, Noraxon, USA) placed perpendicular to the recording lane, at a distance of 5 m (approximate field of view = 6 m wide). IMU data and video were synchronised and captured using MyoResearch 3.14 software (Noraxon, USA).

3.2.4 Data processing

Segment kinematics were obtained from a 9-segment rigid-body model included in the IMU manufacturer's software (MyoResearch 3.14). IMU sensors were calibrated prior to each trial to establish the local coordinate system. The IMU system establishes a 0° reference angle for segment orientations in all planes during calibration, from which subsequent kinematic measurements are based. Within-participant reliability in the calibration position has been demonstrated, given standardised instructions (Berner et al., 2020; Donaldson et al., 2021)(See Appendix A). Participants stood in a neutral upright posture on a calibration board fixed with guides to set the feet in parallel, at approximately hip width for each participant. Participants were instructed to "maintain an upright, neutral posture with hands placed at the sides and head looking forward" and remained in this position until calibration was complete (Figure 3.1E).

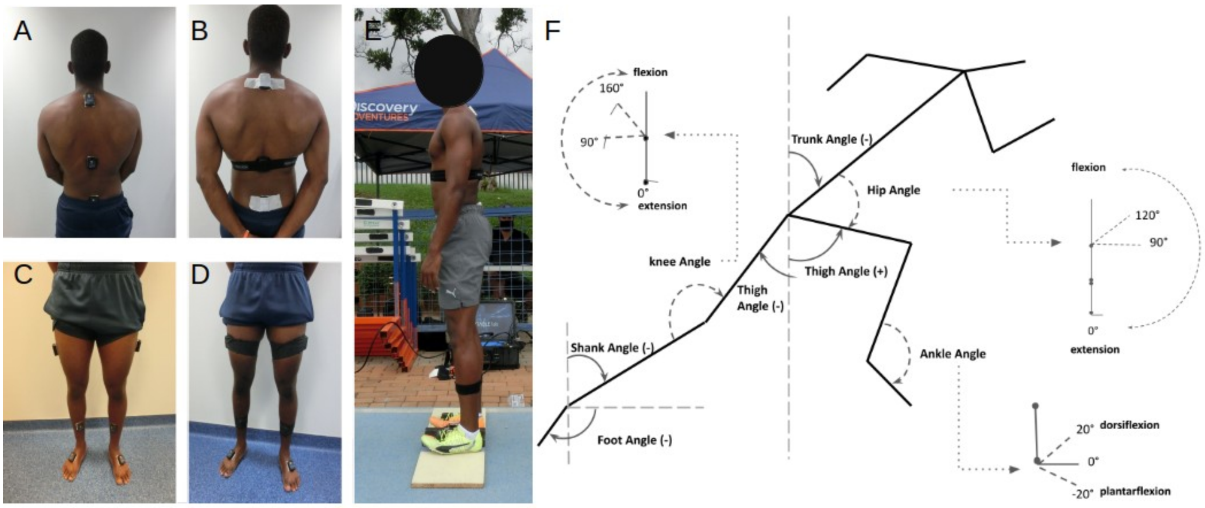

Figure 3.1: Upper body (A and B) and lower body (C and D) IMU sensor placements and attachments. Calibration posture with full sensor setup (E) and segment and joint definitions used in this study (F).

Magnetometer, gyroscope and accelerometer signals were fused during capture using a Kalman filter fusion algorithm applied by the software. A light anti-wobble filter was applied within the MyoResearch software to reduce potential soft-tissue artifact in the signal. The anti-wobble filter used a spherical linear interpolation (SLERP, 300 ms) and a low pass butterworth filter (15 Hz) to smooth IMU signal.

Toe-off (TO) and touchdown (TD) were identified from sagittal plane video. Touchdown was determined as the first frame with visible ground contact and toe-off as the first frame in which the foot no longer visibly contacted the ground. Steps were defined from toe-off to the next toe-off of the contralateral leg, beginning with front-foot block clearance (TO_0). Therefore, flight time was defined as the time from toe-off of one step until touchdown of the contralateral leg in the next step, such that flight time for step 1 represented the time from block clearance (TO_0) to touchdown in step 1 (TD_1). Contact time was defined as time between touchdown and toe-off in the same step. From IMU data, sagittal plane angles for the trunk, thigh, shank and foot segments as well as the hip, knee and ankle joints were normalized to 101 data points for each step. Trunk orientation was determined from the upper spine sensor (T1). Angle definitions are presented in Figure 3.1F. Segment rotations were described as clockwise or anticlockwise relative to a left-to-right direction of motion (Figure 3.2A). Limbs were classified as 'leading' or 'trailing' based on their relative position at each toe-off, such that the swing leg at toe-off was considered 'leading' and stance leg 'trailing' for the duration of the subsequent step. As such, since the limbs' oscillatory motion during running, 'leading' limb at toe-off in step 1 became 'trailing' limb at toe-off in step 2 and vice versa (Figure 3.2B).

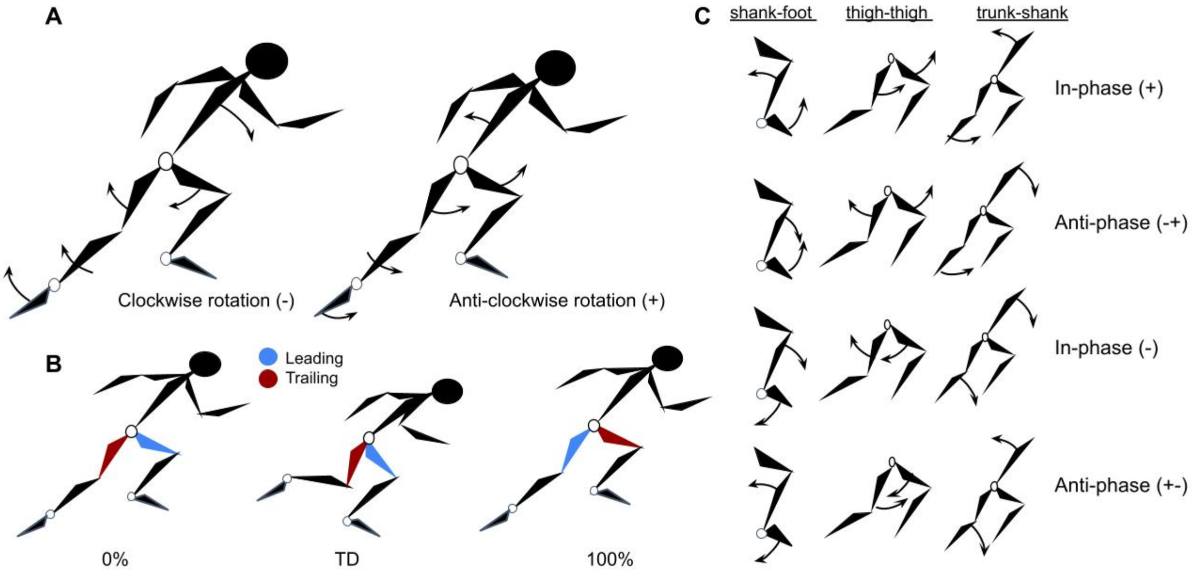

Figure 3.2: Segment rotation (A) and leading leg-trailing leg (B) conventions with coordination direction of rotations (C).

3.2.5 Coordination analysis

Coupling angle mapping was used to profile individual coordination over the first four steps (Needham et al., 2020, 2014). Thigh-thigh, trunk-shank, and shank-foot segment couplings were assessed with a proximal-distal naming convention. For the thigh-thigh coupling, the trailing and leading thigh were designated as proximal and distal respectively. Coupling angles (CA) were calculated from angle-angle plots of segment couplings using a modified vector coding approach (Chang et al., 2008; Needham et al., 2020, 2014). The CA represented the vector angle between adjacent points in the angle-angle diagram relative to the right horizontal, expressed as an angle between 0° and 360° (Figure 3.3A). Thus, for each normalised time point, CA position on the circular plane described the relative rotation of the two segments (Figure 3.3B). For any two segments, rotation could either be in-phase (same direction) or anti-phase (opposite direction) and segments could either rotate clockwise or anticlockwise. Consequently, there were four possible relationships between segments, corresponding to the circular plane's four quadrants. Each quadrant was further divided into two 45° bins based on the dominant segment, i.e. which segment underwent the greatest rotation in a given time period, resulting in eight distinct coordination bins describing the relationship between segment rotations (in-phase or anti-phase), the direction and the dominant segment (Bezodis et al., 2019a; Needham et al., 2020)(Figure 3.3B). The magnitude of segment dominancy (i.e. which segment underwent greater rotation) was quantified according to Needham et al. (Needham et al., 2020). Briefly, since 90° is equal to 100 gradians, each circular plane quadrant can be represented as 0 to 100%. Converting the CA to gradians gives the proximal or distal segment dominancy as a percentage at every normalised time point (Needham et al., 2020)(Figure 3.3B). For example, a 90° CA equals 100 gradians, and therefore 100% segment dominancy. A 100% dominant proximal segment reflects a rotating proximal segment and a completely fixed distal segment, for that time period, while 50% segment dominancy reflects equal rotation. Since bins were defined according to dominant segment and dominant segment switches as 50% mark is crossed, segment dominancy was constrained between 50% and 100%. Primary coordination patterns were classified by colour, and distal or proximal segment dominancy illustrated by light or dark shades of each colour, respectively Therefore, changes between colours represented overall coordination changes and changes in tone within a given colour represented change in dominant segment. Individual coordination was profiled by plotting the segment dominancy over time and each bar colour coded by coordination bin, as determined by CA position on the circular plane (Needham et al., 2020).

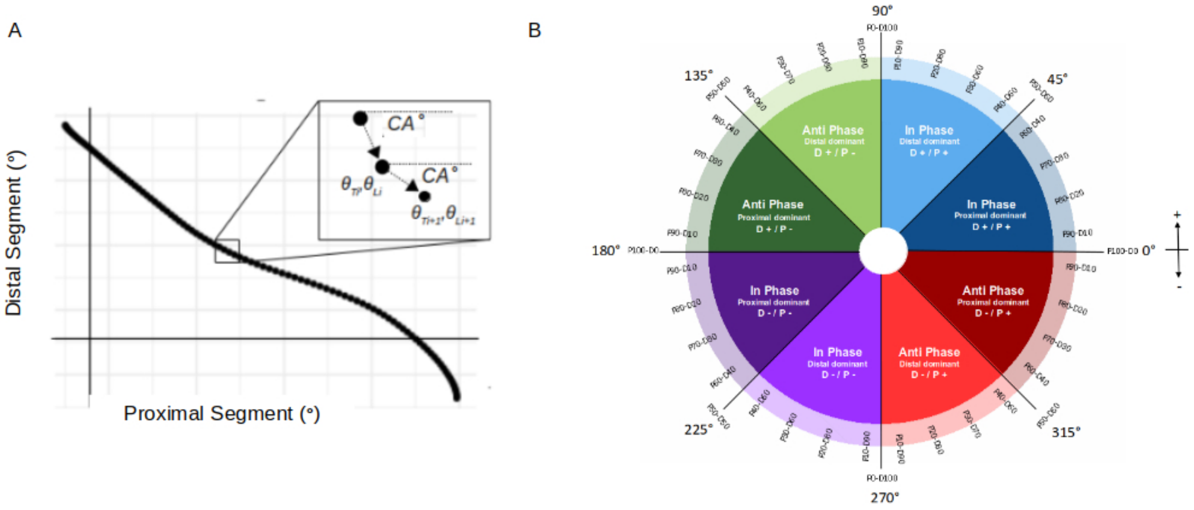

Figure 3.3: **(A)** Angle-angle plot with coupling angle definition. **(B)** Cordination bins and segment dominancy conventions for general proximal and distal segment couplings, adapted from Needham et al. (Needham et al., 2020).

3.2.6 Data analysis

Mean coordination profiles were determined using circular statistics (Chang et al., 2008; Needham et al., 2020). Between-individual variation in coordination was evaluated from the standard deviation at each time point (Needham et al., 2020). Specific between-individual differences in coordination patterns were identified by visually inspecting coordination profiles. Step-to-step coordination changes were assessed using a coupling angle difference score ($\mathrm{CA}_{\mathrm{Diff}}$)(Bezodis et al., 2019a; Brazil et al., 2020). Briefly, the coordination bin at each normalised time point was compared to the corresponding point in the subsequent step and assigned a score between 0 (same bin) and 4 (opposite bin). The total sum of difference scores over the entire step was represented as a percentage of the maximal possible score. A lower $\mathrm{CA}_{\mathrm{Diff}}$ indicated more similar coordination (Bezodis et al., 2019a). Further, the frequency of each bin was compared across steps using non-parametric Friedman's tests and pairwise differences assessed using Wilcoxon signed-rank tests. Touchdown and toe-off angular kinematics were assessed with one-way repeated measures analyses of variance (ANOVA) and pairwise t-tests. All pairwise tests were adjusted for multiple comparisons with a Bonferroni correction. For ANOVAs, sphericity assumptions were assessed with Mauchly's tests and a Greenhouse-Geisser corrections applied to variables that violated the assumption. All tests were performed in R (R Core Team, 2020) using the *rstatix* package (Kassambara, 2021). Alpha level was set at 0.05.

3.3 Results & Discussion

This study aimed to comprehensively describe intra- and inter-limb coordination strategies in well trained sprinters and to quantify between-individual variation and step-to-step changes in coordination.

The current results agree with previous segment and joint kinematics investigations by Nagahara et al. (2014) and von Lieres und Wilkau et al. (2020), finding significant main effects of step for all segment and joint touchdown angles except the ankle, as well as trunk, thigh, shank and foot angles at toe-off (table 3.1). However, particularly at touchdown, pairwise tests revealed step 1 to be different from all subsequent steps while step 2 commonly differed from both step 1 and later steps, with only the knee significantly different between steps 3 and 4. As such, step 1 and 2 touchdown kinematics were different from both each other and later steps.

Both the trunk ($F_{(3,60)} = 11.7$, $p < 0.001$, $\eta^2 = 0.37$) and shank ($F_{(3,60)} = 138.4$, $p < 0.001$, $\eta^2 = 0.874$) became progressively more vertical at touchdown, however trunk angle only differed significantly between step 1 and all subsequent steps. In contrast, the foot contacted the ground in a more vertical orientation in step 1 and decreased progressively, with a sharp decrease between step 1 and 2 ($F_{(2.11,42.3)} = 61.5$, $p < 0.001$, $\eta^2 = 0.754$). Similarly, toe-off foot angle was significantly more vertical in step 1 than later steps ($F_{(3,60)} = 3.1$, $p = 0.032$, $\eta^2 = 0.136$). The thigh was less flexed at touchdown in step 1 compared to later steps ($F_{(3,60)} = 10.2$, $p < 0.001$, $\eta^2 = 0.337$) but more extended at toe-off in step 1 and 2 compared to 3 and 4 ($F_{(3,60)} = 24.7$, $p < 0.001$, $\eta^2 = 0.552$).

Table 3.1: Discrete kinematics and step characteristics for first four steps

Variable	**Step 1**	**Step 2**	**Step 3**	**Step 4**
Step Characteristics				
Flight time (s)	0.074 ± 0.014^{2}	0.053 ± 0.024^{14}	0.067 ± 0.015	0.077 ± 0.018^{2}
Contact time (s)	0.175 ± 0.026^{234}	0.162 ± 0.025^{134}	0.143 ± 0.017^{124}	0.129 ± 0.017^{123}
Step frequency (Hz)	4.0 ± 0.3^{234}	4.6 ± 0.3^{1}	4.7 ± 0.3^{1}	4.8 ± 0.3^{1}
Touchdown Angles (°)				
Hip	58.0 ± 11.4	61.4 ± 17.0^{4}	55.9 ± 11.5	51.3 ± 12.8^{2}
Knee	73.3 ± 6.1^{234}	67.7 ± 7.3^{134}	56.6 ± 6.3^{124}	51.2 ± 7.2^{123}
Ankle	0.1 ± 5.4	0.6 ± 6.3	-2.5 ± 6.7	-3.1 ± 7.4
Trunk	-65.0 ± 9.3^{234}	-59.2 ± 10.5^{1}	-57.7 ± 10.1^{1}	-55.7 ± 11.2^{1}
Thigh	30.0 ± 7.4^{234}	38.6 ± 8.4^{1}	38.5 ± 5.8^{1}	37.1 ± 8.5^{1}
Shank	-39.7 ± 7.8^{234}	-26.4 ± 7.5^{134}	-16.5 ± 6.2^{12}	-13.5 ± 5.8^{12}
Foot	-42.5 ± 9.0^{234}	-26.9 ± 7.6^{134}	-19.9 ± 8.4^{12}	-17.2 ± 7.9^{12}
Thigh Separation	50.1 ± 13.9	56.6 ± 18.0^{4}	49.6 ± 12.8	42.0 ± 15.2^{2}
toe-off Angles (°)				
Hip	-7.1 ± 7.0	-6.6 ± 10.4	-6.2 ± 7.1	-7.9 ± 9.7
Knee	18.2 ± 5.5	19.9 ± 6.3	20.3 ± 7.3	22.7 ± 6.4
Ankle	-31.9 ± 8.3	-27.1 ± 9.5	-30.2 ± 8.5	-30.9 ± 13.2
Trunk	-53.0 ± 10.3	-54.3 ± 11.9^{34}	-48.4 ± 10.5^{2}	-48.0 ± 11.4^{2}
Thigh	-32.8 ± 5.1^{24}	-28.9 ± 5.2^{134}	-25.9 ± 4.8^{2}	-24.1 ± 6.0^{12}
Shank	-48.4 ± 6.2^{3}	-48.1 ± 5.2^{4}	-44.7 ± 6.8^{1}	-45.8 ± 5.0^{2}
Foot	-85.8 ± 10.1^{23}	-78.2 ± 10.4^{1}	-79.2 ± 10.6^{1}	-79.4 ± 14.5
Thigh Separation	88.0 ± 7.5	87.8 ± 7.8	85.6 ± 9.0	87.5 ± 8.5

Data represented as mean ± sd. $^{1\text{-}4}$ Superscript denotes significant difference ($p < 0.05$) from step of that number from pairwise t-tests with bonferroni correction.

There were large step-to-step coordination differences for all couplings, with similar between-step differences in trunk-shank (CA_{Diff}: S1-S2 = $33.5 \pm 9.2\%$, S2-S3 = $22.8 \pm 9.8\%$, S3-S4 = $16.5 \pm 6.6\%$) and shank-foot coordination (CA_{Diff}: S1-S2 = $29.7 \pm 11.3\%$, S2-S3 = $23.6 \pm 6.9\%$, S3-S4 = $16.9 \pm 7.2\%$) while thigh-thigh between-step differences were smaller (CA_{Diff}: S1-S2 = $12.5 \pm 4.0\%$, S2-S3 = $9.0 \pm 3.3\%$, S3-S4 = $9.1 \pm 3.6\%$). In all cases, the largest differences were between steps 1 and 2, indicating between-step coordination became progressively more similar. Moreover, there were significant main effects of step on bin frequencies across all couplings, with the most common pattern being significant differences between step 1 and all three subsequent steps (Figures 3.5-3.7D).

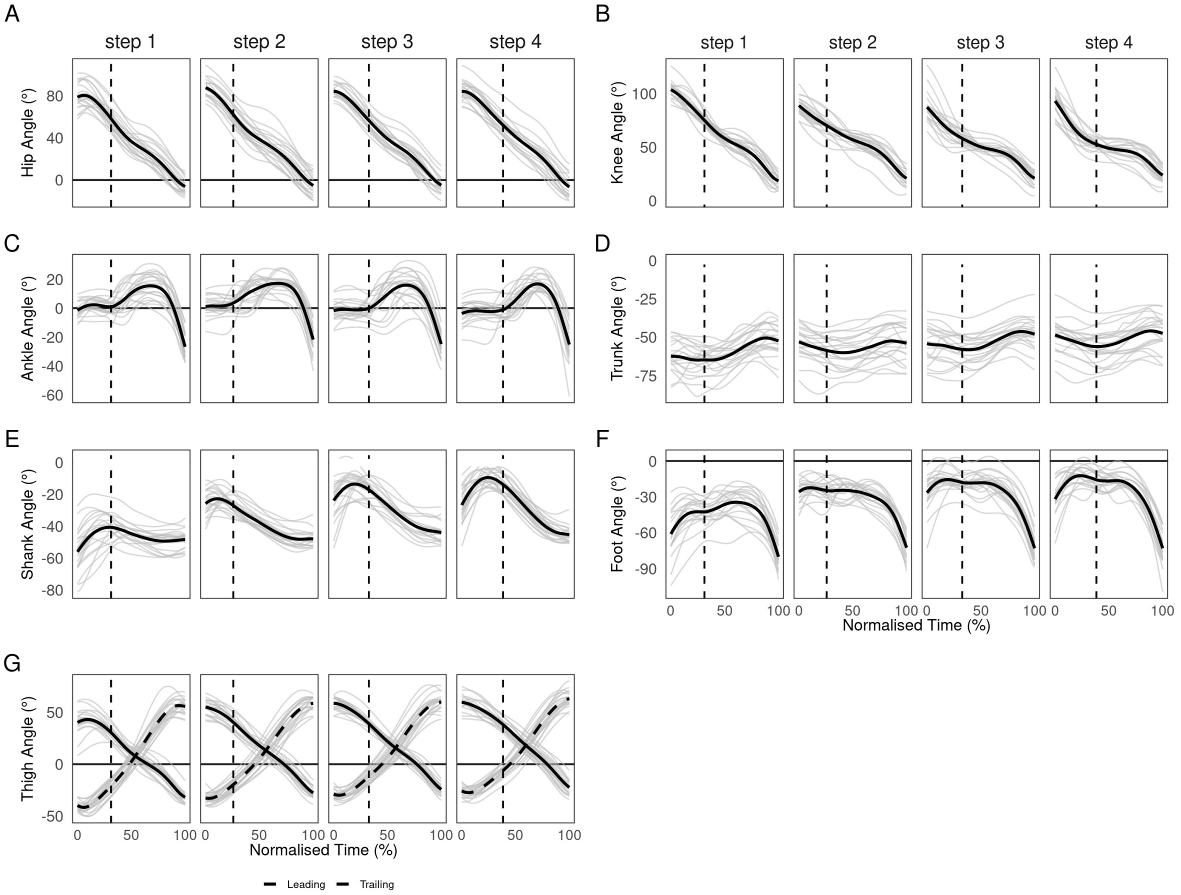

Figure 3.4: Mean (black) and individual (grey) continuous hip (A), knee (B), ankle (C), trunk (D), shank (E), foot (F) and leading and trailing thigh (G) angles for each of the first four steps after block clearance (step 1, 0% time). Vertical dotted line indicates mean touchdown time (%).

The step-to-step differences in both coordination and isolated kinematics suggest the first step is technically different from subsequent steps and the step 1 to 2 transition could be considered an additional breakpoint to the one previously identified around steps 3-6 (Nagahara et al., 2014; von Lieres und Wilkau et al., 2020), which supports the emphasis placed on the first step by elite coaches (Jones et al., 2009). Significant differences at touchdown and in certain coordination bins mean that step 2 could also be considered separately, although step 2 differences from later steps were less consistent than step at touchdown and there were fewer differences in coordination. Coordination differences between step 1 and later steps most likely reflects the unique constraints of block exit in athletic sprinting and may exhibit smaller differences when accelerating from other start positions.

3.3.1 Thigh-thigh coordination

Thigh-thigh coordination was primarily anti-phase and trailing thigh dominant (dark red)(Figure 3.5), reflecting the oscillatory motion associated with bipedal gait (Kiely and Collins, 2016) and supporting the high frequency of anti-phase thigh coordination that Bayne et al. (2020) and Okudaira et al. (2021) respectively reported during acceleration and uphill sprinting. The oscillatory anti-phase thigh motion also aligned with thigh motion reported by Clark and colleagues during maximal velocity sprinting (Clark et al., 2020)(Figure 3.4G), suggesting that thigh angular motion may already be similar to that of maximal velocity sprinting within the first few steps. However, there was substantial trailing leg dominance, such that oscillatory thigh motion appears asymmetric and characterised by faster forward rotation of the trail leg during acceleration. The mean frequency of anti-phase trailing (+)(dark red) decreased progressively from step 1 to step 3, and was significantly higher in step 1 (73%) than step 3 (54%, $p = 0.024$). Trailing leg dominance was typically highest at or shortly after crossover between the two thighs (see Figure 3.5A-B, black vertical line). The magnitude of trailing leg dominance around crossover was highest in step 1, reaching almost 100% dominance in some cases, and this decreased progressively in subsequent steps.

Thigh-thigh coordination variation was highest in early flight, but low for the majority of the step before a gradual increase in late stance. Thus variation in coordination strategy was highest around block clearance and toe-off, owing to the respective timing of flexion and extension reversals during the scissor action. Generally low variation in thigh-thigh coordination implies strong task constraints for inter-limb coordination in acceleration, with greater degrees of freedom potentially available to athletes during transitions between steps. Thigh coordination was visibly different after block clearance compared to after toe-off in subsequent steps. Most participants exhibited anti-phase leading (+)(light green) or trailing (-)(dark green) coordination immediately after block clearance, reflecting trailing thigh rotating clockwise and

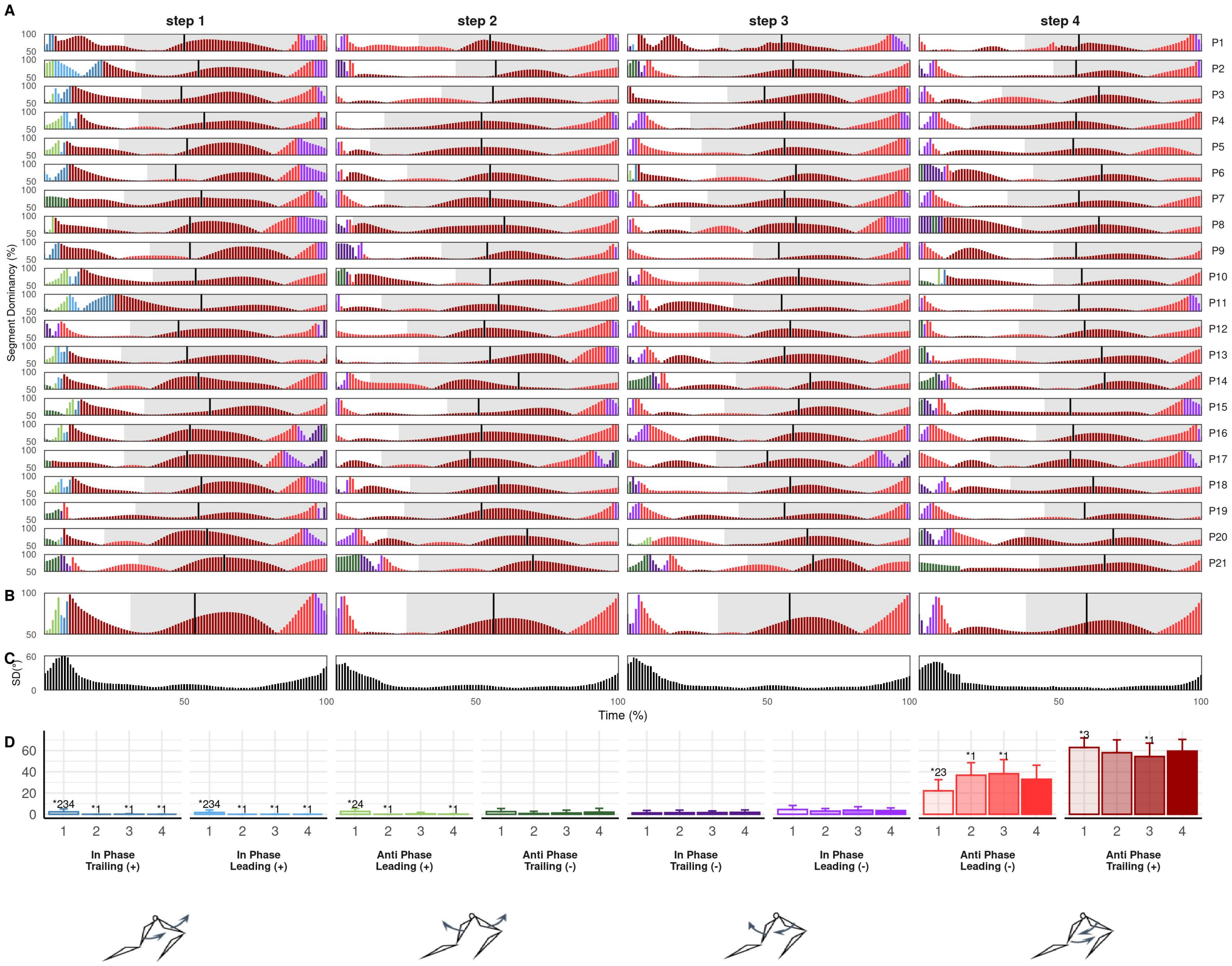

Figure 3.5: Individual (A) and mean (B) thigh-thigh coordination profiles, between-individual standard deviation (C) and mean bin frequencies (D) across steps 1 to 4. Coordination profile bar height shows segment dominancy (50 - 100%) and colour shows bin classification according to colour scale of bin frequency plot (D). Grey shaded area indicates stance, black vertical line indicates point of crossover.

leading thigh anti-clockwise, increasing thigh separation. Further, approximately half of participants displayed a short in-phase (+)(light and dark blue) period (Figure 3.5A), with these observations reflected in significantly higher frequencies of anti-phase leading (+) and in-phase (+) bins compared to later steps (Figure 3.5D). Thus, some athletes may require time in the first flight to sufficiently organise the limbs before initiating the scissor action, particularly for the lead leg. Whether additional time is beneficial or inefficient remains unclear.

The in-phase period (light and dark blue) demonstrates an asymmetric scissor after block exit, starting to pull the trail leg forward slightly before starting to retract the lead leg. Continued lead leg anticlockwise rotation after block clearance could reflect an athlete's intent to achieve maximum drive out the blocks or it could indicate that an athlete hasn't been able to bring the lead leg forward to its full extent before the front leg exits the blocks. Further investigations might determine whether the observed patterns reflect inefficiencies in thigh organisation at block clearance, specific organismic constraints or necessary task constraints associated with exiting the blocks.

In later steps, there were three patterns after toe-off. A minority of participants displayed anti-phase trailing (-)(dark green), the same continued increase of thigh separation seen after block clearance but more trail leg dominant (for example Figure 3.5A, P21). These participants didn't start to pull the trail leg forward or retract the lead leg until after toe-off. Therefore, such an anti-phase pattern might indicate a cyclic leg action since the lead leg doesn't retract immediately at toe-off but continues anticlockwise rotation during the initial flight, possibly inhibiting an athlete's ability to execute cues to 'aggressively switch' or 'hammer' the ground, used by some coaches to emphasise aggressive leg retraction during the scissor action and into the next ground contact.

Most participants exhibited either anti-phase (light and dark red) or in-phase (-)(light and dark purple), where anti-phase showed the scissor had already happened and in-phase indicated both legs rotating clockwise. In-phase coordination in initial flight shows a late switch in trail leg rotation and could be suggestive of what some coaches label 'over pushing'. The individual characteristics that lead an athlete to adopt this pattern and what the implications for performance might be remains unclear.

In late stance, participants either continued anti-phase rotation until toe-off or they displayed in-phase leading (-)(light purple)(Figure 3.5) coordination. In-phase motion was most common in step 1 and reduced in both occurrence (number of athletes) and proportion (% of step) in later steps, a pattern corresponding with greater stance thigh angles at toe-off in step 1 (Table 3.1). In-phase coordination represents a swing thigh (trail thigh at this stage) reaching an earlier maximum angle relative to the stance thigh and beginning to retract before toe-off, and therefore an asymmetric scissor.

Walker et al. (2021) found greater thigh separation at step 1 was associated with greater external horizontal power and postulated that this might be the way athletes maximise thigh angular velocity of the retracting thigh in the next step. Thigh separation angles at toe-off were smaller in the current study than Walker et al. (2021) , and the in-phase coordination present in late stance implies maximum thigh separation occurs prior to toe-off for many participants, especially in step 1. No participant exhibited a perfect scissor, i.e. continuous anti-phase leading (-)(light red) or trailing (+)(dark red) across toe-off, with all requiring some in-phase (-) or anti-phase trailing (-) in either late stance or early flight. Such patterns may be necessary to facilitate the scissor action during acceleration or may indicate than none of the current cohort were able to exhibit a fully sound technical strategy. No studies of inter-limb coordination in maximal velocity sprinting exist, so it remains possible that a perfect scissor action can be achieved in later phases but because of short flight times, long contact times and the asymmetrical push from the blocks during initial acceleration, perfect scissoring is not possible in the first few steps. Future research may determine whether in-phase coordination around toe-off is necessary or represents inefficiencies in scissor execution.

3.3.2 Trunk-shank coordination

Trunk-shank coordination was mostly shank dominant, demonstrating relatively greater shank than trunk rotation over the step cycle, and the frequency of shank dominant coordination, especially during stance, increased significantly from step-to-step (Figure 3.6A & D). However there was prolonged trunk dominance during stance in step 1, with step 1 anti-phase trunk (+)(dark red) and in-phase trunk (+)(dark blue) bin frequencies significantly higher than later steps (Figure 3.6A & D). This likely resulted from more horizontal shank and trunk orientations at block clearance and touchdown in step 1 compared to later steps, producing less clockwise shank rotation and more anticlockwise trunk rotation, potentially indicating specific task constraints associated with block exit (Table 3.1; Figure 3.6). These results agree with Bezodis and colleagues' analysis of the first and third stance, where coordination defined by trunk rotation in mid and late stance in step 1 was absent in step 3 (Bezodis et al., 2019a).

In flight, trunk-shank coordination was anti-phase shank (+)(light green), reflecting clockwise trunk rotation towards the horizontal and anticlockwise shank rotation toward the vertical. From step 2 onwards, there was commonly in-phase shank (-)(light purple) around touchdown before becoming predominantly anti-phase shank (-)(light red)(Figure 3.6). Therefore, typical

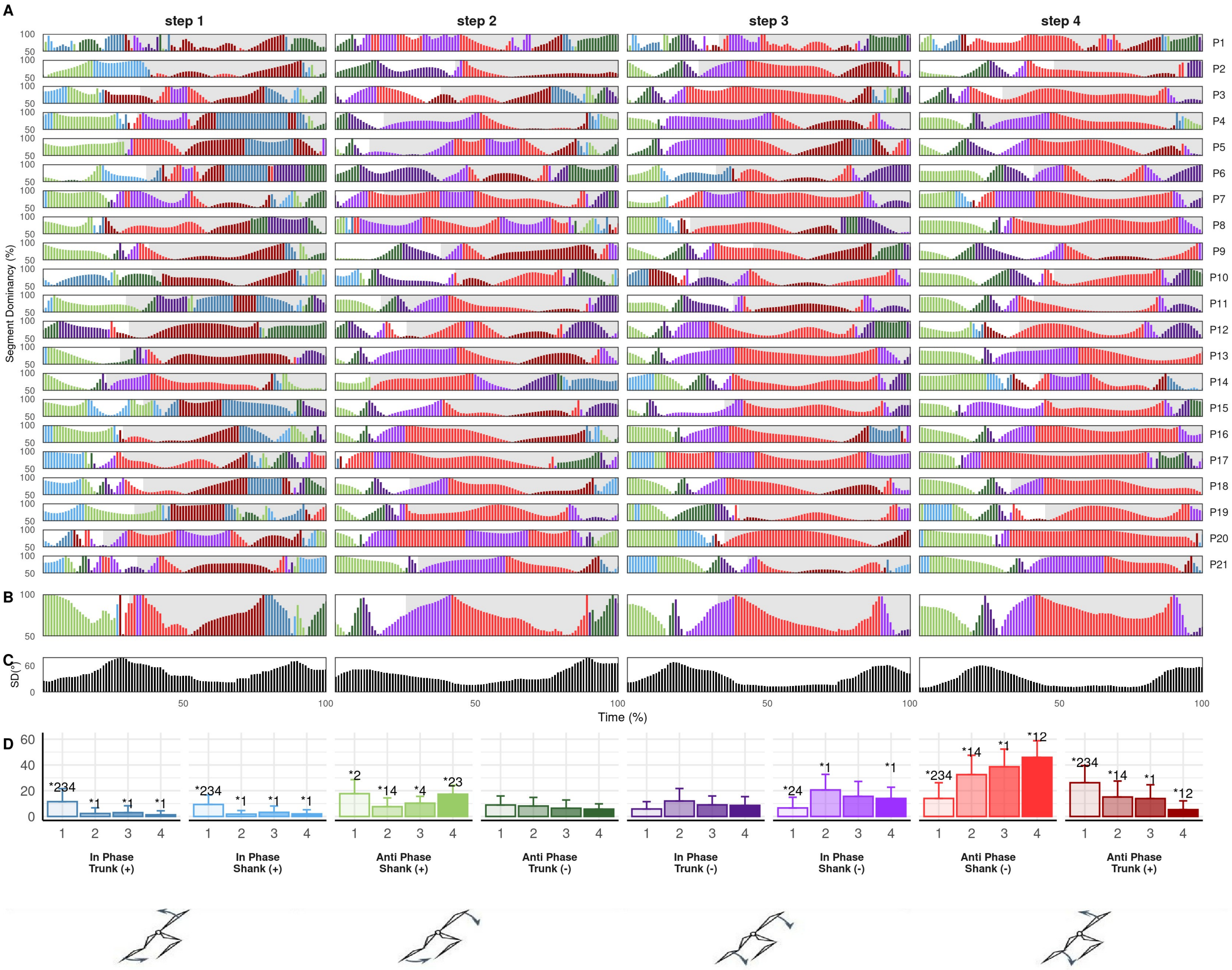

Figure 3.6: Individual (A) and mean (B) trunk-shank coordination profiles, between-individual standard deviation (C) and mean bin frequencies (D) across steps 1 to 4. Coordination profile bar height shows segment dominancy (50 - 100%) and colour shows bin classification according to colour scale of bin frequency plot (D). Grey shaded area indicates stance.

coordination patterns were clockwise trunk and anticlockwise shank rotation during flight and the reverse during stance, in accordance with previously reported trunk and shank motion (Donaldson et al., 2020; Nagahara et al., 2014, 2018; von Lieres und Wilkau et al., 2020). However, in-phase coordination around touchdown reveals novel insight into the relative timing of reversals; the trunk switches direction later than the shank, yielding simultaneous clockwise rotation around touchdown and early stance. Jacobs and van Ingen Schenau (1992) theorised a stereotyped action in sprinters where the CM, through what Alt et al. (2022) have called 'shin roll', achieves forward translation by first rotating over the point of ground contact and then through extension of the lower limb. The current results are consistent with that observation, such that the trunk and shank rotate forward in-phase during Jacobs and Van Ingen Schenau's (1992) rotation stage, before the trunk changes direction of rotation during the subsequent extension stage. Despite differences in coordination bin demarcation, overall trunk-shank coordination patterns observed here are similar to those Bezodis et al. (2019a) reported.

Participants displayed clockwise trunk rotation again in late stance, while shank rotation was reduced (Figure 3.6A-B), producing in-phase trunk (-)(dark purple) or anti-phase trunk (-)(dark green). Thus the trunk and shank converge on the fully extended toe-off body position sometimes discussed by coaches (Jones et al., 2009) from opposing directions, reaching similar toe-off angles (Table 3.1). Thus, through the influence of trunk angle on CM position and the role of the shank in rotating the CM and directing the angle at which the more proximal segments extend, (Alt et al., 2022; Jacobs and van Ingen Schenau, 1992) these two segments appear to work in consort and may help to influence the direction of force output and CM motion at toe-off. However, the shank achieves the desired toe-off position relatively earlier than the trunk. The trunk then adjusts further in late stance, possibly already anticipating clockwise rotation in the next step. Between-individual variation was generally higher in trunk-shank compared to thigh-thigh coordination, with standard deviations reaching as much as 80° (Figure 3.6C), likely due to trunk rotation highly variable in both the magnitude and direction across participants (Figure 3.4D).

Variation was highest in late flight and rose again in late stance. Therefore, variation in trunk-shank coordination increased prior to events in the gait cycle, suggesting athletes might adjust these segments in preparation for achieving the desired body positions at touchdown and toe-off. Specific positions at these events might present challenges which athletes approach in different ways due to varying organismic constraints.

3.3.3 Shank-foot coordination

Several common shank-foot patterns emerged across participants, which may stem from subgroups of athletes with similar constraints, while there was high between-individual variation - primarily due to differences in timing of common coordination features around late flight and early stance (Figure 3.7A-C) and variation in foot angle (Figure 3.4F). Coordination in flight was in-phase foot (+)(light blue) which transitioned to in-phase shank (+)(dark blue). Given the conjoined nature the segments, such in-phase motion during flight may be expected. Before touchdown, particularly in steps 2 to 4, the shank and foot reversed to in-phase foot (-)(light purple) in preparation for ground contact.

A key feature of shank-foot coordination surrounded ankle dorsiflexion during early stance. Dorsiflexion was characterised by anti-phase foot (+)(light green) and shank (-)(dark green) coordination, typically sandwiched by short in-phase shank (-)(dark purple) periods (Figure 3.7A). In dorsiflexion, anti-clockwise foot rotation toward a flat orientation was coupled with clockwise shank rotation over the foot. Segment dominance during dorsiflexion differed between steps 1 and 2 compared to later steps. In step 1, dorsiflexion was associated with foot dominant anti-phase (light green)(Figure 3.7), which remained true for approximately half of participants in step 2, with significantly more anti-phase foot (+) in steps 1 and 2 compared to steps 3 and 4 (Figure 3.7D). Shank dominant dorsiflexion characterised these latter steps. Thus ankle dorsiflexion in initial stance (Bezodis et al., 2014, 2019b; Charalambous et al., 2012) is primarily driven by foot rotation in the first step and shifts to be shank driven in later steps, with a larger role for ‘shin roll’ (Alt et al., 2022) in later steps. The segment dominancy change reflects a transition from more horizontal shank and vertical foot orientations in step 1 towards more vertical shank and flat foot orientations in subsequent steps(Table 3.1; Figure 3.4E & F), as well as less ankle dorsiflexion in earlier steps (Figure 3.4C). More horizontal shank orientations in step 1 may require greater relative foot rotation to facilitate the energy absorption performed by ankle dorsiflexion in early stance (Bezodis et al., 2014), while a more vertical shank and flat foot at touchdown in later steps might require shank dominant coordination for ankle dorsiflexion and forward CM translation.

All participants exhibited dominant clockwise foot rotation (in-phase (light purple) and anti-phase (light red)) from mid stance onwards, with the magnitude of dominance increasing progressively (Figure 3.7A-B). Step 1 had significantly more anti-phase foot (-)(light red) compared to later steps, with the frequency decreasing progressively over steps (Figure3.7D). Anti-phase prominence in the first step may result from geometric constraints (van Ingen Schenau, 1989; van Ingen Schenau et al., 1987) imposed by a more horizontal touchdown shank orientation, whereby the athlete cannot produce further shank rotation without compromising balance and therefore requires foot dominant action to translate the CM forward. Indeed, foot angle was

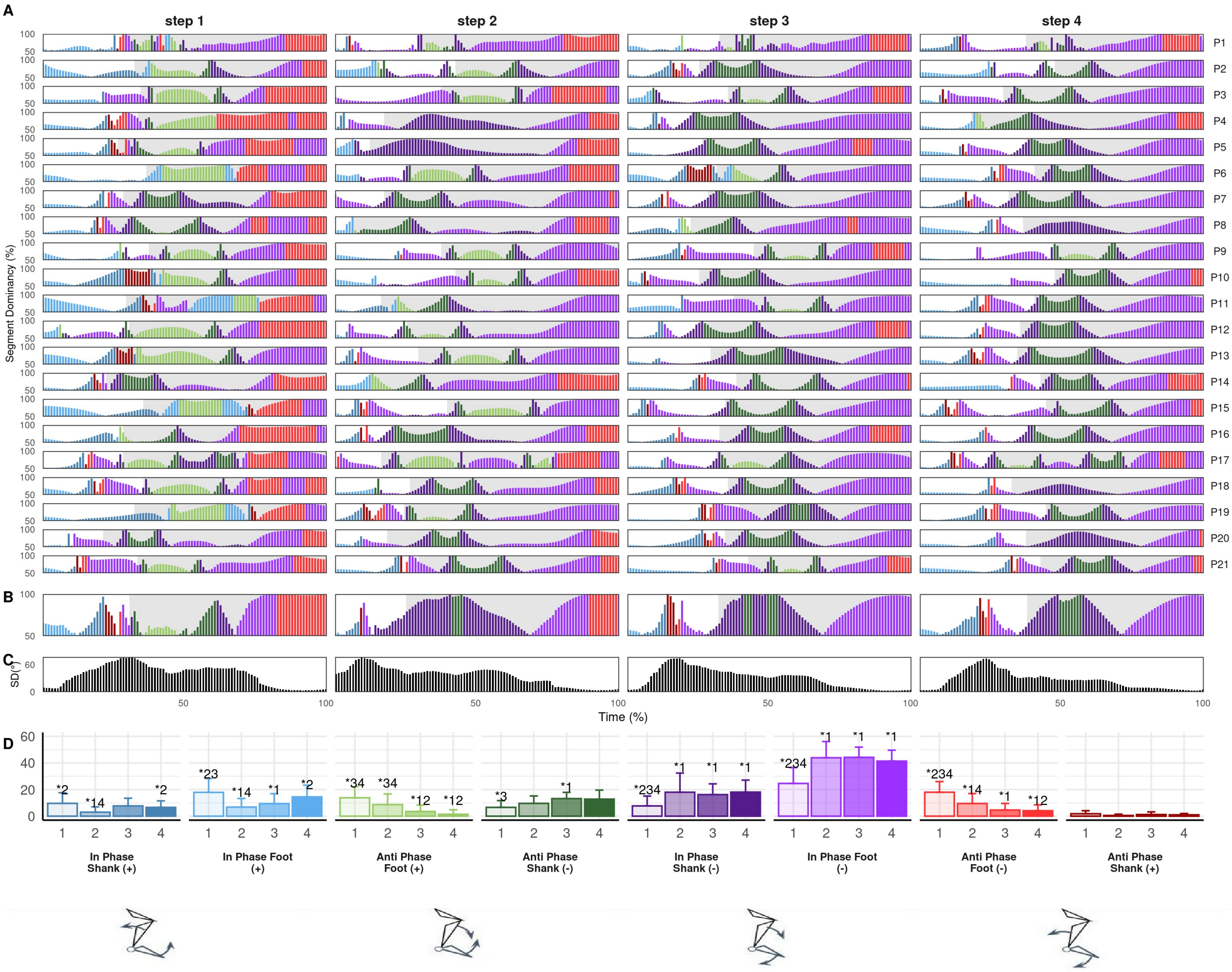

Figure 3.7: Individual (A) and mean (B) shank-foot coordination profiles, between-individual standard deviation (C) and mean bin frequencies (D) across steps 1 to 4. Coordination profile bar height shows segment dominancy (50 - 100%) and colour shows bin classification according to colour scale of bin frequency plot (D). Grey shaded area indicates stance.

significantly more vertical at toe-off (Table 3.1) and the shank approached toe-off angle earlier in step 1 than later steps, supporting the notion that greater foot rotation contributed to the forward CM translation which is an inherent feature of acceleration.

A stable shank angle during late stance may help to enable foot rotation to yield forward CM translation. In subsequent steps, coordination tended to be in-phase, indicative of increasingly vertical shank and flat foot orientations at touchdown and less vertical foot at toe-off. Yet, foot dominant in-phase rotation implies that even with a more vertical shank at touchdown, after the shank rotates over the foot during dorsiflexion, subsequent shank rotation observed during stance is driven by foot rotation. The progressive increase in magnitude of foot dominance suggests a key role for the foot in driving CM translation during initial acceleration, in accordance with the rotate and extend model of Jacobs and van Ingen Schenau (1992) and through the 'shin roll' concept developed by Alt et al. (2022). The initial rotation over the foot corresponds to the initial dorsiflexion observed in early stance, (Bezodis et al., 2014, 2019b; Charalambous et al., 2012) which is primarily shank dominant, but the subsequent ankle plantarflexion that occurs with the proximal-to-distal pattern of joint extension (Bezodis et al., 2014, 2019b; Charalambous et al., 2012; Jacobs and van Ingen Schenau, 1992) is driven by foot dominant rotation. Thus the rapid ankle plantarflexion which translates the CM forward in late stance is almost entirely driven by clockwise foot rotation. The consistency of this pattern across participants highlights potentially strong constraints on available shank-foot coordination strategies during stance.

3.3.4 Implications

While isolated segment kinematics have been well studied, the current study makes several novel contributions to understanding the relationships between segments, the changes in those relationships from step-to-step and the possible constraints on segment coordination during initial acceleration. These results indicate that initial sprint acceleration has relatively strong task constraints which yield broadly similar coordination patterns across a sample of male and female sprinters, including highly-trained and world-class athletes. Furthermore, these task constraints do not appear consistent across all four steps following block exit. While previous studies of step-to-step kinematics identified steps 3-6 as a breakpoint in acceleration (Nagahara et al., 2014; von Lieres und Wilkau et al., 2020), others have suggested the first stance should be considered separately from later steps and phases (Bezodis et al., 2014; Charalambous et al., 2012). The current study supports the latter assertion, indicating that across thigh-thigh, trunk-shank and shank foot couplings, step 1 has unique coordination. Block exit appears to impose constraints on the first step that result in athletes adopting different coordination strategies compared to subsequent steps. Specifically, athletes seem to require relatively longer to organise the thigh segments after block exit than after toe-off in later steps. Moreover, more horizontal trunk and shank orientations and more vertical foot placement at touchdown in step 1 result in more foot dominant shank-foot coordination and more trunk dominant trunk-shank coordination than steps 2-4. Foot dominant coordination from mid stance across all four steps implies a key role for the foot in driving CM translation during sprint acceleration which might have implications for performance related factors like horizontal force application. Finally, there was a novel finding of substantial trail leg dominance in thigh-thigh coordination, highlighting asymmetric thigh rotation during acceleration with faster swing leg rotation. Between-individual variation was highest around touchdown and toe-off, suggesting the main differences between individuals is how they prepare for, and respond to, these events as well as the relative timing in movement transitions associated with them. In particular, individuals' thigh-thigh coordination differed mostly in relation to toe-off and the timing of reversals in thigh rotation. Shank-foot coordination, in contrast, was mostly different around touchdown and early stance. Understanding the potential individual constraints (strength, anatomy, stature etc.) which may contribute to these differences should be the focus of future work. Further investigation is also required to determine whether different coordination strategies may be used to achieve the same performance outcome or whether better performance outcomes align with particular coordination approaches. Assessing the performance and physical capacities of athletes with similar coordination strategies may facilitate such an understanding.

3.4 Conclusion

This study comprehensively described and quantified coordination during initial acceleration across a range of well trained sprinters, identifying both common coordination patterns across the group as well as novel segment dominancy patterns in key relationships. Clear step to step changes in segment organisation and coordination were identified, with unique patterns observed in step 1. There are common coordination patterns amongst trained sprinters related to the task of accelerating, however individualised profiling highlighted potential individual-specific strategies, particularly in preparation for, or as a result of, touchdown and toe-off events. Inter-limb thigh coordination is primarily an anti-phase motion dominated by the trailing leg, while there is clear foot-dominance in shank-foot coordination in flight and late stance during acceleration which may suggest an important role of the foot in intra-limb coordination strategies during acceleration.

3.5 Chapter Summary

This chapter has addressed objective 1: *describe and quantify inter- and intra-limb coordination patterns exhibited by sprinters during early acceleration* and objective 2: *assess step-to-step changes in coordination during initial acceleration* through an assessment of thigh-thigh, trunk-shank and shank-foot during the first four steps of acceleration in 21 highly trained to world class sprinters. In doing so, it has provided the first quantification and description of common coordinative features and general patterns of coordination in this population and, notably, the first quantification of shank-foot coordination in sprinting. Moreover, differences were observed between steps in all segment couplings, providing further context for understanding coordination during initial acceleration.

Thigh-thigh coordination was predominantly trail-thigh dominant anti-phase rotation, with alternative coordination patterns and the greatest variation between participants occurring during the transition between steps at toe-off. Step 1, however, exhibited unique coordination in early flight compared to later steps likely due to the constraints of block exit. Trunk-shank coordination was mostly characterised by sequential anti-phase patterns where trunk and shank rotated toward each other in flight and away from each other in stance, with distinct patterns in step 1 resulting from reduced shank rotation compared to later steps. Finally, shank-foot coordination was substantially foot dominant, at various stages of the step, most notably during stance. In particular, differences between steps and variation between participants were evident during later flight and in the relative shank or foot dominance during early stance ankle dorsiflexion. Between steps, step 1 had the largest differences in kinematics and coordination compared to other steps and the largest step-to-step changes in all couplings occurred from step 1 to step 2, such that consideration of overall strategies during initial acceleration may need to consider step 1 separately from later steps.

Thus primary coordination patterns and major coordinative features were identified in well trained sprinters. However, between-individual variation in patterns was evident, and it is unclear whether there may be particular strategies characterised by specific differences in coordination and associated with sub-groups of athletes. Moreover, the relationship between performance and coordination patterns has not yet been evaluated. These two points formed the basis of objectives 3 and 4, and are considered in chapter 4.

References

Alt, T., Oeppert, T., Zedler, M., Goldmann, J.-P., Braunstein, B. and Willwacher, S. (2022), ‘A novel guideline for the analysis of linear acceleration mechanics - outlining a conceptual framework of ’shin roll’ motion’, *Sports Biomechanics* pp. 1–18.

Balasubramanian, S. (2013), Comparison of Angle Measurements between Vicon and MyoMotion Systems, PhD thesis, Arizona State University.

Bayne, H., Donaldson, B. and Bezodis, N. (2020), ‘Inter-limb Coordination During Sprint Acceleration’, *ISBS Proceedings Archive* **38**(1), 448–451.

Berner, K., Cockcroft, J., Morris, L. D. and Louw, Q. (2020), ‘Concurrent validity and within-session reliability of gait kinematics measured using an inertial motion capture system with repeated calibration’, *Journal of Bodywork and Movement Therapies* **24**(4), 251–260.

Bezodis, I. N., Brazil, A., von Lieres und Wilkau, H. C., Wood, M. A., Paradisis, G. P., Hanley, B., Tucker, C. B., Pollitt, L., Merlino, S., Vazel, P.-J., Walker, J. and Bissas, A. (2019a), ‘World-Class Male Sprinters and High Hurdlers Have Similar Start and Initial Acceleration Techniques’, *Frontiers in Sports and Active Living* **1**, 23.

Bezodis, N. E., Salo, A. I. T. and Trewartha, G. (2014), ‘Lower limb joint kinetics during the first stance phase in athletics sprinting: Three elite athlete case studies’, *Journal of Sports Sciences* **32**(8), 738–746.

Bezodis, N. E., Salo, A. I. T. and Trewartha, G. (2015), ‘Relationships between lower-limb kinematics and block phase performance in a cross section of sprinters’, *European Journal of Sport Science* **15**(2), 118–124.

Bezodis, N. E., Willwacher, S. and Salo, A. I. T. (2019b), ‘The Biomechanics of the Track and Field Sprint Start: A Narrative Review’, *Sports Medicine* **49**(9), 1345–1364.

Brazil, A., Exell, T., Wilson, C. and Irwin, G. (2020), ‘A biomechanical approach to evaluate overload and specificity characteristics within physical preparation exercises’, *Journal of Sports Sciences* **38**(10), 1140–1149.

Chang, R., Van Emmerik, R. and Hamill, J. (2008), ‘Quantifying rearfoot–forefoot coordination in human walking’, *Journal of Biomechanics* **41**(14), 3101–3105.

Charalambous, L., Irwin, G., Bezodis, I. N. and Kerwin, D. (2012), ‘Lower limb joint kinetics and ankle joint stiffness in the sprint start push-off’, *Journal of Sports Sciences* **30**(1), 1–9.

Clark, K. P., Meng, C. R. and Stearne, D. J. (2020), ‘“Whip from the hip”: Thigh angular motion, ground contact mechanics, and running speed’, *Biology Open* p. bio.053546.

Cottam, D. S., Campbell, A. C., Davey, M. P. C., Kent, P., Elliott, B. C. and Alderson, J. A. (2022), ‘Measurement of uni-planar and sport specific trunk motion using magneto-inertial measurement units: The concurrent validity of Noraxon and Xsens systems relative to a retro-reflective system’, *Gait & Posture* **92**, 129–134.

Davids, K., Glazier, P., Araújo, D. and Bartlett, R. (2003), ‘Movement Systems as Dynamical Systems’, *Sports Medicine* **33**(4), 245–260.

Debaere, S., Delecluse, C., Aerenhouts, D., Hagman, F. and Jonkers, I. (2013), ‘From block clearance to sprint running: Characteristics underlying an effective transition’, *Journal of Sports Sciences* **31**(2), 137–149.

Donaldson, B., Bayne, H. and Bezodis, N. (2020), ‘A Comparison of Trunk and Shank Angles between Elite and Sub-elite Sprinters During Sprint Acceleration’, *ISBS Proceedings Archive* **38**(1), 744.

Donaldson, B., Bezodis, N. and Bayne, H. (2021), ‘Within-subject repeatability and between subject variability in posture during calibration of an Inertial Measurement Unit system’, *ISBS Proceedings Archive* **39**(1), 4.

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

Glazier, P. S. (2017), ‘Towards a Grand Unified Theory of sports performance’, *Human Movement Science* **56**, 139–156.

Jacobs, R. and van Ingen Schenau, G. J. (1992), ‘Intermuscular coordination in a sprint push-off’, **25**(9), 953–965.

Jones, R., Bezodis, I. and Thompson, A. (2009), ‘Coaching Sprinting: Expert Coaches’ Perception of Race Phases and Technical Constructs’, *International Journal of Sports Science & Coaching* **4**(3), 385–396.

Kakehata, G., Goto, Y., Iso, S. and Kanosue, K. (2021), 'Timing of Rectus Femoris and Biceps Femoris Muscle Activities in Both Legs at Maximal Running Speed', *Medicine & Science in Sports & Exercise* **53**(3), 643–652.

Kassambara, A. (2021), *rstatix: Pipe-Friendly Framework for Basic Statistical Tests*. R package version 0.7.0.

Kiely, J. and Collins, D. J. (2016), 'Uniqueness of Human Running Coordination: The Integration of Modern and Ancient Evolutionary Innovations', *Frontiers in Psychology* **7**, 262.

Kugler, F. and Janshen, L. (2010), 'Body position determines propulsive forces in accelerated running', *Journal of Biomechanics* **43**(2), 343–348.

McKay, A. K., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Goosey-Tolfrey, V. L., Sheppard, J. and Burke, L. M. (2021), 'Defining Training and Performance Caliber: A Participant Classification Framework', *International Journal of Sports Physiology and Performance* **17**(2), 317–331.

Morin, J.-B., Edouard, P. and Samozino, P. (2011), 'Technical Ability of Force Application as a Determinant Factor of Sprint Performance', *Medicine & Science in Sports & Exercise* **43**(9), 1680–1688.

Nagahara, R., Matsubayashi, T., Matsuo, A. and Zushi, K. (2014), 'Kinematics of transition during human accelerated sprinting', *Biology Open* **3**(8), 689–699.

Nagahara, R., Matsubayashi, T., Matsuo, A. and Zushi, K. (2018), 'Kinematics of the thorax and pelvis during accelerated sprinting', *The Journal of Sports Medicine and Physical Fitness* **58**(9), 1253–63.

Needham, R. A., Naemi, R., Hamill, J. and Chockalingam, N. (2020), 'Analysing patterns of coordination and patterns of control using novel data visualisation techniques in vector coding', *The Foot* p. 101678.

Needham, R., Naemi, R. and Chockalingam, N. (2014), 'Quantifying lumbar–pelvis coordination during gait using a modified vector coding technique', *Journal of Biomechanics* **47**(5), 1020–1026.

Newell, K. (1986), Constraints on the development of coordination, *in* 'Motor Development in Children : Aspects of Coordination and Control', Martinus Nijhoff, pp. 341–360.

Okudaira, M., Willwacher, S., Kawama, R., Ota, K. and Tanigawa, S. (2021), ‘Sprinting kinematics and inter-limb coordination patterns at varying slope inclinations’, *Journal of Sports Sciences* **0**(0), 1–10.

R Core Team (2020), *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria.

Rabita, G., Dorel, S., Slawinski, J., Sàez-de Villarreal, E., Couturier, A., Samozino, P. and Morin, J.-B. (2015), ‘Sprint mechanics in world-class athletes: A new insight into the limits of human locomotion: Sprint mechanics in elite athletes’, *Scandinavian Journal of Medicine & Science in Sports* **25**(5), 583–594.

Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., de Villarreal, E. S.-S. and Morin, J.-B. (2016), ‘A Simple Method for Measuring Power, Force, Velocity Properties, and Mechanical Effectiveness in Sprint Running’, *Scandinavian Journal of Medicine & Science in Sports* **26**(6), 648–658.

Slawinski, J., Bonnefoy, A., Levêque, J.-M., Ontanon, G., Riquet, A., Dumas, R. and Chèze, L. (2010), ‘Kinematic and Kinetic Comparisons of Elite and Well-Trained Sprinters During Sprint Start:’, *Journal of Strength and Conditioning Research* **24**(4), 896–905.

Struzik, A., Konieczny, G., Grzesik, K., Stawarz, M., Winiarski, S. and Rokita, A. (2015), ‘Relationship between lower limbs kinematic variables and effectiveness of sprint during maximum velocity phase’, *Acta of Bioengineering and Biomechanics* **17**(4), 131–138.

Struzik, A., Konieczny, G., Stawarz, M., Grzesik, K., Winiarski, S. and Rokita, A. (2016), ‘Relationship between Lower Limb Angular Kinematic Variables and the Effectiveness of Sprinting during the Acceleration Phase’, *Applied Bionics and Biomechanics* **2016**, 1–9.

van Ingen Schenau, G. (1989), ‘From rotation to translation: Constraints on multi-joint movements and the unique action of bi-articular muscles’, *Human Movement Science* **8**(4), 301–337.

van Ingen Schenau, G., Bobbert, M. and Rozendal, R. (1987), ‘The unique action of bi-articular muscles in complex movements’, *Journal of Anatomy* **155**, 5.

von Lieres und Wilkau, H. C., Irwin, G., Bezodis, N. E., Simpson, S. and Bezodis, I. N. (2020), ‘Phase analysis in maximal sprinting: An investigation of step-to-step technical changes between the initial acceleration, transition and maximal velocity phases', *Sports Biomechanics* **19**(2), 141–156.

Walker, J., Bissas, A., Paradisis, G. P., Hanley, B., Tucker, C. B., Jongerius, N., Thomas, A., von Lieres und Wilkau, H. C., Brazil, A., Wood, M. A., Merlino, S., Vazel, P.-J. and Bezodis, I. N. (2021), 'Kinematic factors associated with start performance in World-class male sprinters', *Journal of Biomechanics* **124**, 110554.

Yoon, T.-L. (2017), 'Validity and Reliability of an Inertial Measurement Unit-Based 3D Angular Measurement of Shoulder Joint Motion', *The Journal of Korean Physical Therapy* **29**(3), 145–151.

Chapter 4

Characterising coordination strategies during initial acceleration in sprinters ranging from highly trained to world class

This chapter has been published in the ***Journal of Sports Sciences*** *as:*
Donaldson BJ., Bezodis NE., Bayne H. (2024) Characterising coordination strategies during initial acceleration in sprinters ranging from highly trained to world class. *Journal of Sports Sciences.*

Abstract

Identifying coordination strategies used by sprinters and features that differentiate these strategies will aid in understanding different technical approaches to initial sprint acceleration. Moreover, multiple effective coordination strategies may be available to athletes of similar ability, which typical group-based analyses may mask. This study aimed to identify sub-groups of sprinters based on thigh-thigh and shank-foot coordination during initial acceleration, and assess sprint performance across different combinations of coordination strategies. Angular kinematics were obtained from 21 sprinters, and coordination determined using vector coding methods, with step 1 and steps 2–4 separated for analysis. Performance was assessed using metrics derived from velocity-time profiles. Using hierarchical cluster analysis, three distinct coordination strategies were identified from thigh-thigh and shank-foot coordination in step 1 and two strategies in steps 2–4. Coordination strategies primarily differed around early flight thigh-thigh coordination and early stance shank-foot coordination in step 1, while timing of reversals in thigh rotation characterised differences in later steps. Higher performers tended to have greater lead thigh and foot dominance in step 1 and early swing thigh retraction in steps 2–4. The novel application of cluster analysis to coordination provides new insights into initial acceleration technique in sprinters, with potential considerations for training and performance.

4.1 Introduction

Acceleration performance depends on positioning body segments and coordinating their rotations to effectively apply forces to the ground to propel the body forward (Kugler and Janshen, 2010; Morin et al., 2011, 2015; Slawinski et al., 2010; von Lieres und Wilkau et al., 2020). In practical settings, a popular method for analysing sprint technique involves a sequence of images from key events, as demonstrated by the *kinogram* method (McMillan and Pfaff, 2018). These images depict 'shapes' (McMillan and Pfaff, 2018), and whilst practitioners may visually consider the relations between segments, biomechanical investigations have typically focused on isolated joints or segments which do not facilitate easy interpretation of the relative motion of these elements - i.e., their coordination. Coordination thus describes the relative rotation of two functionally linked segments, aiding understanding of the transition from one key event ('shape') to another (Bezodis et al., 2019a; Kimura et al., 2021; Okudaira et al., 2021). From a dynamical systems perspective, coordination emerges spontaneously from interacting individual, task and environmental constraints in a self-organising manner (Bernstein, 1967; Davids et al., 2003; Kelso and Schöner, 1988; Newell, 1986). In acceleration, multiple technical strategies could therefore lead to the same performance outcome depending on the particular interaction between the individual, task, and environment - a feature known as degeneracy (Tononi et al., 1999; Wild et al., 2021). Wild et al. (2021) demonstrated this concept by showing that professional rugby backs could be clustered into four distinct sprint acceleration strategies based on the ratios of step length/frequency and contact time/flight time,but that no one strategy led to better acceleration performance. Such a characterisation of strategies remains unexplored from a coordination perspective, or in a well-trained population.

The hip and ankle play important roles during the block phase and first steps of acceleration, with a relatively more minor role for the knee (Bezodis et al., 2014, 2015; Brazil et al., 2016; Charalambous et al., 2012; Debaere et al., 2013). Jacobs and van Ingen Schenau (Jacobs and van Ingen Schenau, 1992) showed that sprinters accelerate the centre of mass through 'rotation' then 'extension' of the stance (i.e., support) limb. This aligns with the 'shin roll' framework proposed by Alt et al. (2022), which describes shank rotation over the foot during stance in sprinting, potentially accounting, at least partly, for the 'rotation' component (Jacobs and van Ingen Schenau, 1992). However, the foot is not a static base during stance and is an important component of ankle dorsi- and plantarflexion motions during ground contact (Bezodis et al., 2014; Brazil et al., 2016; Charalambous et al., 2012). Regarding the hips, bipedal gait inherently requires cyclic limb interchange (Kiely and Collins, 2016), and Clark et al. (2020) have shown the importance of large amplitudes of thigh separation and high frequencies of interchange to maximal velocity performance. Moreover, thigh action helps set up lower limb touchdown positions from which rotation occurs. Thus, characterising inter-limb thigh-thigh coordination can enhance the understanding of this interchange between limbs while intra-limb shank-foot coordination strategies can enhance the understanding of the adjacent segment rotations that comprise ankle motion.

Existing coordination and kinematic studies in acceleration, have typically relied on a priori grouping based on criteria such as performance level, sprint event or task modification, when attempting to identify distinguishing kinematic parameters between groups (Bayne et al., 2020; Bezodis et al., 2019a; Donaldson et al., 2022b; Okudaira et al., 2021). However, such criteria are not always available or appropriate, especially in relatively homogeneous or continuous samples without clear divides. Moreover, a priori grouping ignores potential between individual variation within groups, masking instances where different movement patterns can be used to produce the same performance outcome (Wild et al., 2021). Whilst some researchers have suggested individualised profiling to address this limitation (Needham et al., 2020), such an approach overlooks the possibility that strategy sub-groups exist, owing to similarities in constraints between certain performers, as has been suggested in other running contexts (van Oeveren et al., 2021). Grouping sprinters based on similar coordination strategies and consequently exploring the frequency with which different strategies are adopted, and whether any strategies are typically associated with better performance outcomes, could therefore further develop knowledge regarding initial acceleration technique. While recent studies have described coordination during sprint acceleration (Bezodis et al., 2019a; Donaldson et al., 2022b), none have attempted to understand acceleration technique and performance through sub-groups of coordination strategies. Given the considerable practical interest in the kinematics of effective acceleration, it is important to identify and explain the strategies adopted by sprinters, and the potential performance implications of each strategy. This will assist practitioners in assessing the technical approach of their athletes and designing individual specific interventions for training.

The purpose of this study was, firstly, to identify and characterise sub-groups of sprinters with similar coordination strategies during initial acceleration, and to assess whether different sub-groups are associated with differences in key discrete kinematic measures. Having analysed the coordination strategies of the different sub-groups, the second purpose was to compare performance between the sub-groups with a view to understanding whether certain strategies may be more beneficial for higher initial acceleration performance.

4.2 Methods

Fifteen male (age = 22.0 ± 3.6 yrs, stature = 1.77 ± 0.06 m, mass = 74.6 ± 9.7 kg, 100 m personal best = 9.89 - 11.17 s) and six female (age = 22.8 ± 6.5 yrs, stature = 1.62 ± 0.05 m, mass = 54.1 ± 2.2 kg, 100 m personal best = 11.45 - 12.14 s) sprinters were recruited using convenience sampling and provided informed consent to take part in this study. All participants were 100 m and 200 m specialists, in the competition phase of their season, and injury free at the time of testing. According to the criteria of McKay et al. (2021), fourteen sprinters (9 M, 5 F) were classified as highly trained, five as elite (4 M, 1 F) and two (2 M). For the purposes of our analysis, all were initially considered as part of a single cohort from which the sub-groups were subsequently determined using cluster analysis based on their coordination profiles. All procedures were performed in accordance with the declaration of Helsinki and the institutional research ethics committee approved the protocol (612/2020).

Participants performed three maximal effort sprint trials of at least 20 m, starting from blocks, in their own spikes. These were part of their typical sprint training and took place during regular training sessions in the competition phase of the season. Participants completed their habitual warm ups, and at least five minutes separated each trial to minimise the effect of fatigue.

Three-dimensional (3D) kinematics were recorded using tri-axial inertial measurement units (IMUs) (200 Hz; MyoMotion, Noraxon, USA), the validity and reliability of which have been previously reported (Balasubramanian, 2013; Berner et al., 2020a; Cottam et al., 2022; Yoon, 2017). Nine IMUs were affixed, according to manufacturer instructions, to the upper spine (T1), lower spine (T12), sacrum, lateral aspect of both thighs, antero-medial aspect of both shanks and the dorsal surface of each foot. All were secured using double-sided tape and either self-adhesive bandages or custom velcro straps to limit movement due to impact forces

(Donaldson et al., 2022b)(See Chapter 3). A sagittal plane camera (120 Hz, Ninox-250, Noraxon, USA) recorded the first four steps of each trial. IMU and video data were captured simultaneously and synchronised in real time with the MyoSync device and MyoResearch 3.14 software (Noraxon, USA). IMUs were calibrated in an upright standing posture prior to each trial with standardised instructions to establish the 0° reference angle, according to a previously described protocol (Berner et al., 2020b; Donaldson et al., 2021)(See Appendix A). Touchdown and toe-off were determined from video, with touchdown defined as the first frame with visible ground contact and toe-off the first frame where the foot was no longer visibly contacting the ground. Steps were defined from toe-off until the subsequent toe-off of the contralateral foot, starting from front foot block exit (TO_0). Flight time was determined as the time from toe-off until touchdown of the contralateral foot and contact time as the time from touchdown until toe-off. Limbs were designated as *leading* or *trailing* based on their relative position at the beginning of the step (i.e. toe-off) (Bayne et al., 2020; Okudaira et al., 2021). Due to the cyclic nature of sprinting, whether the right or left leg was leading or trailing alternated at each toe-off. Angles of the trunk, lead and trail thigh, and lead limb shank and foot were extracted and defined according to the 0° reference angle of the standing calibration posture (Berner et al., 2020a; Donaldson et al., 2022b)(See Chapter 3). All kinematic variables were time normalised to 101 data points for each step. Finally, average angular velocity over the entire step was determined for lead and trail thigh according to the methods of Clark et al. (2020).

For each trial, a radar gun recorded instantaneous horizontal velocity (47 Hz; Stalker Pro II ATS, Stalker, USA). A simple macroscopic model was fit to velocity-time data, from which split times and force-velocity variables were extracted (Morin et al., 2019; Samozino et al., 2016) using the *shorts* R package (Jovanović, 2020). Theoretical maximum horizontal force (F_0), theoretical maximum velocity (V_0), maximum power (P_{Max}), maximum ratio of the horizontal force component to the resultant force (ratio of forces; RF_{Max}) and the slope of the relationship between RF and velocity (D_{RF}) were determined from the model outputs, which have been shown to have a grand average bias of 4.7% and reliable within 2.4% for kinetic variables Morin et al. (2019).

Inter-limb thigh-thigh and intra-limb shank-foot coordination were quantified from lead and trail thigh angles and lead limb shank and foot angles, respectively, using a modified vector coding technique (Chang et al., 2008; Donaldson et al., 2022b; Needham et al., 2020). Coupling angles (CA) were calculated as the angle of the vector between adjacent points relative to the right horizontal for each pair of consecutive points on the angle-angle plot, representing a vector between 0 and 360° describing the relative segment motion at each normalised time point (Figure 5.1(i)).

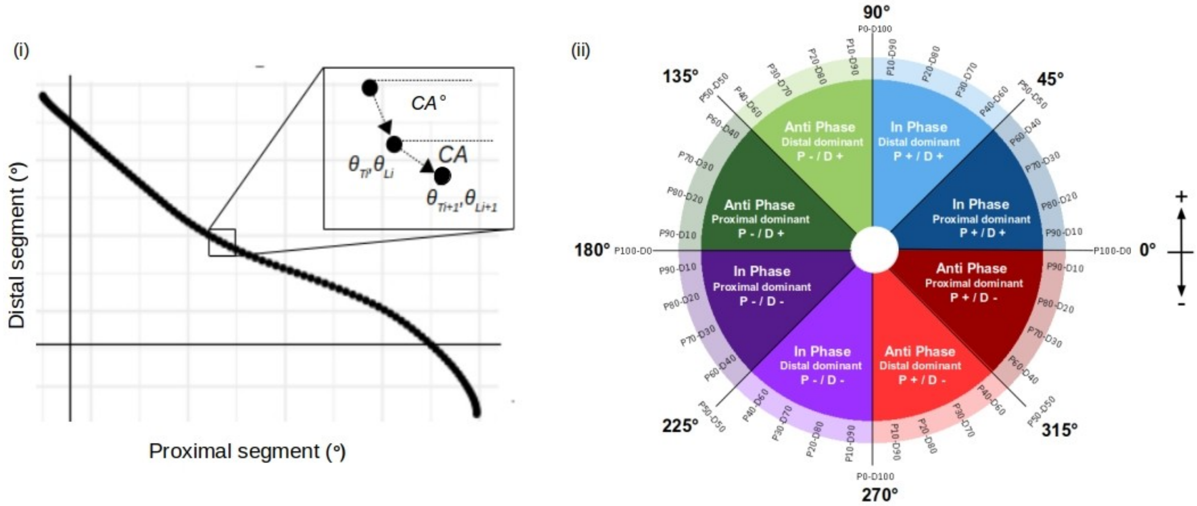

Figure 4.1: Example of angle-angle plot and coupling angle determination (i). Coordination bin classification system (ii), adapted from (Donaldson et al., 2022b; Needham et al., 2020).

Every CA was classified into a discrete bin describing the primary motion and the dominant segment according to the segment dominancy approach presented by Needham et al. (2020)(Figure 5.1(ii)). Couplings were described as proximal-distal, with the trailing thigh designated as the proximal segment. Rotations were described as clockwise-anticlockwise, as viewed from the right hand side, with anticlockwise rotation designated as positive (+) (Donaldson et al., 2022b). Thus, coordination bins are labeled by the relative motion, the dominant segment and the direction of rotation of the dominant segment. For example, thigh-thigh coordination with an anti-phase pattern and anticlockwise leading leg segment dominance is described as anti-phase leading (+) (Figure 5.1)(Donaldson et al., 2022b).

The similarity of coordination for every possible pair of participants, for each coupling, was calculated according to previously described methods (Donaldson et al., 2022a)(See Appendix B), without the final subtraction from 1, producing a pairwise distance matrix of coupling angle distance scores (CA_{dist}). Briefly, at each time point, the angular distance between corresponding CA vectors (Figure 5.1(i)), θ, was calculated as follows:

$$\theta(t) = \begin{cases} 360 - |A - B|, & \text{if } |A - B| > 180^\circ \\ |A - B|, & \text{otherwise} \end{cases} \tag{4.1}$$

For any pair of vectors, the maximum possible value of θ was 180°, representing directly opposite vectors. Therefore the final $\mathrm{CA}_{\mathrm{dist}}$ value was calculated as:

$$CA_{dist}(A, B) = \frac{\sum_0^t \theta(t)}{180t} \tag{4.2}$$

Where t represents the number of normalised time points (i.e. the 100 CA vectors between the 101 time-normalised data points), yielding a value between 0 (identical vector orientations at each time point) and 1 (directly opposite vector orientations at each time point). Distance matrices were computed for all pairwise combinations of participants for thigh-thigh and shank-foot couplings. Previous studies identified step-to-step changes in kinematics during initial acceleration (Nagahara et al., 2014; von Lieres und Wilkau et al., 2020) while coaching (Jones et al., 2009), kinematic (Bezodis et al., 2015; Charalambous et al., 2012) and coordination (Donaldson et al., 2022b) studies suggest that step 1 is different from later steps. Consequently, hierarchical agglomerative clustering analyses with complete linkage method were performed separately for step 1 and steps 2-4. The final number of clusters in each case were identified based on the agglomerative coefficient and visual inspection of the dendrograms (Hair et al., 2009; Nielsen, 2016; Phinyomark et al., 2015; Sarvestan et al., 2020).

4.2.1 Statistical Analysis

Group mean coordination profiles were determined for each cluster in step 1 and steps 2-4, and mean frequency (%) for each coordination bin was calculated. For each variable of interest, the normality assumption was assessed using a Shapiro-Wilks test. Between-cluster differences in bin frequency, linear and angular kinematic variables were assessed with Kruskal-Wallis and one-way analysis of variance (ANOVA) tests. Pairwise interactions between clusters were assessed with independent sample t-tests or Mann-Whitney U tests when two clusters were identified and Tukey or Wilcoxon signed rank tests for more than two clusters. All analyses were performed in R (R Core Team, 2020) using the *rstatix* (Kassambara, 2021) and *stats* (R Core Team, 2020) packages. Alpha level was set at 0.05.

4.3 Results

Three clusters were identified in step 1, labeled A, B and C (Figure 4.2(iii)). Cluster B accounted for 12/21 participants, with four and five in clusters A and C, respectively. Clusters A and B produced similar thigh-thigh coordination, with no significant differences in bin frequencies and only minor temporal visible differences in mean coordination profile (Figure 4.2(i & iv)). In contrast, cluster C produced significantly less in-phase trailing (+)($p = 0.044$) and anti-phase trailing (+)($p = 0.032$) than B (Figure 4.2(iv)). Participants in cluster C almost entirely lacked anti-phase leading (+) and in-phase leading or trailing (+) in early flight (Figure 4.2(i)). With the lower anti-phase trailing (+) frequency, the mean anti-phase leading (-) frequency in cluster C was 16% higher than cluster A and 14% higher than cluster B, but these differences were not significant. (Figure 4.2(iv)). For shank-foot coordination, in-phase foot (+) frequency was significantly higher in cluster A, than both B ($p = 0.022$) and C ($p = 0.048$) while cluster B was also significantly higher than C ($p = 0.007$)(Figure 4.2 (ii & v)).

In cluster A, in-phase shank (-) and anti-phase shank (-) coordination were entirely absent, significantly lower than both B ($p = 0.012$) and C ($p = 0.045$). Cluster A further had significantly less in-phase foot (-) than C ($p = 0.048$)(Figure 2(v)). Thus, during flight, A had prolonged in-phase anti-clockwise rotation before touchdown compared to C, which reversed to in-phase clockwise rotation in mid flight. During early stance, A showed foot dominant anti-phase rotation, compared to shank dominant rotation exhibited by the other clusters.

Two clusters were identified in steps 2-4, labeled X and Y (Figure 4.3(iii)). There were no significant differences in mean bin frequency across steps for any thigh-thigh bin (Figure 4.3(iv)). However, although in-phase leading (-) frequency was similar between clusters X and Y (Figure 4.3(iv), participants in cluster X had in-phase coordination in late stance but those in Y had in-phase coordination during early flight (Figure 4.3(i)). Thus, cluster X began swing leg retraction in late stance whereas cluster Y only began at toe-off while continuing to rotate the stance leg clockwise after leaving the ground.

Cluster X had significantly less in-phase foot (+) than Y ($p = 0.001$), and had 5% more in-phase foot (-) coordination, but this was not significant (Figure 4.3(v)). Therefore, the primary difference between clusters was one of timing; participants in cluster Y spent longer in in-phase

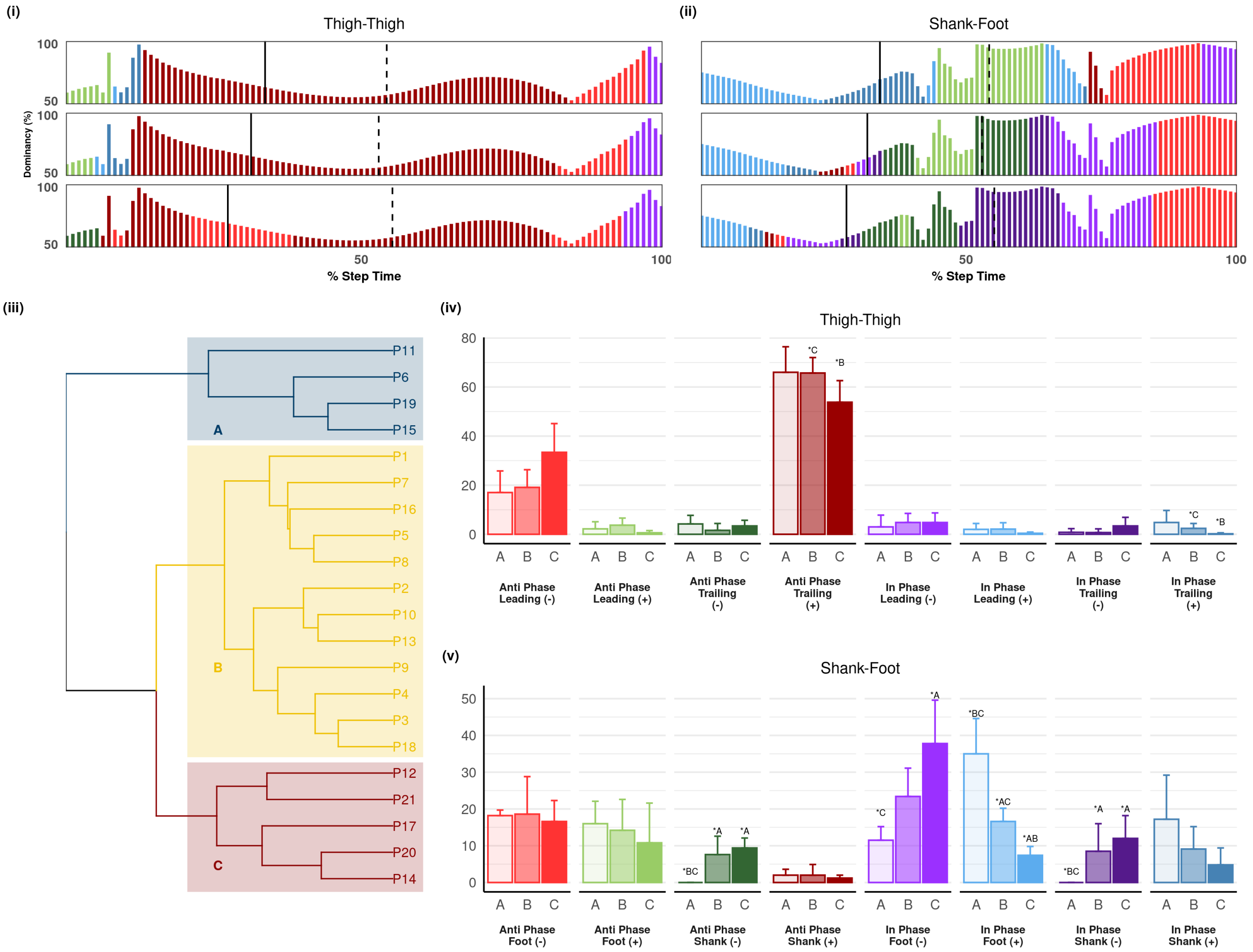

Figure 4.2: Step 1 mean coordination profiles for each cluster for thigh-thigh (i) and shank-foot (ii), dendrogram with clusters highlighted by colour (iii) and cluster mean coordination bin frequencies for each bin for thigh-thigh (iv) and shank-foot (v) couplings. Black vertical lines in figures (i) and (ii)indicate touchdown and dotted lines the thigh crossover in (i). The bin colours in (iv) and (v) serve as legends for (i) and (ii) respectively. *ABC annotations indicate significantly different to the respective (i.e., A, B or C) cluster, $p < 0.05$.

anti-clockwise rotation during flight and delayed the onset of anti-phase shank (-) and in-phase shank (-) coordination during stance (Figure 4.3(ii)).

At block clearance, thigh, shank and foot orientations differed between clusters (Figure 4.4(ii-iv)). Cluster C had significantly more vertical shank and horizontal foot orientations than both B and A, while B and A were also significantly different for both segments (Figure 4.4(iii-iv)). Moreover, C had a significantly more flexed lead thigh at block clearance compared to A and was 13° more flexed than B, but this was not significant (Figure 4.4(ii)).

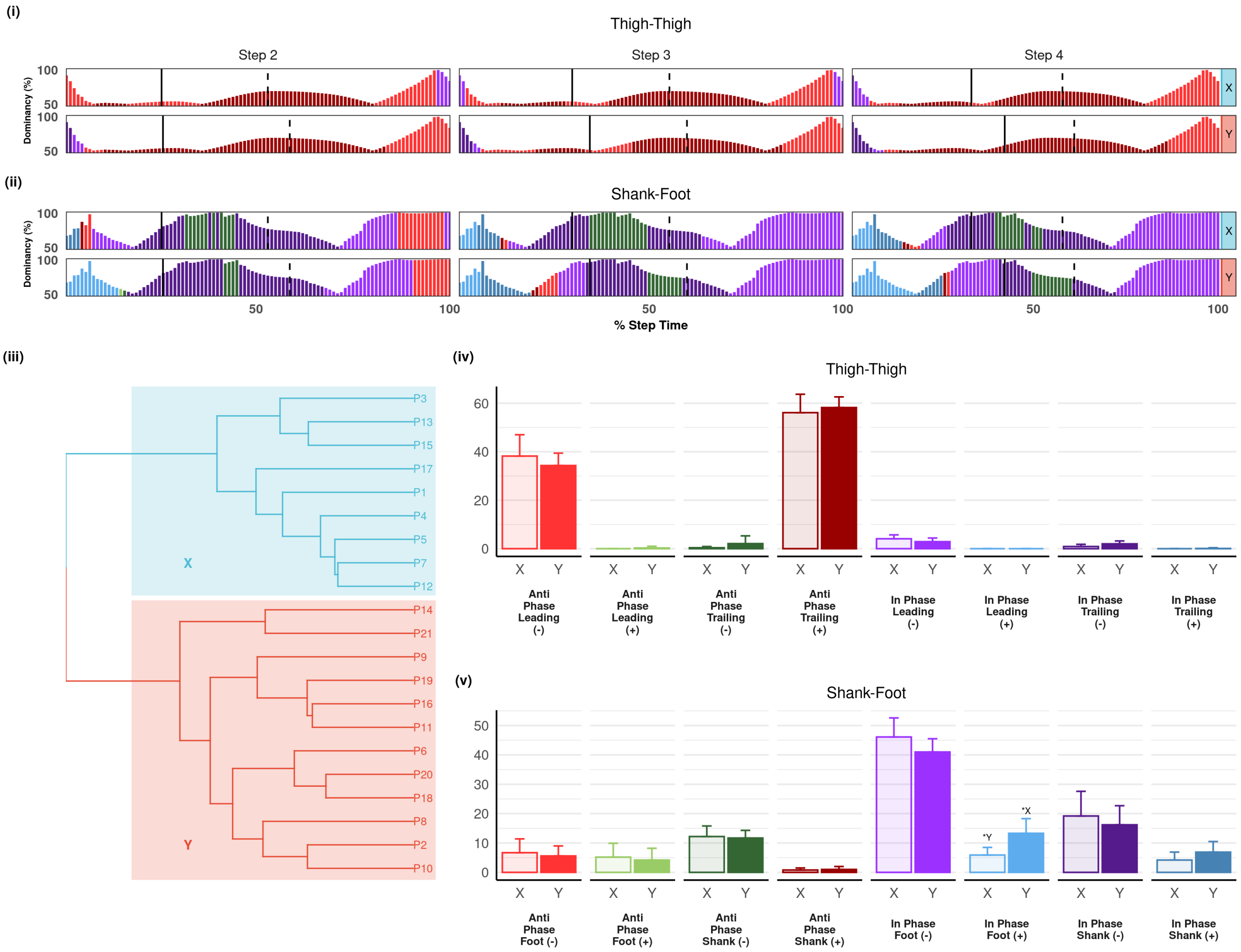

Figure 4.3: Step 2-4 mean coordination profiles for each cluster for thigh-thigh (i) and shank-foot (ii), dendrogram with clusters highlighted by colour (iii) and cluster mean coordination bin frequencies for each bin for thigh-thigh (iv) and shank-foot (v) couplings. Black vertical lines in figures (i) and (ii)indicate touchdown and dotted lines the thigh crossover in (i). The bin colours in (iv) and (v) serve as legends for (i) and (ii) respectively. *XY annotations indicate significantly different to the respective (i.e., X or Y) cluster, $p < 0.05$.

At touchdown, cluster A had significantly more horizontal shank orientations than both B ($p = 0.011$) and C ($p = 0.031$), as well as significantly more vertical foot orientations than C ($p = 0.037$)(Figure 4.4(vii-viii)). In step 1, cluster A had significantly shorter contact times (150 ± 6 ms) than C (194 ± 25 ms, $p = 0.015$), but not B (174 ± 22 ms) while there were no significant differences in flight times (A: 76 ± 9, B: 77 ± 13, C: 71 ± 13 ms) or lead (A: -272 ± 48, B: -270 ± 33, C: -291 ± 21 $^\circ$.sec^{-1}) and trail (A: 382 ± 39, B: 360 ± 46, C: 347 ± 12 $^\circ$.sec^{-1}) thigh angular velocities.

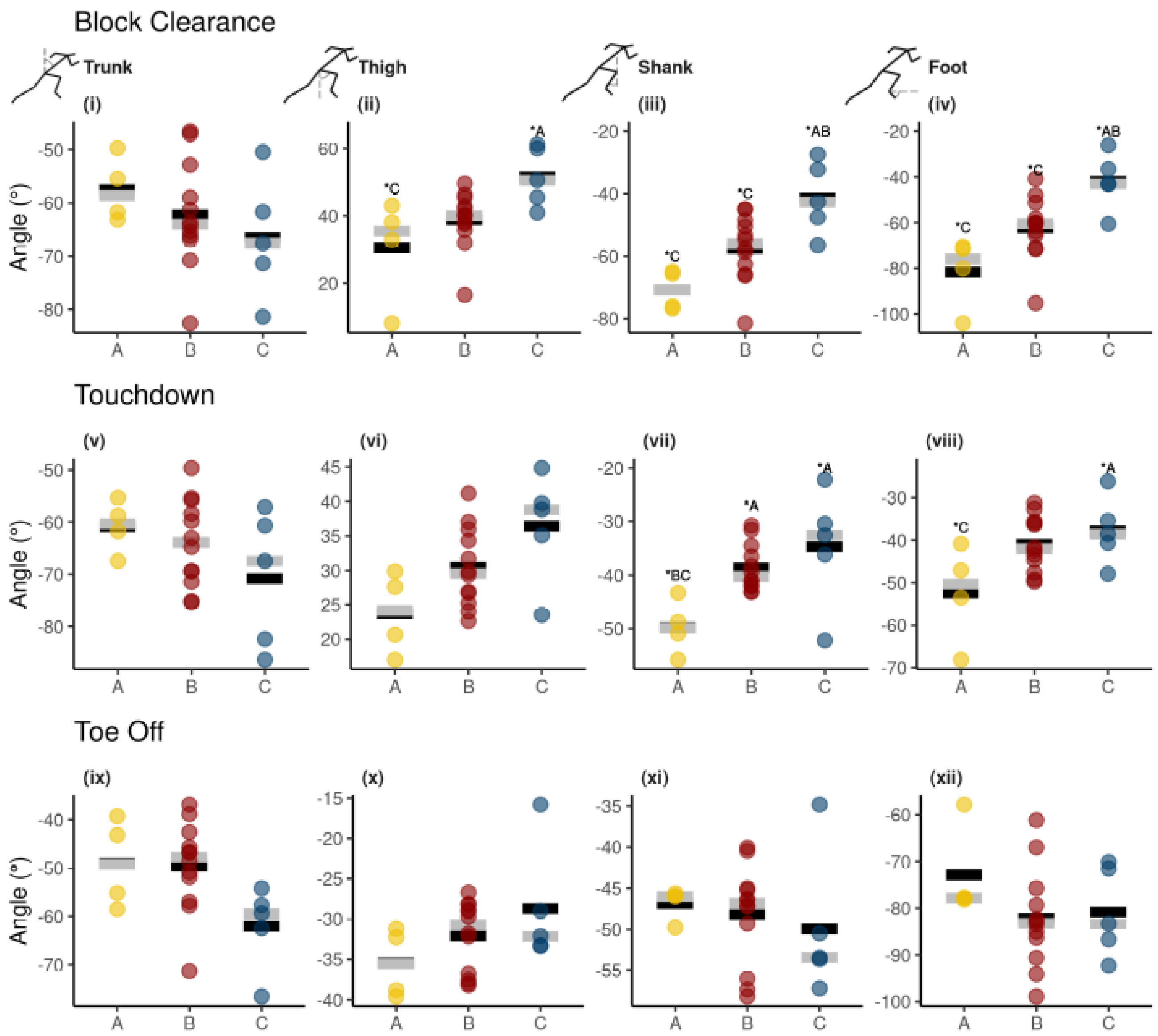

Figure 4.4: Discrete trunk, thigh, shank and foot segment angles at block clearance (i-iv), touchdown (v-viii) and toe-off (iv-xii) in step 1 for coordination clusters A, B and C. All angles are lead limb (designated at block clearance). Black horizontal bar represents the mean and the grey bar represents the median. *ABC annotations indicate significantly different to the respective (i.e., A, B or C) cluster, $p < 0.05$.

In steps 2-4, there were no statistically significant differences in mean touchdown and toe-off angular kinematics (Figure 4.5), nor did clusters differ significantly in contact times (X: 149 ± 17, Y: 141 ± 13 ms) or flight times (X: 60 ± 13, Y: 71 ± 14 ms). However, cluster X had significantly higher average lead thigh angular velocity (-399 ± 32 $^\circ.s^{-1}$) compared to cluster Y (-372 ± 26 $^\circ.s^{-1}$).

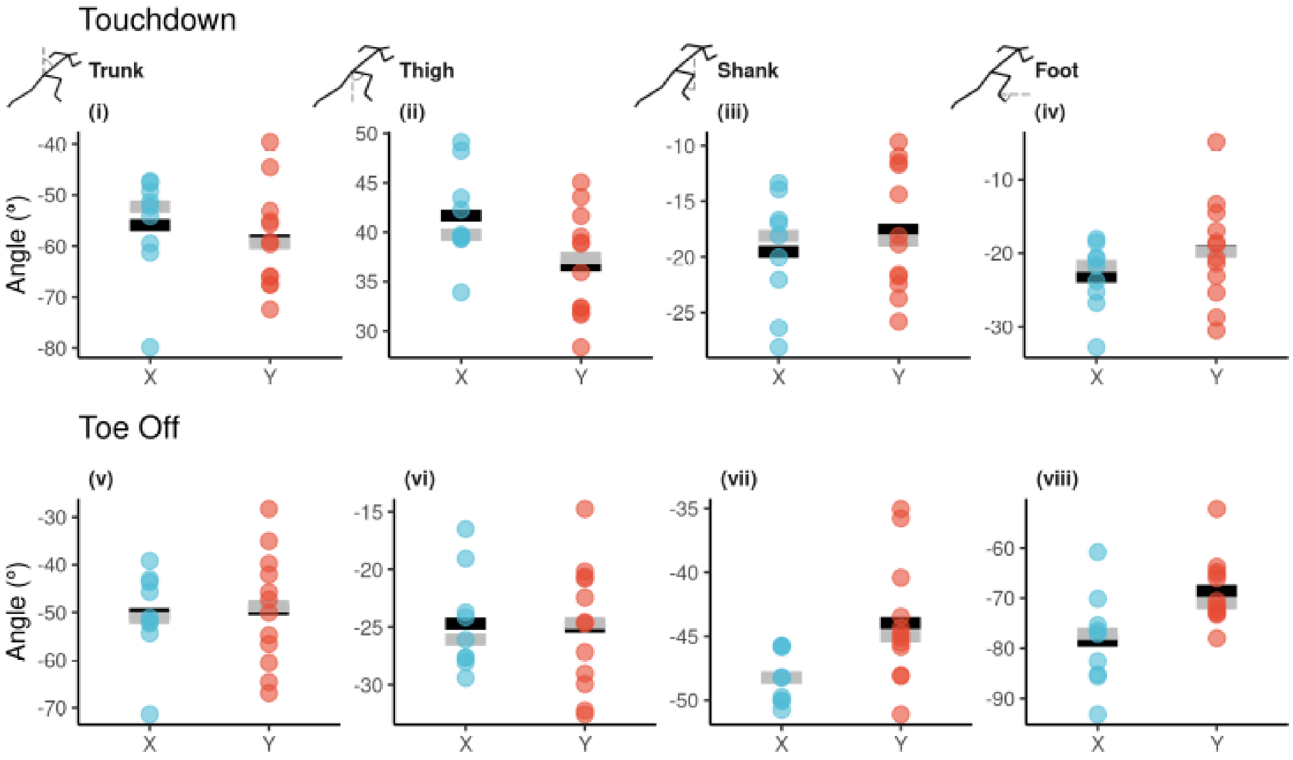

Figure 4.5: Discrete trunk, thigh, shank and foot segment angles averaged across steps 2-4 at touchdown (i-iv) and toe-off (v-viii) for coordination clusters X and Y. All angles are lead limb (designated at toe-off). Black horizontal bar represents the mean and the grey bar represents the median.

Before comparing performance between clusters, male and female participants were compared to ensure that sex distribution across clusters did not influence comparisons. Performance levels in female participants were significantly lower across all performance variables ($p < 0.001$), except D_{RF}, compared to males. Given these between-sex differences in performance and the small number of female participants in the sample, females were excluded from between-cluster statistical comparisons of performance and only male athletes were compared. In males, no significant differences existed between step 1 or steps 2-4 clusters for any performance variable.

Six combinations were possible across the two sets of clusters (Figure 4.6). The two most common combinations resulted from the twelve cluster B participants in step 1 dividing equally into X and Y in steps 2-4. Both world-class and two out of four elite male participants were in B-X, while B-Y and A-Y had one and two elite participants respectively. Given the participant distribution, statistical comparisons between combinations was restricted to the two most common: B-X and B-Y.

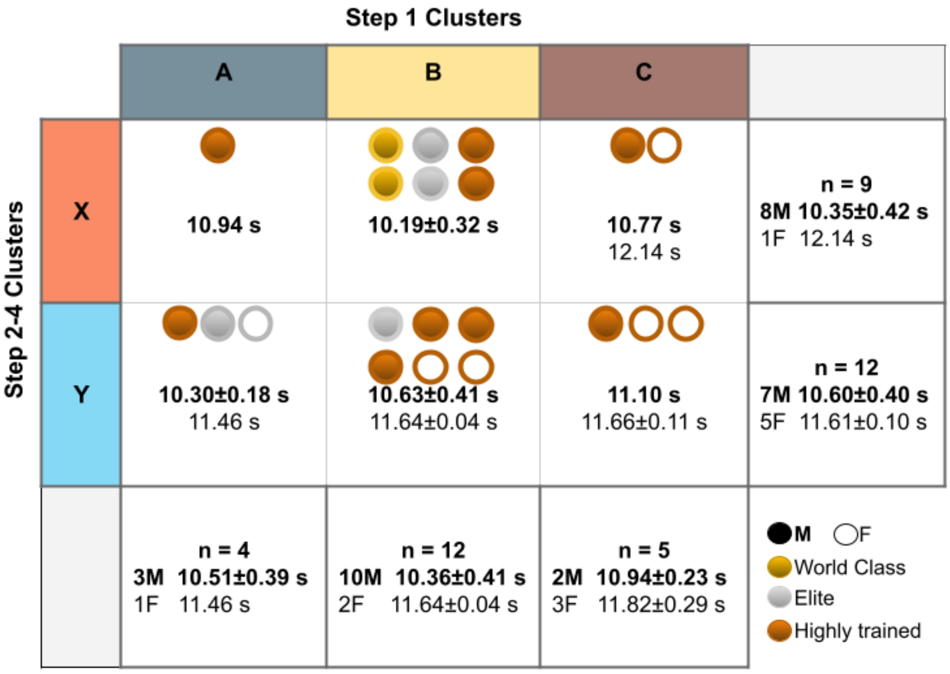

Figure 4.6: Matrix demonstrating step 1 and steps 2-4 cluster combinations with sex, performance level and 100 m personal bests. Gold, silver and bronze colours denote performance level classification according to criteria of McKay et al. (McKay et al., 2021).

Participants in B-X were significantly faster over 20 m (2.97 ± 0.04 s) than those in B-Y (3.18 ± 0.15 s, p = 0.02)(Figure 4.7(i)). Participants in B-X also produced higher F_0 (9.13 ± 0.68 N.kg^{-1}), P_{max} (23.8 ± 1.8 W.kg^{-1}) and RF_{max} (58 ± 2%) than those in B-Y (F_0: 8.25 ± 0.90 N.kg^{-1}; P_{max} (20.0 ± 2.8 W.kg^{-1}; RF_{max} (54 ± 3%), but these differences were not significant.

4.4 Discussion

This study aimed to identify and characterise sub-groups of sprinters with similar coordination strategies during initial acceleration and assess whether different sub-groups are associated with differences in kinematics at key events and acceleration performance. Through a novel application of hierarchical cluster analysis to vector coding data, three distinct lower-limb sprint acceleration coordination strategies were identified in step 1 and two in steps 2-4. Clusters in step 1 were also associated with certain discrete kinematic differences at block clearance and touchdown, while steps 2-4 clusters had no discrete kinematic differences at key events. Sprint performance did not differ between clusters in either step 1 or steps 2-4, however when combined, clusters revealed a potential coordination strategy associated with higher level sprinters

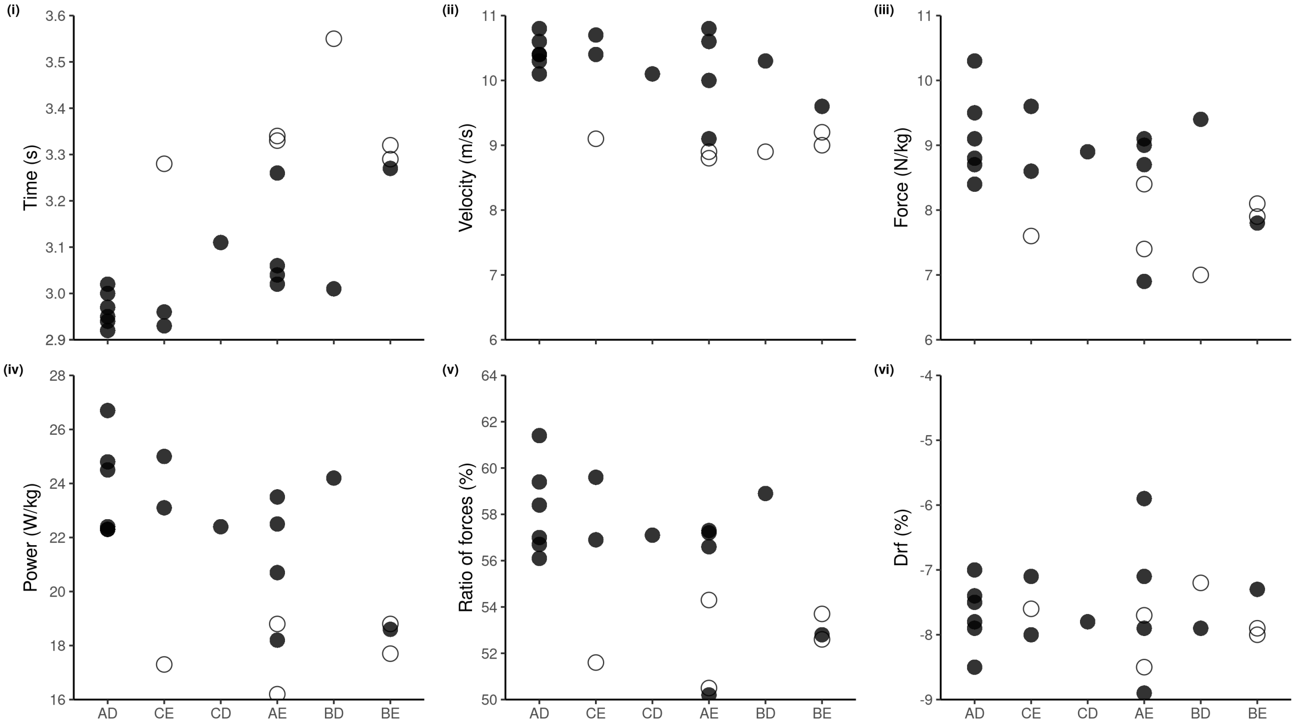

Figure 4.7: Performance variables for step 1 and steps 2-4 cluster combinations, 20 m time (i), theoretical maximal velocity (V_0)(ii), theoretical maximal horizontal force (F_0)(iii), maximal horizontal power (P_{max})(iv), ratio of forces (RF)(v) and degradation of RF (D_{RF})(vi). Closed and open points reflect male and female participants respectively. Note that the y axes do not begin at 0 for any variable to enable the between- and within-group variation to be visualised.

and better sprint times.

In step 1, clusters A and B exhibited similar thigh coordination, characterised by lead thigh dominant anti-phase coordination (increased thigh separation) immediately after block exit followed by in-phase simultaneous thigh flexion before the lead limb reversed direction and retracted and the rear limb continued to flex through. The subsequent limb interchange was trail thigh dominant. Participants in clusters A and B therefore tended to be differentiated more by shank-foot than thigh-thigh coordination. During flight, cluster A displayed only in-phase anti-clockwise shank-foot coordination while B exhibited a shorter period of in-phase rotation and had anti-phase coordination in late flight (Figure 4.8(i)). Thus, cluster B demonstrated 'shin block' (Alt et al., 2022) - a reversal in shank rotation direction before touchdown - which was absent in cluster A. This difference may relate to cluster A displaying more horizontal lead limb shank orientations at block clearance compared to the other clusters (Figure 4.4(iii-iv)) - appearing to 'tuck' the shank beneath the thigh - requiring anti-clockwise rotation in flight to prepare for touchdown. Cluster A dorsiflexion had entirely foot dominant anti-phase coordination, likely reflecting the more horizontal shank orientation observed at touchdown, relying on ‘heel drop’ from a more vertical foot during dorsiflexion and less ‘shin roll’ (Alt et al., 2022) from an already horizontal shank. Cluster B, on the other hand, exhibited shank dominant coordination at the beginning and end of dorsiflexion with foot dominant coordination in-between, suggesting initial ‘shin roll’ followed by ‘heel drop’ before further ‘shin roll’ towards the end of dorsiflexion. These patterns associated with dorsiflexion were relatively longer in cluster A compared to B, implying a relatively longer portion of stance in power absorption given the resultant plantar flexor moments which are known to be present throughout the first stance phase (Bezodis et al., 2014).

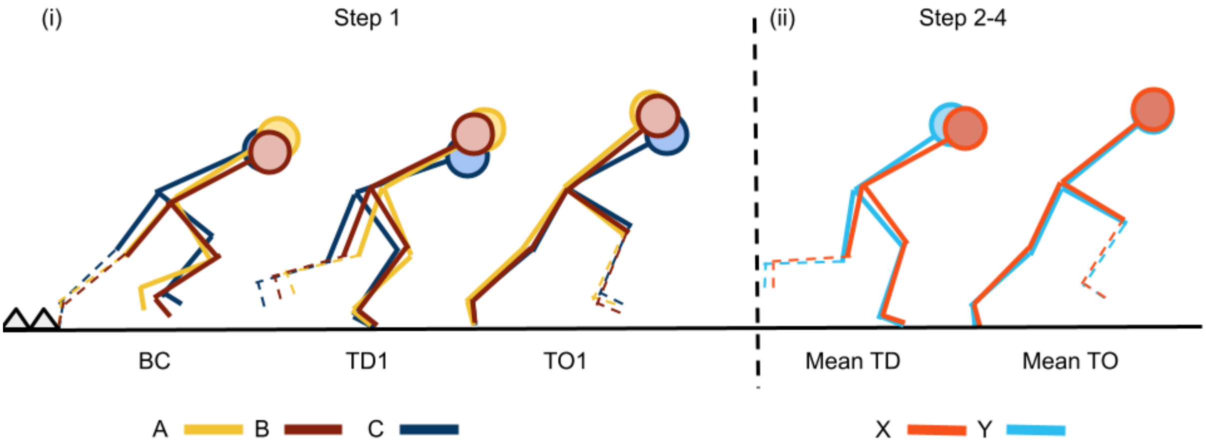

Figure 4.8: Typical body orientations at key events for clusters in step 1 (i) and the average segment orientations over steps 2-4 (ii). Dashed lines indicate the limb that was not analysed. BC = block clearance; TD = Touchdown; TO = Toe-off.

In contrast to A and B, cluster C was trail thigh dominant after block clearance and had no in-phase coordination in early flight (Figure 4.2(i)). Thus, C didn’t exhibit the same pattern of dominant lead thigh flexion, rather appearing to already approach the maximum lead thigh flexion angle at block exit (Figure 4.4(ii); 4.8(i)) and subsequently increased thigh separation after block exit through clockwise trail leg rotation (hip extension). These differences in trail thigh motion may result from differences in timing of muscle actions between groups (Phinyomark et al., 2015) or be related to differences in strength profiles between groups, such that different strength profiles may associate with different thigh-thigh coordination patterns, and further work to more directly explore this is required. Moreover, cluster C had shorter in-phase anticlockwise shank-foot rotation during flight and prolonged in-phase clockwise rotation before touchdown, indicating relatively earlier 'shin block' (Alt et al., 2022) compared to B. Cluster C had correspondingly more vertical shank orientations at both block clearance and touchdown. Thus, after block clearance they continued trail thigh extension before retracting the lead limb relatively earlier than other clusters, 'planting' the leg down into ground contact. In stance, cluster C exhibited more shank dominant anti-phase dorsiflexion, potentially indicating greater reliance on 'shin roll' (Alt et al., 2022) to translate the CM during that period. Such reliance on 'shin roll' might link to the longer contact times observed in C and could also be related to positive touchdown distance (foot ahead of CM), which has previously been associated with lower performance (e.g. Wild et al. (2018)). The current observations suggest that lead leg segment orientations at block clearance may influence coordination during the subsequent flight and ground contact, yet these angles are rarely reported and warrant further attention in both research and practice.

The main difference in thigh-thigh coordination between step 2-4 clusters was one of timing of reversals in thigh rotation (Figure 4.3(i)). Cluster X exhibited an 'early retractor' strategy, retracting the swing thigh before toe-off, resulting in in-phase clockwise coordination in late stance. This pattern continues momentarily in early flight before the trail leg reverses to initiate anti-phase motion. Cluster Y exhibited the same general pattern, but began lead thigh retraction at toe-off and displayed longer in-phase clockwise rotation because the trail thigh continued extending after toe-off. Thus showing a delayed swing leg recovery (Clark et al., 2020) which is sometimes termed 'overpushing' in applied practice. Cluster X was associated with significantly higher lead thigh angular velocities compared to Y, which has been associated with faster running speeds during maximal velocity sprinting (Clark et al., 2020). Thus, early retraction might indicate earlier initiation of accelerating the lead thigh and therefore facilitate higher angular velocities into the next step. By step 4, thigh coordination in X and Y more closely resembled each other, appearing to converge on the strategy typical of cluster Y.

Clusters were also differentiated by timing differences in shank-foot coordination (Figure 4.3(ii)). Cluster X displayed less anti-clockwise shank and foot rotation during flight and a relatively shorter flight time, resulting in a relatively earlier ground contact than Y, likely reflecting the early lead limb retraction. As a result, X exhibited relatively earlier shank dominant anti-phase coordination during dorsiflexion, although dorsiflexion was shank dominant in both clusters. In contrast to step 1, these timing differences between clusters in both couplings were not associated with any differences in kinematics at key events (Figure 4.5, 4.8(ii).

Of the six possible combinations of step 1 and steps 2-4 strategies, the majority of participants were either B-X (6) or B-Y (6) combinations, followed by A-Y (3) and C-Y (3), with A-X (1) and C-X (2) least common (Figure 4.6). Thus, early retraction (X) or delayed swing leg recovery (Y) strategies in steps 2-4 were equally likely from participants in step 1 cluster B, but other step 1 clusters were less likely to correspond with early retraction. Of the two most common strategies, B-X was associated with higher performing athletes - including both world class participants as well as two out of five elite participants whilst B-Y was almost entirely composed of highly trained participants (Figure 4.6). In sprint tests, comparing only male athletes, the B-X combination had the fastest 20 m times and significantly faster times than B-Y. Thus, although there were no significant differences in performance measures between isolated clusters from either step 1 or steps 2-4, the combination of clusters to define a single initial acceleration strategy implies that a B-X strategy could be associated with better performance. Further, although not significant, B-X athletes tended to perform better across force and power variables, but not V_0 or D_{RF}. Thus, initial lead thigh dominant flexion in flight and 'shin block' in late flight (B) in step 1 combined with early swing leg retraction (X) in later steps might be exhibited by physically stronger athletes and therefore reflect a strategy allowing them to express their physical capacities. Further work is required to investigate the relationships between coordination strategies and strength, especially in more nuanced ways than macroscopic associations with force-velocity-power profiles. The performance of the two male athletes that adopted the A-Y strategy, characterised by lead thigh flexion dominant coordination in early flight and shank tuck in step 1 combined with a delayed swing leg recovery in later steps was comparable with that of those exhibiting a B-X strategy (Figure 4.7). The small number of participants who displayed this approach suggest it is less common, and future work could explore what specific individual constraints might be associated with such an approach as it may be an equally effective strategy as the more common B-X.

Comparable performances between B-X and A-Y combinations could potentially indicate degeneracy in these coordination strategies (Wild et al., 2021). These strategies only differed in shank-foot coordination, such that the different shank-foot approaches (i.e. high or low foot dominancy) could be equally effective in combination with the same thigh motion and could possibly result from differences in individual anatomy or strength or coaching. It remains to be explored whether potential degeneracy in coordination could relate to degeneracy observed in linear kinematic strategies during initial acceleration (Wild et al., 2021). However, while these observations imply the potential for degeneracy in some strategies, in totality, the performance results presented here point toward the existence of coordination strategies associated with higher performance in a sample of well-trained sprinters as well as strategies that are more commonly observed in this population.

The current study is the first to apply a clustering approach to coordination in sprinting and has provided new insights into the body organisation during initial acceleration. However, there remain several limitations. Hierarchical clustering facilitated the novel identification of initial acceleration coordination strategies, but the identified strategies are not exhaustive, and these patterns may not generalise outside the current population of experienced, high level sprinters. Whilst increasing the sample could also provide a more robust characterisation of the coordination strategies and their effectiveness, this study intentionally focused only on high level sprinters and the current sample is relatively large in comparison with other studies of such populations. Furthermore, the current study included only segment kinematics since data collection took place in an uninvasive manner during real training sessions. The future measurement of external kinetics would enable a direct assessment of the relationship between coordination and force application for each step, as well as additional consideration of joint kinetics that could enhance the understanding of coordination differences between different patterns, especially with regard to the ankle joint during dorsiflexion, given the important absorption performed during this period (Bezodis et al., 2014; Charalambous et al., 2012).

For practitioners, the approach applied in the current study highlights the potential to quantitatively profile sprinters such that their individual coordination patterns can be understood in the context of the different available strategies. These results suggest that the pattern of thigh interchange after block clearance and the balance of shank or foot dominance during ankle dorsiflexion appear to be important factors which distinguish the different coordination profiles adopted by sprinters during initial acceleration. Different coordination strategies were also associated with differences in discrete kinematics, particularly at block clearance and touchdown in step 1, suggesting coaches should be mindful of the impact on movement patterns that cues to adopt specific body positions might have.

The current study has identified distinct technical strategies from lower limb coordination patterns during acceleration. In a sample of highly-trained to world class sprinters, cluster analysis of similar coordination strategies identified three sub-groups of sprinters in the first step and two sub-groups in the subsequent three steps. The results show that, in males, coordination strategies characterised by lead thigh dominant flexion in early flight and greater foot dominant coordination during early stance dorsiflexion in step 1 combined with early swing thigh retraction in later steps was associated with faster times and higher performers. By classifying the coordination strategies used by high-level sprinters during initial acceleration, this study helps to understand the range of approaches available to sprinters and identify the key coordinative features which distinguish different strategies in this population. This aids coaches and researchers in further understanding the technical approaches used by sprinters as well as the coordination of movement between the positions adopted at key events.

4.5 Chapter summary

This chapter has addressed objective 3: *identify different initial acceleration coordination strategies used by sprinters and characterise the typical features of these patterns*, and objective 4: *explore the associations between the coordination strategies exhibited by sprinters and acceleration performance* by clustering sprinters with similar coordination strategies together and comparing discrete kinematics and performance between sub-groups. Through clustering, different coordination strategies emerged in step 1 and steps 2-4 and the primary coordination features that differentiated sub-groups could be characterised. Although there were no performance differences between clusters when considering step 1 and steps 2-4 separately, combining step 1 and steps 2-4 clusters to describe entire initial acceleration coordination revealed certain strategies adopted by the majority of elite and world class sprinters in the sample and which were associated with better acceleration performance. Thus, through a novel application of clustering to coordination data, this chapter has characterised potential strategies in trained sprinters and provided a basis from which to further explore particular coordination features that may be expressed by higher level sprinters and associated with better performance.

As such, this chapter has extended the empirical analyses from chapter 3 through the first application of clustering approaches to coordination data in sprinters, identifying sub-groups of sprinters exhibiting similar coordination patterns during the first four steps. Coordination characterised by lead thigh flexion after block clearance and foot dominant ankle dorsiflexion in step 1 combined with early swing thigh retraction and reduced swinging out of the shank during flight in steps 2-4 tended to be associated with better performance. However, the results also showed that individuals from certain sub-groups could produce similar performances, suggesting that different coordination patterns could be used to achieve the same level of performance, which may be linked to different individual constraints associated with these sub-groups. To understand the potential influence of individual constraints on coordination and performance, it is necessary to assess the relationships between coordination and important individual qualities like strength. This may be especially valuable if these factors have interactions relevant to acceleration performance. These questions form the basis for chapter 5.

References

Alt, T., Oeppert, T., Zedler, M., Goldmann, J.-P., Braunstein, B. and Willwacher, S. (2022), ‘A novel guideline for the analysis of linear acceleration mechanics - outlining a conceptual framework of ’shin roll’ motion’, *Sports Biomechanics* pp. 1–18.

Balasubramanian, S. (2013), Comparison of Angle Measurements between Vicon and MyoMotion Systems, PhD thesis, Arizona State University.

Bayne, H., Donaldson, B. and Bezodis, N. (2020), ‘Inter-limb Coordination During Sprint Acceleration’, *ISBS Proceedings Archive* **38**(1), 448–451.

Berner, K., Cockcroft, J. and Louw, Q. (2020a), ‘Kinematics and temporospatial parameters during gait from inertial motion capture in adults with and without HIV: A validity and reliability study’, *BioMedical Engineering OnLine* **19**(1), 57.

Berner, K., Cockcroft, J., Morris, L. D. and Louw, Q. (2020b), ‘Concurrent validity and within-session reliability of gait kinematics measured using an inertial motion capture system with repeated calibration’, *Journal of Bodywork and Movement Therapies* **24**(4), 251–260.

Bernstein, N. A. (1967), *Co-Ordination and Regulation of Movements*, Pergamon Press.

Bezodis, I. N., Brazil, A., von Lieres und Wilkau, H. C., Wood, M. A., Paradisis, G. P., Hanley, B., Tucker, C. B., Pollitt, L., Merlino, S., Vazel, P.-J., Walker, J. and Bissas, A. (2019a), ‘World-Class Male Sprinters and High Hurdlers Have Similar Start and Initial Acceleration Techniques’, *Frontiers in Sports and Active Living* **1**, 23.

Bezodis, N. E., Salo, A. I. T. and Trewartha, G. (2014), ‘Lower limb joint kinetics during the first stance phase in athletics sprinting: Three elite athlete case studies’, *Journal of Sports Sciences* **32**(8), 738–746.

Bezodis, N. E., Salo, A. I. T. and Trewartha, G. (2015), ‘Relationships between lower-limb kinematics and block phase performance in a cross section of sprinters’, *European Journal of Sport Science* **15**(2), 118–124.

Brazil, A., Exell, T., Wilson, C., Willwacher, S., Bezodis, I. and Irwin, G. (2016), ‘Lower limb joint kinetics in the starting blocks and first stance in athletic sprinting’, *Journal of Sports Sciences* **35**(16), 1629–1635.

Chang, R., Van Emmerik, R. and Hamill, J. (2008), 'Quantifying rearfoot–forefoot coordination in human walking', *Journal of Biomechanics* **41**(14), 3101–3105.

Charalambous, L., Irwin, G., Bezodis, I. N. and Kerwin, D. (2012), 'Lower limb joint kinetics and ankle joint stiffness in the sprint start push-off', *Journal of Sports Sciences* **30**(1), 1–9.

Clark, K. P., Meng, C. R. and Stearne, D. J. (2020), '"Whip from the hip": Thigh angular motion, ground contact mechanics, and running speed', *Biology Open* **9**(10), bio.053546.

Cottam, D. S., Campbell, A. C., Davey, M. P. C., Kent, P., Elliott, B. C. and Alderson, J. A. (2022), 'Measurement of uni-planar and sport specific trunk motion using magneto-inertial measurement units: The concurrent validity of Noraxon and Xsens systems relative to a retro-reflective system', *Gait & Posture* **92**, 129–134.

Davids, K., Glazier, P., Araújo, D. and Bartlett, R. (2003), 'Movement Systems as Dynamical Systems', *Sports Medicine* **33**(4), 245–260.

Debaere, S., Delecluse, C., Aerenhouts, D., Hagman, F. and Jonkers, I. (2013), 'From block clearance to sprint running: Characteristics underlying an effective transition', *Journal of Sports Sciences* **31**(2), 137–149.

Donaldson, B., Bezodis, N. and Bayne, H. (2021), 'Within-subject repeatability and between subject variability in posture during calibration of an Inertial Measurement Unit system', *ISBS Proceedings Archive* **39**(1), 4.

Donaldson, B., Bezodis, N. and Bayne, H. (2022a), 'Similarity of Coordination Patterns in a group of Highly Trained Sprinters: A Novel Approach', *ISBS Proceedings Archive* **40**(1), 4.

Donaldson, B. J., Bezodis, N. E. and Bayne, H. (2022b), 'Inter- and intra-limb coordination during initial sprint acceleration', *Biology Open* **11**(10), bio059501.

Hair, J. F., Anderson, R. E., Babin, B. J. and Black, W. C. (2009), *Multivariate Data Analysis*, seventh edn, Prentice Hall, London.

Jacobs, R. and van Ingen Schenau, G. J. (1992), 'Intermuscular coordination in a sprint push-off', *Journal of Biomechanics* **25**(9), 953–965.

Jones, R., Bezodis, I. and Thompson, A. (2009), 'Coaching Sprinting: Expert Coaches' Perception of Race Phases and Technical Constructs', *International Journal of Sports Science & Coaching* **4**(3), 385–396.

Jovanović, M. (2020), *shorts: Short Sprints.* R package version 1.1.4.

Kassambara, A. (2021), *rstatix: Pipe-Friendly Framework for Basic Statistical Tests.* R package version 0.7.0.

Kelso, J. A. S. and Schöner, G. (1988), 'Self-organization of coordinative movement patterns', *Human Movement Science* **7**(1), 27–46.

Kiely, J. and Collins, D. J. (2016), 'Uniqueness of Human Running Coordination: The Integration of Modern and Ancient Evolutionary Innovations', *Frontiers in Psychology* **7**.

Kimura, A., Yokozawa, T. and Ozaki, H. (2021), 'Clarifying the Biomechanical Concept of Coordination Through Comparison With Coordination in Motor Control', *Frontiers in Sports and Active Living* **3**, 753062.

Kugler, F. and Janshen, L. (2010), 'Body position determines propulsive forces in accelerated running', *Journal of Biomechanics* **43**(2), 343–348.

McKay, A. K., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Goosey-Tolfrey, V. L., Sheppard, J. and Burke, L. M. (2021), 'Defining Training and Performance Caliber: A Participant Classification Framework', *International Journal of Sports Physiology and Performance* **17**(2), 317–331.

McMillan, S. and Pfaff, D. (2018), *Kinogram Method Ebook*, ALTIS.
URL: *https://altis.world/kinogram-method-ebook/*

Morin, J.-B., Edouard, P. and Samozino, P. (2011), 'Technical Ability of Force Application as a Determinant Factor of Sprint Performance', *Medicine & Science in Sports & Exercise* **43**(9), 1680–1688.

Morin, J.-B., Gimenez, P., Edouard, P., Arnal, P., Jiménez-Reyes, P., Samozino, P., Brughelli, M. and Mendiguchia, J. (2015), 'Sprint Acceleration Mechanics: The Major Role of Hamstrings in Horizontal Force Production', *Frontiers in Physiology* **6**, 404.

Morin, J.-B., Samozino, P., Murata, M., Cross, M. R. and Nagahara, R. (2019), 'A simple method for computing sprint acceleration kinetics from running velocity data: Replication study with improved design', *Journal of Biomechanics* **94**, 82–87.

Nagahara, R., Matsubayashi, T., Matsuo, A. and Zushi, K. (2014), 'Kinematics of transition during human accelerated sprinting', *Biology Open* **3**(8), 689–699.

Needham, R. A., Naemi, R., Hamill, J. and Chockalingam, N. (2020), 'Analysing patterns of coordination and patterns of control using novel data visualisation techniques in vector coding', *The Foot* **44**, 101678.

Newell, K. (1986), Constraints on the development of coordination, *in* 'Motor Development in Children : Aspects of Coordination and Control', Martinus Nijhoff, pp. 341–360.

Nielsen, F. (2016), Hierarchical Clustering, *in* F. Nielsen, ed., 'Introduction to HPC with MPI for Data Science', Undergraduate Topics in Computer Science, Springer International Publishing, Cham, pp. 195–211.

Okudaira, M., Willwacher, S., Kawama, R., Ota, K. and Tanigawa, S. (2021), 'Sprinting kinematics and inter-limb coordination patterns at varying slope inclinations', *Journal of Sports Sciences* **0**(0), 1–10.

Phinyomark, A., Osis, S., Hettinga, B. A. and Ferber, R. (2015), 'Kinematic gait patterns in healthy runners: A hierarchical cluster analysis', *Journal of Biomechanics* **48**(14), 3897–3904.

R Core Team (2020), *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria.

Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., de Villarreal, E. S.-S. and Morin, J.-B. (2016), 'A Simple Method for Measuring Power, Force, Velocity Properties, and Mechanical Effectiveness in Sprint Running', *Scandinavian Journal of Medicine & Science in Sports* **26**(6), 648–658.

Sarvestan, J., Svoboda, Z., Baeyens, J.-P. and Serrien, B. (2020), 'Whole body coordination patterning in volleyball spikes under various task constraints: Exploratory cluster analysis based on self-organising maps', *Sports Biomechanics* **22**(9), 1153–1167.

Slawinski, J., Bonnefoy, A., Levêque, J.-M., Ontanon, G., Riquet, A., Dumas, R. and Chèze, L. (2010), 'Kinematic and Kinetic Comparisons of Elite and Well-Trained Sprinters During Sprint Start:', *Journal of Strength and Conditioning Research* **24**(4), 896–905.

Tononi, G., Sporns, O. and Edelman, G. M. (1999), 'Measures of degeneracy and redundancy in biological networks', *Proceedings of the National Academy of Science* **96**, 3257–3262.

van Oeveren, B. T., de Ruiter, C. J., Beek, P. J. and van Dieën, J. H. (2021), 'The biomechanics of running and running styles: A synthesis', *Sports Biomechanics* pp. 1–39.

von Lieres und Wilkau, H. C., Irwin, G., Bezodis, N. E., Simpson, S. and Bezodis, I. N. (2020), ‘Phase analysis in maximal sprinting: An investigation of step-to-step technical changes between the initial acceleration, transition and maximal velocity phases’, *Sports Biomechanics* **19**(2), 141–156.

Wild, J. J., Bezodis, I. N., North, J. S. and Bezodis, N. E. (2018), ‘Differences in step characteristics and linear kinematics between rugby players and sprinters during initial sprint acceleration’, *European Journal of Sport Science* **18**(10), 1327–1337.

Wild, J. J., Bezodis, I. N., North, J. S. and Bezodis, N. E. (2021), ‘Characterising initial sprint acceleration strategies using a whole-body kinematics approach’, *Journal of Sports Sciences* **40**(2), 203–214.

Yoon, T.-L. (2017), ‘Validity and Reliability of an Inertial Measurement Unit-Based 3D Angular Measurement of Shoulder Joint Motion’, *The Journal of Korean Physical Therapy* **29**(3), 145–151.

Chapter 5

Relationships between coordination, strength and performance during initial sprint acceleration

This chapter is in preparation for submission to the ***Scandinavian Journal of Medicine and Science in Sport*** *as:*
Donaldson BJ., Bezodis NE., Bayne H. (*in preparation*) Relationships between coordination, strength and performance during initial sprint acceleration. *Scandinavian Journal of Medicine and Science in Sport*

Abstract

Despite strong logical and theoretical links between physical qualities and movement coordination, no studies have directly examined the relationship between these factors during initial sprint acceleration, or how they potentially combine to relate to performance outcome. The aim of this study was to assess the associations between initial acceleration coordination and lower body strength, and explore potential interactions between strength and coordination in relation to acceleration performance. Sagittal plane kinematics and velocity-time profiles were obtained for 12 highly trained to world class male sprinters (100 m PB: 9.95 - 11.17 s). Thigh-thigh and shank-foot coordination was determined for the first four steps using vector coding and external kinetic parameters were determined from a mono-exponential fit to the velocity-time profile. Lower body strength was measured with isometric squat (ISqT), countermovement jump (CMJ), repeated hop (HJ) and Nordic hamstring tests. Relationships between coordination and strength were assessed with correlations, and interactions between strength and coordination in relation to performance explored through multiple regression analyses. Large to very large correlations (0.59 - 0.82) existed between ISqT, CMJ, HJ tests and specific coordination features in both step 1 and steps 2-4, but there were no associations with Nordic hamstring performance. Regression analyses suggested specific features of coordination and strength interacted in relation to horizontal force application; relationships between specific co-

ordination patterns and initial acceleration performance changed when given strength capacities were higher or lower. These findings imply a need for individualised consideration of technique in sprint training, especially regarding the influence of strength qualities on the adoption and effectiveness of movement patterns.

5.1 Introduction

Coordination patterns describe the relationships between functionally linked components of the musculoskeletal system over the course of a movement, typically through the relative motion of pairs of joints or segments (Kimura et al., 2021). These relationships represent an important component of technique, and quantifying coordination in sprinting expands on the analyses of isolated joints and segments typical of the sprint literature. From a dynamical systems perspective, patterns of coordination emerge from the interaction of task, environment and organismic constraints that define the range of available strategies afforded within a particular movement context (Davids et al., 2003; Glazier, 2017; Newell, 1985). Organismic constraints refer to factors particular to the individual, including such aspects as psychology, physiology and anatomy. Physical capacities like lower body strength therefore represent a key aspect of a sprinter's organismic constraints. Consequently, the coordination patterns exhibited during sprinting cannot be entirely independent from the strength capacities of the athlete since those strength capacities influence the coordination strategies available to that athlete. Thus, particular coordination patterns may be associated with particular strength characteristics, which could have implications for understanding effective sprint technique and individual coordination (McErlain-Naylor and Needham, 2021; Needham et al., 2020). However, despite these theoretical links between coordination and strength, no studies have investigated the potential relationships between these features. Of the few previous studies of coordination in sprinting, those that have directly considered constraints have centred more on task constraints, such as the inclusion of hurdles or slopes, than organismic constraints (Bezodis et al., 2019a; Okudaira et al., 2021).

Relationships between coordination and strength may also be relevant to understanding performance. Effective acceleration requires the generation of large ground reaction forces (GRFs) that are orientated in a more horizontal direction, with the orientation appearing to be more important for performance than the total magnitude of the GRF (Morin et al., 2011, 2015; Rabita et al., 2015; Slawinski et al., 2010; Weyand et al., 2010). Consequently, numerous studies have investigated the associations between acceleration performance and lower body strength characteristics (e.g. Brady et al. (2020); Healy et al. (2019); Loturco et al. (2019, 2015); Nagahara et al. (2014); Young et al. (1995)) or technical features such as isolated angular kinematics or coordination patterns (e.g. Bayne et al. (2020); Bezodis et al. (2019a); Debaere et al. (2013a); King et al. (2023); Kugler and Janshen (2010); Schache et al. (2019); Slawinski et al. (2010)). However, these factors have been investigated independently, and there is therefore limited understanding of how strength combines with technique to produce acceleration performance.

Given the logical and theoretical links between these features established by dynamical systems theory, a full understanding of acceleration performance necessitates an understanding of not only the relationships between strength and coordination but also how certain strength profiles may interact with the emergent coordination patterns to yield a given performance outcome. Indeed, existing studies just of strength characteristics and their associations with acceleration performance in sprinters have reported somewhat inconsistent results, with some studies reporting no associations between lower body strength and acceleration performance and others reporting strong associations (Brady et al., 2020; Healy et al., 2019; Loturco et al., 2018, 2019; Nagahara et al., 2014; Young et al., 1995).

Such inconsistent findings may result from differences in the samples, execution of the tests or different choices in performance measures, but inconsistent associations between strength and performance may also result from ignoring the potential interactions between technical features and strength. It is conceivable that certain emergent coordination patterns may only be effective in combination with particular lower body strength characteristics and therefore strength may only transfer to performance when that pattern is adopted. This may also contribute to inconsistent associations between acceleration performance and different strength tests, since different strength tests typically assess different physical capacities and therefore different aspects of the organismic constraints governing the exhibited coordination patterns.

Therefore, the purpose of the current study was to (a) assess the relationships between initial acceleration coordination patterns and lower body strength and (b) explore potential interactions between coordination and strength characteristics in relation to acceleration performance in sprinters.

5.2 Methods

5.2.1 Participants

Twelve male sprinters participated in this study, including one world class, four elite and seven highly trained sprinters according to the criteria of McKay et al. (2021). Written informed consent was provided and all procedures were performed in accordance with the Declaration of Helsinki. The Research Ethics Committee of the University of Pretoria (612/2020) approved the protocol.

5.2.2 Sprint tests

Three maximal effort 20 m sprint trials were performed from blocks on an outdoor athletics track during a standard training session in the competition phase of the season. Participants completed their habitual warm up routines and at least five minutes rest was taken between trials.

Force-velocity-power (FVP) profiles were derived from a simple macroscopic model (Morin et al., 2019; Samozino et al., 2016) applied to instantaneous horizontal velocity recorded during each sprint trial with a radar gun (47 Hz; Stalker Pro II ATS, Stalker, USA). The ratio of forces (RF) - the ratio of horizontal force to resultant force - was extracted and the maximal RF (RF_{Max}), determined as the RF value at 0.3 seconds, used as the primary outcome variable using the *shorts* package (Jovanović, 2020) in R (R Core Team, 2021). The trial with the fastest 20 m time was used for analysis.

Three-dimensional kinematics were obtained from tri-axial inertial measurement units (IMU; 200 Hz; Noraxon, USA) fitted during sprint trials, recorded using the MyoResearch software package (version 3.14, Noraxon, USA). The IMU setup has been described in detail previously (Donaldson et al., 2022b)(see Chapter 3). Briefly, sensors were attached at T1, T12, sacrum, lateral aspect of the thigh, medial aspect of the shank and dorsal surface of the foot. Prior to each trial, a static calibration was performed in an upright standing posture with standardised instructions (Berner et al., 2020b; Donaldson et al., 2021)(See Appendix A). Touchdown and toe-off were identified from a synchronised video (120 Hz; Ninox-250, Noraxon, USA) and defined as the first frame with visible ground contact and the first frame where the foot no longer contacted the ground, for touchdown and toe-off respectively. Steps were defined from toe-off to toe-off of the contralateral leg beginning with block clearance (TO_0), and time normalised to 101 data points for each step. Thigh segments were labeled *leading* or *trailing* according to the relative position at the start of flight. Consequently, whether right or left limb was leading or trailing changed at toe-off. All other segment angles refer to lead limb only.

Thigh-thigh and shank-foot coordination were quantified with a modified vector coding approach (Chang et al., 2008; Donaldson et al., 2022b; Needham et al., 2015, 2020)(see detailed description in Chapter 3). Coupling angles (CA) were calculated as the angle of the vector between adjacent points in the angle-angle diagram relative to the right horizontal, resulting in a vector angle between 0 and 360°. At each time point, the CA was placed in a coordination bin describing the relative motion between the two segments according to the position on the 360° plane (Figure 5.1A). The total frequency of each coordination bin for each step was calculated. Rotations were defined from the right hand view as clockwise or anticlockwise, with anticlockwise denoting the positive direction (Figure 5.1B-C).

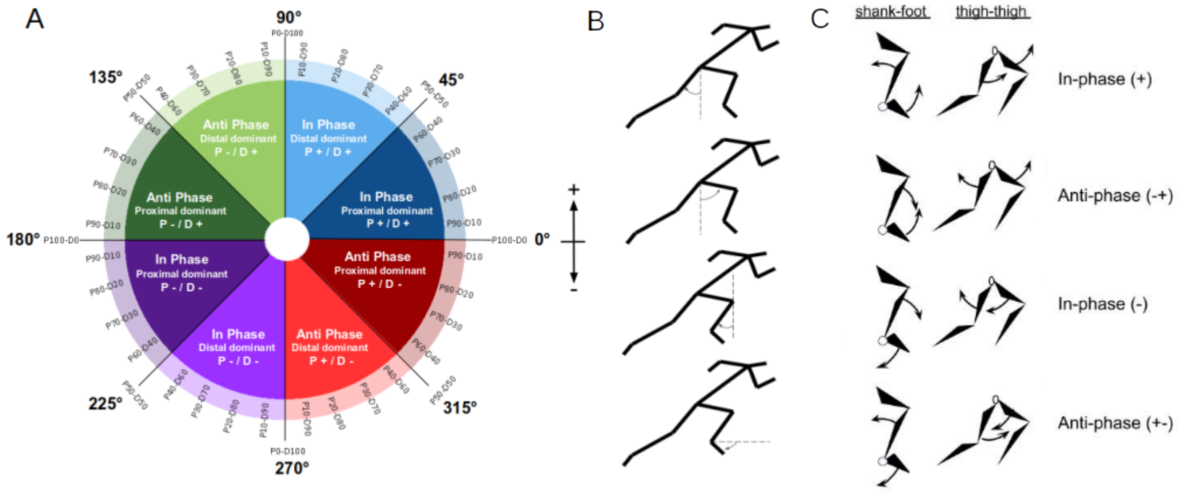

Figure 5.1: Coordination bin classifications (A), segment angle conventions (B) and coordination segment rotation explanations (C) for thigh-thigh and shank-foot coordination couplings. Adapted from (Donaldson et al., 2022b).

5.2.3 Strength tests

As close as possible to sprint tests, given scheduling and training constraints, participants performed strength tests (5.4 ± 5.0 days). All jump and isometric tests were performed on embedded uni-axial dual force plates sampling at 1000 Hz (Bertec, USA) and recorded using ForceDecks software (Vald Performance, Australia). A standardised dynamic warm up was performed at the start of the session. The final component of the warm up consisted of submaximal repetitions of each exercise. Three maximal repetitions were performed, separated by two minutes rest, and the best repetition was selected according to the primary outcome variable.

Countermovement jump (CMJ) tests were performed with participants instructed to keep their hands on their hips for the duration of the jump and to jump as high as possible from a self-selected countermovement depth. Jump height was determined using the impulse-momentum method.

Repeated hop tests were performed according to Harper et al. (2011). Participants were instructed to keep their hands on their hips and perform ten repeated hops, maximising jump height and minimising contact time. Reactive strength index (RSI) was calculated as the mean ratio of jump height (m) to contact time (s) across the five highest jumps with a contact time <250 ms.

Isometric squat (ISqT) tests were performed using a custom rig fitted over the force plates. Bar height was set individually for each participant with the bar settled across the upper back as in a barbell back squat, over the middle of the feet, with hip and knee angles set at approximately 120° as determined via hand-held goniometer. Participants were instructed to push up against the bar as hard and as fast as possible and maintain force for five seconds, with verbal encouragement provided throughout. Peak vertical force was extracted and expressed relative to body mass.

Nordic hamstring tests were performed using a NordBord device (Vald Performance, Australia). Participants kneeled on a raised platform and their ankles secured with adjustable hooks fitted with uni-axial load cells (50 Hz). Participants were instructed to maintain their hands raised alongside their head and slowly lower themselves forward, extending the knee and maintaining flexed hips, until they could no longer resist falling forward onto a mat. Maximal combined force from the left and right leg was extracted and expressed as total force relative to body mass.

5.2.4 Statistical Analysis

Since previous studies have reported there to be differences in kinematics and coordination between step 1 and subsequent steps (e.g. Charalambous et al. (2012); Donaldson et al. (2022a); von Lieres und Wilkau et al. (2020))(see Chapters 3 and 4), coordination was represented independently as step 1 and as the average over steps 2-4. In accordance with the two purposes of the current research, analysis consisted of two parts. First, associations between strength variables and coordination bin frequencies in step 1 and steps 2-4 were assessed with Spearman's rank-order correlations, with correlation effect sizes interpreted according to the thresholds: trivial (0.0), small (0.1), moderate (0.3), large (0.5), very large (0.7), near perfect (0.9) and perfect (1.0) (Hopkins et al., 2009).

Subsequently, to explore potential interactions between coordination and strength characteristics in relation to acceleration performance, selected coordination bin frequencies and strength variables were paired in multiple regression models with interaction effects using the 'enter' method of variable selection. $\mathrm{RF}_{\mathrm{Max}}$ was selected as the dependent variable for regression models as it strongly corresponds to specific initial acceleration performance measures such as normalised average horizontal external power as well as directly measured RF during the initial steps (Bezodis et al., 2019b, 2020), and therefore best represented performance directly during the steps for which coordination was quantified. The coordination variables included in regression models were selected based on their frequency and prominence in the overall pattern, their presence during theoretically notable periods of the step cycle or observations in previous analyses (Bezodis et al., 2019a; Donaldson et al., 2022b) (see Chapters 3 and 4). For visualisation purposes in significant models, strength variables were split into 'high' and 'low' groups by median split to demonstrate interaction effects.

Specifically, anti-phase leading (-) and anti-phase trailing (-) thigh-thigh coordination were selected based on their typically high frequencies and the importance of anti-phase motion to thigh-thigh coordination (Bayne et al., 2020; Donaldson et al., 2022b; Okudaira et al., 2021). Anti-phase leading (+) and in-phase leading (+) thigh-thigh coordination in step 1 were selected due to their more prominent appearance in step 1 and because they appear to differentiate step 1 strategies between between individuals, whilst in-phase (-) thigh-thigh coordination was selected in steps 2-4 based on its presence at the beginning and end of each step - and therefore importance to thigh motion during the transitions between steps (Donaldson et al., 2022b) (see Chapters 3 and 4). For the shank-foot coupling, anti-phase shank (-) in step 1 was selected based on relationships observed with CMJ height and hop test RSI in the first part of the analysis, while in-phase foot (+) and in-phase foot (-) in steps 2-4 were included for the same reason based on associations with isometric squat force. Finally, anti-phase foot (+) was included based on the previously suggested importance of foot dominant ankle dorsiflexion (Donaldson et al., 2022b) (see Chapters 3 and 4). Additional models were developed to assess specific combinations of coordination variables based on relationships observed in the first part of the analysis. Explanatory variables were centered prior to being entered into regressions. Model assumptions were visually assessed with residual plots and the normality of errors was confirmed with Shapiro-Wilk tests. The variance inflation factor for all models was within acceptable limits (<4) (Hair et al., 2009). The alpha level was set at 0.05.

5.3 Results

Table 5.1 presents summary data for sprint and strength tests. Coordination profiles for step 1 and steps 2-4 (mean profile across the three steps) are shown in figure 5.2 for thigh-thigh (A) and shank-foot (B) couplings.

5.3.1 Thigh-thigh coordination and strength

Hop test RSI had a significant large negative correlation with in-phase leading (-) frequency in step 1 ($p = 0.049$) (Table 5.2; Figure 5.3A), such that higher RSI corresponded to less in-phase clockwise thigh rotation. Isometric squat force had a significant large negative correlation with anti-phase leading (-) frequency ($p = 0.017$) and a very large positive correlation with anti-phase trailing (+) frequency ($p = 0.001$) in step 1, thus higher force was associated with more trail thigh dominant and less lead thigh dominant thigh interchange. Finally, isometric squat force also had a large negative correlation with in-phase trailing (+) frequency ($p = 0.017$) frequency in steps 2-4 (Table 5.2; Figure 5.3B-D), with higher force corresponding to less time with trail thigh dominant in-phase clockwise rotation.

Table 5.1: Summary of participant characteristics, sprint and strength test variables.

Variable	**Mean**	**SD**	**Range**
Stature (m)	1.77	0.07	1.68 - 1.91
Mass (kg)	75	11	57 - 98
100 m PB (s)	10.44	0.38	9.95 - 11.17
5 m time (s)	1.22	0.08	1.10 - 1.37
20 m time (s)	3.01	0.10	2.92 - 3.26
V_0 ($m.s^{-1}$)	10.3	0.5	9.1 - 10.8
F_0 ($N.kg^{-1}$)	8.8	0.8	6.9 - 10.3
P_{Max} ($W.kg^{-1}$)	22.8	2.1	18.2 - 26.7
RF_{Max} (%)	57.0	2.6	50.2 - 61.4
D_{RF} ($\%.s.m^{-1}$)	-7.6	0.8	-8.9 - -5.9
CMJ height (cm)	50.6	6.4	37.3 - 60.0
CMJ Peak Power ($W.kg^{-1}$)	69.0	4.8	59.3 - 76.2
HJ mean contact time (ms)	168	32	130 - 250
HJ RSI	1.87	0.38	1.25 - 2.49
ISqT Max Force ($N.kg^{-1}$)	47.5	10.9	28.1 - 65.1
Nordic Max Force ($N.kg^{-1}$)	10.4	1.1	8.4 - 11.6

V_0 = Theoeretical maximal velocity; F_0 = Theoretical maximal horizontal force; P_{Max} = Maximal horizontal power; RF_{Max} = Maximum ratio of forces; D_{RF} = Degradation of RF. CMJ = countermovement jump; HJ = Hop jump test; ISqT = Isometric squat test.

Table 5.2: Inter-correlation matrix of Spearman's rank-order correlation coefficients (ρ) for inter-limb thigh-thigh coordination bin frequencies and lower body strength tests.

	AP Leading (-)	AP Leading (+)	IP Trailing (+)	IP Leading (+)	IP Trailing (+)	IP Leading (-)	IP Trailing (-)	AP Trailing (-)
Step 1								
CMJ height (cm)	0.08	0.38	-0.01	0.19	0.04	-0.44	0.13	0.05
ISqT ($N.kg^{-1}$)	**-0.67**	0.00	**0.82**	-0.21	-0.07	-0.34	0.16	0.53
Nordic ($N.kg^{-1}$)	0.11	0.21	-0.15	0.19	0.26	-0.45	-0.23	-0.02
HJ RSI	0.07	0.50	0.33	-0.22	-0.33	**-0.58**	0.22	0.07
Steps 2-4								
CMJ height (cm)	0.10	0.26	-0.13	-0.19	0.14	0.00	-0.24	0.17
ISqT ($N.kg^{-1}$)	0.10	-0.39	0.06	0.07	-0.17	0.38	**-0.67**	-0.25
Nordic ($N.kg^{-1}$)	0.11	0.39	-0.20	0.13	0.20	-0.20	-0.13	-0.12
HJ RSI	-0.22	0.45	0.19	0.19	0.25	0.09	-0.52	0.30

AP = anti-phase; IP = in-phase. CMJ = countermovement jump; HJ = Hop jump test; ISqT = Isometric squat test; RSI = Reactive strength index.
Bold values represent significant correlations, $p < 0.05$.

5.3.2 Shank-foot coordination and strength

CMJ height had a significant very large negative correlation with in-phase shank (-) frequency ($p = 0.001$)(Table 5.3; Figure 5.4A), and hop test RSI also had a significant large negative correlation with in-phase shank (-) frequency ($p = 0.044$)(Figure 5.4B), such that high CMJ heights and RSI values corresponded to less time in shank dominant in-phase clockwise shank

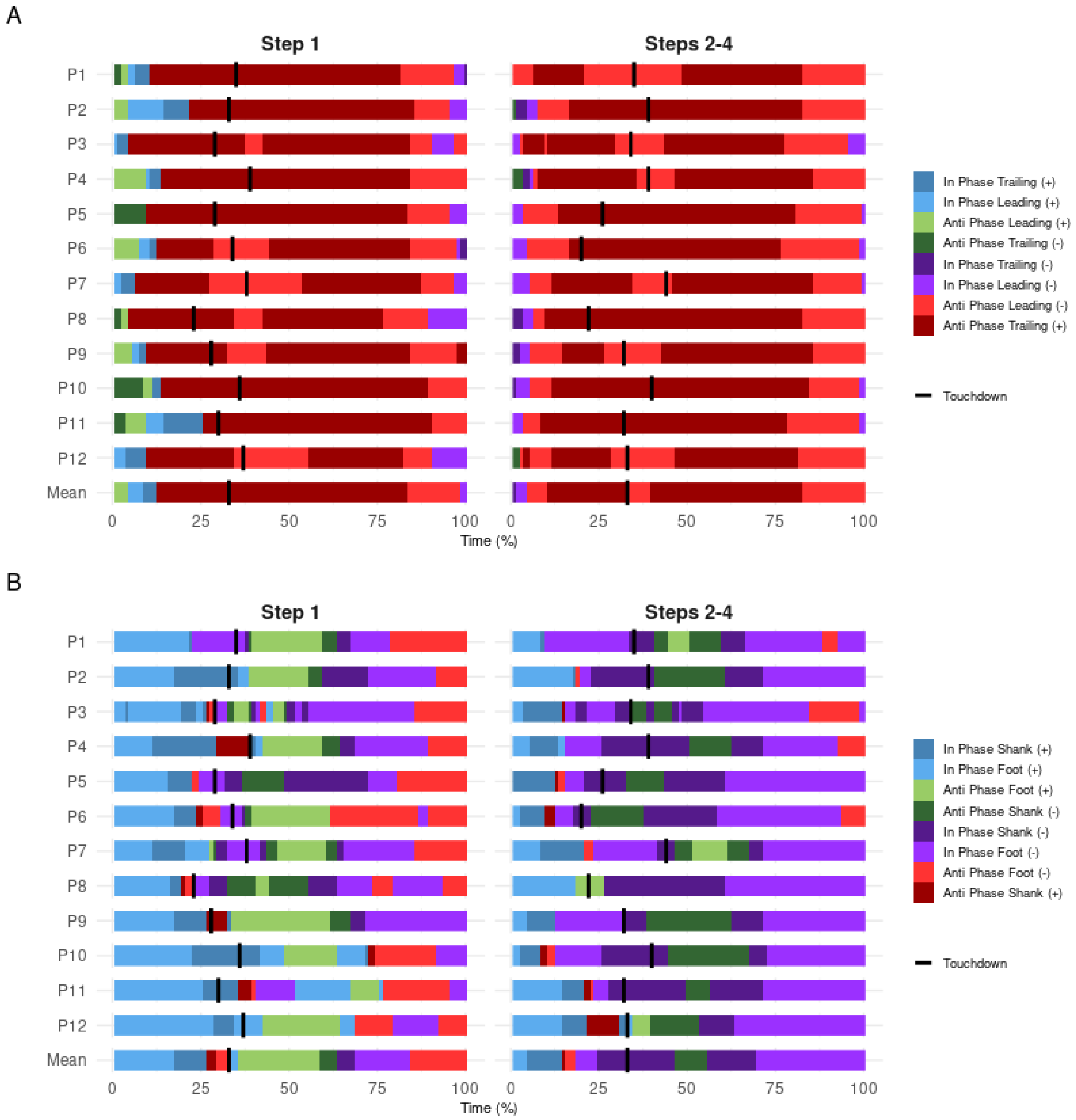

Figure 5.2: Individual and group mean coordination profiles for thigh-thigh (A) and shank-foot (B) couplings in step 1 and steps 2-4. Black vertical lines indicate touchdown.

and foot rotation. Hop test RSI also had a significant large positive correlation with anti-phase shank (+) frequency ($p = 0.04$) in step 1 (Figure 5.4C), showing higher RSI values were associated with increased time spent in shank dominant plantarflexion. Isometric squat force had a significant large negative correlation with in-phase foot (+) in steps 2-4 ($p = 0.015$), and a significant large positive correlation with in-phase foot (-) in these steps ($p = 0.032$)(Figure 5.4D-E), such that higher force tended to be associated with less anti-clockwise foot dominant in-phase rotation but more clockwise foot dominant in-phase rotation.

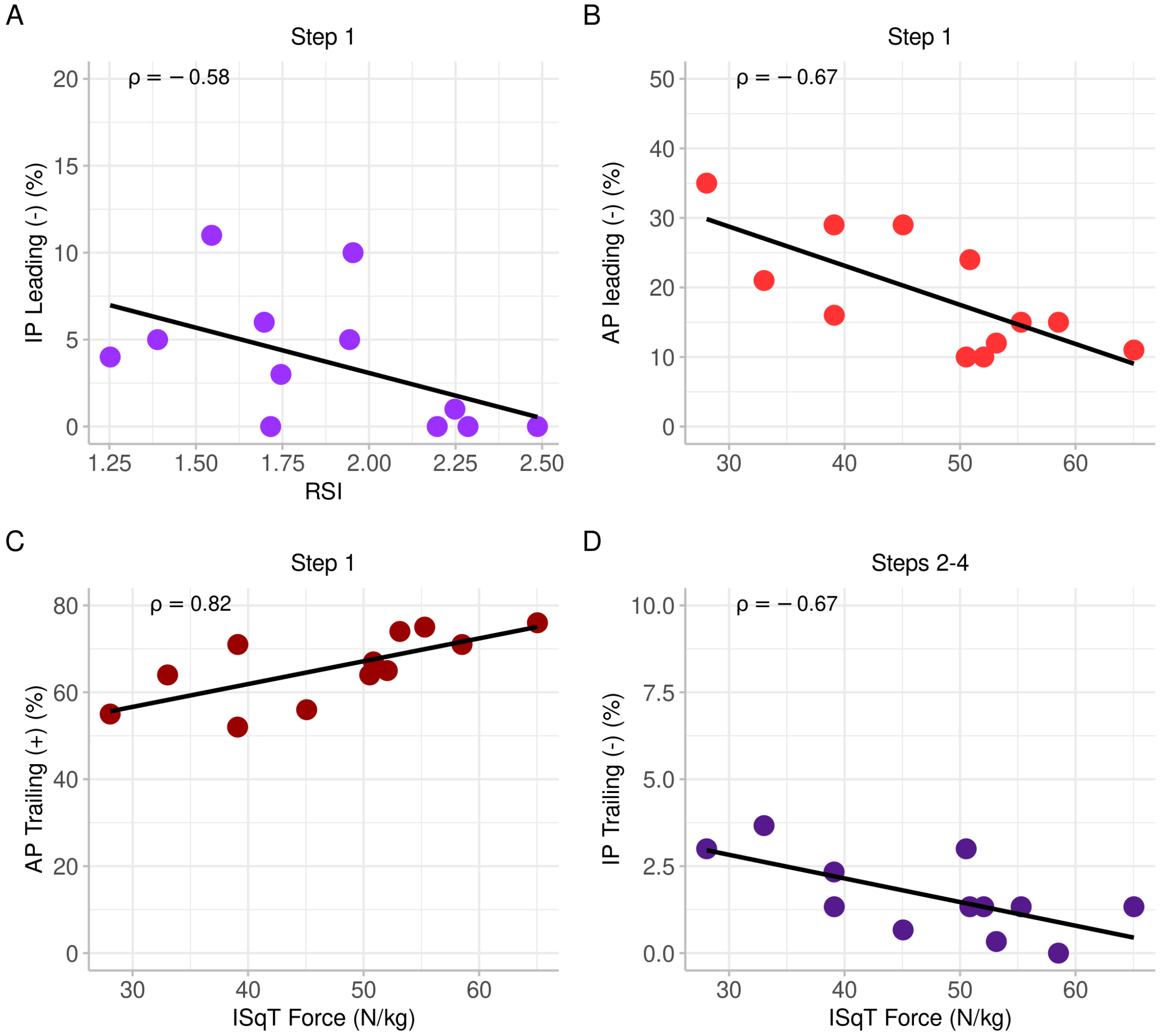

Figure 5.3: Scatter plots to illustrate the significant relationships between strength and thigh-thigh coordination bin frequencies. Note the inclusion of both step 1 and steps 2-4 coordination bin frequencies, Y-axis scales are not consistent across all sub-figures.

5.3.3 Coordination, strength and performance

From the thigh-thigh and shank-foot couplings, the coordination bins selected for regression models included anti-phase leading (-), anti-phase trailing (+), in-phase leading (+), in-phase shank (-), anti-phase foot (-) and anti-phase foot (+) in step 1 as well as in-phase leading (-), anti-phase foot (+), in-phase foot (+) and in-phase foot (-) in steps 2-4 (Table 5.4).

Five regression models had significant overall effects (Adjusted R^2 = 0.49 - 0.89)(Table 5.5).

Table 5.3: Inter-correlation matrix of Spearman's rank-order correlation coefficients (ρ) for intra-limb shank-foot coordination bin frequencies and lower body strength tests.

	AP Foot (-)	AP Foot (+)	AP Shank (+)	IP Foot (+)	IP Shank (+)	IP Foot (-)	IP Shank (-)	AP Shank (-)
Step 1								
CMJ height (cm)	0.08	0.56	0.52	0.37	0.05	-0.34	**-0.81**	-0.52
ISqT (N.kg^{-1})	0.34	-0.13	0.08	0.35	0.09	-0.17	-0.16	-0.31
Nordic (N.kg^{-1})	0.11	-0.01	0.3	-0.01	0.45	-0.28	-0.36	-0.20
HJ RSI	0.12	0.42	**0.60**	-0.17	0.32	-0.54	**-0.59**	-0.33
Steps 2-4								
CMJ height (cm)	-0.04	0.23	0.41	0.06	-0.27	-0.23	0.13	0.07
ISqT (N.kg^{-1})	0.025	-0.04	0.41	**-0.70**	-0.12	**0.62**	-0.03	0.42
Nordic (N.kg^{-1})	-0.20	0.04	0.02	0.34	0.20	0.12	-0.31	0.00
HJ RSI	0.18	-0.17	0.50	-0.08	-0.53	0.03	0.19	0.36

AP = anti-phase; IP = in-phase. CMJ = countermovement jump; HJ = Hop jump test; ISqT = Isometric squat test; RSI = Reactive strength index.
Bold values represent significant correlations, $p < 0.05$.

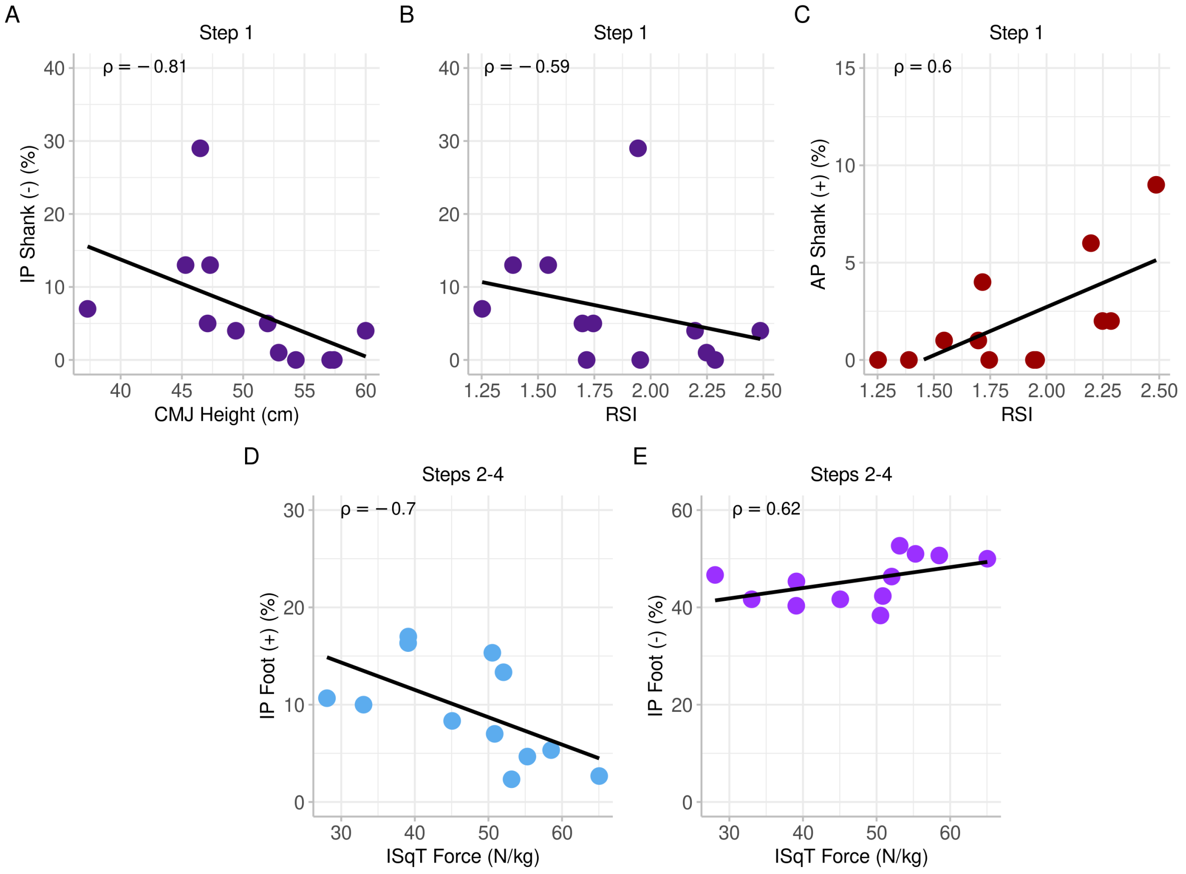

Figure 5.4: Scatter plots for relationships between strength and shank-foot coordination bin frequencies that were significant. Note the inclusion of both step 1 and steps 2-4 coordination bin frequencies, Y-axis scales are not consistent across all sub-figures.

Table 5.4: Summary of multiple regression analyses between RF_{Max} and selected strength and coordination independent variables.

Model	**Adj. R^2**	**F**	**p**
Step 1 interaction models			
ISqT + AP Leading (-) + ISqT*AP Leading (-)	0.34	2.921	0.100
CMJ + AP Leading (-) + CMJ*AP Leading (-)	0.66	8.133	**0.008**
ISqT + AP Trailing (+) + ISqT*AP Trailing (+)	0.11	1.499	0.287
CMJ + AP Trailing (+) + CMJ*AP Trailing (+)	0.89	30.44	<**0.001**
ISqT + AP Leading (+) + ISqT*AP Leading (+)	0.34	2.922	0.100
CMJ + AP Leading (+) + CMJ*AP Leading (+)	0.30	2.547	0.129
ISqT + IP Leading (+) + ISqT*IP Leading (+)	-0.02	0.915	0.476
CMJ + IP Shank (-) + CMJ*IP Shank (-)	0.39	3.346	0.076
HJ RSI + IP Shank (-) + HJ RSI*IP Shank (-)	0.18	1.776	0.229
Nordic + AP Foot (-) + Nordic*AP Foot (-)	-0.31	0.123	0.944
Nordic + AP Foot (+) + Nordic*AP Foot (+)	-0.20	0.399	0.758
Steps 2-4 interaction models			
ISqT + IP Leading (-) + ISqT*IP Leading (-)	-0.06	0.790	0.533
CMJ + IP Leading (-) + CMJ*IP Leading (-)	0.55	5.402	**0.025**
Nordic + IP Leading (-) + Nordic*IP Leading (-)	-0.31	0.130	0.939
CMJ + AP Foot (+) + CMJ*AP Foot (+)	0.84	19.55	<**0.001**
HJ RSI + AP Foot (+) + HJ RSI*AP Foot (+)	0.49	4.522	**0.039**
ISqT + IP Foot (+) + ISqT*IP Foot (+)	-0.02	0.918	0.475
ISqT + IP Foot (-) + ISqT*IP Foot (-)	0.13	1.557	0.274
Additional Models			
ISqT + S1 AP Leading (-) + S1 AP Trailing (+)	0.05	1.180	0.377
ISqT + S1 AP Leading (-) + S1 IP Foot (+)	0.04	1.143	0.389
HJ RSI + S1 IP Shank (+) + S1 AP Shank (+)	0.07	1.286	0.344
ISqT + S24 IP Foot (+) + S24 IP Foot (-)	-0.03	0.883	0.490

AP = Anti-phase; IP = In-phase. RF_{Max} = Maximum ratio of forces (%). CMJ = countermovement; HJ = Hop jump; ISqT = Isometric squat test; RSI = Reactive Strength Index.
p = p-value. * indicates model interaction term. Significant models ($p < 0.05$) are highlighted in bold.

In three of these models only the interaction effects were signficant, one model had both significant main and interaction effects and in the remaining model neither the main effects nor the interaction were significant (Table 5.5; Figure 5.5).

The significant interactions in the absence of significant main effects implies a crossover, such that the direction and magnitude of association between the coordination bin and RF_{Max} tended toward opposite for relatively higher and lower strength variable scores. For illustration purposes, significant interaction effects are presented as coordination bin frequency associations with RF_{Max} by median split of strength into relatively higher or relatively lower groups (Figure 5.5).

All four models with significant interaction effects included CMJ height as the strength

Table 5.5: Summary output of significant multiple regression models.

Model Variables	**Adj. R^2**	**Coef.**	**SE**	*t*	**p**
Step 1 Models					
CMJ	0.66	-0.022	0.088	-0.25	0.809
AP Leading (-)		-0.093	0.057	-1.63	0.142
CMJ*AP Leading (-)		0.027	0.008	3.39	**0.010**
CMJ	0.89	-0.057	0.050	-1.13	0.293
AP Trailing (+)		0.116	0.032	3.58	**0.007**
CMJ*AP Trailing (+)		-0.045	0.006	-7.77	<**0.001**
Steps 2-4 Models					
CMJ	0.55	0.026	0.094	0.28	0.786
IP Leading (-)		0.419	0.279	1.50	0.171
CMJ*IP Leading (-)		-0.238	0.071	-3.37	**0.010**
CMJ	0.84	-0.097	0.070	-1.38	0.205
AP Foot (+)		-0.030	0.115	-0.26	0.802
CMJ*AP Foot (+)		0.085	0.017	5.10	<**0.001**
RSI	0.49	1.201	1.579	0.76	0.469
AP Foot (+)		-0.205	0.182	-1.13	0.293
RSI*AP Foot (+)		0.961	0.434	2.22	0.058

AP = Anti-phase; IP = In-phase. RF_{Max} = Maximum ratio of forces (%). CMJ = countermovement; HJ = Hop jump; ISqT = Isometric squat test; RSI = Reactive Strength Index.
SE = Standard error; p = p-value. * indicates model interaction term. Significant p-values are highlighted in bold ($p < 0.05$).

variable. Thus, the relationships between coordination variables and RF_{Max} were different depending on the CMJ heights achieved by those within the sample. In the first model, anti-phase leading (-) interacted with CMJ height such that anti-phase leading (-) frequency in step 1 was inversely associated with RF_{Max} when CMJ height was relatively lower, but became positively associated with RF_{Max} for relatively higher CMJ heights (Figure 5.5A). In the second model, anti-phase trailing (+) interacted with CMJ height such that anti-phase trailing (+) frequency in step 1 was positively associated with RF_{Max} for relatively lower CMJ heights but was negatively associated for relatively higher CMJ heights (Figure 5.5B).

The remaining two models showed interactions with steps 2-4 coordination. In the third model, CMJ height interacted with in-phase leading (-) thigh-thigh coordination such that for relatively lower CMJ heights, in-phase leading (-) frequency was positively associated with higher RF_{Max}, but became negatively associated for relatively higher CMJ heights (Figure 5.5C). The final model exhibited the only significant interaction with shank-foot coordination. CMJ height interacted with anti-phase foot (+) frequency in steps 2-4 such that anti-phase foot

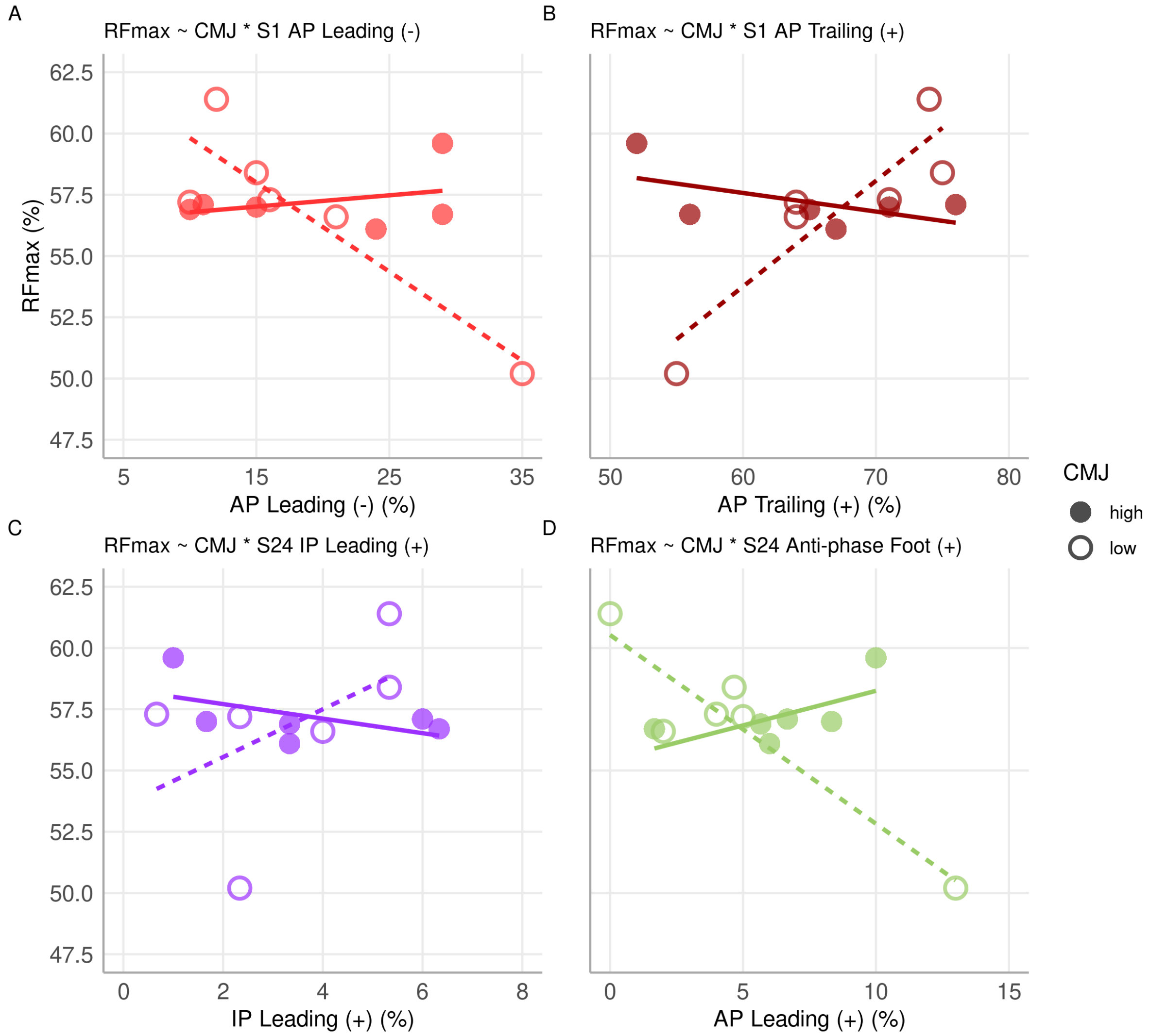

Figure 5.5: Scatter plots of relevant coordination bin frequencies against $\mathrm{RF}_{\mathrm{Max}}$ values with median split of ‘High’ and ‘Low’ countermovement jump values to demonstrate significant interaction effects in multiple regression models. Solid lines and filled points are ‘High’, dotted lines and unfilled points are ‘Low’. $\mathrm{RF}_{\mathrm{Max}}$ = maximum ratio of forces. CMJ = countermovement jump. AP = Anti-phase, IP = In-phase. S1 = step 1 coordination, S24 = steps 2-4 coordination.

(+) was inversely associated with $\mathrm{RF}_{\mathrm{Max}}$ when CMJ height was relatively lower, but became positively associated for relatively higher CMJ heights (Figure 5.5D).

5.4 Discussion

The purpose of the current study was to assess the relationships between initial acceleration coordination patterns and lower body strength, and to subsequently explore potential interactions between coordination and strength characteristics in relation to acceleration performance in sprinters. Isometric squat force, CMJ height and hop test RSI were associated with the frequency of certain thigh-thigh and shank-foot coordination patterns in step 1 and steps 2-4. Although coordination patterns had a larger number of associations with isometric maximal force and hop jump RSI, multiple regression analyses exploring the interaction between coordination and strength found CMJ height to be the only strength measure to interact with coordination when used to predict initial acceleration performance. Potential interactions between CMJ height and coordination suggest the physical capacities reflected by CMJ height may influence the relationships between certain coordination patterns and acceleration performance.

Despite strong theoretical grounds for interacting effects between physical capacities and technique (Davids et al., 2003; Glazier, 2017; Wild et al., 2021), studies assessing lower body strength in relation to aspects of technique such as angular kinematics and coordination are rare. Indeed, the current study is the first to explore these relationships in sprinters, and the first to directly explore these relationships through coordination within the context of dynamical systems theory. Associations between isometric squat force and coordination in step 1 imply athletes with higher force generating capacities are more likely to have more trail thigh dominant thigh-thigh coordination (anti-phase trailing (+)) than their counterparts with lower force generation. As a result, higher maximal force was associated with a pattern of limb interchange in step 1 whereby the trail thigh underwent greater rotation than the lead thigh for a greater proportion of the step. Previous studies have established that thigh-thigh coordination during initial acceleration is primarily anti-phase for almost all the step (Bayne et al., 2020; Okudaira et al., 2021). However, the current results indicate that, at least in step 1, the balance of thigh rotations within that anti-phase pattern may be associated with the ability to generate high maximal forces. The reasons for this association are currently unknown, but it may result from the constraints of block exit, with higher maximal force generation contributing to a more aggressive forward rotation of the trail thigh in step 1 after having an extended time to push during the block phase, and future work could explore this more directly by comparing step 1 thigh-thigh coordination and isometric squat force to external kinetics during the block phase.

In steps 2-4, isometric squat force was negatively associated with trail dominant simultaneous clockwise thigh rotation (in-phase trailing (-)), a pattern occurring in early flight (Figure 5.2A), representing a possible delayed initiation of swing leg recovery after toe-off - sometimes called ‘over pushing’. As such, athletes with higher maximal force generation capacities may be able to initiate forward rotation of the swing leg more effectively after toe-off. Although the absolute frequency of this bin tends to be low, this association suggests that whether an athlete exhibits in-phase (-) thigh-thigh coordination in early flight relates to their maximal force generating capacities and further may be related to the timing of muscle activations during reversals in thigh rotation at the beginning or end of each step which could contribute to the underlying mechanism for this association (Kakehata et al., 2021).

Maximal isometric strength was also negatively associated with in-phase foot (+) coordination and positively associated with in-phase foot (-) during flight in steps 2-4. As Alt et al. (2022) have described, the shank typically ‘swings out’ in anti-clockwise rotation (positive) during flight before it reaches a maximum forward position at the ‘shin block’, and reverses to clockwise rotation (negative) in preparation for touchdown. Consequently, sprinters with greater maximal force generating capacities tended to exhibit an earlier reversal of shank rotation during flight and therefore spent less time with the shank ‘swinging out’ and more in-phase clockwise foot and shank rotation in late flight compared to counterparts with relatively lower force generating capacities who were more likely to exhibit prolonged in-phase anticlockwise rotation during flight. These shank-foot patterns are related to preparing the shank and foot for touchdown from the preceding toe-off position. As such they may indicate that maximal strength influences the toe-off positions of these segments, possibly through an influence on the contact and flight times in the preceding step and therefore the time to organise segments prior to toe-off (Lockie et al., 2012). Alternatively, this association may reflect that athletes with higher maximal force are more capable of of producing muscle actions to reverse the ‘swinging out’ motion (Kakehata et al., 2021). Future research is needed to determine the potential mechanisms by which maximal force generating capacities might influence these shank-foot coordination patterns.

During the ankle dorsiflexion that occurs in early stance (Bezodis et al., 2014; Charalambous et al., 2012), there is commonly some in-phase simultaneous clockwise shank and foot rotation (in-phase shank (-)) either side of the primary anti-phase pattern (Figure 5.2B)). While there tends to be more of this in-phase pattern exhibited in later steps, higher shank dominant in-phase motion in step 1 was associated with both lower hop test RSI and lower CMJ height. Higher RSI and CMJ height are likely performance outcomes achieved by sprinters who have a greater capacity for utilising the stretch-shortening cycle (SSC), and athletes who possess such physical abilities exhibit less shank dominant rotation around dorsiflexion in step 1. This association with SSC movement might relate to the utilisation of ankle dorsiflexion in both the hop and CMJ test, thus these associations could imply that physical characteristics related to the ankle which facilitate performance in these tests also correspond to shank and foot motion around the ankle during the first step. These associations only occurred in step 1, which may be due to more foot dominant dorsiflexion typical in step 1 compared to steps 2-4 and a more vertical foot angle at touchdown which may influence the frequency of in-phase shank coordination either side of dorsiflexion (Donaldson et al., 2022b)(See Chapter 3).

Furthermore, hop test RSI was positively associated with an anti-phase pattern corresponding to ankle plantarflexion (anti-phase shank (+)) in late flight. Such anti-phase coordination reflects continued dominance of anticlockwise forward rotation of the shank into late flight but indicates a reversal in foot rotation to clockwise rotation, implying athletes with greater RSI were more likely to exhibit a reversal in foot motion in preparation for touchdown in step 1. While such a reversal in foot rotation could result from technical cues or drilling, it could reflect the athlete adopting a foot posture that is favourable for utilising their SSC capabilities in accordance with their individual constraints, or a similarity in ankle motion exhibited by the athlete during the hop test and acceleration. Although ankle specific hop test performance has previously only been associated with performance in later steps of acceleration (Nagahara et al., 2014), the current results suggest the reactive strengh capacities reflected by the performance in these kinds of tests could still be related to coordination in earlier steps. Further exploration of relationships between jump tests and coordination might indicate whether these correlations result from similarities between ankle motion and shank-foot coordination in jump tests and during initial acceleration.

The correlations between strength and coordination patterns support the notion that certain physical characteristics are associated with technical characteristics, and in line with dynamical systems theory, highlighting strength as an organismic constraint that may influence the coordination patterns a sprinter adopts (Davids et al., 2003; Glazier, 2017). From a practical perspective, associations between strength and coordination confirm that the emergent coordination patterns are not independent from physical characteristics, which may influence the strategies that athletes adopt. Sprint training programmes typically include both technical and strength training components, and the current results suggest these two training components should be viewed as factors that are related and can influence each other and should be programmed for a given individual. Practitioners should be wary that alterations to strength capacities could alter the constraints on emergent coordination patterns which might result in unexpected changes in coordination. As such, the current results reiterate a need for individualised assessments in order to fully understand an athlete's context and suitably design and assess the physical and technical components of training programmes.

Relationships between strength and coordination also have implications for performance. Particular strength characteristics may not only be associated with particular coordination patterns, but also influence the relationships between coordination and performance. As proposed earlier, such an interaction between aspects of technique and strength may, in part, explain some of the equivocal results previously reported between acceleration performance and strength (e.g. Brady et al. (2020); Healy et al. (2019); Loturco et al. (2019, 2015); Young et al. (1995)). If particular coordination profiles are more or less effective depending on strength characteristics, then the associations between strength and performance across a cohort may appear unclear if different coordination is adopted by different athletes depending on their strength characteristics (Davids et al., 2003; Newell, 1986).

Across four regression models with significant interaction effects, the current study suggested that the lower body capacities represented by CMJ height influence the relationships between coordination bin frequencies and $\mathrm{RF}_{\mathrm{Max}}$, such that the direction of the association between coordination bin frequencies and $\mathrm{RF}_{\mathrm{Max}}$ tended to be different depending on CMJ height. No other strength tests had significant regression models, suggesting that while other measures of strength were associated with particular coordination patterns in this sample, only the physical characteristics represented by CMJ height related to performance. This may align with existing literature where CMJ height has been more consistently associated with acceleration performance than other lower body strength tests (Loturco et al., 2018, 2019, 2015; Nagahara et al., 2014), but suggests that a complete understanding of how the lower body characteristics represented by CMJ height relate to performance needs to account for factors such as coordination during sprinting. Significant interaction effects existed between CMJ height and both anti-phase leading (-) and anti-phase trailing (+), the net result suggesting that a more trail thigh dominant pattern tended to be advantageous to performance when CMJ height was relatively lower but a more lead thigh dominant pattern tended to be advantageous when CMJ height was relatively higher (Figure 5.5A-B). In effect, whether a strategy of more or less lead or trail thigh dominance in limb interchange is effective in terms of performance may depend on whether the athlete has the lower body characteristics exemplified by high or low CMJ height.

CMJ height also appeared to interact with in-phase leading (-) in steps 2-4 (Figure 5.5C), a coordination pattern reflecting simultaneous clockwise thigh rotation that occurs around toe-off (Figure 5.2A). In such an interaction, lower in-phase thigh rotation tended to be advantageous to performance when CMJ height was relatively higher. However, when CMJ height was relatively lower, higher amounts of in-phase rotation tended to be advantageous to performance. In-phase coordination around toe-off reflects the timing of reversals in lead and trail thigh rotations during the transition between steps, such that this interaction implies that for athletes with relatively higher CMJ heights, a more synchronous reversal in thigh rotations is associated with better performance, whereas for athletes with relatively lower CMJ heights, less synchronous reversals in rotation may be more effective. Since this in-phase rotation can occur before and after toe-off, it is unknown whether the timing of this coordination bin may have some effect on this interaction with CMJ height in relation to performance. Previous explorations have noted that in-phase coordination in late stance may be more advantageous for performance than in-phase coordination in early flight (See chapter 4), but it is unclear from the current data whether the timing affects the interaction with CMJ height. However, in steps 2-4, in-phase thigh rotation was more commonly observed at the beginning of the step (Figure 5.2A) and thus this pattern of 'over pushing' may suggest a way that athletes overcome a relative lack of lower body power implied by a relatively lower CMJ height.

The final significant model showed a potential interaction between coordination associated with ankle dorsiflexion during stance in steps 2-4 and CMJ height. Anti-phase foot (+) coordination reflects a greater relative rotation of the foot compared to the shank during ankle dorsiflexion in early stance, such that in interaction with CMJ height, more foot dominant dorsiflexion was associated with greater $\mathrm{RF}_{\mathrm{Max}}$ when CMJ height was relatively higher but the opposite tended to be true for relatively lower CMJ height (Figure 5.5D). As such, a more foot dominant dorsiflexion strategy may be more effective for athletes with the higher lower body power represented by better CMJ performance, but a more shank dominant dorsiflexion strategy may be more effective for athletes who lack those physical characteristics. The effect of this interaction and it's relation to $\mathrm{RF}_{\mathrm{Max}}$ may also be related to the energy absorption role played by the ankle during early stance (Charalambous et al., 2012; Debaere et al., 2013a; Schache et al., 2019) as well as the foot position at touchdown (King et al., 2023). The ankle plays a key role in initial acceleration (Bezodis et al., 2014; Debaere et al., 2013a; Schache et al., 2019), and future research is required to fully develop the understanding of ankle motion, including the relative contributions of shank and foot rotation under different constraints and the influence of foot orientation at key events. This interaction highlights a potential need to also consider factors related to lower body strength in understanding shank, foot and ankle dynamics in acceleration.

In dynamical systems theory, coordination patterns emerge within interacting constraints, of which physical characteristics such as strength are a key component (Davids et al., 2003; Glazier, 2017; Newell, 1986). The current study is the first to quantify the associations between coordination patterns and strength features in sprinters, suggesting that athletes with higher or lower relative levels of certain strength characteristics are more likely to spend more or less time exhibiting particular coordination patterns. From a practical perspective, a tendency for athletes with certain physical profiles to adopt corresponding movement patterns has implications for how coaches consider coordination and kinematics for sprinters with different strength characteristics as well as how they approach strength training for athletes with differences in those technical features. Potentially, the associations in the current study encourage individualised approaches to profiling technique that consider an athlete's specific physical characteristics as opposed to one-size-fits-all technical models. Moreover, since strength training is common in sprint programmes, the current findings imply that practitioners should consider and monitor how alterations to strength profiles correspond to alterations in initial acceleration coordination patterns and performance. Whilst dynamical systems theory accounts for the emergence of coordination patterns, the current study extends this by providing a novel exploration of the interactions between coordination and strength in relation to initial acceleration performance. The findings showed initial evidence that coordination might interact with strength characteristics in relation to performance, such that the relationships between coordination and performance might depend on the strength characteristics of the athletes. Interactions that influence the effectiveness of certain technical approaches depending on strength characteristics could have substantial implications for sprint training and, together with the characterisation of technical strategies (Wild et al., 2021)(see chapter 4), could be important for guiding individualised programmes.

5.5 Conclusion

Several lower body strength characteristics were associated with coordination patterns in step 1 and steps 2-4 during initial acceleration, particularly in relation to the balance of thigh dominance during limb interchange, reversals of thigh rotation between steps and of shank-foot rotation in late flight, as well as shank rotation during ankle dorsiflexion. Exploratory analysis of interactions between coordination and lower body strength in relation to performance suggest that the effectiveness of particular coordination patterns may depend on an athlete's strength characteristics, particularly those assessed during the countermovement jump. The findings presented here highlight the need for more integrated and complex models that include both technical and physical components in order to develop a more complete understanding of initial acceleration performance, and suggest practitioners should consider strength and technical characteristics in an integrated and individualised manner.

5.6 Chapter summary

Chapter 5 has addressed objective 5: *assess the relationship between initial acceleration coordination patterns and strength characteristics in sprinters* through a series of correlation analyses between the features of step 1 and steps 2-4 coordination in relation to lower body strength tests. The chapter further addressed objective 6: *explore potential interactions between coordination and strength characteristics in relation to acceleration performance in sprinters* through multiple regression analyses assessing interactions between strength and coordination with regard to $\mathrm{RF}_{\mathrm{Max}}$. Large to very large correlations existed between strength tests and coordination variables, with the majority of associations in step 1 coordination, while regression analyses suggested countermovement jump height interacted with several coordination bin frequencies to influence their relationships with acceleration performance.

Isometric squat accounted for the majority of correlations with coordination variables, with correlations also existing between coordination variables and CMJ height and hop test RSI. These associations support the notion that physical characteristics, as a component of organismic constraints, influence the coordination patterns exhibited during acceleration. Further, regression models showed that the relationships between certain coordination variables and acceleration performance changed depending on the whether CMJ height was relatively lower or higher within the sample. These models showed the potential for physical qualities to influence the relationships between coordination and performance, where the effectiveness of particular coordination patterns may depend on the individuals physical capacities.

Overall, chapter 5 has extended the work undertaken chapters 3 and 4 by evaluating how bin frequencies for patterns identified in those chapters relate to the strength characteristics of sprinters, and a novel exploration of the interactions between coordination and strength characteristics in relation to performance. These results have provided the first reported observations of these relationships and highlight the need to consider the interactions between physical capacities and technical features to fully understand acceleration performance. Which could be extended to enhance understanding in other sporting movements. In chapter 6, these findings will be discussed in the broader context of the work done in this thesis, and further practical recommendations will be made from the current results in conjunction with those from Chapter 3 and 4.

References

Alt, T., Oeppert, T. J., Zedler, M., Goldmann, J.-P., Braunstein, B. and Willwacher, S. (2022), ‘A novel guideline for the analysis of linear acceleration mechanics – outlining a conceptual framework of ‘shin roll’ motion’, *Sports Biomechanics* **0**(0), 1–18.

Bayne, H., Donaldson, B. and Bezodis, N. (2020), ‘Inter-limb Coordination During Sprint Acceleration’, *ISBS Proceedings Archive* **38**(1), 448–451.

Berner, K., Cockcroft, J., Morris, L. D. and Louw, Q. (2020b), ‘Concurrent validity and within-session reliability of gait kinematics measured using an inertial motion capture system with repeated calibration’, *Journal of Bodywork and Movement Therapies* **24**(4), 251–260.

Bezodis, I. N., Brazil, A., von Lieres und Wilkau, H. C., Wood, M. A., Paradisis, G. P., Hanley, B., Tucker, C. B., Pollitt, L., Merlino, S., Vazel, P.-J., Walker, J. and Bissas, A. (2019a), ‘World-Class Male Sprinters and High Hurdlers Have Similar Start and Initial Acceleration Techniques’, *Frontiers in Sports and Active Living* **1**, 23.

Bezodis, N., Colyer, S., Nagahara, R., Bayne, H., Bezodis, I., Morin, J.-B., Murata, M. and Samozino, P. (2019b), ‘Understanding Ratio of Forces Duirng Early Acceleration’, *ISBS Proceedings Archive* **37**(1), 499–502.

Bezodis, N., Colyer, S., Nagahara, R., Bayne, H., Bezodis, I., Morin, J.-B., Murata, M. and Samozino, P. (2020), ‘Understanding ratio of forces during early acceleration: Calculation considerations and implications for practice’, *SportRXiv* .

Bezodis, N. E., Salo, A. I. T. and Trewartha, G. (2014), ‘Lower limb joint kinetics during the first stance phase in athletics sprinting: Three elite athlete case studies’, *Journal of Sports Sciences* **32**(8), 738–746.

Brady, C. J., Harrison, A. J., Flanagan, E. P., Haff, G. G. and Comyns, T. M. (2020), ‘The Relationship Between Isometric Strength and Sprint Acceleration in Sprinters’, *International Journal of Sports Physiology and Performance* **15**(1), 38–45.

Chang, R., Van Emmerik, R. and Hamill, J. (2008), ‘Quantifying rearfoot–forefoot coordination in human walking’, *Journal of Biomechanics* **41**(14), 3101–3105.

Charalambous, L., Irwin, G., Bezodis, I. N. and Kerwin, D. (2012), ‘Lower limb joint kinetics and ankle joint stiffness in the sprint start push-off’, *Journal of Sports Sciences* **30**(1), 1–9.

Davids, K., Glazier, P., Araujo, D. and Bartlett, R. (2003), ‘Movement Systems as Dynamical Systems: The Functional Role of Variability and its Implications for Sports Medicine’, *Sports Medicine* **33**(4), 245–260.

Debaere, S., Delecluse, C., Aerenhouts, D., Hagman, F. and Jonkers, I. (2013a), ‘From block clearance to sprint running: Characteristics underlying an effective transition’, *Journal of Sports Sciences* **31**(2), 137–149.

Donaldson, B., Bezodis, N. and Bayne, H. (2021), ‘Within-subject repeatability and between subject variability in posture during calibration of an Inertial Measurement Unit system’, *ISBS Proceedings Archive* **39**(1), 4.

Donaldson, B., Bezodis, N. and Bayne, H. (2022a), ‘Similarity of Coordination Patterns in a group of Highly Trained Sprinters: A Novel Approach’, *ISBS Proceedings Archive* **40**(1), 4.

Donaldson, B. J., Bezodis, N. E. and Bayne, H. (2022b), ‘Inter- and intra-limb coordination during initial sprint acceleration’, *Biology Open* **11**(10), bio059501.

Glazier, P. S. (2017), ‘Towards a Grand Unified Theory of sports performance’, *Human Movement Science* **56**, 139–156.

Hair, J. F., Anderson, R. E., Babin, B. J. and Black, W. C. (2009), *Multivariate Data Analysis*, seventh edn, Prentice Hall, London.

Harper, D., Hobbs, S. and Moore, J. (2011), The ten to five repeated jump test. A new test for evaluation of reactive strength., *in* ‘BASES Student Conference’.

Healy, R., Smyth, C., Kenny, I. C. and Harrison, A. J. (2019), ‘Influence of Reactive and Maximum Strength Indicators on Sprint Performance’, *The Journal of Strength & Conditioning Research* **33**(11), 3039–3048.

Hopkins, W., Marshall, S., Batterham, A. and Hanin, J. (2009), ‘Progressive statistics for studies in sports medicine and exercise science’, *Medicine & Science in Sports & Exercise* **41**(1), 3–13.

Jovanović, M. (2020), *shorts: Short Sprints.* R package version 1.1.4.

Kakehata, G., Goto, Y., Iso, S. and Kanosue, K. (2021), ‘Timing of Rectus Femoris and Biceps Femoris Muscle Activities in Both Legs at Maximal Running Speed’, *Medicine & Science in Sports & Exercise* **53**(3), 643–652.

Kimura, A., Yokozawa, T. and Ozaki, H. (2021), ‘Clarifying the Biomechanical Concept of Coordination Through Comparison With Coordination in Motor Control’, *Frontiers in Sports and Active Living* **3**, 753062.

King, D., Burnie, L., Nagahara, R. and Bezodis, N. E. (2023), ‘Relationships between kinematic characteristics and ratio of forces during initial sprint acceleration’, *Journal of Sports Sciences* **40**(22), 2524–2532.

Kugler, F. and Janshen, L. (2010), ‘Body position determines propulsive forces in accelerated running’, *Journal of Biomechanics* **43**(2), 343–348.

Lockie, R. G., Murphy, A. J., Schultz, A. B., Knight, T. J. and Janse de Jonge, X. A. (2012), ‘The Effects of Different Speed Training Protocols on Sprint Acceleration Kinematics and Muscle Strength and Power in Field Sport Athletes’, *Journal of Strength and Conditioning Research* **26**(6), 1539–1550.

Loturco, I., Contreras, B., Kobal, R., Fernandes, V., Moura, N., Siqueira, F., Winckler, C., Suchomel, T. and Pereira, L. A. (2018), ‘Vertically and horizontally directed muscle power exercises: Relationships with top-level sprint performance’, *PLOS ONE* **13**(7), e0201475.

Loturco, I., Kobal, R., Kitamura, K., Fernandes, V., Moura, N., Siqueira, F., Cal Abad, C. C. and Pereira, L. A. (2019), ‘Predictive Factors of Elite Sprint Performance: Influences of Muscle Mechanical Properties and Functional Parameters’, *The Journal of Strength & Conditioning Research* **33**(4), 974–986.

Loturco, I., Pereira, L. A., Cal Abad, C. C., D’Angelo, R. A., Fernandes, V., Kitamura, K., Kobal, R. and Nakamura, F. Y. (2015), ‘Vertical and Horizontal Jump Tests Are Strongly Associated With Competitive Performance in 100-m Dash Events’, *Journal of Strength and Conditioning Research* **29**(7), 1966–1971.

McErlain-Naylor, S. and Needham, R. (2021), Inter-individual Variation in Coordination and Control of Countermovement Jumps, *in* ‘Proceedings of the International Society of Biomechanics’, Vol. 49, Stockholm.

McKay, A. K., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Goosey-Tolfrey, V. L., Sheppard, J. and Burke, L. M. (2021), 'Defining Training and Performance Caliber: A Participant Classification Framework', *International Journal of Sports Physiology and Performance* **17**(2), 317–331.

Morin, J.-B., Edouard, P. and Samozino, P. (2011), 'Technical Ability of Force Application as a Determinant Factor of Sprint Performance', *Medicine & Science in Sports & Exercise* **43**(9), 1680–1688.

Morin, J.-B., Samozino, P., Murata, M., Cross, M. R. and Nagahara, R. (2019), 'A simple method for computing sprint acceleration kinetics from running velocity data: Replication study with improved design', *Journal of Biomechanics* **94**, 82–87.

Morin, J.-B., Slawinski, J., Dorel, S., de villareal, E. S., Couturier, A., Samozino, P., Brughelli, M. and Rabita, G. (2015), 'Acceleration capability in elite sprinters and ground impulse: Push more, brake less?', *Journal of Biomechanics* **48**(12), 3149–3154.

Nagahara, R., Naito, H., Miyashiro, K., Morin, J. B. and Zushi, K. (2014), 'Traditional and ankle-specific vertical jumps as strength-power indicators for maximal sprint acceleration', *The Journal of Sports Medicine and Physical Fitness* **54**(6), 691–699.

Needham, R. A., Naemi, R. and Chockalingam, N. (2015), 'A new coordination pattern classification to assess gait kinematics when utilising a modified vector coding technique', *Journal of Biomechanics* **48**(12), 3506–3511.

Needham, R. A., Naemi, R., Hamill, J. and Chockalingam, N. (2020), 'Analysing patterns of coordination and patterns of control using novel data visualisation techniques in vector coding', *The Foot* **44**, 101678.

Newell, K. (1986), Constraints on the development of coordination, *in* M. Wade and H. Whiting, eds, 'Motor Development in Children : Aspects of Coordination and Control', Martinus Nijhoff, Dordrecht, pp. 341–360.

Newell, K. M. (1985), Coordination, Control and Skill, *in* D. Goodman, R. B. Wilberg and I. M. Franks, eds, 'Advances in Psychology', Vol. 27 of *Differing Perspectives In Motor Learning, Memory, And Control*, North-Holland, pp. 295–317.

Okudaira, M., Willwacher, S., Kawama, R., Ota, K. and Tanigawa, S. (2021), 'Sprinting kinematics and inter-limb coordination patterns at varying slope inclinations', *Journal of Sports Sciences* **39**(21), 2444–2453.

R Core Team (2021), *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria.

Rabita, G., Dorel, S., Slawinski, J., Sàez-de-Villarreal, E., Couturier, A., Samozino, P. and Morin, J.-B. (2015), 'Sprint mechanics in world-class athletes: A new insight into the limits of human locomotion: Sprint mechanics in elite athletes', *Scandinavian Journal of Medicine & Science in Sports* **25**(5), 583–594.

Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., de Villarreal, E. S.-S. and Morin, J.-B. (2016), 'A Simple Method for Measuring Power, Force, Velocity Properties, and Mechanical Effectiveness in Sprint Running', *Scandinavian Journal of Medicine & Science in Sports* **26**(6), 648–658.

Schache, A. G., Lai, A. K. M., Brown, N. A. T., Crossley, K. M. and Pandy, M. G. (2019), 'Lower-limb joint mechanics during maximum acceleration sprinting', *The Journal of Experimental Biology* **222**(22), jeb209460.

Slawinski, J., Bonnefoy, A., Levêque, J.-M., Ontanon, G., Riquet, A., Dumas, R. and Chèze, L. (2010), 'Kinematic and Kinetic Comparisons of Elite and Well-Trained Sprinters During Sprint Start:', *Journal of Strength and Conditioning Research* **24**(4), 896–905.

von Lieres und Wilkau, H. C., Irwin, G., Bezodis, N. E., Simpson, S. and Bezodis, I. N. (2020), 'Phase analysis in maximal sprinting: An investigation of step-to-step technical changes between the initial acceleration, transition and maximal velocity phases', *Sports Biomechanics* **19**(2), 141–156.

Weyand, P. G., Sandell, R. F., Prime, D. N. L. and Bundle, M. W. (2010), 'The biological limits to running speed are imposed from the ground up', *Journal of Applied Physiology* **108**(4), 950–961.

Wild, J. J., Bezodis, I. N., North, J. S. and Bezodis, N. E. (2021), 'Characterising initial sprint acceleration strategies using a whole-body kinematics approach', *Journal of Sports Sciences* **40**(2), 203–214.

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

Chapter 6

General discussion

As Glazier (2017) noted in his outline for a Grand Unified Theory of sports performance, there is a need for biomechanical investigations to go beyond isolated joint and segment analyses of technique, and to adopt more integrated approaches to understanding the coordination of movement from a dynamical systems theory perspective. However, such coordination research in sprinting is rare and, despite the substantial attention initial acceleration has received in the literature, only three studies have previously analysed aspects of coordination in these first steps of the sprint (Bayne et al., 2020; Bezodis et al., 2019a; Okudaira et al., 2021). The research presented in this thesis developed a comprehensive empirical understanding of coordination during initial acceleration, grouped and characterised different coordination patterns, and assessed the relationships between coordination, lower body strength, and acceleration performance. This final chapter provides a brief overview of the work comprising this thesis, before critically synthesising the findings of the studies presented in Chapters 3-5, and discussing the primary conclusions in the context of existing literature. Finally, the strengths, limitations and practical implications of the research are discussed.

6.1 Overview of the research

In Chapter 1, the topic was introduced and the motivations for the current research programme were outlined, from which six objectives were identified. Subsequently, Chapter 2 expanded on the rationale introduced in Chapter 1 through a review of the relevant parts of the literature that form the background of this thesis, including discussion of the initial acceleration phase, the theoretical and practical foundations of coordination and the relationships between strength and acceleration.

Chapter 3 described and quantified thigh-thigh, trunk-shank and shank-foot coordination during the first four steps after block exit as well as assessing between-individual variation in coordination across these steps, satisfying objective 1 to *describe and quantify inter- and intra-limb coordination patterns exhibited by sprinters during initial acceleration.* Chapter 3 further found coordination to differ between steps for all three couplings, with the largest differences between step 1 and all other steps, and therefore objective 2 to *assess step-to-step changes in coordination during initial acceleration* was also addressed in this chapter.

In Chapter 4, cluster analysis was used to assess possible sub-groups based on thigh-thigh and shank-foot coordination, revealing distinct strategies in both step 1 and steps 2-4. Clear coordination and kinematic differences were found between clusters, thus addressing objective 3, to *identify different initial acceleration coordination strategies used by sprinters and characterise the typical features of these patterns.* When considered separately for just step 1 or steps 2-4, the clusters did not differ in performance outcomes. However, when step 1 and steps 2-4 clusters were combined to describe entire initial acceleration coordination strategies, there were patterns adopted more commonly by higher level sprinters and associated with better performance compared to other combinations. Thus, objective 4 to *explore the associations between the coordination strategies exhibited by sprinters and their performance during acceleration* was met by Chapter 4.

Finally, Chapter 5 evaluated the relationships between coordination and strength measures, finding several correlations between the proportion of time spent in particular coordination bins and lower body strength variables, for coordination profiles exhibited during both step 1 and steps 2-4. These associations revealed isometric squat force to be the strength variable most commonly associated with different coordination bins. This chapter therefore satisfied objective 5, *to assess the relationship between initial acceleration coordination patterns and strength characteristics in sprinters.* In addition, multiple regression analyses in Chapter 5 suggested possible interactions between the frequencies of particular coordination bins and performance in the countermovement jump in relation to acceleration performance. This represented the first attempt to investigate sprint performance through the interaction of coordination and strength and in doing so addressed objective 6, to *explore potential interactions between coordination and strength characteristics in relation to acceleration performance in sprinters.*

6.2 Synthesis

The coordination patterns observed in Chapter 3 supported the only previous descriptions of intra- or inter-limb coordination during initial acceleration, with similar overall trunk-shank and thigh-thigh coordination reported by Bezodis et al. (2019a) and Bayne et al. (2020) respectively, and extended the understanding obtained from both studies with novel observations. In particular, this chapter identified asynchronous reversals of trunk and shank rotation around touchdown and toe-off events and specific thigh-thigh coordination patterns after block clearance as well as during the scissor action during the transition between steps. Moreover, Chapter 3 included the first analysis of shank-foot coordination in the literature. Despite the importance of the ankle in power absorption and generation in initial acceleration (Bezodis et al., 2014; Brazil et al., 2016; Charalambous et al., 2012; Schache et al., 2019), no studies had previously investigated the relative motion of its component segments. Three key periods of shank-foot coordination appeared to correspond to the preparation for touchdown in late flight, ankle dorsiflexion in early stance and ankle plantarflexion through mid to late stance.

Step-to-step differences in touchdown angular kinematics were observed in Chapter 3, which have previously been suggested as a determining feature of this phase (Nagahara et al., 2014; von Lieres und Wilkau et al., 2020a), and thus confirming these previous observations in a higher level sample including elite and world class athletes. Moreover, step-to-step differences in coordination were reported for the first time in the literature, showing that not only do isolated kinematics shift across the initial steps, so do the relationships between those segments. Indeed, all three segment couplings exhibited changes across steps, highlighting that there are whole body changes in segment organisation across the initial acceleration phase. Furthermore, the results presented in Chapter 3 showed that the step 1 discrete kinematics and coordination profiles were significantly different from all other steps. These differences between consecutive steps then declined with each subsequent step, and therefore step 1 could be considered separately from a technique perspective. This may be viewed as a breakpoint within the initial acceleration phase, prior to the subsequent breakpoint between initial acceleration and transition that has previously been identified around step 4 (Nagahara et al., 2014; von Lieres und Wilkau et al., 2020a). Such a distinction may be especially relevant for approaches that average technical features over the entire initial acceleration phase. Specifically, the observations in Chapter 3 revealed thigh-thigh coordination in early flight in step 1 to exhibit patterns wholly different from early flight in later steps, while trunk-shank and shank-foot coordination differed from later steps primarily through shifts in inter-segment patterns during stance. It appears that these may be the key periods generally for differentiating coordination, since the early flight thigh-thigh and early stance shank-foot coordination that differentiated between steps in Chapter 3 were the same that differentiated between the different step 1 coordination subgroups identified by cluster analysis in Chapter 4.

After block clearance, the thighs primarily exhibit coordination with lead thigh anti-clockwise rotation (i.e., flexion) as the athlete continues to pull the lead thigh forward during early flight. The results presented in Chapter 4 showed that step 1 strategies were differentiated by the proportion of the step that different participants continued this lead thigh motion and the extent of lead thigh dominance, while the results in Chapter 3 showed this early flight pattern to be entirely absent in later steps.

In shank-foot coordination, differences between steps seemed in large part to centre on the extent of foot dominance during ankle dorsiflexion in early stance. In step 1, participants tended to have mostly or completely foot dominant coordination in this phase, transitioning to shank dominance in later steps. While this pattern was consistent across the majority of participants, the cluster analysis in Chapter 4 implied that relative foot and shank dominance in step 1 separates different strategies in this step, with some indication that foot dominant ankle dorsiflexion in step 1 may be associated with better sprinters. In both Chapters 3 and 4, more foot dominant coordination during dorsiflexion was associated with more vertical foot angles at touchdown, which has, in turn, been associated with higher RF during initial acceleration (King et al., 2023). It is unclear whether such foot dominant coordination is a necessary by-product of vertical foot angles, such that the ankle dorsiflexion required in early stance can only be achieved through the dropping of the heel with a relatively stable shank orientation, or whether such foot dominant coordination may contribute to superior RF by aiding the positioning of the shank in a more horizontal orientation where it can help direct a greater component of the force in the horizontal direction during subsequent joint extensions. The current associations between foot angle at touchdown and foot dominant coordination have provided an initial view of how foot orientation and the components of the ankle might interact in acceleration. Further research including the underlying kinetics would be helpful in order to understand how foot or shank dominant ankle dorsiflexion correspond to the ankle joint power absorption patterns which have been shown to be important in the first step, and how that may be affected by foot orientation at touchdown (Bezodis et al., 2015; Brazil et al., 2016; Charalambous et al., 2012; Schache et al., 2019).

Shank-foot patterns in flight were also somewhat different in later steps compared to step 1, specifically with less in-phase anti-clockwise rotation during early flight and more in-phase clockwise rotation prior to touchdown. Once again, this pattern differentiated strategies identified by clusters in both step 1 and steps 2-4 in Chapter 4, suggesting this pattern of coordination during flight characterises both changes in technique across steps as well as different strategies between sub-groups. Moreover, Chapter 5 showed higher maximal isometric squat force was associated with less in-phase anti-clockwise rotation and more in-phase clockwise rotation in steps 2-4, implying the adoption of one strategy or the other may relate to an athlete's physical characteristics, in particular their maximal force generating capacities. These patterns all relate to the reversal in anti-clockwise shank rotation in late flight termed 'shin block' by Alt et al. (2022), and imply that this event in the step cycle may be an important consideration in the strategies adopted by sprinters with regard to the distal components of the system.

Previous research has shown thigh-thigh motion to be mostly characterised by anti-phase rotations as the thighs oscillate during the step cycle, approximating a sine-wave (Bayne et al., 2020; Clark et al., 2020, 2021; Okudaira et al., 2021). The results of Chapter 3 confirmed this general pattern but also revealed that the thighs do not necessarily rotate at the same rate and that the timing of reversals in thigh rotation typically do not occur simultaneously, but rather asynchronously, even in the elite and world class sprinters studied in the current thesis. Consequently, the relative balance of lead or trail thigh dominance during anti-phase coordination changes over the step cycle, and Chapter 3 shows the overall distribution of lead or trail thigh dominance also changes across steps. Anti-phase thigh interchange is predominantly trail thigh dominant, but there is relatively more lead thigh dominant coordination in step 1. Further, the results of Chapter 4 found one cluster of sprinters to exhibit a relatively more lead thigh dominant coordination strategy compared to the other clusters. This cluster tended to be associated with lower performance in Chapter 4, but the adoption of this strategy may be linked to physical characteristics, with findings in Chapter 5 indicating that sprinters with more lead thigh dominant - and therefore less trail thigh dominant - anti-phase coordination tended to also exhibit lower maximal isometric squat force. In fact, further results from Chapter 5 suggest that strength factors might interact with this balance of lead or trail thigh dominance during anti-phase rotation in relation to performance. Countermovement jump height showed interactions with both anti-phase leading (-) and anti-phase trailing (+) frequency in Chapter 5, such that whether a greater proportion of lead or trail thigh dominant coordination was associated with performance depended on whether countermovement jump values were relatively higher or lower. Thus, more lead thigh dominant patterns may only be advantageous for performance for those athletes with higher levels of strength and power while more trail thigh dominant patterns may benefit performance for those with lower levels of strength and power.

A difference in the timing of thigh rotation reversals resulted in the novel observation of in-phase clockwise thigh rotation around the transition between steps. The results of Chapter 3 showed the frequency of this in-phase activity to be mostly consistent across steps, but the timing shifted from occurring in late stance in earlier steps to early flight in later steps. Further, examination of the sub-groups in Chapter 4 revealed that the timing, but not necessarily the frequency, of this in-phase activity differentiated strategies between clusters, with the steps 2-4 clusters separated not by the total amount of in-phase motion over the step but by whether the in-phase coordination tended to occur before or after toe-off. Thus, Chapter 4 shows this timing of reversals to demonstrate two different strategies for transitioning between steps: one of early retraction of the lead thigh during late stance and the other with 'over-pushing' of the trail thigh after toe-off. Chapter 4 further suggests early retraction to be associated with better performance, at least in combination with particular step 1 strategies. However, physical capacities may have an influence here. Chapter 5 showed greater in-phase activity in step 1 in sprinters with lower reactive strength capacities, while there was an interaction between in-phase frequency in steps 2-4 and countermovement jump height in relation to performance. As such, the amount of in-phase rotation, and whether it positively or negatively influences performance, might depend on the lower body power capacities of the athlete. However, since the analyses in Chapter 5 only examined the relationships between total frequency of in-phase motion relative to lower body strength, the results were not able to determine whether the timing of thigh reversals were related to, or interacted with, any strength characteristics. Clarifying the effect of timing of in-phase motion in this context would be a valuable addition to future work in this area. Nevertheless, the current observations could have valuable practical implications, these are discussed further below.

6.3 Strengths & limitations of the research

A notable strength of the current research is a focus on, and inclusion of, sprinters at a high level of performance. The setting for this study in high level sprint training groups allowed for a sample where a third of participants were classified as 'elite' or 'world class' according to the definitions of McKay et al. (2021). Athletes of such calibre are typically difficult to include in studies owing to their intensive training and travel schedules, and an understandable reluctance to interfere with their training or potentially increasing the risk of injury by adding intrusive measurement protocols or devices. This is especially true of sprinters, where the best athletes are spread out internationally across a large number of small training groups and the total global population of high level sprinters is small relative to most team sports or endurance runners, for example. Indeed, by including sub-10 s sprinters, the current sample has included two of only an estimated 158 total sprinters who had run under 10 s in the 100 m up to the year of data collection. As such, the sample size included in the current research was limited, especially for female participants, and this consequently limited the scope and strength of certain statistical considerations. However, owing to the constraints above, sample sizes in sprint studies are typically small and the current sample is consistent with typical samples in the sprint literature, many of which have studied sprinters of lower levels of performance (e.g. Debaere et al. (2013); King et al. (2023); Nagahara et al. (2014)); the current research has a sample size larger than most sprint biomechanics studies that include elite and world class athletes (e.g. Rabita et al. (2015); Slawinski et al. (2010); Walker et al. (2021)).

A further strength of this research was the collection of data during 'real world' training sessions. This ensured that trials were performed under conditions with high ecological validity, whilst also being performed under coach supervision, and they were therefore of a high intensity. Moreover, data was collected during the competition phase of the season when athletes were racing frequently and therefore physically and mentally closer to their peak levels of performance compared to other stages of the season. With high level athletes, it is often easier to collect data during less busy parts of the season, but this means athletes may not produce trials that closely reflect their peak performance. To facilitate data collection during training sessions, IMUs were used to record 3D kinematics instead of 'gold standard' optical motion capture methods. While some considerations are required for the use of IMUs, and caution should be exercised in directly comparing angular values between IMU and optical motion capture systems, previous studies have demonstrated the validity and reliability of the Noraxon system in the sagittal plane (Balasubramanian, 2013; Berner et al., 2020a,b; Cottam et al., 2022; Yoon, 2017). Furthermore, since IMUs are calibrated to establish reference angles from a standing calibration posture, the reliability of the standing posture within participants was checked prior to commencing this research (see Appendix A) and a consistent protocol was adopted throughout data collection. The use of IMUs provided the advantage of collecting data under ecologically valid conditions during real training sessions, which would not have been possible using optical motion capture, as well as enabling a larger sample size to be obtained since the processing could be achieved far more rapidly than a manual video approach.

With regards to the vector coding methods employed in this study, the binning approach adopted here (Needham et al., 2020) added greater nuance to interpretations compared to the binning convention utilised previously in sprinting (Bayne et al., 2020; Bezodis et al., 2019a) as it incorporated segment dominancy into coordination profiles. This facilitated novel observations in all three segment couplings and offered a substantial advantage over previous conventions. However, as in previous studies, the coordination bins adopted here only capture the direction of the coupling angle vector and therefore fail to account for the magnitude of the vector, i.e., they fail to describe the distance between points on the angle-angle plot and therefore the speed of change. The speed of change could be interpreted as the degree of 'control' an athlete has over the particular coordination pattern, and therefore could provide an additional consideration with regard to typical coordination patterns (McErlain-Naylor and Needham, 2021; Needham et al., 2020). However, the best methodological approaches for determining and interpreting control are yet to be established, and the inclusion of such an additional measure was beyond the scope of what was required to address the research objectives of this thesis. Future coordination studies building on the current work might benefit from the inclusion of a measure of control, although careful consideration must be given to the methods adopted. For example, determining the inter-data point range of motion or using angular velocity in place of angular displacement values in coupling angle determination are two potential avenues for quantifying control as an additional variable in coordination (Needham et al., 2020; Stock et al., 2022).

The current research has provided a comprehensive quantification of coordination in initial acceleration and of the variability in these coordination patterns between participants, but within-individual coordination variability was not considered. Whilst the variability of coordination patterns within-individuals can be important for understanding the consistency of movement patterns within athletes as well as the impact of any variability on performance, given the objectives and scope of the work included in this thesis, within-individual variability did not align with the central goals of the work. Moreover, reliable determination of variability requires a relatively large number of repeated step cycles for which the step-to-step kinematic changes during initial acceleration would have required a number of trials for each athlete that would have been unrealistic to obtain in the context of the applied data collection setting for this work (Hafer and Boyer, 2017). No studies have so far evaluated coordination variability in sprint acceleration, and future research in this area may find it useful to incorporate variability to extend on some of the findings presented here and expand the understanding of initial acceleration coordination (Hamill et al., 2000; Heiderscheit et al., 2002; Kimura et al., 2021).

Finally, the consideration of relationships and interactions between coordination and strength factors was the first of its kind in sprinting and included strength tests covering a range of lower limb capacities. The inclusion of strength data in relation to both coordination and performance enabled coordination to be analysed in the context of the underpinning dynamical systems theory which has framed the analyses in this thesis. These initial observations broaden the scope for future research, while also adding valuable further knowledge to the general physical capacities of sprinters and suggest that the effectiveness of particular coordination patterns may depend on an athlete's physical capacities. The inclusion of technique, strength and performance variables together enabled greater context for considering the factors that may influence the coordination patterns adopted and the conditions under which different emergent coordination patterns may be effective. However, the use of high level athletes in an ecologically valid setting meant ground reaction forces or horizontal external power could not be measured directly at each step which would have enbled coordination in a particular step to be assessed directly with the horizontal force component and RF for that specific step. Rather, the external kinetics related to acceleration performance were estimated indirectly from the velocity data. Although direct measurement of GRFs would be the 'gold standard' and facilitate a more direct step by step assessment of associations and interactions between coordination, strength and performance, the indirect methods employed are commonly used in applied settings and have shown to be both valid and reliable (Morin et al., 2019; Samozino et al., 2015), with the derived $\mathrm{RF}_{\mathrm{Max}}$ value that was used as the primary performance measure in the current thesis corresponding excellently to direct performance measures (Bezodis et al., 2019b). Thus, the current study has used a robust and established performance measure, albeit unable to assess relationships at the level of the individual step. Direct force plate measured GRFs may be able to further expand on the nuance in the interactions between strength and coordination in relation to performance, and in particular why they might differ between steps.

6.4 Practical implications

This thesis resulted from applied biomechanics support to sprinters, and the results have raised several implications for practitioners. The current research developed out of a recognition that the body is a linked segment system and therefore the segments must act in concert to produce resulting movement patterns, necessitating approaches going beyond the isolated joint and segment analyses common to sprint biomechanics studies (Bezodis et al., 2019a; Glazier, 2017). The studies presented in Chapters 3-5 have enhanced the knowledge available to practitioners with respect to the relationships between segments in segment couplings with direct functional relevance. In practical settings, coaches often consider overall organisation of the body at key events in the sprint through tools such as the 'kinogram' which provide a visual representation of this whole body organisation, or 'shapes', at specific events (McMillan and Pfaff, 2018). The comprehensive empirical analysis of Chapter 3 and the characterisation of patterns in Chapter 4 provide greater context for the organisation of segments between these key events, and in doing so also provide a quantitative assessment of the inter-relation of segments to support the qualitative judgements coaches may make from the images in the kinogram. Moreover, both Chapter 3 and Chapter 4 indicated associations between specific coordination patterns and touchdown or toe-off angles, while between individual variability in coordination was highest in preparation for, or in the aftermath of, these key events in the gait cycle. This highlights that aiming for specific segment organisations (i.e., 'shapes') at key events could influence the movement patterns in other parts of the step to unknown effect.

Previous studies have suggested coaches take into account step-to-step kinematic changes and their implications for the magnitude and direction of force application during initial acceleration (Colyer et al., 2018; Nagahara et al., 2014; von Lieres Und Wilkau et al., 2020b; von Lieres und Wilkau et al., 2020a). The observations in Chapter 3 suggest the inter-relationships between segments also change across steps, and these changes also warrant consideration by coaches. Furthermore, some sprint coaches have tended to consider the first step independently from later steps with regards to technique (Jones et al., 2009). The results of Chapter 3 support that assertion from a coordination perspective by demonstrating distinct step 1 coordination across segment couplings and implying the constraints of block clearance warrant independent consideration for the inter-relation of segments in step 1.

In Chapter 4, the results showed the potential for profiling coordination strategies in order to characterise the available approaches sprinters might adopt. This highlighted the possibility of multiple effective technical approaches depending on the constraints of individuals, which has been found in professional rugby players (Wild et al., 2021). However, these results also suggested that certain strategies adopted by highly trained and elite sprinters may be less effective, in particular strategies exhibiting less lead thigh anticlockwise rotation during early flight and more shank dominant ankle dorsiflexion in step 1 in combination with late trail thigh reversal (i.e., over-pushing) in later steps. Chapter 4 further showed the potential of coordination profiling to assist coaches in determining and quantifying the strategies adopted by their athletes and characterising the range of effective strategies for achieving desired performance outcomes. Another aspect highlighted by the results of Chapter 4 is that sprinters with similar coordination in one period of the sprint do not necessarily adopt similar approaches in another. Sprinters in this sample with similar step 1 coordination did not always adopt the same approach as each other in steps 2-4. Coaches may need to consider which individual factors might lead sprinters to adopt similar or different approaches in different phases or steps compared to other competitors and whether this is beneficial or not.

Indeed, Chapter 5 highlights the possible relationships between physical and technical capacities. Given the prominence of strength training in addition to technical training in most sprint programmes, the potential relationships between specific strength factors and coordination features reported in Chapter 5 should give coaches some considerations as to the possible influence that changes in strength might have on the technique an athlete tends to adopt. Future work and practical investigations might also consider whether these associations have any implications for the specificity of strength training exercises in relation to sprinting (Brazil et al., 2020). However, Chapter 5 also found that strength and coordination may interact with respect to acceleration performance, such that whether a particular coordination pattern is effective or not in terms of performance may depend on the particular strength profile of the athlete. Thus it may be best for coaches to consider particular movement patterns and strength profiles for their athletes individually when prescribing technical or physical training. Moreover, such interactions would imply that it would be beneficial for practitioners to monitor the impact that changes in strength might have on an athlete's technique, but also to consider that increases in strength might require concomitant changes in technique to potentially enable the transfer to improved performances.

6.5 Final Remarks

This thesis emerged out of a need for more integrated approaches to understanding acceleration technique, taking into account the linked nature of the human body in the context of task and organismic constraints. Through a series of investigations utilising highly trained, elite and world class sprinters, this research programme has established a broader empirical understanding of coordination during initial acceleration, demonstrated changes in coordination over the first four steps, explored the characterisation of coordination strategies employed by highly trained to world class sprinters and provided the first exploration of interactions between lower body strength and coordination in the context of acceleration performance. In doing so, this thesis has expanded the knowledge of coordination and provided a number of practical implications for sprint coaches. Furthermore, it now provides a strong, evidence based, platform for future research to take more integrated approaches to understanding sprint technique.

References

Alt, T., Oeppert, T. J., Zedler, M., Goldmann, J.-P., Braunstein, B. and Willwacher, S. (2022), ‘A novel guideline for the analysis of linear acceleration mechanics – outlining a conceptual framework of ‘shin roll’ motion’, *Sports Biomechanics* **0**(0), 1–18.

Balasubramanian, S. (2013), Comparison of Angle Measurements between Vicon and MyoMotion Systems, PhD thesis, Arizona State University.

Bayne, H., Donaldson, B. and Bezodis, N. (2020), ‘Inter-limb Coordination During Sprint Acceleration’, *ISBS Proceedings Archive* **38**(1), 448–451.

Berner, K., Cockcroft, J. and Louw, Q. (2020a), ‘Kinematics and temporospatial parameters during gait from inertial motion capture in adults with and without HIV: A validity and reliability study’, *BioMedical Engineering OnLine* **19**(1), 57.

Berner, K., Cockcroft, J., Morris, L. D. and Louw, Q. (2020b), ‘Concurrent validity and within-session reliability of gait kinematics measured using an inertial motion capture system with repeated calibration’, *Journal of Bodywork and Movement Therapies* **24**(4), 251–260.

Bezodis, I. N., Brazil, A., von Lieres und Wilkau, H. C., Wood, M. A., Paradisis, G. P., Hanley, B., Tucker, C. B., Pollitt, L., Merlino, S., Vazel, P.-J., Walker, J. and Bissas, A. (2019a), ‘World-Class Male Sprinters and High Hurdlers Have Similar Start and Initial Acceleration Techniques’, *Frontiers in Sports and Active Living* **1**, 23.

Bezodis, N., Colyer, S., Nagahara, R., Bayne, H., Bezodis, I., Morin, B., Murata, M. and Samozino, P. (2019b), ‘Understanding Ratio of Forces During Early Acceleration’, *ISBS Proceedings Archive* **37**(1), 499–502.

Bezodis, N. E., Salo, A. I. T. and Trewartha, G. (2014), ‘Lower limb joint kinetics during the first stance phase in athletics sprinting: Three elite athlete case studies’, *Journal of Sports Sciences* **32**(8), 738–746.

Bezodis, N. E., Salo, A. I. T. and Trewartha, G. (2015), ‘Relationships between lower-limb kinematics and block phase performance in a cross section of sprinters’, *European Journal of Sport Science* **15**(2), 118–124.

Brazil, A., Exell, T., Wilson, C. and Irwin, G. (2020), 'A biomechanical approach to evaluate overload and specificity characteristics within physical preparation exercises', *Journal of Sports Sciences* **38**(10), 1140–1149.

Brazil, A., Exell, T., Wilson, C., Willwacher, S., Bezodis, I. and Irwin, G. (2016), 'Lower limb joint kinetics in the starting blocks and first stance in athletic sprinting', *Journal of Sports Sciences* **35**(16), 1629–1635.

Charalambous, L., Irwin, G., Bezodis, I. N. and Kerwin, D. (2012), 'Lower limb joint kinetics and ankle joint stiffness in the sprint start push-off', *Journal of Sports Sciences* **30**(1), 1–9.

Clark, K. P., Meng, C. R. and Stearne, D. J. (2020), '"Whip from the hip": Thigh angular motion, ground contact mechanics, and running speed', *Biology Open* **9**(10), bio.053546.

Clark, K. P., Ryan, L. J., Meng, C. R. and Stearne, D. J. (2021), 'Evaluation of maximum thigh angular acceleration during the swing phase of steady-speed running', *Sports Biomechanics* pp. 1–14.

Colyer, S. L., Nagahara, R. and Salo, A. I. T. (2018), 'Kinetic demands of sprinting shift across the acceleration phase: Novel analysis of entire force waveforms', *Scandinavian Journal of Medicine & Science in Sports* **28**(7), 1784–1792.

Cottam, D. S., Campbell, A. C., Davey, M. P. C., Kent, P., Elliott, B. C. and Alderson, J. A. (2022), 'Measurement of uni-planar and sport specific trunk motion using magneto-inertial measurement units: The concurrent validity of Noraxon and Xsens systems relative to a retro-reflective system', *Gait & Posture* **92**, 129–134.

Debaere, S., Delecluse, C., Aerenhouts, D., Hagman, F. and Jonkers, I. (2013), 'From block clearance to sprint running: Characteristics underlying an effective transition', *Journal of Sports Sciences* **31**(2), 137–149.

Glazier, P. S. (2017), 'Towards a Grand Unified Theory of sports performance', *Human Movement Science* **56**, 139–156.

Hafer, J. F. and Boyer, K. A. (2017), 'Variability of segment coordination using a vector coding technique: Reliability analysis for treadmill walking and running', *Gait & Posture* **51**, 222–227.

Hamill, J., Haddad, J. M. and McDermott, W. J. (2000), 'Issues in Quantifying Variability from a Dynamical Systems Perspective', *Journal of Applied Biomechanics* **16**(4), 407–418.

Heiderscheit, B. C., Hamill, J. and van Emmerik, R. E. (2002), 'Variability of Stride Characteristics and Joint Coordination among Individuals with Unilateral Patellofemoral Pain', *Journal of Applied Biomechanics* **18**(2), 110–121.

Jones, R., Bezodis, I. and Thompson, A. (2009), 'Coaching Sprinting: Expert Coaches' Perception of Race Phases and Technical Constructs', *International Journal of Sports Science & Coaching* **4**(3), 385–396.

Kimura, A., Yokozawa, T. and Ozaki, H. (2021), 'Clarifying the Biomechanical Concept of Coordination Through Comparison With Coordination in Motor Control', *Frontiers in Sports and Active Living* **3**, 290.

King, D., Burnie, L., Nagahara, R. and Bezodis, N. E. (2023), 'Relationships between kinematic characteristics and ratio of forces during initial sprint acceleration', *Journal of Sports Sciences* **40**(22), 2524–2532.

McErlain-Naylor, S. and Needham, R. (2021), Inter-individual Variation in Coordination and Control of Countermovement Jumps, *in* 'Proceedings of the International Society of Biomechanics', Vol. 49, Stockholm.

McKay, A. K., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Goosey-Tolfrey, V. L., Sheppard, J. and Burke, L. M. (2021), 'Defining Training and Performance Caliber: A Participant Classification Framework', *International Journal of Sports Physiology and Performance* **17**(2), 317–331.

McMillan, S. and Pfaff, D. (2018), *Kinogram Method Ebook*, ALTIS.
URL: *https://altis.world/kinogram-method-ebook/*

Morin, J.-B., Samozino, P., Murata, M., Cross, M. R. and Nagahara, R. (2019), 'A simple method for computing sprint acceleration kinetics from running velocity data: Replication study with improved design', *Journal of Biomechanics* **94**, 82–87.

Nagahara, R., Matsubayashi, T., Matsuo, A. and Zushi, K. (2014), 'Kinematics of transition during human accelerated sprinting', *Biology Open* **3**(8), 689–699.

Needham, R. A., Naemi, R., Hamill, J. and Chockalingam, N. (2020), 'Analysing patterns of coordination and patterns of control using novel data visualisation techniques in vector coding', *The Foot* **44**, 101678.

Okudaira, M., Willwacher, S., Kawama, R., Ota, K. and Tanigawa, S. (2021), 'Sprinting kinematics and inter-limb coordination patterns at varying slope inclinations', *Journal of Sports Sciences* **39**(21), 2444–2453.

Rabita, G., Dorel, S., Slawinski, J., Sàez-de-Villarreal, E., Couturier, A., Samozino, P. and Morin, J.-B. (2015), 'Sprint mechanics in world-class athletes: A new insight into the limits of human locomotion: Sprint mechanics in elite athletes', *Scandinavian Journal of Medicine & Science in Sports* **25**(5), 583–594.

Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., de Villarreal, E. S.-S. and Morin, J.-B. (2015), 'A Simple Method for Measuring Power, Force, Velocity Properties, and Mechanical Effectiveness in Sprint Running', *Scandinavian Journal of Medicine & Science in Sports* (26), 648–658.

Schache, A. G., Lai, A. K. M., Brown, N. A. T., Crossley, K. M. and Pandy, M. G. (2019), 'Lower-limb joint mechanics during maximum acceleration sprinting', *The Journal of Experimental Biology* **222**(22), jeb209460.

Slawinski, J., Bonnefoy, A., Levêque, J.-M., Ontanon, G., Riquet, A., Dumas, R. and Chèze, L. (2010), 'Kinematic and Kinetic Comparisons of Elite and Well-Trained Sprinters During Sprint Start:', *Journal of Strength and Conditioning Research* **24**(4), 896–905.

Stock, H. A., Wilson, C., van Emmerik, R. E. and Preatoni, E. (2022), 'Angular dynamics in vector coding: A new approach based on angular velocity', *Sports Biomechanics* **0**(0), 1–16.

von Lieres Und Wilkau, H. C., Bezodis, N. E., Morin, J.-B., Irwin, G., Simpson, S. and Bezodis, I. N. (2020b), 'The importance of duration and magnitude of force application to sprint performance during the initial acceleration, transition and maximal velocity phases', *Journal of Sports Sciences* **38**(20), 2359–2366.

von Lieres und Wilkau, H. C., Irwin, G., Bezodis, N. E., Simpson, S. and Bezodis, I. N. (2020a), 'Phase analysis in maximal sprinting: An investigation of step-to-step technical changes between the initial acceleration, transition and maximal velocity phases', *Sports Biomechanics* **19**(2), 141–156.

Walker, J., Bissas, A., Paradisis, G. P., Hanley, B., Tucker, C. B., Jongerius, N., Thomas, A., von Lieres und Wilkau, H. C., Brazil, A., Wood, M. A., Merlino, S., Vazel, P.-J. and Bezodis, I. N. (2021), 'Kinematic factors associated with start performance in World-class male sprinters', *Journal of Biomechanics* **124**, 110554.

Wild, J. J., Bezodis, I. N., North, J. S. and Bezodis, N. E. (2021), 'Characterising initial sprint acceleration strategies using a whole-body kinematics approach', *Journal of Sports Sciences* **40**(2), 203–214.

Yoon, T.-L. (2017), 'Validity and Reliability of an Inertial Measurement Unit-Based 3D Angular Measurement of Shoulder Joint Motion', *The Journal of Korean Physical Therapy* **29**(3), 145–151.

Appendices

Appendix A

Conference paper: IMU calibration

WITHIN-SUBJECT REPEATABILITY AND BETWEEN-SUBJECT VARIABILITY IN POSTURE DURING CALIBRATION OF AN INERTIAL MEASUREMENT UNIT SYSTEM

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Inertial measurement units (IMUs) are a valuable tool for field based sports research, but within- and between-subject comparisons may be affected by variation in the 0° position established by a standing calibration position. This study assessed within-subject repeatability and between-subject variability in IMU sensor orientations during calibration. Calibration posture was reliable within-subjects given standardised instructions (typical error < 1.9°). Sensor angles relative to a global vertical axis had large between-subject ranges for upper spine (21–35°), lower spine (1–23°) and pelvis (11–35°), while lower limb segment angles had much lower variability (0-6°). Thus, a standing calibration posture is repeatable within participants given suitable instructions, however variability in standing posture may need to be accounted for before making between-subject comparisons, particularly with regard to spine and pelvis segments.

KEYWORDS: IMU, repeatability, calibration, variability.

INTRODUCTION: Inertial measurement units (IMU) are a practical field-based alternative to optical motion capture (OMC) systems for 3D motion capture, allowing researchers to assess technique in ecologically valid environments such as training and competition, as well as in research labs. Further, IMUs can facilitate research in elite athletes – whose scheduling often precludes lab testing outside their regular training program – during dynamic sports movements such as sprinting where absolute segment angles (eg. shin and trunk) are common technique measures. However, there may be certain constraints that must be considered before using IMUs. A wide range of IMU systems exist, with differences in both hardware and fusion algorithms. Consequently, the validity and reliability of each system needs to be considered separately and specifically in the context of the intended use.

The Noraxon MyoMotion IMU system (Noraxon, USA) has been shown to be valid and reliable compared to optical systems for static knee flexion angles (Balasubramanian, 2013), walking gait (Berner, Cockcroft, Morris, et al., 2020; Seidel et al., 2015), shoulder external rotation (Yoon, 2017) and trunk range of motion tasks and cricket bowling (Cottam, 2019). However, while Mundt et al. (2017), Berner et al. (2020) and Seidel et al. (2015) reported similar changes in direction and magnitude between IMU and OMC systems, there were differences between absolute angles reported by each system. These differences appear to stem from differences in the calibration procedures and models used by each system. IMUs are calibrated in a neutral standing posture to establish the 0° reference position in a local coordinate system, as opposed to OMCs that determine segment orientations based on anatomical landmarks in relation to the global coordinate system. As such, the calibration may introduce differences in the zero positions, which, if unaccounted for in the model, increase differences in absolute segment angles reported by IMUs and OMCs (Berner, Cockcroft, Morris, et al., 2020; Mundt et al., 2017). For IMUs, postural calibration is repeated before each trial recording – reducing potential drift error between each short trial typical in sprinting or cricket bowling. Participants therefore repeat calibration multiple times in performing multiple trials. Thus, reliability in performing the calibration position could have considerable influence on recorded segment angles for repeated trials. Standing posture may also vary across individuals, thus between-subject differences in angular recordings may simply reflect differences in their reference position and not a practically meaningful difference in technique.

Due to the influence of the calibration posture as the 0° position from which subsequent segment angles are determined, this study aimed to quantify the within-subject repeatability and between-subject variability of sagittal plane segment angles in the calibration posture in order to provide context for within- and between-subject comparisons made using this IMU system.

METHODS: Six participants (two male, four female) volunteered to be a part of this study (age = 23.7 ± 2.1 years, stature = 167 ± 2 cm, mass = 65.7 ± 7.5 kg). Ethical approval was provided by the institutional research ethics comittee. Tests were performed using a commercially available IMU system (MyoMotion, Noraxon, USA) sampling at 200 Hz. A synchronised sagittal plane video (Ninox-250, 100 Hz) recorded the calibration position. Video and IMU data were captured and processed using the MyoResearch 3.14 software (Noraxon, USA). Participants were fitted with nine IMU sensors attached to the upper spine (T1), lower spine (T12), pelvis (sacrum) and lateral aspects of each thigh, medial aspects of each shank and the dorsal surface of each foot according to the manufacturer's instructions. Sensors were secured with custom Velcro straps and double sided tape. For the lower limbs, the exact sensor placement was chosen to minimise sensor movement due to soft tissue artefact in order to reflect locations that would be used in research contexts such as sprinting or cricket bowling. Participants stood in an upright vertical posture on a calibration board which aligned the feet at hip width, facing forward. Participants were given standardised instructions to "maintain an upright, neutral posture with hands placed at the sides and head looking forward". Sensor calibration was performed in this position, after which participants were allowed to walk around freely as desired. After approximately one minute, they resumed the calibration position and maintained it for at least 30 seconds. This was repeated three times such that each participant recorded an initial calibration and three subsequent repeats of the calibration position.

Sensors recorded continuously from the completion of the initial calibration until the end of the third repeat of the calibration position, resulting in a single recording for each participant. Mean and standard deviation of the sagittal plane segment angle over a 20 second period was calculated for each repeat of the calibration position from IMU sensor recordings, a 20 second period was chosen as the initial calibration lasts 20 seconds. The measured angle during each repeat represented the change from the 0° established during the initial calibration.

To assess repeatability, typical error was calculated from this change according to Hopkins (Hopkins, 2000) for each repeat of the calibration position. Additionally, typical error was calculated from the change in angle between each repeat calibration (cal-3 vs cal-2, cal-2 vs cal-1). During the initial calibration and each subsequent repeat, the absolute angle of the upper spine, lower spine and pelvis sensors relative to a 0° absolute vertical was recorded using a mobile phone inclinometer application (Clinometer, plaincode app development, USA). Finally, sagittal plane angles of the right thigh (greater trochanter to lateral femoral condyle) and shank (lateral femoral condyle to lateral malleolus) segments during the initial calibration and each repeat were measured from the sagittal plane video digitised using the open source Kinovea software package (Kinovea 0.8.15).

RESULTS: Relative to the initial calibration, typical error ranged from 0.44° to 1.36° for the first repeat, 0.43° to 1.90° for the second and 0.56° to 1.38° for the third (Table 1). Typical error between repeats was similar, with ranges of 0.31 – 1.17° between repeat 1 and 2 and 0.24 – 1.00° between repeat 3 and 2.

Table 1: Typical error (°) values for each repeat of the calibration position relative to the initial calibration, between each repeat and overall mean typical error

Sensor	Cal - 1	Cal - 2	Cal - 3	Cal 2 - 1	Cal 3 - 2	Mean
Upper Spine	1.32	1.90	1.38	1.17	0.91	1.34
Lower Spine	1.36	1.49	1.37	0.75	0.55	1.10
Pelvis	1.28	1.39	1.32	0.58	0.51	1.01
Left Thigh	0.99	1.24	0.97	0.91	0.75	0.97
Right Thigh	1.12	0.98	0.27	0.58	1.00	0.79
Left Shank	0.47	0.43	0.56	0.42	0.65	0.51
Right Shank	0.44	0.54	0.56	0.31	0.24	0.42

Absolute sensor angles relative to the global 0° vertical for the trunk segment were variable between participants, ranging from 21 – 35° and 11 – 35° for the upper spine and pelvis sensors (anterior tilt) respectively and 1 – 23° for the lower spine (posterior tilt) (Figure 1A). Sagittal plane angles for the lower body segments were less variable, 0 – 6° and 0 – 5° for thigh and shank respectively and were closer to the absolute reference angle of 0°. Mean sagittal plane angles for the thigh segment were 3.2 ± 1.3°, 2.0 ± 1.7° and 2.5 ± 1.2° for the first, second and third repeat of the calibration position respectively. For the shank the respective values were 2.7 ± 1.0°, 2.5 ± 1.4° and 2.5 ± 1.5°.

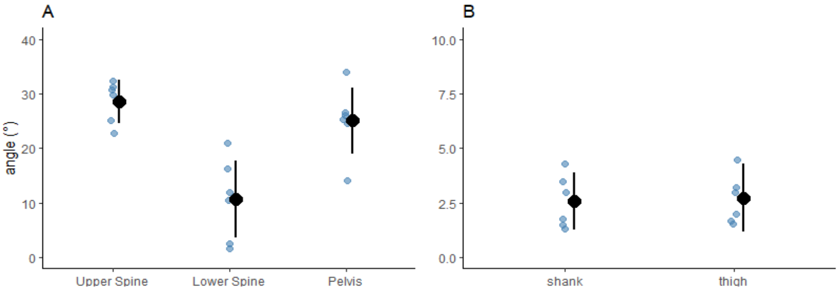

Figure 1: Mean, standard deviation and individual absolute angles relative to the global 0° vertical for (A) trunk segment sensors and (B) lower limb segments.

DISCUSSION: This study assessed the within-subject repeatability and the between-subject variability of the segment orientations of a standing calibration position in a commercially available IMU system. The calibration position was repeatable to less than 2.5° within participants when given standardised instructions. Between participants, sagittal plane sensor orientations of upper body segments varied by up to 23°, but the thigh and shank segment orientations were contained in a much narrower range of 6°. Repeats of the calibration position were characterised by low typical error values for each repeat relative to the initial calibration as well as between repeats, with all typical error values below 2°, for all segments (Table 1). This suggests that within-subject the calibration position can be reliably repeated given a calibration frame and a standardised set of instructions. These observations support results reported by Berner et al. (2020) who reported a similarly narrow range of joint and segment angles (SEM 0.3 – 2.2°).

The absolute angle of sensors for the upper spine, lower spine and pelvis deviated by as much as 35° from the 'true vertical' and showed large variation between participants (Figure 1). This may be due to greater degrees of freedom in the trunk compared to more distal segments closer the stable base of the feet or differences in the curvature of the spine and musculature of the upper back which may also influence sensor placement and orientation. These results align with those of Berner et al. (2020) which indicated that joint and segment angles for the pelvis and lower limbs in the calibration pose differed from 0° as measured by an OMC system, suggesting that , despite standardised instructions, differences in standing posture occur between different people. Thus caution is needed in making between participant comparisons for upper body segments based on IMU measurements alone. Depending on the research question, investigators may need to account for the differences in the reference position. For some research questions these differences may be advantageous - for example, if researchers are interested in participants' relative deviation from their standing posture rather than angles in absolute space. Sagittal plane angles of the thigh and shank were typically less than 3.2° from a true 0° vertical and within a narrow range (< 4°), less than the 5° limit for clinically meaningful differences suggested by McGinley et al. (2009), and in the context of a dynamic movement such as sprinting, similar to between-subject variation in peak thigh flexion and extension angles during maximal effort sprinting (standard error range 0.7-3.8°) reported by Clark et al. (2020).

Thus, between-subject sagittal plane lower limb segment angles are more similar than upper body segments in the standing posture. As such, researchers can have more confidence making between-subject comparisons in angles for these segments, however it may still be advisable to account for differences in the standing posture depending on the application and population.

This study had several limitations. Primarily, it had a small sample size and only considered sagittal plane segment orientations. Further research is needed to determine between-subject differences in other movement planes. Lastly, absolute sensor orientations were measured using a mobile phone application and digitisation rather than a gold standard OMC system.

Previous literature suggests that while IMU and OMC systems demonstrate similar trends and magnitudes in recorded angles, they measure something slightly different owing to differences in the reference position (Berner, Cockcroft, Morris, et al., 2020; Mundt et al., 2017; Seidel et al., 2015). The results here suggest differences in standing posture between participants may also require consideration. That said, the calibration position shows good within-subject repeatability. The Noraxon MyoMotion system presents a reliable method of assessing angular kinematics in the field, with accurate sensor tracking over time, and good within-subject reliability (Berner, Cockcroft, & Louw, 2020; Berner, Cockcroft, Morris, et al., 2020), offering researchers working with athletes in applied settings - where OMC systems are typically not a viable option - a reliable alternative for investigating 3D motion.

Researchers should be wary of the instructions and procedure during calibration and careful attention should be paid to the sensor attachment for the pelvis and spine. Depending on the goals of the research, differences in standing posture between participants may need to be accounted for before making between-subject comparisons.

CONCLUSION: A standing calibration position can be reliably repeated by participants when given standardised instructions and a suitable reference frame. However, this posture deviates from a true 0° relative to the global coordinate plane and may vary between participants, particularly in trunk segments. Researchers may need to account for differences in standing posture when using an IMU system to make between-subject comparisons, especially for the spine and pelvis.

REFERENCES

Balasubramanian, S. (2013). *Comparison of angle measurements between Vicon and MyoMotion Systems* [Arizona State University]. http://www.noraxon.com/wp-content/uploads/2015/06/myoMOTION-Validation-Study.pdf

Berner, K., Cockcroft, J., & Louw, Q. (2020). Kinematics and temporospatial parameters during gait from inertial motion capture in adults with and without HIV: A validity and reliability study. *BioMedical Engineering OnLine*, *19*(1), 57. https://doi.org/10.1186/s12938-020-00802-2

Berner, K., Cockcroft, J., Morris, L. D., & Louw, Q. (2020). Concurrent validity and within-session reliability of gait kinematics measured using an inertial motion capture system with repeated calibration. *Journal of Bodywork and Movement Therapies*, *24*(4), 251–260. https://doi.org/10.1016/j.jbmt.2020.06.008

Clark, K. P., Meng, C. R., & Stearne, D. J. (2020). 'Whip from the hip': Thigh angular motion, ground contact mechanics, and running speed. *Biology Open*, *9*(10), bio053546. https://doi.org/10.1242/bio.053546

Cottam, D. S. (2019). *Field based quantification of trunk and pelvis motion in cricket bowling: A wearable technology approach*. 250.

Hopkins, W. G. (2000). Measures of Reliability in Sports Medicine and Science. *Sports Med*, 15.

McGinley, J. L., Baker, R., Wolfe, R., & Morris, M. E. (2009). The reliability of three-dimensional kinematic gait measurements: A systematic review. *Gait & Posture*, *29*(3), 360–369. https://doi.org/10.1016/j.gaitpost.2008.09.003

Mundt, M., Wisser, A., David, S., Dupré, T., Quack, V., Bamer, F., Tingart, M., Potthast, W., & Markert, B. (2017). *The influence of motion tasks on the accuracy of kinematic motion patterns of an IMU-based measurement system*.

Seidel, D. H., D'Souza, S. F., Alt, W. W., & Wachowsky, M. (2015). Comparison of an inertial sensor based motion measurement system with a 3D-reflex marker based motion capture system. *Gait & Posture*, *42*, S75. https://doi.org/10.1016/j.gaitpost.2015.06.139

Appendix B

Conference paper: Coordination similarity

40th International Society of Biomechanics in Sports Conference, Liverpool, UK: July 19-23, 2022

SIMILARITY OF COORDINATION PATTERNS IN A GROUP OF HIGHLY TRAINED SPRINTERS: A NOVEL APPROACH

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Understanding coordination patterns aids technical understanding and potential grouping of athletes that exhibit similar movement patterns. This study assessed between-individual similarity in initial sprint acceleration coordination in highly trained to world class sprinters using a novel pairwise approach. Similarity between participants was higher for thigh-thigh coordination compared to shank-foot and trunk-shank coordination. Mean similarity increased from step 1 to step 4 in shank-foot (0.74 to 0.83) and trunk-shank (0.68 to 0.79) couplings but remained consistent in the thigh-thigh coupling (0.89 to 0.91). Researchers and practitioners should consider that coordination between sprinters converges over initial acceleration, but between any two individuals coordination similarity might increase or decrease across steps.

KEYWORDS: lower-limb coordination, coupling angle difference, sprint.

INTRODUCTION: In many biomechanics contexts, researchers are interested in assessing similarity in movement patterns across groups or individuals, in order to identify features of movement patterns which may be associated with particular performance outcomes, injury risks or pathologies. Coordination analysis is a useful technique to understand movement organisation as a component of technique in a given task. In popular coordination analysis techniques like modified vector coding (Chang et al. 2008), differences between groups are typically assessed using broad measures like the proportion of time spent in a particular coordination pattern (i.e. bin frequency) over the entire course of a movement or a relevant sub-phase. However, bin frequencies provide only a high level view of similarity in coordinative approach and it is logically plausible for different coordination strategies to yield similar bin frequencies over an entire phase or movement. Such bin frequencies reveal neither similarity in the sequence of bins over time nor easily quantify the degree of similarity between two profiles, considering that the difference between different bins is not uniform. A one-to-one comparison for each time point taking into account the structure of the underlying data may help solve this problem. Further, while groups can often be clearly defined based on a priori criteria (e.g. pathology, experience, skill or physical capacities), sometimes group classifications may be arbitrary or of little use and it would be more suited to particular research questions to categorise individuals with similar movement strategies, an approach common in many unsupervised machine learning algorithms. This may facilitate grouping athletes with similar movement strategies to understand the particular constraints around the way they move for training purposes and injury risk profiles.

While initial sprint acceleration may generally be considered a cyclic movement, step-to-step kinematic changes do occur (Nagahara et al., 2014; von Lieres und Wilkau et al., 2018). This may result in differences in coordination similarity between individuals over the course of initial sprint acceleration. Understanding this may be useful in trying to identify athletes with common technical approaches to the sprint start, where it may be of value to know whether strategies are consistent at the level of the individual step or the whole phase, or if coordination strategies diverge or converge between certain individuals. However, to date this has not yet been studied. Therefore, the purpose of this study was to evaluate coordination similarity between individuals in three segment couples (thigh-thigh, trunk-shank, shank-foot) during the first four steps of sprint acceleration and assess whether similarity between individuals changes between steps.

METHODS: Twenty-one highly trained to world-class male and female sprinters (100 m PB: M = 10.47 ± 0.42 s; F = 11.79 ± 0.24 s) gave written consent to participate in this study, approved by the institutional research ethics committee. On an outdoor track, following their habitual warm up, sprinters performed three maximal effort sprint trials of at least 20 m from starting blocks, from which their fastest trial was included for analysis. Trials were performed in participants' own spikes with at least 5 minutes rest between efforts. Sagittal plane kinematics were obtained from tri-axial inertial measurement units (IMU; 200 Hz, Myomotion, Noraxon, USA) fitted prior to performing sprint trials. Sensors were attached to the upper spine (T1), lower spine (T12), sacrum, lateral aspect of both thighs, medial aspect of both shanks and the dorsal surface of both feet using double-sided tape and secured with custom velcro straps or self-adhesive bandages. A static calibration procedure in an upright standing posture was performed, establishing the 0° reference angle (Berner et al., 2020). A synchronised sagittal plane video camera (100 Hz, Ninox-250, Noraxon, USA) recorded the first four steps of each trial and was used to identify touchdown and toe off. Video and IMU data were recorded and processed using MyoResearch 3.14 (Noraxon, USA). A step was defined from toe off to the next toe off of the contralateral foot. Sagittal plane kinematic variables for each of the first four steps were time normalised to 101 data points, with block clearance representing 0% time in step 1.

Coupling angles (CA) for thigh-thigh, trunk-shank and shank-foot segment couplings were obtained from angle-angle plots using modified vector coding techniques (Chang et al., 2008; Needham et al., 2020). Coordination similarity was assessed pairwise for all combinations of participants for each of the four steps and each segment coupling. Coordination similarity was defined using a modified version of the CA difference score used by Bezodis et al. (Bezodis et al., 2019), applied to the raw CA. For each pairwise participant combination, the angular distance between corresponding CA vectors for participants A and B was calculated using equation 1 for each point in time.

$$\theta = \begin{cases} 360 - |A - B|, & \text{if } |A - B| > 180^\circ \\ |A - B|, & \text{otherwise} \end{cases} \tag{1}$$

Therefore, the maximum possible distance between any two vectors was 180°. The sum of angular distances over the entire step was divided by the maximum possible difference score and subtracted from 1, resulting in a CA similarity score between 0 and 1. A score of 0 indicated direct opposite CA vectors at every time point and 1 indicated identical CA vectors at every time point. Similarity scores were computed between every possible pair of participants and represented in a similarity matrix for each step. Between-step differences in coordination similarity were assessed using one-way repeated measures ANOVAs and pairwise t-tests with Bonferroni corrections.

RESULTS: Pairwise similarity was typically higher for thigh-thigh coordination (mean[range]: step (S) 1 = 0.89[0.74 - 0.97], S2 = 0.92[0.75 – 0.98], S3 = 0.91[0.78 – 0.97], S4 = 0.91[0.80 – 0.98]) compared to shank-foot (mean[range]: S1 = 0.74[0.44 - 0.95], S2 = 0.76[0.47 - 0.91], S3 = 0.79[0.60 – 0.96], S4 = 0.83[0.60 – 0.96]) and trunk-shank (mean[range]: S1 = 0.68[0.39 - 0.86], S2 = 0.72[0.47 – 0.88], S3 = 0.76[0.59 – 0.92], S4 = 0.79[0.57 – 0.95]) (Figure 1, Figure 2). There was a significant effect of step on coordination similarity for the shank-foot ($F_{(2.6,535)}$ = 44.49, $p < 0.001$, $\eta^2 = 0.176$), trunk-shank ($F_{(2.4,502)}$ = 98.80, $p < 0.001$, $\eta^2 = 0.321$) and thigh-thigh ($F_{(2.4,508)}$ = 38.64, $p < 0.001$, $\eta^2 = 0.156$) couplings. For shank-foot and trunk shank couplings, all step combinations, except step 1 – step 2 (p = 0.44) in shank-foot, were significantly different ($p < 0.001$). Step 1 was significantly different to all other steps for thigh-thigh ($p < 0.0001$), as was step 2 – step 3 (p = 0.021). While mean similarity increased across the whole group between steps, for any given pair of participants, whether similarity increased or decreased was variable (Figure 1, Figure 2).

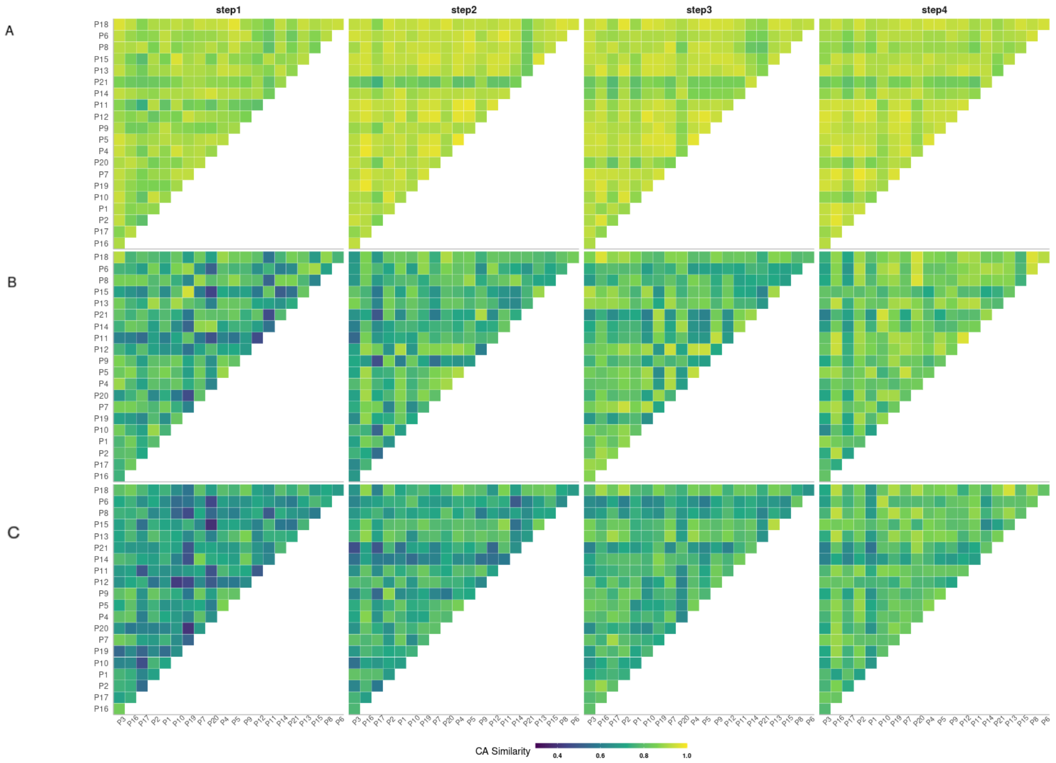


Figure 1: Coupling angle (CA) similarity matrices of all pairwise combinations of participants for shank-foot (A), thigh-thigh (B) and trunk-shank (C) segment couplings

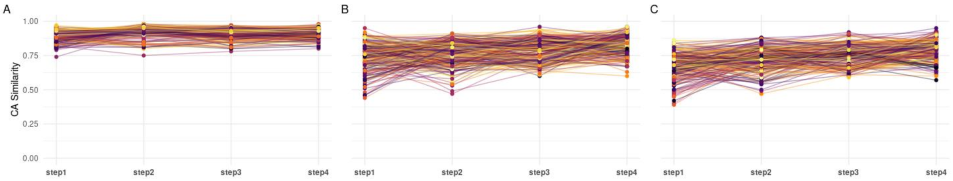


Figure 2: Progression of coordination similarity over the first four steps in all pairwise participant combinations for shank-foot (A), thigh-thigh (B) and trunk-shank (C) segment couplings

DISCUSSION:

The purpose of this study was to evaluate pairwise coordination during sprint acceleration and assess whether similarity changed between steps. Pairwise coordination similarity across a group of sprinters was typically higher in the thigh-thigh coupling compared to the shank-foot and trunk-shank couplings over the first four steps of acceleration. Pairwise similarity increased over the four steps with significant differences between steps, suggesting a convergence of coordination patterns. The high level of similarity in thigh-thigh coordination suggests strong constraints on thigh motion. Indeed, the general increase in similarity over the four steps implies the spectrum of available coordination strategies gets narrower throughout initial acceleration. The presence of both high and relatively low similarity scores in step 1 and 2 suggest potential sub-groups with greater differences in coordination strategies than later steps. Despite the group-wide trends towards increased similarity across the four steps, for any given pair of sprinters the tendency to exhibit increased or decreased similarity between steps was variable (Figure 1, Figure 2). Indeed, in some cases there were changes of up to 0.5, or 50%, in similarity scores between steps. These results suggest that in complex movements such as acceleration, similarity between individuals and therefore potential sub-groups may change as the movement progresses. Unlike more cyclic tasks where coordination between steps may be more consistent, in acceleration one athlete might have similar coordination to another in one step but not the next.

In a range of contexts, researchers and practitioners may be interested in identifying sub-groups of athletes with similar coordination patterns in order to make sense of individual profiling and understand the constraints that guide the movement patterns of their athletes. This study applies a simple approach for assessing coordination similarity between individuals from the modified vector coding derived coordination profiles which facilitate intuitive visual profiling via colour coding of coordination bins. The simple similarity score can be further used to compute the distance matrix required by clustering algorithms to objectively identify sub-groups of coordination patterns.

Thus, researchers might consider whether they are interested in coordination similarities in specific phases of an action or over whole events when comparing athletes, and carefully consider their desired outcome when using machine learning tools like cluster analysis based on coordination data as inputs. From a practical perspective, sprinters generally appear to converge on similar coordination strategies as initial acceleration progresses, possibly suggesting emphasis be placed on the first two steps when categorising athletes for coaching purposes.

CONCLUSION: This study presented a novel approach to assessing similarity between coordination profiles. At a whole group level, similarity in coordination patterns between sprinters increases over the course of initial acceleration, however for any two individuals similar patterns in one step may not reflect similarity in another. Future research is needed to determine the implications of such changes..

REFERENCES:

Berner, K., Cockcroft, J., Morris, L. D., & Louw, Q. (2020). Concurrent validity and within-session reliability of gait kinematics measured using an inertial motion capture system with repeated calibration. *Journal of Bodywork and Movement Therapies*, *24*(4), 251-260.

Bezodis, I. N., Brazil, A., von Lieres und Wilkau, H. C., Wood, M. A., Paradisis, G. P., Hanley, B., Tucker, C. B., Pollitt, L., Merlino, S., Vazel, P.-J., Walker, J., & Bissas, A. (2019). World-Class male sprinters and high hurdlers have similar start and initial acceleration techniques. *Frontiers in Sports and Active Living*, *1*, 23. https://doi.org/10.3389/fspor.2019.00023

Chang, R., Van Emmerik, R., & Hamill, J. (2008). Quantifying rearfoot–forefoot coordination in human walking. *Journal of Biomechanics*, *41*(14), 3101–3105. https://doi.org/10.1016/j.jbiomech.2008.07.024

Hafer, J. F., Peacock, J., Zernicke, R. F., & Agresta, C. E. (2019). Segment coordination variability differs by years of running experience: *Medicine & Science in Sports & Exercise*, *51*(7), 1438–1443. https://doi.org/10.1249/MSS.0000000000001913

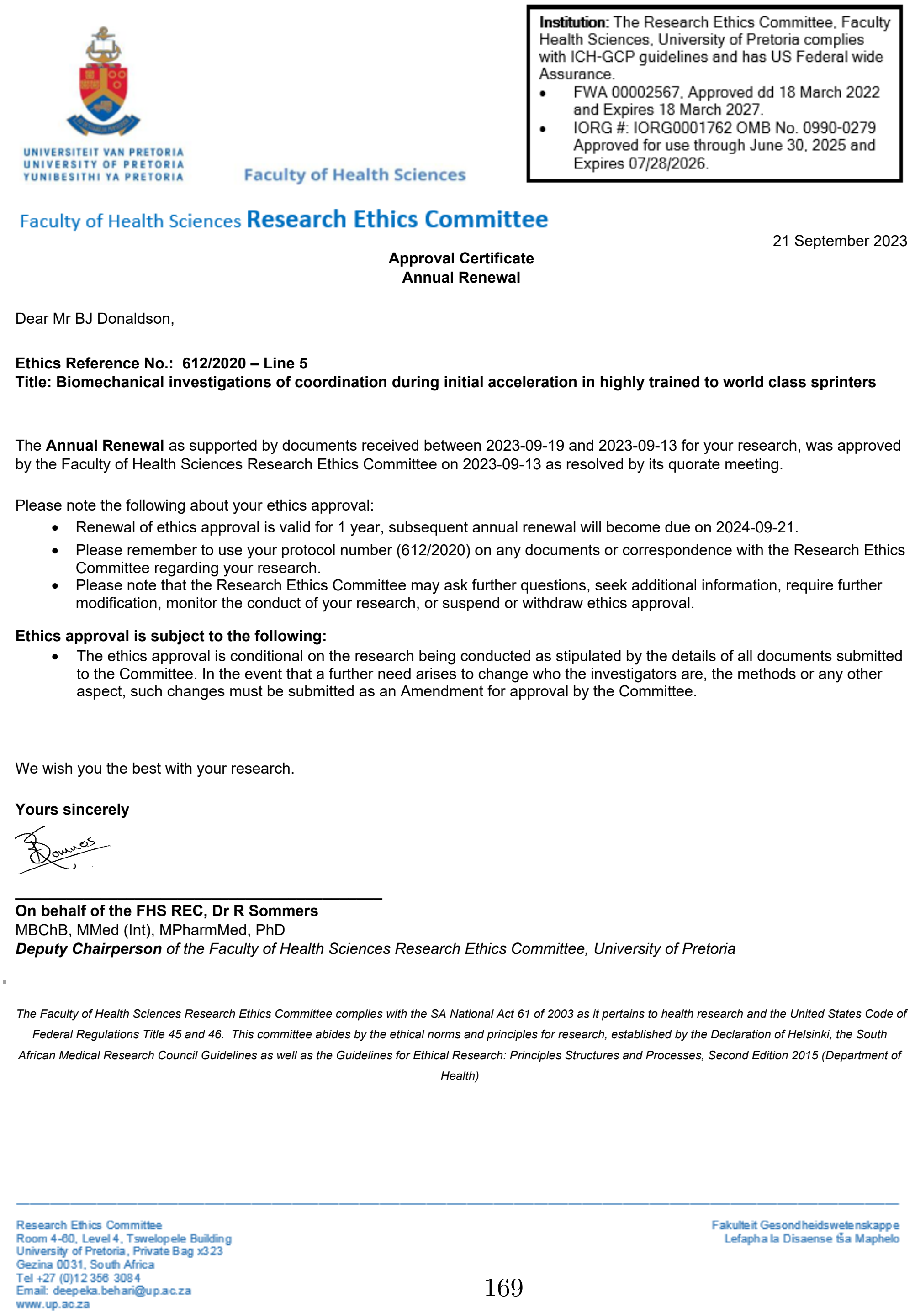
Nagahara, R., Matsubayashi, T., Matsuo, A., & Zushi, K. (2014). Kinematics of transition during human accelerated sprinting. *Biology Open*, *3*(8), 689–699. https://doi.org/10.1242/bio.20148284

Needham, R. A., Naemi, R., Hamill, J., & Chockalingam, N. (2020). Analysing patterns of coordination and patterns of control using novel data visualisation techniques in vector coding. *The Foot*, 101678. https://doi.org/10.1016/j.foot.2020.101678

von Lieres und Wilkau, H. C., Irwin, G., Bezodis, N. E., Simpson, S., & Bezodis, I. N. (2018). Phase analysis in maximal sprinting: An investigation of step-to-step technical changes between the initial acceleration, transition and maximal velocity phases. *Sports Biomechanics*, 1–16. https://doi.org/10.1080/14763141.2018.1473479

Appendix C

Ethical Approval



UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences

Faculty of Health Sciences **Research Ethics Committee**

Institution: The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.

- FWA 00002567, Approved dd 18 March 2022 and Expires 18 March 2027.
- IORG #: IORG0001762 OMB No. 0990-0279 Approved for use through June 30, 2025 and Expires 07/28/2026.

21 September 2023

Approval Certificate
Annual Renewal

Dear Mr BJ Donaldson,

Ethics Reference No.: 612/2020 – Line 5
Title: Biomechanical investigations of coordination during initial acceleration in highly trained to world class sprinters

The **Annual Renewal** as supported by documents received between 2023-09-19 and 2023-09-13 for your research, was approved by the Faculty of Health Sciences Research Ethics Committee on 2023-09-13 as resolved by its quorate meeting.

Please note the following about your ethics approval:

- Renewal of ethics approval is valid for 1 year, subsequent annual renewal will become due on 2024-09-21.
- Please remember to use your protocol number (612/2020) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, monitor the conduct of your research, or suspend or withdraw ethics approval.

Ethics approval is subject to the following:

- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

On behalf of the FHS REC, Dr R Sommers
MBChB, MMed (Int), MPharmMed, PhD
***Deputy Chairperson** of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria*

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes, Second Edition 2015 (Department of Health)

Research Ethics Committee
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Fakulteit Gesondheidswetenskappe
Lefapha la Disaense tša Maphelo

Appendix D

Informed Consent

RESEARCH PARTICIPANT'S INFORMATION AND INFORMED CONSENT DOCUMENT

Study title: Sport science services at the University of Pretoria: An umbrella protocol
Principal investigator: Dr H Bayne
Contact details: helen.bayne@up.ac.za / (012) 420 6084
Participating institutions: Division of Biokinetics and Sport Science, Department of Physiology, Faculty of Health Sciences, University of Pretoria
Sport, Exercise Medicine and Lifestyle Institute (SEMLI), University of Pretoria

Date and time of informed consent discussion: ____________________ Date ________________ Time

As a client of the Sport, Exercise Medicine and Lifestyle Institute at the University of Pretoria, you will be participating in prescribed exercise, testing, training, evaluation, monitoring, rehabilitation and/or a gymnasium program (hereinafter the "program"). Researchers from the University of Pretoria may wish to analyse data gathered during consultation and the program for scientific purposes. The information in this document is to help you to decide if you would like to participate. Before you agree to take part in this study you should fully understand what is involved. If you have any questions, which are not fully explained in this document, do not hesitate to ask the researcher or sport scientist who is leading your program. You should not agree to take part unless you are completely happy about all the procedures involved.

The aim of the study is to analyse the data collected during standard sport science practice in order to improve our understanding of sports performance, exercise training prescription, athlete wellbeing, and injury risk. The sport scientist will use questionnaires to gather information about your training and injury history, and to monitor any exercise that is prescribed. Testing and evaluation will consist of standard sport science assessments for a variety of components that contribute to sports performance, such as body composition, flexibility, strength, fitness, and technique.

The completion of questionnaires is not associated with any risk. Some sport science assessments require physical tasks that involve some risk of injury. However, all tasks will involve similar loads and movements that you engage in during regular training and competition. All reasonable precautions to reduce the risk of injury will be taken, and all testing will be conducted by appropriately qualified staff.

You will receive the results of all of these assessments as part of your program. The anticipated benefits of the study are that the results will further our understanding of athlete health and performance. You will not be paid to take part in the study. There are no costs involved for you to be part of the study.

If you choose not to provide consent for your data to be included in the research project, this will not alter your participation in the program in any way. You may choose to withdraw your consent in writing at any time without further question.

All data will be kept confidential and secure, and will not be made available to any party other than the research team without the consent of the individual participant. All data and images will be deidentified prior to analysis (by assigning an alphanumeric code, e.g. A001) and processed anonymously into research reports or presentations in order to maintain confidentiality of your information.

The proposal for this study has been submitted to the Faculty of Health Sciences Research Ethics Committee (Level 4, Tswelopele Building, Prinshof Campus, Tel: 012 356 3084/5) (reference number: 869/2019) and all associated studies will be approved by this committee prior to publication of any findings as required. The study has been structured in accordance with the Declaration of Helsinki (last update: October 2013), which deals with the recommendations guiding doctors in biomedical research involving human/subjects. A copy of the Declaration may be obtained from the investigator should you wish to review it.

If you have any questions concerning this study, you should contact the principal investigator using the details provided on page one.

--

Consent to participate in this study

- I confirm that the person requesting my consent to take part in this study has told me about the nature and process, any risks or discomforts, and the benefits of the study.
- I have also received, read and understood the above written information about the study.
- I have had adequate time to ask questions and I have no objections to participate in this study.
- I am aware that the information obtained in the study, including personal details, will be anonymously processed and presented in the reporting of results.
- I understand that I will not be penalised in any way should I wish to discontinue with the study and that withdrawal will not affect my further treatments.
- I am participating willingly.
- I have received a signed copy of this informed consent agreement.

____ Participant’s name (Please print)	________________________ Date
____ Participant’s signature	________________________ Date
____ Researcher’s name (Please print)	________________________ Date
____ Researcher’s signature	________________________ Date

Appendix E

Parent / Guardian Consent

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

SEMLI
Sport, Exercise Medicine & Lifestyle Institute

INFORMATION AND INFORMED CONSENT FORM: PARENT/LEGAL GUARDIAN OF A PARTICIPANT AGED 7 – 17 YEARS

Study title: Sport science services at the University of Pretoria: An umbrella protocol
Principal investigator: Dr H Bayne
Contact details: helen.bayne@up.ac.za / (012) 420 6084
Participating institutions: Division of Biokinetics and Sport Science, Department of Physiology, Faculty of Health Sciences, University of Pretoria
Sport, Exercise Medicine and Lifestyle Institute (SEMLI), University of Pretoria

Date and time of informed consent discussion: ______________________ Date _________________ Time

As a client of the Sport, Exercise Medicine and Lifestyle Institute at the University of Pretoria, your child will be participating in prescribed exercise, testing, training, evaluation, monitoring, rehabilitation and/or a gymnasium program (hereinafter the “program”). Researchers from the University of Pretoria may wish to analyse data gathered during consultation and the program for scientific purposes. The information in this document is to help you to decide if you would like your child to participate. Before you agree that your child may take part, you should fully understand what is involved. If you have any questions, which are not fully explained in this document, do not hesitate to ask the researcher or sport scientist who is leading your child’s program. You should not agree to take part unless you are completely happy about all the procedures involved.

The aim of the study is to analyse the data collected during standard sport science practice in order to improve our understanding of sports performance, exercise training prescription, athlete wellbeing, and injury risk. The sport scientist will use questionnaires to gather information about your child’s training and injury history, and to monitor any exercise that is prescribed. Testing and evaluation will consist of standard sport science assessments for a variety of components that contribute to sports performance, such as body composition, flexibility, strength, fitness, and technique.

The completion of questionnaires is not associated with any risk. Some sport science assessments require physical tasks that involve some risk of injury. However, all tasks will involve similar loads and movements that your child engages in during regular training and competition. All reasonable precautions to reduce the risk of injury will be taken, and all testing will be conducted by appropriately qualified staff.

You will receive the results of these assessments as part of the program. The anticipated benefits of the study are that the findings will further our understanding of athlete health and performance. You/your child will not be paid to take part in the study.

If you choose not to provide consent for your child’s data to be included in the research project, this will not alter their participation in the program in any way. You may choose to withdraw your consent in writing at any time without further question.

All data will be kept confidential and secure, and will not be made available to any party other than the research team without the consent of the individual participant. All data and images will be deidentified prior to analysis (by assigning an alphanumeric code, e.g. A001) and processed anonymously into research reports or presentations in order to maintain confidentiality.

The proposal for this study has been submitted to the Faculty of Health Sciences Research Ethics Committee (Level 4, Tswelopele Building, Prinshof Campus, Tel: 012 356 3084/5) (reference number: 869/2019) and all associated studies will be approved by this committee prior to publication of any findings as required. The study has been structured in accordance with the Declaration of Helsinki (last update:

October 2013), which deals with the recommendations guiding doctors in biomedical research involving human/subjects. A copy of the Declaration may be obtained from the investigator should you wish to review it.

If you have any questions concerning this study, you should contact the principal investigator using the details provided on page one.

--

Consent to participate in this study

- I confirm that the person requesting my consent for my child to take part in this study has told me about the nature and process, any risks or discomforts, and the benefits of the study.
- I have also received, read and understood the above written information about the study.
- I have had adequate time to ask questions and I have no objections for my child to participate in this study.
- I am aware that the information obtained in the study, including personal details, will be anonymously processed and presented in the reporting of results.
- I understand that my child will not be penalised in any way should I wish to discontinue with the study and that withdrawal will not affect my further treatments.
- My child is participating willingly.
- I have received a signed copy of this informed consent agreement.

____	________________________
Parent / Legal Guardian’s name (Please print)	Date
____	________________________
Parent / Legal Guardian’s signature	Date
____	________________________
Researcher’s name (Please print)	Date
____	________________________
Researcher’s signature	Date

Appendix F

Chapter 3 published article

RESEARCH ARTICLE

Inter- and intra-limb coordination during initial sprint acceleration

Byron J. Donaldson[1], Neil E. Bezodis[2] and Helen Bayne[1,*]

ABSTRACT

In complex movements, centre of mass translation is achieved through effective joint and segment rotations. Understanding segment organisation and coordination is therefore paramount to understanding technique. This study sought to comprehensively describe inter- and intra-limb coordination and assess step-to-step changes and between-individual variation in coordination during initial sprint acceleration. Twenty-one highly trained to world class male (100 m PB 9.89-11.15 s) and female (100 m PB:11.46-12.14 s) sprinters completed sprint trials of at least 20 m from which sagittal plane kinematics were obtained for the first four steps using inertial measurement units (200 Hz). Thigh-thigh, trunk-shank and shank-foot coordination was assessed using a modified vector coding and segment dominancy approach. Common coordination patterns emerged for all segment couplings across sexes and performance levels, suggesting strong task constraints. Between-individual variation in inter-limb thigh coordination was highest in early flight, while trunk-shank and shank-foot variation was highest in late flight, with a second peak in late stance for the trunk-shank coupling. There were clear step-to-step changes in coordination, with step 1 being distinctly different to subsequent steps. The results demonstrate that inter-limb coordination is primarily anti-phase and trailing leg dominant while ankle motion in flight and late stance appears to be primarily driven by the foot.

KEY WORDS: Dynamical systems, Kinematics, Segment dominancy, Sprinting, Technique

INTRODUCTION

Acceleration from a stationary block position in athletic sprinting is a complex task with important implications for race performance (Bezodis et al., 2015; Bezodis et al., 2019b; Walker et al., 2021). Initial acceleration consists of the first 3-6 steps after block exit and is distinguished from later phases by step-to-step kinematic changes (Nagahara et al., 2014; von Lieres und Wilkau et al., 2018). As such, researchers and coaches approach initial acceleration as a unique technical component of the sprint (e.g. Debaere et al., 2013; Bezodis et al., 2019a; Walker et al., 2021; Jones et al., 2009). Effective acceleration depends more on force vector orientation than total magnitude of the resultant force generated (Morin et al., 2011; Kugler and Janshen, 2010; Rabita et al., 2015), with more horizontally directed forces corresponding to a further forward centre of mass (CM) (Slawinski et al., 2010; Kugler and Janshen, 2010). Since CM position is a function of overall musculoskeletal system organisation, a horizontal CM position, and horizontal force application, results from effectively organising the linked segment system (Nagahara et al., 2014; von Lieres und Wilkau et al., 2018; Kugler and Janshen, 2010; Slawinski et al., 2010). Whilst existing literature has quantified isolated joint and segment kinematics during initial acceleration (e.g. Walker et al., 2021; von Lieres und Wilkau et al., 2018; Nagahara et al., 2014, 2018; Slawinski et al., 2010; Debaere et al., 2013), an evaluation of the relative movement these system components is needed to understand how sprinters coordinate the motion of their available degrees of freedom to satisfy the task constraints (Glazier, 2017; Davids et al., 2003; Newell, 1986). By quantifying this in a cohort of highly skilled sprinters, the importance of both organismic and task constraints can be understood by assessing the aspects of emergent coordination patterns unique to individuals (organismic) and the similarity of coordination patterns between individuals (task) during maximal sprint acceleration efforts.

In linear sprinting, the vast majority of movement is in the sagittal plane, and therefore most research and coaching analyses of segment kinematics are focused on sagittal plane trunk and lower limb motion (e.g. Nagahara et al., 2014, 2018; Debaere et al., 2013; Clark et al., 2020). During initial acceleration, there is a step-to-step raising of the CM in part due to step-to-step shifts toward more vertical shank and trunk segments (Nagahara et al., 2014; von Lieres und Wilkau et al., 2018). Better performers exhibit smaller shifts towards a vertical trunk orientation over the initial steps (von Lieres und Wilkau et al., 2018; Kugler and Janshen, 2010) while a more horizontal trunk at toe off is associated with better performance during the first stance of world class sprinters (Walker et al., 2021). However, as a more proximal segment, trunk motion during stance could be a function of more distal (stance leg) segment orientations. The trunk typically rotates clockwise (as viewed from the right) during flight before reversing direction during stance (Nagahara et al., 2018; Donaldson et al., 2020), whilst the shank does the opposite - rotating anticlockwise toward a vertical orientation during flight and the opposite during stance, rotating back toward a horizontal orientation (Nagahara et al., 2014; von Lieres und Wilkau et al., 2018; Donaldson et al., 2020). However, the relationship between the timing and relative magnitude of these rotations is unclear. Given the coaching interest in the relationship between trunk and shank angles at key events (Donaldson et al., 2020; von Lieres und Wilkau et al., 2018) and the role both the shank and the trunk play in facilitating more forward CM positions and orienting force in the horizontal direction (Kugler and Janshen, 2010; Jacobs and van Ingen Schenau, 1992; von Lieres und Wilkau et al., 2018; Alt et al., 2022), understanding of this inter-segmental relationship is needed. In the only study to so far investigate trunk-shank coordination in sprinting, Bezodis et al. (2019a) found

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Received 21 June 2022; Accepted 6 September 2022

Biology Open

Appendix G

Chapter 4 published article

Characterising coordination strategies during initial acceleration in sprinters ranging from highly trained to world class

Byron Donaldson[a], Neil Bezodis[b] and Helen Bayne[a]

[a]Sport, Exercise Medicine and Lifestyle Institute (SEMLI) and Division of Biokinetics and Sport Science, Department of Physiology, University of Pretoria, Pretoria, South Africa; [b]Applied Sports, Technology, Exercise and Medicine (A-STEM) Research Centre, College of Engineering, Swansea University, Swansea, UK

ABSTRACT

Identifying coordination strategies used by sprinters and features that differentiate these strategies will aid in understanding different technical approaches to initial sprint acceleration. Moreover, multiple effective coordination strategies may be available to athletes of similar ability, which typical group-based analyses may mask. This study aimed to identify sub-groups of sprinters based on thigh-thigh and shank-foot coordination during initial acceleration, and assess sprint performance across different combinations of coordination strategies. Angular kinematics were obtained from 21 sprinters, and coordination determined using vector coding methods, with step 1 and steps 2–4 separated for analysis. Performance was assessed using metrics derived from velocity-time profiles. Using hierarchical cluster analysis, three distinct coordination strategies were identified from thigh-thigh and shank-foot coordination in step 1 and two strategies in steps 2–4. Coordination strategies primarily differed around early flight thigh-thigh coordination and early stance shank-foot coordination in step 1, while timing of reversals in thigh rotation characterised differences in later steps. Higher performers tended to have greater lead thigh and foot dominance in step 1 and early swing thigh retraction in steps 2–4. The novel application of cluster analysis to coordination provides new insights into initial acceleration technique in sprinters, with potential considerations for training and performance.

ARTICLE HISTORY

Received 9 March 2023
Accepted 13 December 2023

KEYWORDS

Acceleration; kinematics; performance; sprinting; track and field

Introduction

Acceleration performance depends on positioning body segments and coordinating their rotations to effectively apply forces to the ground to propel the body forward (Kugler & Janshen, 2010; Morin et al., 2011, 2015; Slawinski et al., 2010; von Lieres et al., 2018). In practical settings, a popular method for analysing sprint technique involves a sequence of images from key events, as demonstrated by the kinogram method (McMillan & Pfaff, 2018). These images depict "shapes" (McMillan & Pfaff, 2018), and whilst practitioners may visually consider the relations between segments, biomechanical investigations have typically focused on isolated joints or segments which do not facilitate easy interpretation of the relative motion of these elements, i.e., their coordination. Coordination thus describes the relative rotation of two functionally linked segments, aiding understanding of the transition from one key event ("shape") to another (Bezodis et al., 2019; Kimura et al., 2021; Okudaira et al., 2021). From a dynamical systems perspective, coordination emerges spontaneously from interacting individual, task and environmental constraints in a self-organising manner (Bernstein, 1967; Davids et al., 2003; Kelso & Schöner, 1988; Newell, 1986). In acceleration, multiple technical strategies could therefore lead to the same performance outcome depending on the particular interaction between the individual, task, and environment – a feature known as degeneracy (Tononi et al., 1999; Wild et al., 2021). Wild et al. (2021) demonstrated this concept by showing that professional rugby backs could be clustered into four distinct sprint acceleration strategies based on the ratios of step length/frequency and contact time/flight time, but that no one strategy led to better acceleration performance. Such a characterisation of strategies remains unexplored from a coordination perspective, or in a trained-trained population.

The hip and ankle play important roles during the block phase and first steps of acceleration, with a relatively more minor role for the knee (Bezodis et al., 2014, 2015; Brazil et al., 2016; Charalambous et al., 2012; Debaere et al., 2013). Jacobs and van Ingen Schenau (1992) showed that sprinters accelerate the centre of mass through "rotation" then "extension" of the stance (i.e., support) limb. This aligns with the "shin roll" framework proposed by Alt et al (Alt et al., 2022), which describes shank rotation over the foot during stance in sprinting, potentially accounting, at least partly, for the "rotation" component (Jacobs & van Ingen Schenau, 1992). However, the foot is not a static base during stance and is an important component of ankle dorsi- and plantarflexion motions during ground contact (Bezodis et al., 2014; Brazil et al., 2016; Charalambous et al., 2012). Regarding the hips, bipedal gait inherently requires cyclic limb interchange (Kiely & Collins, 2016), and Clark et al. (2020) have shown the importance of large amplitudes of thigh separation and high frequencies of interchange to maximal velocity performance. Moreover, thigh action helps set up