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DATE DEPOSITED
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BIOMECHANICS AND MOTOR CONTROL OF EARLY ACCELERATION: ENHANCING THE INITIAL SPRINT PERFORMANCE OF PROFESSIONAL RUGBY UNION BACKS

A thesis submitted to the University of Surrey for the degree of Doctor of Philosophy by:

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ABSTRACT

Biomechanics and motor control of early acceleration: Enhancing the initial sprint performance of professional rugby union backs

Sprint acceleration is an important performance feature in many sports. For professional rugby union backs, short distance sprints are frequently carried out in training and competition, but how technique and strength-based characteristics contribute to their acceleration performance during these initial steps is not currently well understood. A series of investigations were therefore undertaken to, firstly, advance the understanding of this area and, secondly, to apply this information by prescribing individual-specific interventions to enhance initial acceleration performance.

Three initial investigations sought to determine how technical features and strength-based qualities of professional rugby union backs related to their sprint performance (quantified as normalised average horizontal external power) during the initial steps. Findings from these investigations highlighted that focussing on the contribution of discrete technical variables to acceleration performance in isolation is an overly reductionist approach which overlooks how complex systems achieve high sprint performance. Findings also highlighted how important information on individuals can be lost using group-based study designs, since different inter-athlete strategies were adopted to achieve similar performance outcomes.

In the fourth investigation, four sub-groups of participants were identified, using cluster analysis, based on their whole-body kinematic strategies. At the intra-individual level, the variables which portrayed their individual strategies remained stable (CV: 1.9% to 6.7%) across multiple separate occasions. This characterisation of whole-body strategies was used to develop a novel and rigorous approach to longitudinally assess the efficacy of technical-based acceleration interventions. Demonstrating the application of this approach in the final investigation, several individual-specific interventions were prescribed to professional rugby union backs based on within-individual relationships of their technique strategies and strength-based capabilities with acceleration performance. Changes in within-individual technique and acceleration performance were measured at multiple time points across an 18-week intervention period where meaningful enhancements in acceleration were observed. This demonstrated that individual-specific technical interventions were effective in manipulating aspects of acceleration technique and performance. The outcome of these investigations provides a novel approach for practitioners working to individualise sprint-based practices.

PUBLICATIONS ARISING FROM THIS PROGRAMME OF RESEARCH

Wild, J., Bezodis, I., North, J., & Bezodis, N. (2022). Characterising initial sprint acceleration strategies using a whole-body kinematics approach. *Journal of Sports Sciences, 40* (2), 203-214. doi.org/10.1080/02640414.2021.1985759

Wild, J., Bezodis, I., North, J., & Bezodis, N. (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. doi.org/10.1080/17461391.2018.1490459

ACKNOWLEDGMENTS

There are too many people to thank. However, I would specifically like to express thanks to my supervisory team – Dr Neil Bezodis, Dr Ian Bezodis and Dr Jamie North – for their hard work, patience, and contribution to the work produced in this thesis. I can say with confidence that your scientific and research expertise has positively impacted my applied practice beyond what I thought would have been possible from working towards a PhD. I am very grateful to you for this.

I would like to dedicate the work in this thesis to Ina Sharpe. I am sorry I didn’t complete it before you left, but I know you would have been proud.

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CHAPTER 1: INTRODUCTION

1.1 Research overview

Within professional rugby union (hereafter referred to as ‘rugby’), sprinting is deemed an important physical ability. Performance during the sprint acceleration phase, in particular, has been shown to relate to key performance indicators during matches and to discriminate between playing standards (Cunningham et al., 2018; Hamlin et al., 2021; Smart et al., 2014). Given that the typical sprint duration in rugby is between one and three seconds (Deutsch et al., 2007; Roberts et al., 2008), the initial steps of a sprint are important for rugby players. Of the two major positional groups in rugby (backs and forwards), backs are typically the fastest players during sprint acceleration (Crewther et al., 2009; Cross et al., 2015). This is logical given that one of the role requirements for backs is to out-manoeuvre opposing players (Duthie et al., 2003) and that backs complete a higher number of sprints during competition and training than forwards (Campbell et al., 2018; Duthie et al., 2006). Despite this, little is known about the factors that contribute to the early acceleration performance of rugby backs at the professional level, such as how their technical features or strength-based capacities relate to sprint performance during the initial steps. Therefore, a greater understanding of these contributory factors is needed to enhance the knowledge and sprint-training practices of practitioners working with professional rugby backs.

The existing research that has investigated the technical features of trained to world class level performers (Tier 2 to 5; McKay et al., 2022) during the initial steps of acceleration (approximately ≤ 5 m) has focused predominantly on track and field sprinters (e.g., Bezodis et al., 2014; Bezodis et al., 2015; Debaere et al., 2013a; Debaere et al., 2015; Walker et al., 2021). Clearly, sprinters represent the fastest of all athletes. Therefore, the techniques they adopt to enhance their ground reaction force (GRF) characteristics, which ultimately determine their sprint performance (Morin et al., 2011; Morin et al., 2015a; Rabita et al., 2015), are of interest to practitioners working with team sport players. However, unlike sprinters who train for the sole performance goal of enhancing their sprinting ability, rugby backs are required to train for a variety of performance goals in the context of their sport, and the extent to which the information collected through research on sprinters can be used to enhance the acceleration of rugby backs is unclear due to the inherent differences in their ecological constraints (Newell, 1986).

According to Newell (1986) there are three types of constraint that influence movement – environmental, task and organismic (hereafter referred to as ‘performer’). Accordingly, differences in the environmental (e.g., running surface), task (e.g., sprint start conditions) and performer (e.g., physical characteristics) constraints between sprinters and rugby backs imply that different technical features may be necessary to achieve high initial acceleration performance in their respective sports, and will likely emerge as a function of the sprint demands specific to their individual training and competition settings. Furthermore, from an ecological dynamics perspective, although the fundamental movements necessary to sprint effectively during the initial steps (e.g., a sequential cycle of contralateral upper and lower limb flexion and extension) are broadly the same for everyone, a one-size-fits-all ideal movement template may not exist (Glazier & Mehdizadeh, 2018; Seifert et al., 2013). This suggests that similar initial acceleration performance could be achieved through different sprint techniques between and within athlete groups, and this may explain the conflicting perspectives on the importance of even broad technical features such as spatiotemporal variables (i.e., step length, step rate, contact time and flight time) during the initial steps of a sprint in studies of both team sport players and sprinters (e.g., Debaere et al., 2013b; Murphy et al., 2003; Nagahara et al., 2018a). Therefore, questions remain concerning which technical features are important for rugby backs during the initial steps and how they may be manipulated to enhance their acceleration performance in the context of their environmental, task and performer constraints.

Regarding performer constraints, movement preferences adopted during initial acceleration between athlete groups will likely be influenced by their physical capabilities (Holt, 1998; Thelen, 1995). Therefore, different performer constraints between athlete groups, and between individuals within a group, such as strength-based capacities, may result in different movement strategies during initial acceleration. However, previous investigations on the strength-based capacities of team sport players have largely sought to determine how these physical characteristics relate to early acceleration *performance* in isolation, without consideration of the techniques adopted (e.g., Boraczyński et al., 2020; Cronin & Hansen, 2005; Wisloff et al., 2004; Zabaloy et al., 2020). Considering how these strength-based capacities interact with the technical features adopted during the initial steps and how combinations of technical and strength-based features collectively associate with performance is needed to give a better understanding on how high performance is achieved by rugby backs during early acceleration.

A better understanding of the technical features important for the initial sprint acceleration performance of professional rugby backs, under the environmental and task constraints associated with sprint acceleration requirements in rugby and how they are influenced by performer constraints, is therefore needed. Furthermore, knowledge of how this information can be applied to impact the initial acceleration performance of rugby backs would have wide-reaching appeal to coaches and practitioners tasked with enhancing their acceleration abilities.

1.2 Thesis aim

The overarching aim of this thesis was to understand how the technical and strength features of professional rugby backs related to their sprint performance during the initial steps and, informed by this advance in knowledge, to develop and apply an individual-specific intervention framework to enhance initial acceleration performance.

1.3 Development of Research questions

Most of the current understanding of effective sprint technique during the initial steps is based on that of track and field sprinters. This is potentially problematic for practitioners looking to enhance the acceleration abilities of athletes in any domain outside of track and field sprinting, due to the different ecological constraints that act on the performer (Newell, 1986). For instance, regarding task constraints, professional rugby backs will commence maximal accelerations from a more upright stance (e.g., 2-point position) compared with sprinters who are required to commence sprinting from a crouched 4-point start in blocks during competition. Therefore, research comparing the technical features and performances of rugby players with sprinters during the initial steps can help practitioners working in rugby to understand the extent to which information on the technical features of sprinters can be used to help inform the sprint training of rugby backs. This therefore led to the first research question:

I. **What are the differences in spatiotemporal variables and linear kinematics between professional rugby players and sprinters during the initial steps of a sprint, and how do they relate to performance?**

Previous research investigating technical features associated with sprint performance during initial acceleration found that more favourable GRF characteristics for acceleration performance were achieved when the whole-body centre of mass (CM) was moved further forwards of the stance foot towards the end of the contact phase (Kugler & Janshen, 2010). However, to understand the technical features which may be manipulated to affect this forward leaning position and how they relate to initial acceleration performance, further investigations are required. This will help provide information to explain how better sprint performance can be achieved by rugby backs. Therefore, a second research question was posed as follows:

II. **How do angular kinematics and normalised spatiotemporal variables relate to the toe-off distance and initial acceleration performance of professional rugby backs?**

To understand how some of the performer constraints influence the technical features observed during the initial steps, knowledge of how strength-based qualities relate to the movement characteristics adopted, and acceleration performance achieved, would provide further insight into how the different acceleration strategies observed in this sprint phase may be influenced. Two further research questions were therefore developed to address this area:

III. **How are lower limb strength qualities related to the performance of professional rugby backs during initial acceleration?**

IV. **What are the relationships between lower limb strength qualities and technical features, and how do their interactions associate with initial acceleration performance in professional rugby backs?**

The approaches used to answer the first four research questions would provide useful information to help identify how movement characteristics and strength qualities of rugby backs associate with high initial acceleration performance at the whole group level. However, due to the inter-individual differences in movement tendencies likely adopted during initial sprint acceleration, owing to differences in performer constraints, the results obtained at a whole group level may not necessarily be representative of different strategies adopted within the group (Dufek et al., 1995; Fisher et al., 2018; Glazier & Mehdizadeh, 2018). Therefore, information would be required to identify whether different acceleration strategies exist across rugby backs. Determining a rugby back's initial sprint acceleration strategy through 'whole-body' kinematic parameters, such as their spatiotemporal characteristics, may offer a macroscopic perspective on these potential strategies. This would be consistent with an ecological dynamics approach where information on system behaviour at a more holistic level is deemed "richer" than the makeup of its individual constituent parts (Button et al., 2020). Therefore, this led to the fifth and sixth research questions as follows:

V. **To what extent do whole-body kinematic strategies differ within a group of professional rugby backs according to the combination of their normalised spatiotemporal variables during the first four steps, and what are the differences in technical features and strength qualities between these strategies?**

VI. **How stable are intra-individual whole-body kinematic strategies during initial acceleration in professional rugby backs?**

If whole-body acceleration strategies are stable (i.e., reliable) at the intra-individual level, it would be possible to longitudinally monitor these acceleration strategies for individuals. Since optimum technique can be considered as the motions yielding maximum performance for a given individual under the constraints applied to them (Hatze, 1973), this may provide a way to determine the technical variables of interest that individuals are reliant on for better acceleration performance, building on similar, previous work conducted on elite to world class level (Tiers 4 to 5; McKay et al., 2022) sprinters and their performance during 100 m races (Salo et al., 2011). This information could then be used to apply individual-specific training interventions aimed at changing the acceleration strategies of rugby backs to enhance their sprint performance during the initial steps. Two further research questions were thus developed:

VII. **What are the within-individual relationships of whole-body kinematic strategies and normalised spatiotemporal variables with the initial acceleration performance of professional rugby backs during the first four steps?**

VIII. **How do longitudinal individual-specific training interventions that focus on the variable(s) which specific professional rugby backs are reliant upon for better sprint performance affect their acceleration capabilities?**

Finally, for practitioners to obtain actionable information to inform their sprint training interventions in a timely manner, the ability to reduce the time it takes to collect information is important. The use of a sprint performance measure like NAHEP was important so that acceleration performance could be assessed over the steps in which technical features were obtained. However, the way in which NAHEP was calculated in this thesis required multiple body locations to be digitised so that the CM could be determined at touchdown and toe-off. A more time-efficient way to measure acceleration performance during the initial steps that can provide the same insight as NAHEP, would reduce the time it would take practitioners to produce the information needed to individualise the sprint training of rugby backs. This led to a final research question:

IX. **How closely can the within-individual relationships of whole-body kinematic strategies and normalised spatiotemporal variables with NAHEP, and the within-individual changes of these variables following individual-specific training interventions, be replicated using a more practical performance measure than NAHEP?**

1.4 Organisation of chapters

1.4.1 Chapter 2

A review of the literature relevant to this thesis is provided in Chapter 2. This includes literature investigating the kinetic and kinematic aspects of sprint technique adopted by sprinters and team-sport athletes during the initial steps and the strength-based qualities of team sport players. How these technique and strength-based features are known to be associated with initial acceleration performance is also discussed, with perspectives given from an ecological dynamics standpoint to explain the control of movement features adopted during early acceleration due to the constraints operating on the performer.

1.4.2 Chapter 3

An investigation into the spatiotemporal and linear kinematic technical features of professional rugby forwards and backs and sprinters during the first three steps of sprinting is presented in Chapter 3. The relationships of the technical features adopted by rugby forwards, rugby backs and sprinters with sprint performance are determined and the between group differences of these variables are also analysed to identify important technical features of interest for the initial acceleration performance of rugby backs.

1.4.3 Chapter 4

Focussing on rugby backs, in Chapter 4 the relationships of touchdown and toe-off angular kinematic variables with acceleration performance and the technical features of interest identified in Chapter 3 are determined. Selected technical features are also investigated to ascertain how, when combined in multiple linear regression models, they can collectively explain variation in initial acceleration performance to provide a more in-depth understanding of how high acceleration performance can be achieved through the adoption of different combinations of technical features.

1.4.4 Chapter 5

Chapter 5 presents the results of a study exploring the strength-based qualities of rugby backs. Relationships of strength-based qualities with initial acceleration performance and technique aspects of interest identified in Chapters 3-4 are determined to identify important strength capacities for the sprint performance of rugby backs during the initial steps.

1.4.5 Chapter 6

Using hierarchical cluster analysis to identify sub-groups of rugby backs according to their normalised combined spatiotemporal variables during the first four steps, this chapter identifies different acceleration strategies adopted by these athletes during initial sprint acceleration. The technical and strength-based features underpinning these different strategies are also presented and a reliability analysis of the characterisation of initial acceleration strategies is conducted, thus providing a rigorous and evidence-based framework for practitioners to longitudinally measure their technical sprint-training interventions.

1.4.6 Chapter 7

Applying the framework developed in Chapter 6, Chapter 7 presents the findings on how initial acceleration performance and technique change following individual-specific interventions applied to multiple individual professional rugby back case-studies across a 19-week period. The interventions applied are based on the specific needs of each individual whereby the whole-body kinematic strategies, and individual normalised spatiotemporal variables, of each rugby back are measured across multiple occasions to identify the variable(s) they are reliant on for better initial acceleration performance. The results of these interventions demonstrate the potential effectiveness of an evidence-based approach for practitioners working with rugby backs or other team sport players to individualise their sprint-based practices, applying the understanding developed from the empirical research undertaken in Chapters 3-6 to a genuine high-performance environment in Rugby.

1.4.7 Chapter 8

The major findings from the research within this thesis are synthesised and discussed in Chapter 8. The research questions posed in Chapter 1 are addressed using the results from the investigations conducted in Chapters 3 to 7. The increased understanding of how professional rugby backs achieve high acceleration performance and a framework for practitioners to enhance the sprinting performance of these athletes during the initial steps using an individualised approach are highlighted. Finally, limitations of the current research and potential directions for future work are discussed.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Introduction

This chapter reviews previously published work which has provided knowledge on kinematic and kinetic aspects of technique and strength-based qualities relevant to the performance of athletes during the initial steps of sprinting. Regardless of the sprint phase concerned, performance of any athlete is governed by their GRF characteristics. Although rugby backs will undertake training for a variety of performance reasons, to enhance their initial acceleration capabilities the purpose of developing technique and strength-related qualities should therefore be to yield the most favourable GRF during the initial steps of sprinting. Consequently, after introducing some of the key sprinting requirements for rugby backs during match-play the GRF determinants of early acceleration performance are discussed, before describing relevant technical features during the initial steps and the associations of strength-based qualities with the acceleration performance of athletes.

No studies to date have investigated the GRF characteristics and technical features of rugby backs during initial acceleration. Therefore, given that most of the work in sprint biomechanics has been conducted on sprint athletes, a large proportion of the sections on GRF and technique during initial acceleration will be discussed in the context of this population with comparisons made with team sport players where possible. Finally, the efficacy of different interventions in the scientific literature aimed at enhancing early acceleration performance of team sport players are detailed. For the purposes of this current review, it can be assumed unless specified otherwise that the sprint efforts completed by sprinters and team sport players discussed in the research commenced from block and standing two-point split stance positions, respectively. The participants in the literature discussed are male unless otherwise stated and participant ability levels are described based on the Participant Classification Framework proposed by McKay et al. (2022) to provide an objective comparison of participants. This framework is also used throughout this thesis and a copy of the table defining the tiers used to describe participant ability levels from McKay et al. (2022; Table 1, p.319) can be found in Table A.1 (Appendix A).

2.2 Match-play sprinting demands for rugby backs

A rugby union match is characterised by high-intensity activities performed intermittently by players for two 40-minute halves separated by a half-time break of no longer than 15 minutes. Within each team (n = 15 players), each player is designated their own position based on the requirements of their role in the different aspects of the game. Due to the different role requirements between the two major positional groups (backs and forwards) the predominance and type of activities they each undertake during a match and training differs. For example, at the professional level, it has been shown that sprinting accounts for 45% of the high intensity activities undertaken by backs during a match compared with approximately 26-30% of the high intensity activities completed by forwards (Austin et al., 2011a). For backs sprinting also accounts for a higher percentage of the total distance travelled during a match compared with forwards (e.g., in Cahill et al. [2012] backs covered 35% more of their total distance sprinting than forwards). Both anecdotally, and as shown by research in controlled testing settings (e.g., Duthie et al., 2006; Crewther et al., 2009; Zabaloy et al., 2020), backs accelerate faster and reach higher maximum sprint velocities compared with forwards. However, forwards are involved in more static exertions than backs (e.g., scrummaging, rucking, mauling; [e.g., Austin et al., 2011a; Deutsch et al., 2007; Roberts et al., 2008]), and typically possess greater absolute maximum strength levels (e.g., Zabaloy et al., 2020). These differences highlight the need for specialised training for each of these respective positional groups to prepare them for the competitive demands of the game.

Owing to their role during competition, compared to forwards, backs generally operate in larger open-field spaces where speed is an important quality to penetrate the defensive line when attacking the opposition or during defensive cover situations (Till & Jones, 2015). On average, backs have been shown to perform between nine and 40 sprints during matches (Austin et al., 2011b; Deutsch et al., 2007; Duthie et al., 2006; Roberts et al., 2008). Since the mean duration and distances of these sprints are typically between one to three seconds (Duthie et al., 2006; Deutsch et al., 2007; Roberts et al., 2008) and less than 20 m (Austin et al., 2011a; Austin et al., 2011b; Roberts et al., 2008) respectively, the initial acceleration capabilities of backs is important for high performance in rugby. Although the mean total sprint distance achieved by backs during a match is small relative to the mean total distance they cover (e.g., 207 m vs. 6127 m in Roberts et al. [2008] and 738 m vs. 5435 m in Austin et al., [2011b]), sprinting occurs during key game moments and players with higher acceleration capacities have previously been shown to penetrate defensive lines and evade opposition players more frequently and score more tries (e.g., Smart et al., 2014). Collectively, this evidence highlights the importance of training interventions aimed at enhancing the sprint acceleration capabilities of rugby backs to prepare them for the specific demands of their on-field positional requirements.

2.3 Ground reaction force production during initial sprint acceleration

Ground reaction forces during sprinting can be separated into three orthogonal components: vertical, anteroposterior (hereafter termed "horizontal") and mediolateral. Vertical and horizontal GRF have received the most attention within the literature and are of most interest in performance across all sprint phases (e.g., Mero, 1988; Morin et al., 2015a; Nagahara et al. 2018a; Weyand et al., 2000). Horizontal GRF during the stance phase of a sprint are typically divided into braking (negative) and propulsive (positive) phases. A braking GRF acts posteriorly and takes place early in stance, while a propulsive GRF acts anteriorly and occurs after the braking force. The impulses which are produced during stance are the product of the respective braking and propulsive forces and the durations they are applied for. Net propulsive impulse is then the propulsive impulse (time-integral of the anterior GRF) minus the braking impulse (time-integral of the posterior GRF). If net propulsive impulse is positive, then acceleration during a step will have taken place in the horizontal direction. If the net vertical impulse is positive (where the time-integral of the vertical GRF exceeds that of the weight of the athlete's body), then acceleration during a step will have taken place in the upwards vertical direction. Due to the impulse-momentum relationship, when expressed relative to body mass, vertical and horizontal impulses describe the change in velocity of an athlete's CM (ignoring the effects of air resistance).

2.3.1 Horizontal braking ground reaction force impulse characteristics

As early as 1930, Fenn found that a runner loses some momentum when their foot strikes the ground (Fenn, 1930). This loss in momentum, and reduction in CM horizontal velocity, is indicative of the braking effects during early stance. If braking impulses can be reduced without negatively affecting the magnitude of propulsive impulse generated then, theoretically, net propulsive impulse will increase and so too will an athlete's horizontal CM velocity throughout the acceleration phase. However, the reduction in velocity resulting from braking impulses produced by trained (Tier 2) sprinters (Macadam et al., 2019; Mero, 1988; Salo et al., 2005) and recreational (Tier 1) to trained

(Tier 2) team sport players (Bezodis et al., 2017; Kawamori et al., 2013; Murata et al., 2018; Nagahara et al., 2018a; Wdowski & Gittoes, 2020) during the initial steps (e.g., steps one to four) is small (0.01 to 0.04 m/s) and currently there is little support in the scientific literature that minimising the effects of braking will positively influence acceleration performance.

Morin et al. (2015a) aimed to establish whether highly trained to elite (Tiers 3 and 4) sprinters (n = 9; 100 m PB range 9.95-10.60 s) produced smaller braking impulses, greater propulsive impulses, or both during the acceleration phase. When comparing participants, they showed the maximum braking GRF of the fastest sprinter (100 m PB 9.95 s; Tier 4) to be at least twice that of the slowest sprinter (100 m PB 10.60 s; Tier 3) during the first step (approximately -8 N/kg vs. -3 N/kg) with visible differences during step three (approximately -8 N/kg vs. -5 N/kg) and step five (approximately -10 N/kg vs. -7 N/kg). Moreover, they found no significant relationship between braking impulse and sprint performance over 40 m (r = -0.295, p = 0.441).

Over the course of a subsequent three-year period (2018-2021), five studies published findings demonstrating that the effects of braking were *not* significantly related to the performance of sprinters during the initial steps of acceleration, although they *were* significantly related to their performance in later acceleration phases (Murata et al., 2018; Nagahara et al., 2018b; Nagahara et al., 2021; Colyer et al., 2018; von Lieres Und Wilkau et al., 2020a). Regarding only the early acceleration phase, in the first step of trained (Tier 2) soccer players (Wdowski & Gittoes, 2020), neither maximum braking force (r = 0.21 [95% CI, -0.27 to 0.61], p = 0.38) nor braking impulse (r = 0.35 [95% CI, -0.18 to 0.69], p = 0.15) were significantly related to 5 m sprint time. In trained (Tier 2) team sport players, although Bezodis et al. (2017) observed time to 10 m to be significantly less (p < 0.01) in the control condition compared with two experimental conditions when different foci of attention were applied, the braking impulse and maximum braking GRF at 5 m (approximately step 3) were not significantly different between conditions (p = 0.99 and 0.92). Furthermore, for trained (Tier 2) soccer players, a moderate negative and statistically significant relationship (approximately r = -0.38, p < 0.05) was found between braking impulse averaged over the first four steps and average velocity when controlling for stature and body mass (Murata et al., 2018). That is, greater braking impulses were associated with higher velocities over these initial steps. Furthermore, in the trained (Tier 2) team sport players investigated by Kawamori et al. (2013), braking impulse during the first step and at the 8 m mark was not shown to be significantly related to 10 m sprint time (r = -

0.22 and 0.06, $p < 0.01$). Both Murata et al. (2018) and Kawamaori et al. (2013) reasoned that the magnitude of braking impulse in the initial acceleration phase is so small that any attempt to maximise it (Murata et al., 2018) or to minimise it (Kawamori et al., 2013) may not contribute meaningfully to acceleration performance, thus supporting the findings discussed regarding the likely lack of influence of braking on the initial acceleration performance of sprinters.

The prospect of braking providing some advantages to sprint performance cannot be ruled out either. For example, the braking force could be involved in the storage of elastic energy (Cavagna et al., 1971). Others have also ruminated whether it is possible that an attempt to minimise braking may possibly reduce the potential to generate propulsion for the remainder of the stance phase (e.g., Haugen et al., 2019a). While the effects of braking GRF characteristics on sprint performance during the initial steps may appear to be small, research conducted on sprinters conclusively demonstrates the influence of propulsive GRF characteristics on early acceleration performance, although the findings are not so conclusive in the research of team sport athletes, as discussed next.

2.3.2 Horizontal propulsive ground reaction force impulse characteristics

Over successive steps in acceleration the reductions in propulsive impulse which occur have been shown to contribute mainly to the decrease in net propulsive impulse, and thus the decrease in horizontal CM change in velocity, produced across the acceleration phase of sprinters (Morin et al., 2015a). The same researchers also observed a very large positive relationship between propulsive impulse and sprint performance over 40 m ($r = 0.80$; $p = < 0.01$). When comparing the ‘fastest’ and ‘slowest’ athletes, higher maximum propulsive GRF were produced by the former during the early steps of the sprint (steps one, three and five; Morin et al., 2015a). These data suggest that producing large propulsive GRF and propulsive impulses are important to performance during the acceleration phase.

At the 2.9 ± 0.2 metre mark (55% of maximal running speed of participants), Nagahara et al. (2018b) showed that the propulsive (approximately 0.95 m/s), but not the net propulsive (approximately 0.91 m/s) impulse produced by sprinters was significantly associated with instantaneous acceleration derived from the velocity-time curve (standardised β coefficient = 0.72, $p = 0.03$). They also showed that both the average propulsive and average net propulsive GRF produced were significantly associated with acceleration at that instant (standardised β coefficients = 0.60, p = 0.01 and 0.40, p 0.01; Nagahara et al. 2018b). Macadam et al. (2019) found the start condition (block start) resulting in better performance (time to 5 m) of sprinters also resulted in statistically significant larger net propulsive impulses (increase in velocity of 0.819 ± 0.053 m/s vs. 0.766 ± 0.041 m/s, d = -1.12 [-2.06 to -0.17]) and propulsive impulses (0.858 ± 0.045 m/s vs. 0.800 ± 0.041 m/s, d = -1.35 [-2.32 to -0.37]) averaged over the first four steps, compared with the 5 m times in the worse performing condition (standing two-point split-stance start). Nagahara et al. (2021) observed large to very large (approximately r = 0.60 to 0.80, all p < 0.05) significant positive relationships between the mean net propulsive GRF of sprinters during each of their first four steps and their acceleration magnitude. Large to very large relationships (approximately r = 0.55 to 0.72, all p = < 0.05) were observed between average propulsive GRF and acceleration in steps one to three, although the same relationship in step four was small and not statistically significant (approximately r = 0.29, p > 0.05). However, the relationships between maximum propulsive force and acceleration in each of the four initial steps were trivial to moderate and not statistically significant (Nagahara et al., 2021). Although large mean horizontal GRF are clearly important for achieving high propulsive impulse and appear to be important for the initial acceleration performance of sprinters, given that impulse is the product of force *and* time, the duration over which impulses are produced also need to be considered. However, few studies have investigated how important the time aspect is when producing these impulses (e.g., von Lieres Und Wilkau et al., 2020a) which, when considering the aim of a sprint is to cover a specific distance in the shortest timeframe possible, is surprising.

In the third step, von Lieres Und Wilkau et al. (2020a) observed very large significant relationships of mean horizontal and propulsive impulse produced by male and female trained (Tier 3 sprinters with NAHEP (both approximately r > 0.75, p < 0.001). The researchers also observed very large to practically perfect positive and significant relationships of NAHEP in the third step with maximum propulsive GRF (approximately r = 0.80, p < 0.001), average propulsive GRF and average horizontal GRF (r ≥ 0.90, p < 0.001). Moreover, a very large negative significant relationship between propulsive duration and NAHEP in the third step was found (r = -0.80, p < 0.001). That is, higher magnitudes of NAHEP were produced by sprinters in the third step who also produced propulsive forces rapidly. The importance of the time of propulsive GRF application was reinforced through their regression analysis where the combination of average propulsive GRF and propulsive time contributed the most (61%) to the variance in NAHEP in the third step (von Lieres Und Wilkau et al., 2020a). Producing large magnitudes of propulsive GRF and propulsive impulse and in short propulsive timeframes appear to be important for the performance of sprinters during the initial steps. However, the importance of these GRF characteristics to the initial acceleration performance of team sport players is less clear.

In team sport players, a change in velocity of 0.52 ± 0.10 m/s to 1.14 ± 0.27 m/s has been observed in the first step of sprinting and a number of GRF characteristics in this step have been correlated to 5 m and 10 m sprint time (Kawamori et al., 2013; Wdowski & Gittoes, 2020). In recreationally active to trained (Tiers 1 to 2) participants competing in a range of team sports, only small statistically non-significant relationships were observed for the net propulsive impulse (r = -0.28) and propulsive impulse (r = -0.29) produced in their first step with their 10 m time (Kawamori et al., 2013). In Tier 2 soccer players, only trivial to small statistically non-significant relationships were observed (r = -0.01 [95% CI, -0.46 to 0.45] to r = -0.29 [95% CI, -0.66 to 0.19]) for the propulsive impulse (1.02 ± 0.12 m/s), maximum propulsive GRF (7.95 ± 0.69 N/kg) and mean horizontal GRF (4.41 ± 0.49 N/kg) produced in their first step with their 5 m time (Wdowski & Gittoes, 2020). Bezodis et al. (2017) also obtained the GRF of team sport players in a single step (at the 5 m mark) during 10 m sprints and observed statistically significantly worse (i.e., longer) 10 m times during the experimental conditions (when an internal or external focus of attention was applied). However, no significant change in net propulsive impulse (control condition was 0.46 ± 0.05 m/s), propulsive impulse (control condition, 0.51 ± 0.06 m/s), maximum propulsive GRF or mean horizontal GRF were found between conditions (p = 0.20 to 0.97; Bezodis et al., 2017). Although a single step (e.g., first step or a step at 5 m) during a short sprint is clearly important to the early acceleration phase, sprint performance over a given distance is influenced by all steps taken during that sprint. The other steps taken by the participants in these investigations may therefore have masked the contribution of the GRF characteristics produced to their 10 m (Bezodis et al., 2017; Kawamori et al., 2013) or five-metre (Wdowski & Gittos, 2020) sprint performance.

Lockie et al. (2013) obtained GRF measures from three steps taken by 22 trained (Tier 2) team sport players (mass 83.6 ± 7.4 kg) during 10 m sprints. The relationships of mean velocity over distance intervals (0-5, 5-10 and 0-10 m) with GRF and impulses during the first, second and final contact phase of 10 m sprints were determined. They reported that the changes in velocity due to horizontal impulses produced during the first (0.18 ± 0.03 m/s), second (0.26 ± 0.05 m/s) and last contact phase of ten metre sprints (0.16 ± 0.04 m/s) were not significantly related to mean velocity over any of the distance intervals (r = -0.16 to 0.19, p = 0.28 to 0.98). They also found no significant relationships of maximum propulsive force during the first (1.00 ± 0.18 N/kg), second (1.11 ± 0.14 N/kg) and last contact phase (0.92 ± 0.22 N/kg) of 10 m sprints to exist with mean velocity over any of the sprint distance intervals (r = -0.23 to 0.15, p = 0.28 to 0.84; Lockie et al., 2013). These findings conflict with the aforementioned research on sprinters which suggests the production of large propulsive GRF and propulsive impulses are important to their performance during the acceleration phase. However, the GRF of participants were obtained by Lockie et al. (2013) on a separate day to when their sprint performance over the distance intervals was measured. Therefore, it is feasible that the relationships observed by the researchers could have been different had the mean horizontal impulses and maximal propulsive forces of participants been obtained during the sprint efforts in which their acceleration performance was measured. Furthermore, impulse was not calculated correctly (force was divided, rather than multiplied, by time) by Lockie et al. (2013), which explains why the impulse values reported are noticeably lower than in the other research discussed in this literature review. Therefore, the impulse findings from this study should be disregarded.

When the relationships between impulse measures averaged over the first four steps and mean velocity over the same steps were determined for soccer players (Murata et al., 2018), similar findings were observed to the previous findings in sprinters discussed in this literature review. Controlling for stature and body mass, the changes in velocity due to net propulsive impulse (0.72 ± 0.04 m/s) and propulsive impulse (0.76 ± 0.04 m/s) were largely and significantly related to mean velocity during the first four steps (approximately r = 0.65 and 0.70, respectively). However, since the velocity of an athlete increases with distance and each successive step during acceleration (as shown by the same authors; Murata et al., 2018), higher mean step velocities are likely to be influenced by the magnitude of the step lengths being produced during the first four steps. That is, those with longer step lengths could feasibly produce higher velocities averaged over the first four steps since they will have advanced further in a sprint compared with those who produce shorter step lengths (provided the differences in step rate are not sufficient to offset the influence of step length on step velocity). This is supported by the relationship Murata et al. (2018) observed between step length and mean velocity over the first four steps, which was large and statistically significant (approximately $r = 0.70$, $p > 0.05$). If the sprint distance was standardised over which sprint performance was measured (e.g., time to 5 m), it is feasible that different magnitudes in the relationships of net propulsive impulse, propulsive impulse and step length with acceleration performance would have been observed (Murata et al., 2018). Furthermore, the velocities athletes have attained by the instant of the first contact phase will also affect the magnitude of their successive step velocities, thus mean velocity may not have been a 'true' measure of their acceleration performance over the first four steps. An alternative and commonly used measure of initial acceleration performance, such as NAHEP (e.g., Bezodis et al., 2010; von Lieres Und Wilkau et al., 2020a), which accounts for the velocity of the athlete prior to commencing the step(s) over which their acceleration performance is being measured may have been a more appropriate choice and may have resulted in different findings than those observed by Murata et al. (2018).

The data discussed in this literature review so far suggests that attempting to minimise braking impulses and braking GRF may not be beneficial to the acceleration performance of sprinters or team sport players. Furthermore, whilst maximising propulsive impulse and mean propulsive GRF during short propulsive times appears to be important for sprinters, it is not clear to what extent this is true for team sport players due to the limited amount of research and the potential limitations of the methods as discussed in the context of team sport players.

2.3.3 Vertical ground reaction force impulse characteristics

The production of sufficient vertical impulse is necessary to overcome the negative (downwards) vertical acceleration due to gravity in order to support bodyweight. However, no significant relationships have been observed between vertical impulse (total or net) and initial acceleration performance in sprinters (e.g., von Lieres Und Wilkau et al., 2020a), or in team sport players (Kawamori et al., 2013; Lockie et al., 2013; Murata et al., 2018; Wdowski & Gittoes, 2020). In fact, significant negative relationships have been shown between vertical impulse and acceleration magnitude at the 2.9 ± 0.2 m mark (Nagahara et al., 2018b) and with acceleration performance across the whole acceleration phase (Morin et al., 2015a; Rabita et al., 2015) of sprinters. Significantly greater vertical impulses at 5 m have also been shown to be produced during significantly longer 10 m sprint times of team sport players (Bezodis et al., 2017). Likely positive moderate relationships were observed between the maximum and mean vertical GRF produced during the third step of sprinters and NAHEP in the same step (approximately $r = 0.49$ and 0.45, p

< 0.05; von Lieres Und Wilkau et al., 2020a), although other studies have *not* found significant relationships between vertical GRF and the acceleration performance of sprinters or team sport players during the initial steps (e.g., Lockie et al., 2013; Nagahara et al., 2021; Nagahara et al., 2018b; Wdowski & Gittoes, 2020). On the whole, vertical impulses and for the most part maximum and mean vertical GRF are not key determinants of initial acceleration performance.

Given the negative associations which have been observed between vertical impulse and acceleration performance (e.g., Morin et al., 2015a; Nagahara et al., 2018b) attempts to increase vertical impulse during initial sprint acceleration may negatively affect sprint performance since this would lead to greater flight times and therefore proportionally less time during ground contact accruing horizontal propulsive impulse. This is supported by Nagahara et al. (2018a) and Rabita et al. (2015), where the former found vertical impulses of soccer players to be significantly correlated to flight time during the first four steps ($r = 0.48$; $p = 0.002$; Nagahara et al., 2018a) whilst the latter observed elite (Tier 4) sprinters to produce substantially smaller flight times ($d = 1.04$-1.14) and smaller averaged relative vertical GRF ($d = 0.59$) relative to well-trained (Tier 3) sprinters and no substantial differences in contact times were evident ($d = 0.00$-0.07) over 40 m (Rabita et al., 2015). These data suggest that limiting vertical GRF may be of value to early acceleration performance which, if the resultant GRF magnitude is not altered in the process, would result in a greater horizontal GRF component (i.e., a more anteriorly directed GRF vector) which has previously been shown to be a key determinant of sprint acceleration performance (e.g., Morin et al., 2011).

2.3.4 Ground reaction force vector orientation during acceleration

Whilst considering the horizontal and vertical force components can aid the understanding of sprinting, they are part of a single GRF vector and thus cannot be independently altered. Higher vertical forces during acceleration would likely result in either shortened contact times or longer flight phases. The former would potentially reduce the time during which propulsive forces could be applied whereas the latter may delay subsequent steps and consequently CM acceleration. The most favourable impulse profile for acceleration, it has been suggested, is one in which sufficient vertical impulse is generated to overcome gravity and create a flight time long enough for repositioning of the lower limbs, whilst all other ‘strength reserves’ are applied horizontally in order to maximise acceleration (Hunter et al., 2005). A more forward oriented resultant GRF vector would therefore seem important for forward propulsion during acceleration. This was evident in a cross-sectional study which investigated GRF relating to body position in the first step of a sprint from a standing start and at 2.5 m during accelerations from rolling starts (Kugler & Janshen, 2010). They found that the mean angle of the GRF vector to the vertical when maximum resultant GRF was produced by physical education students (training status was not provided; 28 males, mass 74 ± 8 kg; 13; females, mass 63 ± 6 kg) was 22° (standard deviations were not reported, but estimated to be approximately 4°) and very strongly and significantly correlated with propulsive impulse (r = 0.96, p = 0.001), but not to the maximum GRF magnitude. Greater propulsive impulses were demonstrated by the faster participants during the second half of stance where they were shown to achieve greater CM angles (i.e., angle of the CM to the point of ground contact with respect to the vertical). The faster runners attained higher running speeds by applying more forward oriented, but not greater maximum ground reaction forces (Kugler & Janshen, 2010).

Morin et al. (2011) found that the total GRF (1170 ± 151 N) averaged over the first four seconds of a sprint on an instrumented treadmill did not correlate significantly to acceleration performance (measured as distance covered in four seconds on a synthetic running track during a 100 m sprint). However, they observed that the ability of the 12 trained (Tier 2) physical education students to produce more net propulsive GRF as a proportion of the mean resultant GRF (mean ratio of force [RF] over the four second sprints) did correlate significantly (r = 0.69, p < 0.05) with acceleration performance. This relationship was similar to that between mean net propulsive GRF relative to mass (3.2 ± 0.5 N/kg) and acceleration performance on the running track (r = 0.62, p < 0.05; Morin, et al., 2011). This suggests that the RF produced is likely a key determinant of acceleration performance over four second sprints, although from this information, it is not clear how important the RF is for acceleration performance during the initial steps alone.

Subsequent to the work of Morin et al. (2011), the RF has been shown to relate significantly to the initial acceleration performance of sprinters (e.g., Bezodis et al. 2020; von Lieres Und Wilkau et al., 2020a). The RF (31.0 ± 3.2%) was very strongly related to NAHEP during the third step of sprinters (approximately r = 0.90, p < 0.001; von Lieres Und Wilkau et al., 2020a). In an investigation by Bezodis et al. (2020) who aimed to establish the importance of RF to the early acceleration performance of 24 trained (Tier 2) sprinters, very large relationships were observed between the ability to produce a high mean RF over the first four steps from block and standing starts (r = 0.88

and 0.84 respectively, $p = 0.001$). Interestingly, when mean RF and mean resultant GRF magnitude were added to a multiple regression model to predict performance, the standardised β coefficient for mean RF ($\beta = 0.82$, $p < 0.001$) was more than eight times greater than that for the mean resultant GRF magnitude ($\beta = 0.10$, $p = 0.47$) from a block start, whereas from a standing start the standardised β coefficients were noticeably more comparable ($\beta = 0.58$, $p < 0.001$ [RF mean] and 0.42, $p < 0.01$ [mean resultant GRF]; Bezodis et al., 2020). This suggests that, whilst a high mean RF is important to early acceleration performance of sprinters, the mean resultant GRF magnitude over the initial steps may also be important from a standing start, which has obvious connotations for team sport players, like rugby backs who do not start from the blocks when sprinting maximally in competition and training.

Utilising four different start conditions, Slawinski et al. (2017) aimed to determine which type of start resulted in better 5 m sprint performances of trained (Tier 2) physical education students who competed in a range of sports, and how these different start conditions altered the GRF characteristics of these participants. Compared to other experimental conditions (parallel, false and jump starts), significantly greater ($p \leq 0.05$) mean RF (35.9 ± 4.0% vs. 20.6 ± 5.5% to 28.4 ± 3.1%) *and* mean total GRF during the start (defined from the instant the rear foot first left the ground to the instant the front foot left the ground) were observed when participants employed a crouched three-point split-stance start, which also led to significantly faster 5 m sprint times. During a single step at the five-metre mark, Bezodis et al. (2017) observed the 10 m sprint times of team sport players were likely quickest during the control condition where RF was also highest compared with the experimental conditions (25.2 ± 2.5% vs. 23.5 ± 3.1% and 23.9 ± 2.2%, $p = 0.02$), but significant differences were *not* observed between maximum or mean resultant GRF magnitudes. These studies highlight the importance of a more horizontally directed GRF vector during initial acceleration, but not necessarily the magnitude of the resultant GRF vector. Despite this research which reinforces the importance of RF and GRF vector orientation to the initial acceleration performance, the significance of these features to the acceleration performance of team sport players during the initial steps is not always supported (e.g., Lockie et al., 2013; Wdowski & Gittoes, 2020).

In soccer players during the first step, Wdowski and Gittoes (2020) found neither the maximum GRF angle or mean resultant GRF angle (37.9 ± 3.9° and 19.7 ± 1.2° respectively) were significantly related to the 5 m times of participants (r = -0.19 [95% CI -0.59 to 0.29], p = 0.22 and r = 0.13 [95% CI -0.35 to 0.55], p = 0.31 respectively). Similarly, the RF and angle of the resultant GRF during the first (46.5 ± 6.7% and 27.8 ± 4.2°), second (48.7 ± 5.5% and 29.2 ± 3.6°) and last contact phase (34.7 ± 8.4% and 20.4 ± 5.2°) in 10 m sprints were not significantly related (r range: RF = -0.22 to 0.08; angle of resultant GRF: -0.37 to -0.11) to 5 m and 10 m sprint times or to the 5-10 m split of team sport players (Lockie et al., 2013). The lack of significant relationships was unexpected given the practically perfect positive relationship observed by Kugler and Janshen (2010) between the angle of the resultant GRF at the instant of maximum GRF application and the magnitude of propulsive impulse during the first step of physical education students. However, Lockie et al. (2013) suggested that the participants in their research had developed a 'suitable' RF for acceleration, resulting from the requirement to frequently complete short sprints in their sport, which was superior to that measured by Kugler and Janshen (2010). For instance, the team sport players (Tier 2; Lockie et al., 2013) produced a greater RF in the first and second steps (by approximately 9 and 11%) compared with the RF of the physical education students (RF in Kugler and Janshen [2010] was estimated by Morin et al. [2011] to be 37.5%). The angles of the resultant GRF during the first and second steps (Lockie at al., 2013) were also greater than the angle of the resultant GRF at the instant of maximum GRF application observed by Kugler and Janshen (2010) in physical education students (Tier 1) by approximately 6 and 7°, respectively. These findings suggest that the magnitude of RF and GRF orientation achieved by athletes, as well as their training status, may influence the contribution of these features to initial acceleration performance.

Although not always clear in the context of team sport players, collectively the research discussed in this section of the literature review suggest that achieving rapid and large propulsive GRF and a high RF are important factors for initial acceleration performance. While the external kinetic determinants of initial acceleration performance are relatively well established in the literature, the aspects of technique adopted by athletes to achieve high initial acceleration performance is less clear. This is likely due to the complex multi-articular nature of sprinting where multiple degrees of freedom (independent components; muscles, joints, body and limb segments) are required to coordinate to yield these favourable GRF characteristics. An understanding of the kinematic features of technique (e.g., spatiotemporal variables, body position and joint kinematics) and joint kinetics during the initial steps, therefore, would provide insights into the movement strategies adopted by athletes, and the relative muscular contributions, to bring about favourable changes to GRF characteristics and thus initial sprint acceleration performance.

2.4 Touchdown and toe-off characteristics and joint kinematic and kinetic research

Body configuration and joint kinematics provide descriptions of an athlete's technique during sprinting. While an accurate description of the movement patterns used during sprinting can be obtained from such data, knowledge of the underlying joint kinetics is required for a more complete understanding of the causes of the movement. In the following section, touchdown and toe-off characteristics and joint kinematic and kinetic research will be discussed during the late swing and stance phases of accelerative sprinting. Attempts to link technique to favourable GRF production as identified above – namely maximising RF and large propulsive GRF – will form the primary focus of the literature reviewed.

2.4.1 Touchdown velocities

The velocity of the foot at touchdown has previously been linked to the GRF application of athletes during initial acceleration (e.g., von Lieres Und Wilkau, 2017), mid-acceleration (e.g., Hunter et al., 2005) and maximum velocity (e.g., Clark et al., 2017) sprint phases and is a function of the hip and knee angular velocities achieved at touchdown For example, studies investigating joint mechanics during the first two steps of a sprint have shown that coupled hip extensor and knee flexor moments are utilised during the late swing phase (e.g. Debaere et al., 2017; Debaere, et al., 2013a) likely to decelerate the limb prior to foot contact, which, in turn, has previously been reported to be a factor which affects braking GRF and impulse magnitudes during acceleration (Hunter et al., 2005; von Lieres Und Wilkau, 2017). Furthermore, a greater angular velocity of the thigh during the late swing phase has been suggested to lead to greater lower limb vertical velocity at touchdown and, in turn, the production of higher mass specific vertical GRF (e.g., Clark et al., 2020). Although findings during maximum velocity sprinting are not necessarily replicated in the initial acceleration phase, it is logical to deduce that the angular velocities of the hip and knee, and their constitutent segments, as well as hip and knee joint moments will directly influence the acceleration of the foot into the ground and consequently the GRF characteristics produced.

Angular velocities at touchdown and late swing joint moment and power peaks for the hip and knee can be found in Tables 2.1 and 2.2 respectively for initial steps of acceleration. Caution should be applied when comparing such data between studies due to differences in methodology, participant ability and the accuracy through which such data can be obtained. Late swing phase hip and knee joint kinematics and kinetics are variable across the literature. In late swing during the initial steps, a hip extensor moment and positive hip power are present as the hip extends into ground contact (Debaere et al., 2013a; Debaere et al., 2017). Hip moments and power peak shortly before contact while hip angular velocity reaches its maximum at the instant of touchdown (Debaere et al., 2013a; Debaere et al., 2017). After the swing leg hip reaches its minimum angle during the late swing phase, the ipsilateral knee begins to extend as a knee flexor moment decelerates the rate of knee extension (energy absorption). During the initial steps the knee has also been shown to continue to extend into ground contact (Debaere et al., 2013a; Debaere et al., 2017). The majority of research investigating hip and knee joint mechanics in the late swing phase during the intial steps has been conducted descriptively and without investigating associations with other technical features of interest, GRF characteristics or acceleration performance.

Only one study has attempted to link hip and knee angular velocity at touchdown with technical features of interest during the initial steps of a sprint. Bezodis et al. (2017) investigated the effects verbal instructions on alterations to the force vector orientation within 18 male team sport players during a step at the 5 m mark of a 10 m sprint. They found in the control condition (where the only instructions given were to “complete the 10 m sprint as quickly as possible”) that athletes produced superior sprint performance (10 m times) compared with the conditions in which additional internal and external cues were given (Bezodis et al., 2017). The enhanced performance was mainly attributed to an increase in RF (control condition = 25.2 ± 2.5%; internal focus condition = 23.5 ± 3.1%; external focus condition = 23.9 ± 2.2%) which was accompanied by a possible or likely change in hip extension angular velocity at touchdown (a greater extension angular velocity was evident in the control condition which produced the highest RF and better [i.e., shorter] 10 m sprint times). However, hip extension angular velocity was not associated with touchdown distance (horizontal distance between the foot and CM at touchdown), foot touchdown velocity or braking force and braking impulse. Furthermore, no significant main effect of the acute interventions was evident on knee angular velocity at touchdown and therefore it is not possible to imply whether any associations may exist between this variable and other technical features of interest (Bezodis et al., 2017). Interestingly, there was a significant main effect on ankle angle and knee angle at touchdown where the ankle and knee joints were more dorsiflexed and flexed at touchdown, respectively. Thus, these touchdown kinematics and greater hip extension angular velocity at touchdown may precede a more horizontally oriented force vector during the stance phase in the initial sprint steps.

Due to the scarcity of research investigating joint mechanics during the late swing and at touchdown and their associations with potentially important technical aspects during initial sprint acceleration, it is not clear whether achieving high hip and knee extension velocities at the instant of touchdown are advantageous to sprint performance. More cross-sectional comparisons would be necessary to determine whether such relationships are apparent. Nor is it possible to ascertain fully how hip and knee angular velocities during the late swing phase and at touchdown influence the touchdown velocity of the foot during the initial acceleration phase.

Table 2.1. Late swing hip extensor moment and hip positive power peaks, and peak hip extension angular velocity at the instant of touchdown across a number of different steps and distances within initial sprint acceleration. Standard deviations are absent where precise values have not been reported in the original source. Mean data for participants are presented.

Step number	Distance (to nearest m)	Source	Athlete status	Peak hip extensor moment (Nm)	Peak hip power (W)	Hip extension angular velocity (°/s)
1	-	Debaere et al. (2013)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	220 ± 9	2000	600
1	-	Debaere et al. (2017)	43 developmental (Tier 2) male and female sprinters ranked within the top 20 nationally of their age category (11 under 16 and 18 under 18 age groups and 14 adults)	294 ± 8	2590 ± 75	-
1	-	Charalambous et al. (2012)	1 elite (Tier 4) sprint hurdler (PB 110m hurdles = 13.48)	-	-	184
1	-	Bezodis et al. (2014)	3 elite (Tier 4) sprinters (2 males, PB 100 m = 10.14 and 10.28 s; 1 female, PB 100 m hurdles = 12.72 s)	-	-	644
2	-	Debaere et al. (2013)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	286 ± 1	2328	600
2	-	Debaere et al. (2017)	43 developmental (Tier 2) male and female sprinters ranked within the top 20 nationally of their age category (11 under 16 and 18 under 18 age groups and 14 adults)	321 ± 5	-	-
-	5 m	Bezodis et al. (2017)	18 trained (Tier 2) team sport players (Gaelic football, rugby union, soccer)	-	-	474 ± 111

Table 2.2. Late swing phase knee moment and power peaks and touchdown extension angular velocity, during different steps and distances within a sprint. Standard deviations are absent where precise values have not been reported in the original source. Mean data for participants are presented.

Step number	Distance (to nearest m)	Source	Athlete status	Peak knee extension angular velocity (°/s)	Knee extension angular velocity at touchdown (°/s)	Peak knee flexor moment (Nm)	Peak negative knee power (W)
1	-	Debaere et al. (2013)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	460	400	93 ± 3	665
1	-	Debaere et al. (2017)	43 developmental (Tier 2) male and female sprinters ranked within the top 20 nationally of their age category (11 under 16 and 18 under 18 age groups and 14 adults)	-	-	100 ± 4	700 ± 37
1	-	Charalambous et al. (2012)	1 elite (Tier 4) sprint hurdler (PB 110m hurdles = 13.48)	-	80	-	-
1	-	Bezodis et al. (2014)	3 elite (Tier 4) sprinters (2 males, PB 100 m = 10.14 and 10.28 s; 1 female, PB 100 m hurdles = 12.72 s)	-	-	-	480
2	-	Debaere et al. (2013)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	570	285	120 ± 1	665
2	-	Debaere et al. (2017)	43 developmental (Tier 2) male and female sprinters ranked within the top 20 nationally of their age category (11 under 16 and 18 under 18 age groups and 14 adults)	-	-	113 ± 3	-
-	5 m	Bezodis et al. (2017)	18 trained (Tier 2) team sport players (Gaelic football, rugby union, soccer)	-	66 ± 130	-	-

Minimising the forward horizontal velocity of the foot (foot touchdown velocity) immediately before contact has previously been reported to be a factor which affects braking GRF and impulse magnitudes during acceleration (Hunter et al., 2005; von Lieres Und Wilkau, 2017). However, the effect of foot touchdown velocity on propulsive GRF characteristics is not typically considered, and only a limited number of studies have investigated foot touchdown velocity during the initial steps.

During the first post-block step, Bezodis et al. (2014) measured the foot touchdown velocities of three elite (Tier 4) sprint athletes (males: n = 2, mass 82.6 and 86.9 kg, 100 m PB 10.14 and 10.28 s; female: mass 60.5 kg, 100 m hurdle PB 12.72 s). They observed foot touchdown velocity to increase concurrently with maximum braking force magnitude in the three participants during the first step (0.003 ± 0.178; 0.779 ± 0.132 and 2.293 ± 1.506; data were normalised to dimensionless numbers by dividing values by $[\text{gravity/leg length}]^{½}$). However, a pattern was not observed between foot touchdown velocity and maximum propulsive GRF or average horizontal external power (Bezodis et al., 2014). During the first stance phase of World Class (Tier 5) sprinters (mean ± SD: 60 m PB 6.51 ± 0.01 s; mass not obtained) foot touchdown velocities of 0.24 ± 0.86 m/s were observed and, although the relationship between this technical feature and GRF characteristics were not investigated, a small statistically insignificant relationship (r = 0.15) was found between foot touchdown velocity and NAHEP (Walker et al., 2021). By the third step the braking impulse magnitudes of ten trained (Tier 3) sprinters (mean ± SD: mass 75.1 ± 3.4 kg, 100 m PB: 10.85 ± 0.30 s) produced by accelerations at the foot-floor interface, von Lieres Und Wilkau et al. (2017) showed foot touchdown velocity to be 0.57 ± 0.91 m/s, generating 143 ± 72% of the total relative braking impulse.

Whilst foot touchdown velocity may be related to the braking horizontal GRF of sprinters, its correlation to the propulsive GRF is not clear. In a mix of team sport players and track & field athletes (Tier 1 to Tier 3), Morin and colleagues (2015b) found backwards horizontal velocity (5.27 ± 0.77 m/s) of the foot relative to the ipsilateral greater trochanter just before initial foot-ground contact was not related to the net propulsive GRF of 14 males familiar with sprint running during six second sprints on an instrumented motorised treadmill. They suggested that the efficacy of a common desired technical outcome to “paw back” the foot just prior to ground contact with the aim of generating a greater backwards pushing action (i.e., a higher horizontal GRF) during ground contact is therefore in question. Collectively, these findings suggest that reducing foot touchdown velocity is likely to reduce the braking effects during the early stance phase but given the previously discussed lack of an association between braking GRF and performance during early acceleration (Section 2.2.1) there is no evidence to suggest that foot touchdown velocity plays a significant role in the enhancement of initial acceleration performance. This may be due to the phase of the ground contacts during the initial steps which are more important to acceleration performance. For example, an increase in the vertical velocity of the foot at touchdown has been linked to the ability to produce higher vertical GRF early in the stance phase during maximum velocity sprinting – a key determinant of performance in that sprint phase (Clark et al., 2017). However, the initial steps of acceleration have been shown to be more associated with horizontal GRF production during the mid-late propulsion of stance rather than that produced early in the stance phase (e.g., Colyer et al., 2018). Therefore, the kinematic aspects of technique and athletes' internal joint kinetic features from touchdown onwards during the stance phase may be more influential to their initial acceleration performance than the mechanics used during the late swing phase to optimise foot-ground interaction.

2.4.2 Touchdown distance

Hip and knee angular velocities and moments, and foot touchdown velocity, will likely affect where the foot is placed at the start of the contact phase. The horizontal distance between the foot and the CM at the instant of touchdown is known as touchdown distance (Figure 2.1) – a technical feature which has received attention in the scientific (e.g., Bezodis et al., 2015; Mero et al., 1983; Nagahara et al., 2014a) and coaching (e.g., Mann, 2015) sprint acceleration biomechanics literature. From a block start in highly trained (Tier 3) sprinters, Mero et al. (1983) found the CM to be ahead of the point of contact (negative touchdown distance) by 0.13 (± 0.06) m which decreased to 0.04 (± 0.05) m during the second contact phase. At the beginning of the third phase the CM was already behind the point of contact (positive touchdown distance) by 0.05 (± 0.04) m. The CM has also been shown to progressively move further back relative to the foot with each successive step during the initial acceleration of 12 trained (Tier 2) sprinters (mean ± SD: mass 68.1 ± 4.2 kg; 100 m PB 10.71 ± 0.33 s; Nagahara et al., 2014a). During the first three contacts, Mann (2015) identified proficient sprinters as those who touch down with their foot behind the whole-body centre of mass. This technical feature has previously been linked to the orientation of the GRF vector during the first step of an elite (Tier 4) sprinter (Bezodis et al., 2105) and recreationally active (Tier 1) physical education students (Kugler & Janshen, 2010), and therefore may be of interest to coaches.

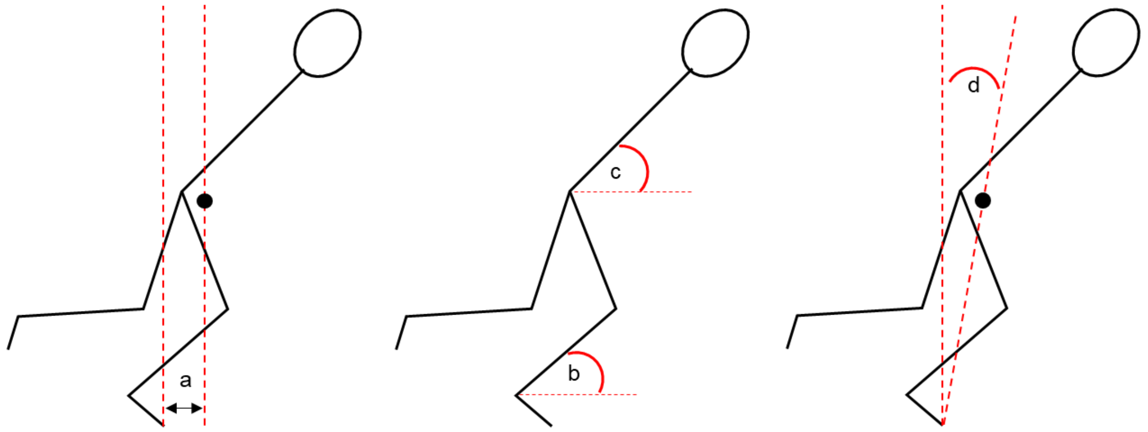

Figure 2.1. Selected kinematic aspects of technique at touchdown

a, touchdown distance; b and c, shank and trunk angles; d, centre of mass angle
The black markers (circles) depict the whole-body centre of mass location

Upon touchdown, sprinters have been observed to rotate the CM forward of the point of contact during the second stance phase prior to extending the contact leg (Jacobs & van Ingen Schenau, 1992). Foot placement behind the CM upon touchdown seems appealing therefore since it would likely reduce the amount of time before the athlete starts producing leg extension. Furthermore, it may also facilitate a greater shank angle (proximal end of the shank rotated more towards the direction of sprinting) during the initial acceleration phase which, in tandem with a similar trunk angle, is a technique deemed desirable by coaches (Goodwin et al., 2018). A depiction of shank and trunk orientations are shown in Figure 2.1. Producing this technique will enable an athlete to direct their CM more horizontally during the stance phase when extending the stance leg. This premise is partially supported by the observation of Kugler and Janshen (2010) who noted that the higher propulsive impulses and greater CM angles (Figure 2.1) produced later in stance by faster participants during the first step from rolling start were facilitated by a greater CM angle at touchdown (i.e., the foot was placed further back in relation to the CM at touchdown; Kugler & Janshen, 2010). However, a small statistically insignificant relationship (r = -0.24) was observed between the touchdown distance of world class sprinters (-0.12 ± 0.06 m) and the magnitude of NAHEP produced during the first stance phase (Walker et al., 2021). At a group level, therefore, it is not possible to determine whether touchdown distance is meaningfully related to initial acceleration performance.

Foot placement too far behind the CM during the initial steps of a sprint may not be favourable. For example, a study using a computer simulation model to investigate the effects of touchdown distance on performance (external power) of an elite (tier 4) sprinter (mass 86.9 kg; 100m PB 10.28 s) during the first stance revealed a curvilinear relationship between these variables (Bezodis et al., 2015). That is, when positioning the foot slightly further behind the CM, performance was improved due to favourable horizontal force production. However, continuing to increase this distance between the foot and CM (> 0.09 m) led to decreased performance due to an inability to generate sufficient force. Additionally, a linear relationship was observed between touchdown distance and vertical impulse production. Vertical impulse production increased as the foot was placed less far behind the CM at touchdown and decreased the when the foot was further behind the CM (Bezodis et al., 2015). Limiting how far posterior the foot makes contact relative to the CM may therefore be important in producing a sufficient vertical GRF necessary to maintain balance. Consequently, it would seem possible that a favourable touchdown distance exists which is idiosyncratic to each individual based on their technical and strength abilities, musculoskeletal structure and how advanced through the acceleration phase they are. Furthermore, in an investigation of team sport players, Bezodis et al. (2017) found that an increase in the RF at 5 m (following a standing start) was associated with different stance leg joint kinematics, but not with the overall touchdown distance and that the ratio of force could be manipulated without a change in touchdown distance.

2.4.4 Hip joint kinematics and kinetics during ground contact

Achieving a high angular velocity of the hip during stance has been theorised as important to maximising propulsive GRF during sprinting (Mann & Sprague, 1983; Mann et al., 1984; Wiemann & Tidow, 1995). The data presented in Tables 2.3 and 2.4 detail a number of the hip joint kinematic and kinetic measures obtained from the literature during the stance phase of initial acceleration. The hip extends throughout the initial steps (Charalambous et al., 2012; Debaere et al., 2013a; Debaere et al., 2017; Jacobs & van Ingen Schenau, 1992) although in some participants the hip has been shown to flex just prior to toe-off (e.g., Brazil et al., 2017). Peak joint angular velocities and timings however appear to differ across the literature (Table 2.3) which may be indicative of technical differences between individuals and/or methods used to determine these angular velocities.

Despite hip extension velocities during stance being theorised as important to maximising propulsive GRF and therefore potentially propulsive impulse, few studies have investigated associations between hip angular velocity and propulsive GRF characteristics. In the first step of world class (Tier 5) sprinters, Walker et al. (2021) found a trivial, statistically insigificant relationship (r = 0.07) between maximum hip angular velocity during the first stance phase (202 ± 41°/s) and the magnitude of NAHEP. Only two studies to the author's knowledge have investigated the hip angular velocities of team sport players during acceleration (Hunter et al., 2005; Murphy et al., 2003). Hunter et al. (2005) observed no association between peak hip angular velocity and propulsive impulse at the 16 m mark in 28 trained (Tier 3) athletes from a mix of track & field and team sports (mean ± SD: mass 74 ± 6 kg). They did find however that mean hip extension velocity was significantly different (p < 0.05) between 'high propulsion' (570 ± 61°/s) and 'low propulsion' (558 ± 58°/s) trials (Hunter et al., 2005). However, given these data were obtained during the mid-acceleration phase the findings can not be generalised to the initial steps and in Murphy et al. (2003), no significant differences were observed between the mean hip extension velocities of the 'fast' (step 1: 225 ± 37°/s; step 3: 233 ± 57°/s) and 'slow' (step 1: 241 ± 37°/s; step 3: 239 ± 54°/s) groups of team sport players studied (n = 20; mass 82.6 ± 13.1 kg; no information on participant sporting ability were provided). Nonetheless, acceleration performance was measured as the horizontal velocity of the hip at the instant of toe-off at the beginning of the third step by Murphy et al. (2003) and does not account for the time taken to reach this point or the distance at which the velocity measure is taken. Therefore, limited information exists on the associations of mean hip extension velocity during stance and initial acceleration performance, especially in team sports players, and further investigation is warranted.

In all sprint phases, a net extensor moment is present at the hip at touchdown and the magnitude of this has been suggested to be important to acceleration performance (e.g., Johnson & Buckley, 2001). During initial acceleration this is supported by the work of Schache et al. (2019) who observed that the sprint performance during the first or second step of eight participants (three were female) was strongly related (r = 0.67, p < 0.01) to the impulses (integral over time) of their hip extensor moments which explained 45% of the magnitude of forward acceleration achieved. No indication of the athletes' ability was provided, but the researchers referred to them as 'sub-elite' track & field athletes. The hip has also been shown to generate 37 to 54% (Brazil et al., 2017; Debaere et al., 2013a) and 35% (Jacobs & van Ingen Schenau, 1992) of the sum of all lower limb joint powers exhibited by sprinters during the first and second stance phase, respectively. Furthermore, the hip extensor muscles have been identified as likely important contributors to horizontal GRF and sprint acceleration performance during early acceleration (Morin et al., 2015b; Pandy et al., 2021). Collectively, these findings suggest that the ability to produce large hip extensor moments and powers appear to be important for acceleration performance during the initial steps.

Interestingly, Debaere et al. (2015) found, in their torque-driven simulation of seven (five females) trained (Tier 2) sprinters (mean ± SD: mass 59.7 ± 9.9 kg, 100 m PB 11.97 ± 0.42) that the hip extensor moment contribution to horizontal acceleration of the CM during the first step from a block start was only 10.3% (biceps femoris 5.4%, gluteus medius 5.6%) and noticeably less than the contribution of the plantarflexors (67.1%). By the second step, no contribution of the hip extensors to horizontal acceleration was evident, while the plantarflexors contributed 93% to the horizontal acceleration observed (Debaere et al., 2015). These results seem surprising and given the strong association between the extensor moment impulses of the hip and forward acceleration magnitude (Schache et al., 2019) and of the hip extensors with horizontal GRF production during acceleration (Morin et al., 2015b). The reasons for the inconsistency in these results is not clear, although it is possible that the reduced contribution of the hip extensor moment to CM horizontal acceleration observed by Debaere et al. (2015) may be due to inaccuracies resulting from modelling assumptions when using an inverse dynamics approach (Faber et al., 2018). However, the ankle plantarflexor joint kinetics have typically been shown to contribute more substantially to initial acceleration performance compared with the hip extensor joint kinetics (e.g., Charalambous et al., 2011; Debaere et al., 2015; Schache et al., 2019).

Whilst the ankle joint may contribute the most to acceleration performance during the initial steps, the hip extensor moments may contribute substantially to CM acceleration specifically during the early portion of the stance phase. Higher peak hip extensor moments compared with peak plantarflexor moments have typically been observed during the early stance phase (approximately ≤ 20% of stance) in early acceleration (e.g., Bezodis et al., 2014; Charalambous et al., 2012;

Debaere et al., 2017; Debaere et al., 2013a; Jacobs & van Ingen Schenau, 1992; Schache et al., 2019). Furthermore, the hip joint is in an advantageous position to accelerate the CM in the early stance phase during the initial steps given its distance from the GRF vector and the forward inclination of the trunk. For example, Schache et al. (2019) proposed that the positive work produced by the hip (30% of total lower limb positive work) during the first or second step was likely due to the increased hip extensor load during the early stance where the forward inclination of the trunk was shown to be approximately 63° (with respect to the vertical). They suggested that with this orientation of the trunk, the GRF vector was positioned anterior to the hip joint during early stance which, in turn, increased the capacity of the hip joint to contribute to forward propulsion (Schache et al., 2019).

An induced acceleration analysis approach was used by Veloso et al. (2015) to identify the contribution of the lower limb joint moments and muscles to the horizontal and vertical acceleration of the CM during the first step of an elite (Tier 4) sprinter from a block start (Veloso et al., 2015). They observed that the hip extensor moments produced during the first quarter of the stance phase exhibited the greatest contribution to horizontal and vertical acceleration (compared with knee and ankle joint moments), resulting from considerable force produced by the hip extensors. However, this contribution is only realised with an effectively functioning ankle joint, whereby the plantarflexor moments counteract those produced by the hip extensors, thus providing a stable position with regards to the foot to ground interface, so that the hip extensors can generate horizontal acceleration of the CM (Veloso et al., 2015). The synergistic interplay between the hip and ankle joint during the stance phase of sprinting, which has also been highlighted previously at higher running velocities (Dorn et al., 2012), will be discussed later in this section of the literature review.

By toe-off, the hip joint moment has changed to flexor dominance to absorb energy and reduce the rate of extension at the hip joint before terminating ground contact. The time at which the dominance switches from extensor to flexor takes place is not consistent (Table 2.4). Whilst this could be influenced by the methods used and the accuracy with which these data can be determined using current inverse dynamics analyses (and the propagation of errors as the analysis progresses up the leg), it may be due to individual ability and differences in technique between the studied athletes. For example, since step rate is the inverse of step time, terminating the ground contact phase sooner may be a characteristic of athletes who produce greater step rates.

Alternatively, athletes with strong hip extensors capable of producing more powerful hip extension contractions may require an earlier switch to flexor dominance in order to prevent the duration of the stance phase increasing. Although hip extensor strength of the three sprinters in the study of Bezodis et al. (2014) was not measured, the switch from net extensor to flexor moment appeared to take place sooner in the hips of the two better performing athletes compared to the slowest (approximately 75 vs. 85%). Interestingly, the fastest sprinter performed greater negative work at the hip joint (Bezodis et al., 2014) suggesting that the strategy of limiting the rate of hip extension to arrest ground contact may be important to early acceleration performance.

Table 2.3. Select hip joint kinematic variables during ground contact. Standard deviations are absent where precise values have not been reported in the original source. Mean data for participants are presented.

Step number	Source	Athlete status	Hip angle at touchdown (°)	Hip range of motion (°; extension)	Peak hip angular velocity (°/s; extension)	Timing of peak hip angular velocity (extension)
1	Debaere et al. (2013a)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	121.2 ± 11.3	40	515	Beginning of stance
1	Charalambous et al. (2012)	1 elite (Tier 4) sprint hurdler. PB 110m hurdles = 13.48	90	-	229 ± 11.5	70% stance
1	Bezodis et al. (2014)	3 elite (Tier 4) sprinters (2 males, PB 100 m = 10.14 and 10.28 s; 1 female, PB 100 m hurdles = 12.72 s)	90	80	200[a]	75% stance
1	Walker et al. (2021)	8 world class (Tier 5) sprinters (data collected during a 60 m race = 6.51 ± 0.10 s)	-	-	202 ± 0.10 s	-
1	Brazil et al. (2017)	10 well trained (Tier 3) to elite (Tier 4) sprinters (PB 100m = 10.50 ± 0.27 s)	-	-	160[a]	Beginning of stance
1 or 2[b]	Schache et al. (2019)	8 track & field athletes (5 male, 3 females; no ability levels indicated)	65	60	-	-
2	Jacobs & van Ingen Schenau (1992)	7 trained (Tier 3) sprinters (mean PB 100m = 10.60 s)	99.1 ± 3.4	74	686 ± 20.6	79% of stance
2	Debaere et al. (2013a)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	124.4 ± 11.3	55	573	Beginning of stance

[a]angular velocity data were normalised by dividing the value by (gravity / leg length)½

[b]data were collected during the step in which forward acceleration magnitude was greatest

Table 2.4. Select hip joint kinetic variables during ground contact. Standard deviations are absent where precise values have not been reported in the original source. Mean data for participants are presented.

Step number	Source	Athlete status	Peak hip extensor moment	Peak hip flexor moment	Timing of switch from hip extensor to hip flexor moment	Peak hip power generation	Peak hip negative power
1	Debaere et al. (2013a)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	165 Nm 2.5 Nm/kg	279 Nm 4.1 Nm/kg	25% of stance	1663 W 24.5 W/kg	1330 W 19.6 W/kg
1	Veloso et al. (2015)	1 male elite (Tier 4) sprinter (100m PB 10.21)	335 Nm 4.2 Nm/kg	80 Nm 1.1 Nm/kg	80% of stance	-	-
1	Charalambous et al. (2012)	1 elite (Tier 4) sprint hurdler (PB 110m hurdles = 13.48)	200 Nm 2.6 Nm/kg	250 Nm 3.3 Nm/kg	70% of stance	1400 W 18.6 W/kg	1450 W 19.5 W/kg
1	Bezodis et al. (2014)	3 elite (Tier 4) sprinters (2 males, PB 100 m = 10.14 and 10.28 s; 1 female, PB 100 m hurdles = 12.72 s)	Range: 0.273 to 0.359[a]	Range: 0.297 to 0.432[a]	Range: 75 to 85% of stance	Range: 0.842 to 1.450[b]	Range: 0.474 to 0.870[b]
1	Brazil et al. (2017)	10 well trained (Tier 3) to elite (Tier 4) sprinters (PB 100m = 10.50 ± 0.27 s)	0.330 ± 0.071[a]	0.400[a]	65% of stance	0.908 ± 0.185[b]	0.740 ± 0.257[b]
1 or 2[c]	Schache et al. (2019)	8 track & field athletes (5 male, 3 females; no ability levels indicated)	155 ± 4.0 Nm 2.3 ± 0.1 Nm/kg	198 ± 6.3 Nm 2.8 ± 0.1 Nm/kg	65% of stance	987W 13.7 W/kg	845 W 12.0 W/kg
2	Jacobs & van Ingen Schenau (1992)	7 trained (Tier 3) sprinters (mean PB 100m = 10.60 s)	233 Nm 3.0 Nm/kg	233 Nm 3.0 Nm/kg	70% of stance	1556 W 19.6 W/kg	1556 W 19.6 W/kg
2	Debaere et al. (2013a)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	230 Nm 3.4 Nm/kg	133 Nm 2.0 Nm/kg	80% of stance	1330 W 19.6 W/kg	1330 W 19.6 W/kg

[a]moment data were normalised by dividing the value by (weight x leg length)

[b]power data were normalised by dividing the value by (body mass x gravity$^{3/2}$ x leg length$^{1/2}$)

[c]data were collected during the step in which forward acceleration magnitude was greatest

2.4.5 Knee joint kinematics and kinetics during ground contact

The data presented in Tables 2.5 and 2.6 detail a number of the knee joint kinematic and kinetic measures obtained from the available literature during the stance phase of early acceleration. The knee typically continues to extend upon touchdown whilst a net flexor moment during the first few milliseconds is observed (Bezodis et al., 2014; Brazil et al., 2017; Charalambous et al., 2012; Debaere et al., 2017; Debaere et al., 2013a; Jacobs & van Ingen Schenau, 1992). An extensor moment then dominates for the remainder of stance and in some cases the stance knee has been shown to flex slightly just prior to toe-off (Charalambous et al., 2012; Brazil et al., 2017; Jacobs & van Ingen Schenau (1992). The net work done by the knee extensors of sprinters explained a significantly large amount (42%) of the variance in their forwards acceleration magnitude during the first or second step (Schache et al., 2019). However, a trivial and statistically insignificant relationship (r = 0.01, p = 0.74) between the impulses (integral over time) of their knee extensor moments and their forwards acceleration magnitudes were observed (Schache et al., 2019), suggesting that the ability to produce a large knee extension range of motion, rather than the ability to produce large knee extensor moments may be more important for initial acceleration performance.

Bezodis et al. (2014) proposed that the knee has an important role in the generation of positive power, and thus acceleration of a sprinter, in the first step. The potential importance of knee power generation during the initial steps of a sprint would be supported by the high knee positive powers evident in a number of other early acceleration studies (e.g., Charalambous et al., 2012; Debaere et al., 2013a). Interestingly, Bezodis et al. (2014) observed the better performing sprinter to generate 363 and 188% more energy at the knee than the second fastest and slowest athletes respectively. This was due to both an earlier rise in the resultant knee joint moment and a higher peak. The better performing athlete was able to generate knee extensor resultant moments from the instant of touchdown and the researchers suggest that this ability may have been facilitated by the sprinter's lower foot touchdown velocity (Bezodis et al. 2014). Their touchdown technique may therefore have contributed to the decreased peak braking and greater propulsive GRF they produced and ultimately the highest average horizontal external power (Bezodis et al., 2014).

Debaere et al. (2013a) reported the contribution of the knee to maximum power to be substantial in the first step (31%), but small in the second (9%). They attributed this to the more upright position adopted during the second step, where the knee will contribute more to upwards velocity of the CM, whereas the more forward leaning position in the first results in greater contribution of the knee joint to horizontal acceleration (Debaere et al., 2013a). This finding highlights potential differences in the mechanics required during block starts and standing starts where a more upright position is adopted during the latter task. This difference is therefore of interest to team sport players who are required to start in this more upright position when they accelerate.

Table 2.5. Select knee joint kinematic variables during ground contact. Standard deviations are absent where precise values have not been reported in the original source. Mean data for participants are presented.

Step number	Source	Athlete status	Knee angle at touchdown (°)	Movement pattern of knee	Peak knee angular velocity (extension; °/s)	Timing of peak knee angular velocity (extension)
1	Debaere et al. (2013a)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	111.6 ± 9.1	Extension throughout	515	75% of stance
1	Charalambous et al. (2012)	1 elite (Tier 4) sprint hurdler. PB 110m hurdles = 13.48	115	Extension with slight flexion taking place at 95% stance	189 ± 5.7	75% of stance
1	Bezodis et al. (2014)	3 elite (Tier 4) sprinters (2 males, PB 100 m = 10.14 and 10.28 s; 1 female, PB 100 m hurdles = 12.72 s)	Range: 90 to 100	Extension throughout	200[a]	Range: from the instant of touchdown and between 75 to 90% of stance
1	Brazil et al. (2017)	10 well trained (Tier 3) to elite (Tier 4) sprinters (PB 100m = 10.50 ± 0.27 s)	-	Extension with flexion taking place at 80% stance	150[a]	75% stance
1 or 2[b]	Schache et al. (2019)	8 track & field athletes (5 male, 3 females; no ability levels indicated)	62	Extension throughout	-	-
2	Jacobs & van Ingen Schenau (1992)	7 trained (Tier 3) sprinters (mean PB 100m = 10.60 s)	111.7 ± 1.7	Extension with slight flexion just prior to toe-off	548 ± 27.5	81% of stance
2	Debaere et al. (2013a)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	115.6 ± 6.2	Extension throughout	570	80% of stance

[a]angular velocity data were normalised by dividing the value by (gravity / leg length)$^{1/2}$
[b]data were collected during the step in which forward acceleration magnitude was greatest

Table 2.6. Select knee joint kinetic variables during ground contact. Standard deviations are absent where precise values have not been reported in the original source. Mean data for participants are presented.

Step number	Source	Athlete status	Peak knee extensor moment	Peak knee flexor moment	Knee moment pattern	Timing of switch between knee flexor and extensor moments	Peak negative power	Peak power generation
1	Debaere et al. (2013a)	21 trained (Tier 3) sprinters (11 males, PB 100 m = 10.62 s; 10 females, PB 100 m = 11.89 s)	166 Nm 2.5 Nm/kg	67 Nm 1.0 Nm/kg	Flexor - extensor – flexor	Highly varied	665 W 9.8 W/kg	1330 W 19.6 W/kg
1	Charalambous et al. (2012)	1 elite (Tier 4) sprint hurdler. PB 110m hurdles = 13.48	100 Nm 1.4 Nm/kg	25 Nm 3.3 Nm/kg	Flexor - extensor - flexor - extensor – flexor	-	-	300 W 4.0 W/kg
1	Bezodis et al. (2014)	3 elite (Tier 4) sprinters (2 males, PB 100 m = 10.14 and 10.28 s; 1 female, PB 100 m hurdles = 12.72 s)	Range: 0.087 to 0.216[a]	0.075[a]	Flexor - extensor – flexor	Highly varied	Range: 0.000 to 0.362[b]	Range: 0.148 to 0.422[b]
1	Brazil et al. (2017)	10 well trained (Tier 3) to elite (Tier 4) sprinters (PB 100 m = 10.50 ± 0.27 s)	0.242 ± 0.068[a]	0.1500[a]	Flexor - extensor	10% of stance	0.150[b]	0.468 ± 0.145[b]
1 or 2[c]	Schache et al. (2019)	8 track & field athletes (5 male, 3 females; no ability levels indicated)	115 ± 5 Nm 1.7 ± 0.1 Nm/kg	99 Nm 1.4 Nm/kg	Flexor – extensor - flexor	< 5% then 75%	280 W 3.8 W/kg	560 W 8.0 W/kg
2	Jacobs & van Ingen Schenau (1992)	7 trained (Tier 3) sprinters (mean PB 100 m = 10.60 s)	140 ± 55 Nm 1.8 ± 0.7 Nm/kg	92 Nm 1.2 Nm/kg	Flexor – extensor	10% of stance	622 W 8.5 W/kg	705 ± 59 W 9.0 ± 0.8 W/kg
2	Debaere et al. (2013a)	21 trained (Tier 3) sprinters (11 males, PB 100 m = 10.62 s; 10 females, PB 100 m = 11.89 s)	100 Nm 1.5 Nm/kg	67 Nm 1.0 Nm/kg	Flexor - extensor – flexor	Highly varied	166 W 2.5 W/kg	665 W 9.8 W/kg

[a]moment data were normalised by dividing the value by (weight x leg length)
[b]power data were normalised by dividing the value by (body mass x gravity$^{3/2}$ x leg length$^{1/2}$)
[c]data were collected during the step in which forward acceleration magnitude was greatest

2.4.6 Ankle joint kinematics and kinetics during ground contact

The data presented in Tables 2.7 and 2.8 detail a number of the ankle joint kinematic and kinetic measures obtained from the literature during the stance phase of initial sprint acceleration. During all steps within a sprint, the ankle initially dorsiflexes after touchdown, before plantarflexing for the remainder of stance. This 'switch' from dorsiflexion to plantarflexion is variable across the literature over the first two steps ranging from 30 to 50% of stance (Table 2.7) while the muscles surrounding the ankle joint create a plantarflexor moment for all steps within a sprint. Following touchdown, this resultant joint moment helps to reduce the negative vertical velocity of the body through energy absorption about the ankle for approximately 30% of stance during early acceleration (Charalambous et al., 2012; Debaere et al., 2013a). Once this has been achieved and the dorsiflexion has ceased, the plantarflexor moment then serves to generate energy (Table 2.8) for the remainder of the stance phase to plantarflex the ankle joint and help propel the body into the subsequent flight phase. During initial acceleration, the total work due to energy absorption at the ankle joint during early stance is less than the subsequent work done by almost a factor of 3 (Debaere et al., 2013a).

The role of the ankle has been shown to be crucial for high initial acceleration performance. For instance, Bezodis et al. (2014) noted that the better performer in their study generated more ankle energy (0.223 ± 0.213 [work data were divided by weight × leg length]) during the second half of stance than the second fastest (0.175 ± 0.156) and slowest athlete (0.163 ± 0.138). Debaere et al. (2015) observed the ankle plantarflexor moments produced by to be the main contributor to horizontal acceleration during the first (67.1%) and second (92.9%) steps. Compared with the hip and knee, the amount of work done by the plantarflexors of sprinters studied by Schache et al. (2019) during the first or second step was 40 and 58% greater, respectively, and a very large relationship between the net work done by the ankle and forward acceleration magnitude was observed ($r = 0.80$, $p < 0.01$). Furthermore, both peak plantarflexor moments and the impulses (integral over time) of the positive portion of the plantarflexor moments were 30 and 49%, and 53 and 58%, greater than those produced by the hip and knee, respectively. The plantarflexor moment impulses were also highly and significantly related to acceleration magnitude in the first or second step ($r = 0.69$, $p = < 0.01$). The researchers surmised that the hip and, more so, the ankle are key to the positive work produced to achieve high forward acceleration magnitudes (Schache et al., 2019).

Although the ankle joint appears to contribute considerably to horizontal acceleration during the initial steps as a result of its capacity to generate high amounts of energy during the latter two thirds of the stance phase, its function during the initial third of stance, whilst absorbing energy, may also play an important role. As alluded to earlier within this literature review, the ankle works synergistically with the hip during the initial steps of a sprint. During the early portion of the stance phase, the hip extensor moment acts to accelerate the ipsilateral heel towards the ground as the ankle begins to dorsiflex. The plantarflexor moment produced to oppose the hip extensor moment serves to stabilise the ankle joint, thus providing a foundation from which the hip extensors are able to accelerate the CM (Veloso et al., 2015). The ability of the ankle joint to attenuate the degree of dorsiflexion during this early stance phase may therefore be a technique worthy of consideration since a greater proportion of force produced by the hip extensors is likely to be transmitted to the ground. This supposition is supported by Bezodis et al. (2015) who demonstrated that reducing dorsiflexion during the early stance phase of the first step appeared potentially beneficial for improving acceleration performance during the first step. They observed, through simulation, that when the amount of ankle dorsiflexion was reduced during the early stance phase, average horizontal power increased exponentially. The increased power was shown to derive from both a shorter contact time and an increase in net horizontal impulse (Bezodis et al., 2015). Reducing the amount of dorsiflexion during ground contact likely requires a greater level of ankle stiffness.

Charalambous et al. (2012) found increases in ankle joint stiffness during the negative (ankle power absorption) phase of ground contact in the first step (28.33 ± 2.57 Nm/°) of an international hurdler to be related to take-off CM horizontal velocity ($r = 0.74$, $p = 0.02$). No correlation was found however between ankle stiffness during the whole contact (5.93 ± 0.75 Nm/°) and 5 m sprint time, although during the positive (ankle power generating) phase of contact it was reported to relate to greater take-off CM vertical velocity ($r = 0.85$, $p = 0.01$). It was suggested that the push-off at the end of the first contact following block exit requires a greater increase in vertical CM position than later sprint phases (acceleration and maximum velocity), so increased ankle stiffness may have an important role to play (Charalambous et al., 2012). Further research is required to ascertain the favourable amount of ankle stiffness necessary for an individual to elicit the required vertical displacement while maximising horizontal velocity during acceleration. However, the ability to attenuate the degree of dorsiflexion during the early stance phase may be a technique (and a physical quality) of interest for coaches working to enhance the initial sprint acceleration capabilities of rugby players.

Table 2.7. Select ankle joint kinematic variables during ground contact. Standard deviations are absent where precise values have not been reported in the original source. Mean data for participants are presented.

Step number	Source	Athlete status	Ankle angle at touchdown (°)	Degree of ankle dorsiflexion and plantarflexion[a] (°)	Timing of transition from ankle dorsiflexion to plantarflexion[b]	Peak ankle angular velocity (°/s; plantarflexion)	Timing of peak ankle angular velocity (plantarflexion)
1	Debaere et al. (2013a)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	70.6 ± 5.8	-15 +55	30% stance	1088	90% of stance
1	Charalambous et al. (2012)	1 elite (Tier 4) sprint hurdler. PB 110m hurdles = 13.48	105	-10 +37	40% stance	320	90% of stance
1	Bezodis et al. (2014)	3 elite (Tier 4) sprinters (2 males, PB 100 m = 10.14 and 10.28 s; 1 female, PB 100 m hurdles = 12.72 s)	Range: 100 to 115	-15 +50	50% stance	Range: 300 to 400[c]	90% of stance
1	Brazil et al. (2017)	10 well trained (Tier 3) to elite (Tier 4) sprinters (PB 100m = 10.50 ± 0.27 s)	-	-	50% stance	300[c]	90% stance
1 or 2[d]	Schache et al. (2019)	8 track & field athletes (5 male, 3 females; no ability levels indicated)	101	-14 +56	50% stance	-	-
2	Jacobs & van Ingen Schenau (1992)	7 trained (Tier 3) sprinters (mean PB 100m = 10.60 s)	80.2 ± 2.9	-15 +58	30% stance	1232 ± 42	93% of stance
2	Debaere et al. (2013a)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	72.4 ± 7.1	-15 +50	30% stance	1146	Just prior to toe-off

[a]Values are split into the initial dorsiflexion magnitude and the subsequent plantarflexion magnitude, unless otherwise stated (e.g. - 15 + 55 represents 15° of dorsiflexion) followed by 55° of plantarflexion

[b]Percentage of stance phase during which the ankle switches from a dorsiflexion to plantarflexion

[c]Angular velocity data were normalised by dividing values by (gravity/leg length)½

[d]data were collected during the step in which forward acceleration magnitude was greatest

Table 2.8. Select ankle joint kinetic variables during ground contact. Standard deviations are absent where precise values have not been reported in the original source. Mean data for participants are presented.

Step number	Source	Athlete status	Peak ankle plantarflexor moment	Peak ankle power absorption	Peak ankle power generation
1	Debaere et al. (2013a)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	133 ± 20 Nm 2.0 ± 0.3 Nm/kg	334 W 4.9 W/kg	998 W 14.7 W/kg
1	Charalambous et al. (2012)	1 elite (Tier 4) sprint hurdler. PB 110m hurdles = 13.48	350 Nm 4.7 Nm/kg	300 W 4.0 W/kg	2250 W 30.4 W/kg
1	Bezodis et al. (2014)	3 elite (Tier 4) sprinters (2 males, PB 100 m = 10.14 and 10.28 s; 1 female, PB 100 m hurdles = 12.72 s)	Range: 0.378 to 0.452[a]	Range: 0.363 to 0.419[b]	Range: 1.206 to 1.488[b]
1	Brazil et al. (2017)	10 well trained (Tier 3) to elite (Tier 4) sprinters (PB 100m = 10.50 ± 0.27 s)	0.388 ± 0.035[a]	0.317 ± 0.108[b]	1.093 ± 0.069[b]
1 or 2[c]	Schache et al. (2019)	8 track & field athletes (5 male, 3 females; no ability levels indicated)	225 ± 25 Nm 3.2 ± 0.3 Nm/kg	563 W 8.0 W/kg	2112 W 30.0 W/kg
2	Jacobs & van Ingen Schenau (1992)	7 trained (Tier 3) sprinters (mean PB 100m = 10.60 s)	245 ± 8 Nm 3.1 ± 0.1 Nm/kg	778 W 9.8 W/kg	2192 ± 190 W 28.4 ± 2.5 W/kg
2	Debaere et al. (2013a)	21 trained (Tier 3) sprinters (11 males, PB 100m = 10.62 s; 10 females, PB 100 m = 11.89 s)	166 Nm 2.5 Nm/kg	665 W 9.8 W/kg	1662 W 24.5 W/kg

[a]moment data were normalised by dividing the value by (weight x leg length)
[b]power data were normalised by dividing the value by (body mass x gravity$^{3/2}$ x leg length$^{1/2}$)
[c]data were collected during the step in which forward acceleration magnitude was greatest

2.4.7 Toe-off kinematics

By the end of the stance phase in the initial steps, the CM will have reached its furthest point beyond the point of contact during stance and the CM angle (Figure 2.2a) will be at its greatest with respect to the vertical (Kugler & Janshen, 2010; Walker et al., 20201; von Lieres Und Wilkau et al., 2020b). The stance ankle, knee and hip will be at, or close to, their most extended positions, and the hip of the swing leg reaches its peak flexion angle during the contact phase (Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013a; Jacobs & van Ingen Schenau, 1992; Schache et al., 2019), creating a large 'separation' of the thighs (Walker et al., 2021) at toe-off in preparation for rapidly accelerating the swing foot back down to the ground. The importance of technical features at the point of toe-off during the initial steps as a function of an effective 'push-off' during the stance phase have previously been cited as useful technical markers for coaches (e.g., Kugler & Janshen, 2010; Walker et al., 2021).

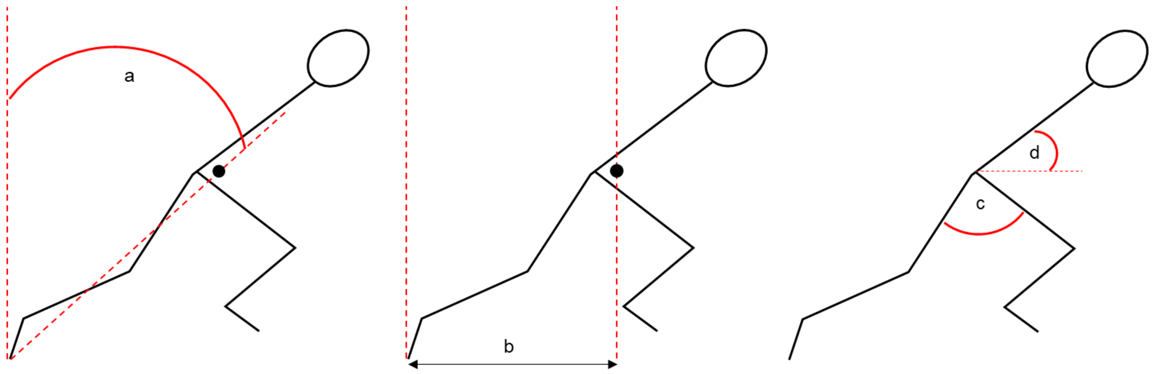

Figure 2.2. Selected kinematic aspects of technique at toe-off

a, centre of mass angle; b toe-off distance; c and d, thigh separation and trunk angles
The black markers (circles) depict the whole-body centre of mass location

Kugler and Janshen (2010) observed that the CM of the faster physical education students during the first step from a standing start in their study was further ahead of the stance foot during the last portion of the contact phase where a practically perfect significant relationship between the GRF vector angle in the sagittal plane at maximum GRF application and CM angle at toe-off was found ($r = 0.93$, $p \leq 0.001$). They identified that the faster participants achieved a greater CM angle towards the end of stance through producing significantly longer contact times (0.21 ± 0.02 s vs. 0.19 ± 0.02 s; $p < 0.05$). They stated that the longer ground contact times resulted in greater CM angles at toe-off since the CM moves further forward during ground contact (Kugler & Janshen, 2010). During the third step of trained sprinters, von Lieres Und Wilkau et al. (2020a) found the mean CM angle during the stance phase was strongly and significantly positively associated with larger NAHEP (approximately $r = 0.65$, $p < 0.001$). Whilst this technical feature was not reported at the end of the stance phase, it is likely that a large average CM angle during the stance phase will contribute substantially to a large CM angle at toe-off. However, Walker et al. (2021) found a small statistically insignificant relationship ($r = 0.12$, $p < 0.05$) existed between the toe-off distance (a function of CM angle; Figure 2.2) of world class sprinters during the first step (-0.87 ± 0.03 m) and their NAHEP magnitudes. Further research is required to determine whether the positions of the stance foot and the CM at toe-off is an important technical feature of athletes during the initial steps.

Whilst Walker et al. (2021) did not find a significant relationship between toe-off distance and NAHEP magnitude during the first stance phase, they did observe that the thigh separation angle at toe-off (102 ± 7°; angle between stance and swing thighs, Figure 2.2) and trunk angle at toe-off (43 ± 3°; relative to the horizontal, Figure 2.2) were strongly related ($r = 0.62$ and -0.59 respectively, both $p < 0.05$) to the NAHEP magnitudes of sprinters. When combined, these technical features were able to predict 89% of NAHEP produced (Walker et al., 2021) - that is, the participants who produced greater NAHEP were also those who achieved larger thigh separation angles and more forward inclined trunk orientations at toe-off. Walker et al. (2021) suggested, when citing research by Clark et al. (2020) which linked the production of greater thigh angular velocity with greater lower limb touchdown velocities and higher maximum velocity performance, that the large thigh separation angles observed in their study at toe-off (Walker et al., 2021) may have positioned the sprinters favourably to produce large thigh angular velocities at touchdown. In turn, they proposed this may have been a way to optimise mechanics of the foot-ground interaction at touchdown. However, as demonstrated by the inconsistencies in the associations between CM angle (Kugler & Janshen, 2010) or toe-off distance (Walker et al., 2021) and acceleration performance in the first step, the conclusions drawn from a study on one population may not always translate to another, likely due to the differences in their task, performer, and environmental constraints (Newell, 1986). Therefore, since the constraints of professional rugby backs differ compared with physical education students (e.g., Kugler & Janshen, 2010) and sprinters (e.g., Walker et al., 2021), it is important that the toe-off kinematics discussed in this literature review are investigated in the context of professional rugby backs to determine whether they may be important to acceleration performance in this population.

2.5 Spatiotemporal variables

Spatiotemporal kinematic variables during sprinting represent the 'whole-body' movement outcomes resulting from the interaction between the angular kinematics and internal (joint) and external (GRF characteristics) kinetics produced during sprinting. Step length, step rate, contact time and flight time are the highest order spatiotemporal variables and will form the focus of this next section. Whilst no studies have investigated these technical features solely in professional rugby backs during initial acceleration, the spatiotemporal variables of a range of team sport players during short sprint distances (approximately ≤ 5 m) have received a lot of attention in the literature (e.g., Bezodis et al., 2017; Lahti et al., 2020; Lockie et al., 2015; Lockie et al., 2014a; Lockie et al., 2014b; Lockie et al., 2013; Lockie et al., 2012; Lockie et al., 2011; Murata et al., 2018; Murphy et al., 2003; Nagahara et al., 2018a; Spinks et al., 2007; Standing & Maulder, 2017). Therefore, unless otherwise stated, the literature discussed in this section of the literature review will focus on team sport players.

2.5.1 Initial acceleration spatiotemporal variables of team sport players

Tables 2.9 to 2.11 show the spatiotemporal data of team sport players during the initial steps reported in a number of studies, their relationships with initial acceleration performance, the differences between 'faster' and 'slower' groups and their changes following training interventions. Despite the relatively large coverage of spatiotemporal variables during the initial steps of sprinting, there is a lack of consistency concerning the relationships between these variables and the initial acceleration performance of team sport players (Table 2.9). For instance, longer step length and shorter contact time (Nagahara et al., 2018a), longer step length and longer flight time (Lockie et al., 2013) and longer step length alone (Murata et al., 2018) have all been related to faster initial sprint acceleration performance. Other researchers have reported higher step rates and shorter flight times as sharing the strongest relationships of all step characteristics with initial sprint acceleration performance (Standing & Maulder, 2017), whereas no relationships between spatiotemporal variables and the sprint performance of team sport players during the initial steps have also been observed (Lockie et al., 2014a).

These mixed findings as to which step characteristics are related to initial sprint acceleration performance may be explained by several factors. Differences in the performer constraints (Newell, 1986) between and within athlete cohorts investigated, the sprinting distance or number of steps used, the variables selected to assess sprint performance, and the way in which step characteristics have been measured may account for the inconsistent results observed. From an ecological dynamics standpoint (Davids et al., 2008), inter-individual differences in physical characteristics (e.g., anthropometric [leg length, body mass] qualities) will affect the movement adopted during a sprint. For instance, the longer legs of an athlete with greater stature likely results in longer step lengths and lower step rates (Hunter et al., 2004; Nagahara et al., 2018a). Therefore, leg length or stature could be considered as one explanatory reason for the different findings of group study designs. Accordingly, correcting for unequal stature or leg length using dimensionless units (e.g., Hof, 1996) for spatiotemporal variables may provide further insight in this area.

The uncertainty about which, if any, step characteristics are more important for initial acceleration performance is compounded further by research which has compared ‘faster’ and ‘slower’ team sport players (Table 2.10) and training intervention studies (Table 2.11). For instance, faster groups during initial acceleration have been shown to produce significantly shorter contact times than slower groups (Lockie et al., 2011; Murphy et al., 2003), whereas sprint training interventions resulting in significantly better initial acceleration performance have also significantly increased the contact times of the team sport players involved (Lockie et al., 2014b; Lockie et al., 2012). In fact, enhanced initial acceleration performance may seemingly be achieved alongside a different combination in changes to spatiotemporal variables following sprint, plyometric and resisted sprint training (Lockie et al., 2014b; Lockie et al., 2012; Spinks et al., 2007). Moreover, following verbal instructions, changes in step characteristics have been observed without discernible changes to sprint performance during the initial steps (Nagahara et al., 2019), whereas changes in sprint performance have also been observed without meaningful changes to step characteristics during the first three steps (Lahti et al., 2020) or at the 5 m mark (Bezodis et al., 2017) of a sprint. Collectively, the findings on which step characteristics are important to initial sprint acceleration performance would suggest that different strategies may be adopted by different athletes to achieve similar sprint performance outcomes.

How acceleration strategies can be classified and how they may differ within rugby backs (or any team sport player) is not currently known. One way to identify homogenous groups of athletes according to their characteristics' during sprinting is by cluster analysis (Karamanidis et al., 2011; Mackala et al., 2015; Naito et al., 2015). For instance, using cluster analysis sprinters have been classified according to their performance level over 100 m (Karamanidis et al., 2011), step length and step rate at maximum velocity (Naito et al., 2015). The approach has also been used to cluster physical education students according to their sprint performance over a range of distances, their step length and step rate, and a range of strength qualities and anthropometrics characteristics (Mackala et al., 2015). Cluster analysis has also been used to classify injured and healthy runners into homogenous groups according to a range of spatiotemporal variables and joint angular kinematics during running (Jauhiainen et al., 2020; Phinyomark et al., 2015; Watari et al., 2018). However, it is yet to be demonstrated how this information can be used to help improve the sprinting or running performances of athletes, and whether different acceleration strategies of rugby backs exist, and can be identified using cluster analysis, remains to be seen. Addressing these areas would provide a more detailed understanding of the biomechanics and motor control of rugby backs and may offer insight into the efficacy of training interventions aimed at enhancing their acceleration performance.

Table 2.9. Spatiotemporal variables observed in team sport players during the initial steps of sprinting and their relationships with initial acceleration performance

Source	Athlete information	Step(s) / distance over which spatiotemporal data were obtained	Initial acceleration performance	Methods to obtain data	Spatiotemporal variables (mean ± SD unless otherwise stated)	Relationships with sprint performance (Pearson's correlation coefficient unless otherwise stated)
Lockie et al. (2014a)	18 highly trained (Tier 3) cricketers (mass: 79.7 ± 10.4 kg; stature 1.81 ± 0.06 m)	Steps 1-2	5 m time = 1.066 ± 0.037 s	3D motion capture (200 Hz) to collect spatiotemporal variables. Timing gates to measure time to 5 m during 10 m sprints (participants were positioned 0.30 m behind the first gate at the start)	SL: first step = 0.96 ± 0.12 m; second step = 1.13 ± 0.11 m	First step r = -0.40; second step r = -0.17
					SR: first step = 4.05 ± 0.33 Hz; second step = 4.16 ± 0.33 Hz	First step r = -0.00; second step r = -0.141
					CT: first step = 0.174 ± 0.013 s; second step = 0.152 ± 0.016 s	First step r = -0.28; second step r = 0.27
					FT: first step = 0.073 ± 0.017 s; second step = 0.089 ± 0.016 s	No data reported
Standing & Maulder (2017)	10 trained (Tier 2) teams sport players (mass: 87.3 ± 11.8 kg; stature 1.80 ± 0.06 m)	Steps 1-3	5 m time = 1.090 ± 0.060 s	Timing gates to measure time to 5 m (participants started 0.50 m behind the first gate). Two high-speed cameras (120 Hz) to collect spatiotemporal variables	SL: step 1 = 0.99 ± 0.14 m; step 2 = 1.12 ± 0.09 m; step 3 = 1.26 ± 0.12 m	Step 3 with 5 m time: r = -0.28 (CI: -0.69 to 0.37; qualitative inference: very small)
					SR: step 1 = 4.54 ± 0.37 Hz; step 2 = 4.70 ± 0.28 Hz; step 3 = 4.70 ± 0.32 Hz	Step 3 with 5 m time: r = -0.39 (CI: -0.77 to 0.21; qualitative inference: small)
					CT: step 1 = 0.185 ± 0.020 s; step 2 = 0.165 ± 0.020 s; step 3 = 0.150 ± 0.015 s	Step 3 with 5 m time: r = -0.09 (CI: -0.61 to 0.49; qualitative inference: very small)
					FT: step 1 = 0.039 ± 0.018 s; step 2 = 0.047 ± 0.005 s; step 3 = 0.150 ± 0.015 s	Step 3 with 5 m time: r = 0.40 (CI: -0.20 to 0.78; qualitative inference: small)

*Statistically significant ($p \leq 0.05$)
**Statistically significant ($p \leq 0.01$)

Table 2.9 (continued)

Source	Athlete information	Step(s) / distance over which spatiotemporal data were obtained	Initial acceleration performance	Methods to obtain data	Spatiotemporal variables (mean ± SD unless otherwise stated)	Relationships with sprint performance (Pearson's correlation coefficient unless otherwise stated)
Lockie et al. (2013)	22 trained (Tier 2) team sport players (mass: 83.6 ± 7.4 kg; stature 1.81 ± 0.07 m)	0-5 meters	Average velocity = 3.76 ± 0.21 m/s	High speed video camera (200 Hz) during 10 m sprints to collect spatiotemporal variables. A velocimeter to measure average velocity over 5 m	SL: 1.19 ± 0.13 m	r = 0.50*
					SR: 4.13 ± 0.12 Hz	r = -0.19
					CT: 0.148 ± 0.015 s	r = -0.22
					FT: 0.098 ± 0.015 s	r = 0.52*
Murata et al. (2018)	37 trained (Tier 2) soccer players (mass: 66.0 ± 6.2 kg; stature 1.71 ± 0.06 m)	Steps 1-4	Change in running speed = 5.60 m/s[a]	Spatiotemporal variables and GRF impulses calculated over 50 force plates across 50 m sprints	SL: 1.20 m[a]	r = 0.70[b]*
					SR: 4.65 ± 0.24 Hz	r = -0.20[ab]
					CT: 0.160 s[a]	r = 0.10[ab]
					FT: 0.055 s[a]	r = 0.05[ab]
Nagahara et al. (2018a)	39 trained (Tier 2) soccer players (mass: 66.3 ± 6.1 kg; stature 1.71 ± 0.06 m)	Steps 1-4	Average velocity = 5.40 m/s[a]	Spatiotemporal variables and GRF impulses calculated over 50 force plates across 60 m sprints	SL: 1.20 m[a]	r = 0.60**
					SR: 4.50 Hz[a]	r = 0.16
					CT: 0.165 s[a]	r = -0.46*
					FT: 0.065 s[a]	r = 0.11

[a]Estimated from figures

*Statistically significant ($p \leq 0.05$)

**Statistically significant ($p \leq 0.01$)

[b]Partial correlation coefficients controlling for body mass and stature

Table 2.10. Differences in the spatiotemporal variables between 'faster' and 'slower' team sport players during initial acceleration

Source	Athlete information	Step(s) / distance over which spatiotemporal data were obtained	Initial acceleration performance	Methods to obtain data	Spatiotemporal variables (mean ± SD unless otherwise stated)	Differences between groups
Murphy et al. (2003)	20 team sport players (rugby union, Australian football, soccer; competition standard not stated; mass: 82.6 ± 13.1 kg; stature 1.79 ± 0.06 m)	Steps 1-2 (first step started at toe-off at the end of the initial push off at the start)	Linear horizontal hip velocity for fast group = 5.98 ± 0.15 m/s; Linear horizontal hip velocity for slow group = 5.39 ± 0.29 m/s	High speed video camera (100 Hz) during 15 m sprints to measure spatiotemporal variables and linear hip velocity at the instance of toe-off at the beginning of the third step	SL: faster group = 1.05 ± 0.08 m; slower group = 1.03 ± 0.07 m	Difference not significant (ANOVA)
					SR: faster group = 3.64 ± 0.24 m; slower group = 3.34 ± 0.48 m	Difference significant (ANOVA)**
					CT: faster group = 0.185 ± 0.015 s; slower group = 0.210 ± 0.03 s	Difference significant (ANOVA)**
					FT: faster group = 0.055 ± 0.010s; slower group = 0.055 ± 0.030 s	Difference not significant (ANOVA)
Lockie, et al. (2011)	22 team sport players (competition standard not stated; mass: 80.5 ± 8.5 kg; stature 1.81 ± 0.07 m)	0-5 m	Average velocity for fast group = 3.91 ± 0.13 m/s Average velocity for slow group = 3.56 ± 0.10	High speed video camera (100 Hz) during 10 m sprints to collect spatiotemporal variables. A velocimeter to measure average velocity over 5 m	SL: faster group = 1.17 ± 0.15 m; slower group = 1.16 ± 0.14 m	*d* = 0.07
					SR: faster group = 3.39 ± 0.45 m; slower group = 3.11 ± 0.36 m	*d* = 0.69
					CT: faster group = 0.190 s[a]; slower group = 0.220 s[a]	*d* = 1.18*
					FT: faster group = 0.105 s[a]; slower group = 0.100 s[a]	-

[a]Estimated from figures

*Statistically significant (p ≤ 0.05)

**Statistically significant (p ≤ 0.01)

Table 2.11. Changes in initial acceleration spatiotemporal variables following interventions

Source	Athlete information	Step(s) / distance over which spatiotemporal data were obtained	Initial acceleration performance	Methods to obtain data	Spatiotemporal variables (mean ± SD unless otherwise stated)	Changes in spatiotemporal variables following intervention
Spinks et al. (2007)	30 highly trained (Tier 3) soccer (n = 8), rugby union (n = 12) and Australian football (n = 10) players (mass: 83.3 ± 8.7 kg; stature 1.82 ± 0.06 m)	Steps 1-2	Average velocity (0-5 m) group range pre interventions = 3.51 ± 0.32 m/s to 3.62 ± 0.25 m/s Average velocity (0-5 m) group range post interventions = 3.69 ± 0.19 m/s to 3.95 ± 0.30 m/s	High speed video camera (100 Hz) during 20 m sprints to collect spatiotemporal variables. A velocimeter to measure average velocity over 5 m	SL: pre interventions (mean across all groups) = 1.02 ± 0.15 m; post interventions (mean across all groups) = 1.01 ± 0.13 m	No significant effects evident
					SR: pre interventions (mean across all groups) = 3.81 ± 0.40 Hz; post interventions (mean across all groups) = 3.95 ± 0.47 Hz	No significant effects evident
					CT: pre interventions (mean across all groups) = 0.178 ± 0.020 s; post interventions (mean across all groups) = 0.170 ± 0.017 s	Decreased following resisted and non-resisted sprint training in the first step (11.8%** and 6.3%**)
					FT: pre interventions (mean across all groups) = 0.073 ± 0.02 s; post interventions (mean across all groups) = 0.073 ± 0.02 s	No significant effects evident
Lahti et al. (2020)	32 elite (Tier 4) soccer players (mass: 76.7 ± 7.7 kg; stature 1.80 ± 0.10 m)	Steps 1-3	Time to 5m pre intervention = 1.39 ± 0.04 s) Time to 5m post intervention = 1.35 ± 0.04 s)	High speed video camera (240 Hz) during 30 m sprints to collect spatiotemporal variables. 5 m split time was derived from a radar device	SL: pre interventions (mean across all groups) = 1.12 ± 0.08 m; post interventions (mean across all groups) = 1.15 ± 0.09 m	No significant effects evident
					SR: pre interventions (mean across all groups) = 4.22 ± 0.21 Hz; post interventions (mean across all groups) = 4.32 ± 0.34 Hz	No significant effects evident
					CT: pre interventions (mean across all groups) = 0.190 ± 0.01 s; post interventions (mean across all groups) = 0.183 ± 0.02 s	No significant effects evident

*Statistically significant ($p \leq 0.05$)
**Statistically significant ($p \leq 0.01$)

Table 2.11 (continued)

Source	Athlete information	Step(s) / distance over which spatiotemporal data were obtained	Initial acceleration performance	Methods to obtain data	Spatiotemporal variables (mean ± SD unless otherwise stated)	Changes in spatiotemporal variables following intervention
Lockie et al. (2012)	35 trained (Tier 2) team sports players (mass: 83.1 ± 8.6 kg; stature 1.82 ± 0.10 m)	0-5 m	Average velocity group range pre interventions = 3.68 ± 0.13 m/s to 3.81 ± 0.30 m/s Average velocity group range post interventions = 3.99 ± 0.25 m/s to 4.08 ± 0.26 m/s	High speed video camera (200 Hz) during 10 m sprints to collect spatiotemporal variables. A velocimeter to measure average velocity over 5 m	SL: pre interventions range 1.14 ± 0.08 m to 1.29 ± 0.13 m; post interventions range = 1.25 ± 0.10 m to 1.39 ± 0.11 m	Increased following each intervention; range = *d* = 0.83 to 1.99*
					SR: pre interventions range 2.97 ± 0.36 Hz to 3.32 ± 0.20 Hz; post interventions range = 2.96 ± 0.34 Hz to 3.25 ± 0.29 Hz	Increased following the free sprint training intervention; *d* = 1.10*
					CT: pre interventions range 0.141 ± 0.014 s to 0.157 ± 0.019 s; post interventions range = 0.142 ± 0.007s to 0.156 ± 0.017 s	Increased following the free sprint training intervention; *d* = 1.00*
					FT: pre interventions range 0.089 ± 0.007 s to 0.096 ± 0.014 s; post interventions range = 0.084 ± 0.009s to 0.095 ± 0.017 s	Decreased following the free sprint training intervention *d;* = 0.69*
Lockie et al. (2014b)	16 trained (Tier 2) team sport players (Australian football [n = 5], rugby union [n = 4], soccer [n = 4], and rugby league [n = 3]; mass: 80.5 ± 5.9 kg; stature 1.81 ± 0.05 m)	0-5 m	Mean 5 m sprint time pre interventions = 1.300 s[a] Mean 5 m sprint time post interventions = 1.250 s[a]	High speed video camera (200 Hz) during 10 m sprints to collect spatiotemporal variables. A velocimeter to measure 10 m sprint time	SL: pre interventions (mean across all groups) = 1.17 ± 0.11 m; post interventions (mean across all groups) = 1.30 ± 0.11 m	Increased following sprint training (*d* = 1.79**) and plyometric training (*d* = 0.83**)
					SR: pre interventions (mean across all groups) = 4.14 ± 0.24 Hz; post interventions (mean across all groups) = 4.13 ± 0.31 Hz	No significant effects evident
					CT: pre interventions (mean across all groups) = 0.146 ± 0.010 s; post interventions (mean across all groups) = 0.152 ± 0.010 s	Increased following sprint training (*d* = 1.22*)
					FT: pre interventions (mean across all groups) = 0.100 ± 0.016 s; post interventions (mean across all groups) = 0.095 ± 0.016 s	Decreased following sprint training (*d* = 0.71**)

*Statistically significant ($p \le 0.05$)
**Statistically significant ($p \le 0.01$)
†Greater than the smallest worthwhile change/difference

Table 2.11 (continued)

Source	Athlete information	Step(s) / distance over which spatiotemporal data were obtained	Initial acceleration performance	Methods to obtain data	Spatiotemporal variables (mean ± SD unless otherwise stated)	Changes in spatiotemporal variables following intervention
Nagahara et al. (2019)	14 (6 females) recreationally active (Tier 1) adults (mass: 72.0 ± 16.1 kg; stature 1.79 ± 0.13 m)	Steps 1-4	Velocity over each step. Average velocity over 4 steps = 4.15 m/s[a]	Spatiotemporal variables and GRF impulses calculated over force plates across 50 m sprints	SL: 1.15 m[a]	Shorter during the first step with intentional forward body lean; *d* = 0.25[a†]
					SR: 3.70 Hz[a]	Higher during the first 2 steps with intentional forward body lean; *d* = 0.25 to 0.50[a†]
					CT: 0.195 s[a]	Shorter during the first step with intentional forward body lean; d = 0.25[a†]
					FT: 0.075 s[a]	Shorter during the first 4 steps with intentional forward body lean; *d* = -0.50 to -0.25[a†]
Bezodis et al., (2017)	18 trained (Tier 2) team sport players (Gaelic football, rugby union, soccer) athletes (mass: 78.2 ± 10.5 kg; stature 1.76 ± 0.10 m)	A single step at the 5 m mark	10 m sprint time range across conditions range = 1.936 ± 0.095 s to 1.992 ± 0.120 s	3D motion capture to collect spatiotemporal variables. Timing gates to measure 10 m sprint time (front foot just behind first gate at the start)	SL: 1.40 ± 0.10 m (mean across conditions)	No significant effects evident
					SR: 4.41 ± 0.12 Hz (mean across conditions)	No significant effects evident
					CT: 0.147 ± 0.066 s (mean across conditions)	No significant effects evident
					FT: 0.080 ± 0.015 s (mean across conditions)	No significant effects evident

[a]Estimated from figures
*Statistically significant ($p \leq 0.05$)
**Statistically significant ($p \leq 0.01$)
†Greater than the smallest worthwhile change/difference

2.6 An ecological dynamics perspective on technical features during initial acceleration

Ecological dynamics is an approach to study human movement which merges principles from ecological psychology and dynamical systems theory. Ecological psychology places emphasis on performer-environment interaction (Gibson, 1979). As a performer is provided with opportunities to engage with the environment, they explore the perceptual-motor workspace and the opportunities for action which the environment affords (Seifert et al., 2016). This ongoing interaction between performer and environment is central to understanding human movement from an ecological psychology perspective and is epitomised in Gibson's (1979) quote that "we must perceive in order to move, but we must also move in order to perceive" (p. 223). Dynamical systems accounts consider the human as a complex system from which coordinated behaviours/actions emerge through a continual interaction of components of the system (Mayer-Kress et al., 2006; Rickles et al., 2007). Such an approach considers that there is no single 'correct' action, but rather different movement solutions will be available given the number of degrees of freedom available to solve the task. This was termed the 'degrees of freedom problem' (Bernstein, 1967) and it is proposed that the performer produces coordinated actions through a process of self-organisation. Through combining key features from these two different but complementary theoretical perspectives has led to the relatively recent emergence of ecological dynamics in which performer-environment interactions offer a series of interacting constraints from which behaviours emerge through a process of self-organisation as the individual seeks to control the degrees of freedom to discover movement solutions (Davids et al., 2013).

From an ecological dynamics perspective, humans are complex adaptive systems with multiple interacting components (Davids et al., 2014) which is thought to result in different patterns of emergent behaviours. In this regard, athletes have an array of different strategies available to them, when sprinting, to achieve the same outcome – a concept known as degeneracy (Tononi et al., 1999). The process through which the system self-organises and behaviour emerges is considered spontaneous and is explained by dynamical systems theory which describes the arrangement of dynamical patterns as a function of the interaction of the performer (athlete), task and environmental constraints (Newell, 1986). Therefore, variation in the technique strategies adopted during initial sprint acceleration is likely, given the different interacting constraints at any one point. Consequently, the different constraints which exist between different participant groups may explain the difficulty in finding consistent relationships between technical features and initial acceleration performance (see Sections 2.3 and 2.4).

The majority of the research discussed in Section 2.2 to 2.4 was conducted on sprint athletes or on team sport players competing in sports other than rugby. Although some studies included rugby players within their cohort of participants, these players did not compete at the professional level (generally Tier 3 or lower) and were also considered within a wider group of non-rugby team sport players. The body mass (e.g., mean ± SD: 92.9 ± 9.7 kg; McHugh et al., 2021) and stature (e.g., mean ± SD: 1.83 ± 0.08 m; Posthumus et al., 2020) of senior professional (> Tier 3) rugby backs is substantially greater than the body mass and stature of participants studied in the literature discussed in Sections 2.2 to 2.4 (mean values for body mass and stature ranged from 64 to 87 kg and 1.71 to 1.82 m respectively). Furthermore, the strength-related capacities of rugby backs have been shown to differ significantly compared with team sport players (soccer) and sprinters (Loturco et al., 2021; Loturco et al., 2018). Therefore, there are clearly differences in performer constraints between rugby backs and other team sport players and sprinters during initial acceleration. In addition, there are obvious differences in environmental (e.g., running surface – track vs. grass/artificial turf) and task (e.g., sprint start conditions, different match-play physical, technical and tactical demands) constraints between rugby backs and other athletes. Collectively, these differences in the constraints between rugby backs and other team sport players and sprinters will likely influence the way they interact with their environment when sprinting during the initial steps (Fajen et al., 2008), and will likely require different movement solutions for the specific task at hand (Newell, 1986; Thelen, 1989). This highlights the specific need to study rugby backs so that findings from the research can be applied to this population.

Ecological dynamics theory provides a rationale as to why the technical features which yield high initial acceleration may differ between sports as a result of the different constraints imposed on athletes competing in these sports. However, this theory would suggest that the same explanation may apply to athletes within the same sport. For example, the favourable technical features produced by one rugby back to achieve high sprint performance during the initial steps may not translate to another rugby union back, owing to differences in their constraints. That is, an optimal ‘one-size-fits-all’ technique during initial acceleration may not exist within rugby backs. While this is yet to be proven, some research exists to suggest that the technical features athletes exhibit for better sprinting performance may differ at the inter-individual level. For example, Salo et al. (2011) observed that elite to world class (Tiers 4 and 5) sprinters were typically individually reliant on the production of either higher step length or higher step rate (when averaged over multiple 100 m races) for better 100 m race performance. Although the same findings do not necessarily translate to rugby backs during the initial acceleration, a similar approach which seeks to determine the favourable techniques which are associated with the sprint performance of rugby backs at the intra-individual may provide direction for the individualisation of sprint training interventions of practitioners tasked with enhancing the acceleration performance of rugby backs.

2.7 Associations between strength qualities and initial acceleration performance

For skilled coaches, it is possible to manipulate various constraints during training in an attempt to affect the emergent movement behaviour of an athlete. In a sprinting context, for example, a strength-based manipulation would endeavour to change the human system and alter the performer constraints to elicit changes in technique. There is a paucity of research concerning relationships between different lower limb physical qualities and movement strategies adopted by athletes during initial sprint acceleration. However, due to the high force and power requirements during the initial steps of a sprint, the relationships between the performance of team sport players during the initial acceleration phase and their strength-related capacities have been the subject of much research (e.g. Barr & Nolte, 2011; Cunningham et al., 2013; Dowson, et al., 1998; Habibi et al., 2010; Harris et al., 2008; Lockie, et al., 2011; Lockie, et al., 2015; Loturco et al., 2015; Marques, et al., 2011; McBride et al., 2009; Newman et al., 2004; Robbins & Young, 2012; Schuster & Jones, 2016; Sleivert & Taingahue, 2004; Turner et al., 2015; Wisloff, et al., 2004; Zabaloy et al., 2020). However, no study to date has investigated the strength qualities of professional rugby backs and their relationships with acceleration during only the initial steps (e.g., steps 1 to 4 or time to ≤ 5 m). Therefore, relevant literature which has investigated the associations between the strength qualities of a range or team sport players and their acceleration performance over 10 m or less will form the focus of this discussion. The strength of relationships will be defined as (±) < 0.10, trivial; 0.10 to 0.30, small; 0.31 to 0.50, moderate; 0.51 to 0.70, large; 0.71 to 0.90, very large; 0.90 to 1.00, practically perfect (Hopkins, 2002).

2.7.1 Maximum lower limb strength

During the sprint start the body is accelerated from stationary and the large horizontal propulsive GRF and impulses produced have been shown to be important during the initial steps of a sprint (e.g., Bezodis et al., 2014; Kawamori et al., 2013; Kugler & Janshen, 2010; Mero, 1988; Rabita et al. 2015). During the initial steps these GRF are produced during the longest timeframes of all sprint phases – shown to range from approximately 0.22 to 0.14 s during the first three steps (Atwater, 1982, Murphy et al., 2003; Salo et al., 2005) – thus enabling the production of greater horizontal propulsive GRF and impulse relative to later stages in a sprint (Morin et al., 2015a). Logically therefore, a number of studies have investigated the relationships between maximum strength measures and initial acceleration performance.

Table 2.12 provides a summary of the findings from studies which have investigated the relationships between the maximum strength of team sport players and their initial acceleration performance. When values are normalised to body mass, relationships are generally larger (absolute, mean r = -0.18; relative to body mass, mean r = -0.37), which is logical since the ability produce large mass-specific forces when sprinting has been shown to be a determinant of performance regardless of the sprint phase concerned (e.g., Weyand et al. 2000; Morin et al., 2015a). However, the strength of the relationships (range, r = 0.04 to -0.94) observed is inconsistent between studies and cannot seemingly be explained by differences in sport or participant status. For example, moderate and large statistically significant negative relationships has been observed between the 1RM relative back squat and 5 m sprint times of highly trained rugby forwards (Zabaloy et al., 2020) and the 10 m sprint times of elite rugby players (Cunningham et al., 2013; playing positions not reported), respectively. However, only a small statistically non-significant positive relationship was shown between the 1RM relative back squat of highly trained rugby backs and their 5 m sprint times (Zabaloy et al., 2020). Trivial to small statistically non-significant relationships were also observed by Tillin et al. (2013) between maximal force produced during an isometric squat and the 5 m sprint times of university rugby players. It is difficult to determine therefore the importance of maximum strength to the initial acceleration performance of rugby backs with the currently available literature.

Obtaining maximum strength measures during multi-joint exercises such as the back squat appear to be favoured over the measurement of single joint maximum strength. Given the high levels of intermuscular coordination required to sprint, opting for multi-joint strength measures over single joint strength measures would seem valid in the context of initial acceleration. However, single joint strength measures should not be dismissed. For example, Morin et al. (2015b) found no significant relationships between isokinetic variables (hip extension peak torque) and propulsive horizontal GRF averaged over the first ten steps. However, using a linear regression model, a significant moderate relationship was revealed ($r^2 = 0.44$, $p = 0.04$) between the combination of gluteal EMG activity during the end of the swing phase and hip extension (gluteal) concentric peak torque (120°/s) and average propulsive horizontal GRF during the first ten steps. A similar relationship was also observed ($r^2 = 0.45$, $p = 0.04$) between average propulsive horizontal GRF during this sprint phase and the combination of biceps femoris EMG activity during the late swing phase and peak concentric knee flexion torque (120°/s) produced under isokinetic testing conditions (Morin et al., 2015b). Whilst this suggests that single joint strength measures are worth considering, it also implies that multiple factors (strength and technique) are likely to operate together to optimise GRF impulses, so that initial sprint acceleration performance can be maximised. Therefore, future research should consider using multiple regression models to investigate the combined contribution of different strength qualities and technical features to initial sprint acceleration performance, as this may be more informative than correlation analysis alone.

Table 2.12. Relationships between the lower limb maximum strength capacities of team sport players and sprint acceleration performance.

Source	Athlete status	Strength measure	Acceleration performance measure	Pearson's correlation coefficient	Strength performance values reported
Chelly et al. (2010)	23 highly trained (Tier 3) soccer players (64.7 ± 6 kg)	1RM half back squat	Average velocity over the first step and 5m	-0.58** (1st step) -0.66** (5m)	-
Lockie et al. (2015)	28 (Tier 2) team sport players (82.4 ± 7.6 kg)	3RM back squat (smith machine)	Average velocity over the first 5 m	-0.02	119.1 ± 20.6 kg
		3RM back squat (smith machine) relative to body mass		-0.11	1.44 ± 0.20 kg/kg
Zabaloy et al. (2020)	27 highly trained (Tier 3) rugby backs (80.4 ± 8.0 kg)	1RM back squat	5 m sprint time	0.04	127.5 ± 19.2 kg
		1RM back squat relative to body mass		0.11	1.59 ± 0.22 kg/kg
		Theoretical maximum force derived during squat jump force-velocity profiling		-0.14	37.0 ± 6.2 N/kg
Zabaloy et al. (2020)	24 highly trained (Tier 3) rugby forwards (96.3 ± 14.0 kg)	1RM back squat	5 m sprint time	-0.44*	142.9 ± 22.6 kg
		1RM back squat relative to body mass		-0.48*	1.50 ± 0.25 kg/kg
		Theoretical maximum force derived during squat jump force-velocity profiling		-0.19	33.4 ± 5.0 N/kg
McBride et al. (2009)	17 highly trained (Tier 3) American football athletes (85.9 ± 8.8 kg)	1RM back squat relative to body mass	4.6 m and 9.1 m sprint time	-0.45 (4.6m) -0.54* (9.1m)	166.5 ± 34.1 kg (1.94 ± 0.33 kg/kg)

*Statistically significant ($p \leq 0.05$)
**Statistically significant ($p \leq 0.01$)

Table 2.12 (continued)

Source	**Athlete status**	**Strength measure**	**Acceleration performance measure**	**Pearson correlation coefficient**	**Strength performance values reported**
Cronin and Hansen (2005)	26 highly trained to elite (Tiers 3 and 4) rugby league players (97.8 ± 11.8 kg)	3RM back squat (thigh to parallel)	5m and 10m sprint time	-0.05 (5 m) -0.01 (10 m)	13 fastest = 190 kg 13 slowest = 169 kg
		Peak knee concentric extension torque at 60°/s		-0.34 (5 m) -0.31 (10 m)	13 fastest = 324 Nm 13 slowest = 294 Nm
		Peak knee concentric flexion torque at 60°/s		-0.19 (5 m) -0.05 (10 m)	13 fastest = 172 Nm 13 slowest = 166 Nm
Baker and Nance (1999)	20 elite (Tier 4) rugby league players (93.4 ± 11.7 kg)	3RM back squat	10m sprint time	-0.06	157.9 ± 18.8 kg
		3RM back squat relative to body mass		-0.39*	1.69 ± 0.20 kg/kg
Wisloff et al. (2004)	17 elite (Tier 4) soccer players (76.5 ± 7.6 kg)	1RM half back squat (knee angle to 90°) raised to the power of 0.67	10m sprint time	-0.94**	171.7 ± 21.2 kg (2.2 ± 0.30 kg/kg; allometrically scaled to 0.67: 9.4 ± 1.5)
Cunningham et al. (2013)	20 elite (Tier 4) rugby players (105.5 ± 11.9 kg)	3RM back squat	10m sprint time	0.17	186.2 ± 22.6 kg
		3RM back squat relative to body mass		-0.55*	1.76 ± 0.21 kg/kg

*Statistically significant ($p \leq 0.05$)
**Statistically significant ($p \leq 0.01$)

2.7.2 Explosive strength

The capacity to produce high levels of lower limb energy generation is necessary during the initial steps for high acceleration performance (e.g., Bezodis et al., 2014; Debaere et al., 2013a; Jacobs & van Ingen Schenau, 1992; Schache et al., 2019). Moreover, the ability to transfer this energy at a high rate, and thus power, is clearly important since the ground contact times in early acceleration typically range from approximately 0.20 s in the first step of a sprint decreasing consecutively to approximately 0.15 s by step three in trained to elite athletes (Atwater, 1982; Murphy et al., 2003; Salo et al., 2005). Whilst these durations are longer compared to later sprint phases, they are still short with regards to the typical time needed for muscles to reach their maximum force production capabilities (e.g., Thornstensson et al., 1976). Therefore, the explosive strength qualities of individuals (i.e., in this context the ability to generate high levels of lower limb power within short timeframes) may be more important to their initial acceleration performance than their maximum strength capacity.

Table 2.13 summarises a number of studies which have investigated the relationships between explosive strength and acceleration performance. Generally, the strength of these relationships appears greater compared with maximum strength measures and the same sprint phase. This is likely due to the greater rate of energy generation requirements needed for better performance in the explosive strength assessments and their greater compatibility with accelerative sprint performance with regards to the time constraints imposed.

Numerous metrics have been used as a measure of explosive strength during different assessments (Table 2.13). Of all explosive strength measures, various jump-based performances appear to correlate the highest to acceleration performance. Regardless of the metric used, when such measures are expressed relative to the athlete’s body mass relationships with sprint acceleration performance appear greater, which is consistent with the relationships between maximum strength and acceleration performance (Table 2.12). This is logical given that the production of force output per unit of body mass is essential for maximising performance during initial sprint acceleration (e.g., Rabita et al., 2015). However, Zabaloy et al. (2020) observed only small statistically non-significant relationships of peak mean power derived from the squat jump force-velocity profiling of Samozino et al. (2013) and jump height during squat jumps and countermovement jumps with the 5 m sprint times of highly trained rugby backs (Zabaloy et al., 2020). This finding aside, based on the moderate to very large statistically significant relationships shown between acceleration performance and jump based performance, the findings suggest high levels of concentric explosive strength are beneficial to acceleration performance and are supported by the literature showing that high levels of lower limb energy generation are necessary during the initial steps for high acceleration performance (e.g., Bezodis et al., 2014; Debaere et al., 2013a; Jacobs & van Ingen Schenau, 1992; Schache et al., 2019).

Table 2.13. Relationships between the lower limb explosive strength capacities of team sport players and sprint acceleration performance.

Source	Athlete status	Strength measure	Acceleration performance measure	Pearson's correlation coefficient	Strength performance values reported
Lockie et al. (2015)	28 (Tier 2) team sport players (82.4 ± 7.6 kg)	Countermovement jump height	Average velocity over the first 5 m	0.40*	0.39 ± 0.05 m
		Countermovement jump power index ($\sqrt{4.9} \cdot body\ mass \cdot \sqrt{jump}\ height$)		0.31	113 ± 14
Loturco et al. (2015)	27 (Tier 3) highly trained soccer players (74.4 ± 9.5 kg)	Squat jump using a load which elicited peak mean power (smith machine from a 100° knee angle) power relative to body mass	Average velocity over the first 5 m	0.71**	698 ± 113 W (9.42 ± 1.6 W/kg)
		Olympic push press using a load which elicited peak mean propulsive power relative to body mass		0.41*	727 ± 135 W (9,78 ± 1.69 W/kg)
Zabaloy et al. (2020)	27 highly trained (Tier 3) rugby backs (80.4 ± 8.0 kg)	Theoretical peak mean power derived during squat jump force-velocity profiling	5 m sprint time	0.18	2061 ± 359 W (25.6 ± 4.8 W/kg)
		Squat jump height		0.11	0.309 ± 0.415 m
		Countermovement jump height		0.13	0.355 ± 0.464 m

*Statistically significant ($p \leq 0.05$)
**Statistically significant ($p \leq 0.01$)

Table 2.13 (continued)

Source	Athlete status	Strength measure	Acceleration performance measure	Pearson correlation coefficient	Strength performance values reported
Sleivert and Taingahue (2004)	30 trained (Tier 2) rugby and basketball players (90.6 ± 9.3 kg)	Squat jump average power relative to body mass[a]	5m sprint time	-0.64**	641 ± 11.6 W 7.07 ± 1.25 W/kg
		Split squat jump average power relative to body mass[b]		-0.68**	663 ± 121.4 W 7.32 ± 1.34 W/kg
		squat jump peak power relative to body mass[a]		-0.66**	1593 ± 258.1 W 17.58 ± 2.85 W/kg
		Split squat jump peak power relative to body mass[b]		-0.65**	1549 ± 285.4 W 17.10 ± 3.15 W/kg
		squat jump peak force relative to body mass[a]		-0.59**	1348 ± 201.1 W 14.88 ± 2.22 W/kg
		Split squat jump peak force relative to body mass[b]		-0.49**	1731 ± 294.5 W 19.10 ± 3.25 W/kg
		Squat jump peak RFD relative to body mass[a]		-0.40*	2993 ± 791.8 N/s 33.04 ± 8.74 N/s/kg
		Split squat jump peak RFD relative to body mass[b]		-0.54**	3724 ± 1140.7 N/s 41.10 ± 12.59 N/s/kg
		Squat jump peak velocity[a]		-0.40*	1.97 ± 0.13 m/s
		Split squat jump peak velocity[b]		-0.45**	1.64 ± 0.17 m/s

*Statistically significant ($p \leq 0.05$)
*Statistically significant ($p \leq 0.01$)
[a]performed in a smith machine with a load equivalent to 40% 1RM smith machine squat
[b]performed in a smith machine with a load equivalent to 40% 1RM smith machine split squat

Table 2.13 (continued)

Source	Athlete status	Strength measure	Acceleration performance measure	Pearson correlation coefficient	Strength performance values reported
Marques et al. (2011)	25 trained (Tier 2) physical education students competing in team sports (68.3 ± 5.4 kg)	Countermovement jump bar displacement	5 m sprint time	-0.68**	-
		Countermovement jump bar displacement time duration		-0.70**	
		Countermovement jump propulsive time duration		-0.74**	
		Countermovement jump time to peak bar velocity		-0.66**	
		Countermovement jump mean bar velocity		-0.23	
		Countermovement jump peak bar velocity		-0.31	
		Countermovement jump mean force		-0.38	
		Countermovement jump mean force until peak velocity		-0.68**	
		Countermovement jump mean propulsive force		-0.80**	
		Countermovement jump peak force		-0.43	
		Countermovement jump time to peak force		-0.13	
		Countermovement jump mechanical impulse		-0.70**	
		Countermovement jump maximum RFD		-0.35	
		Countermovement jump time to maximum RFD		-0.07	
		Countermovement jump mean power		-0.23	
		Countermovement jump mean power until peak velocity		-0.65**	
		Countermovement jump mean propulsive power		-0.72**	
		Countermovement jump peak power		-0.50	
		Countermovement jump time to peak power		-0.66**	

*Statistically significant ($p \leq 0.05$)
**Statistically significant ($p \leq 0.01$)

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Table 2.13 (continued)

Source	Athlete status	Strength measure	Acceleration performance measure	Pearson correlation coefficient	Strength performance values reported
Zabaloy et al. (2020)	24 highly trained (Tier 3) rugby forwards (96.3 ± 14.0 kg)	Theoretical peak mean power derived during squat jump force-velocity profiling	5 m sprint time	-0.30	2315 ± 359 W (24.0 ± 6.0 W/kg)
		Squat jump height		-0.43*	0.288 ± 0.493 m
		Countermovement jump height		-0.54**	0.331 ± 0.557 m
Cronin and Hansen (2005)	26 highly trained to elite (Tiers 3 and 4) rugby league players (97.8 ± 11.8 kg)	Peak knee concentric extension torque at 300°/s	5 m and 10 m sprint time	-0.04 and 0.00 (300°/s for 5 m and 10 m, respectively)	13 fastest = 180 Nm 13 slowest = 168 Nm
		Peak knee concentric flexion torque at 300°/s		-0.13 and -0.05 (300°/s for 5m and 10m, respectively)	13 fastest = 127 Nm 13 slowest = 126 Nm
		Countermovement jump height (no arm swing)		-0.60* (5 m) -0.62* (10 m)	13 fastest = 0.47 m 13 slowest = 0.37 m
		Squat jump height (30kg loaded bar)		-0.64* (5 m) -0.66* (10 m)	13 fastest = 0.31 m 13 slowest = 0.27 m
		Average power during squat jump (30kg loaded bar)		-0.13 (absolute at 5 m) -0.55* (relative to body mass at 5 m) -0.11 (absolute at 10 m) -0.54* (relative to body mass at 10 m)	13 fastest = 2227 W (22.4 W/kg) 13 slowest = 2144 W (21.4 W/kg)

*Statistically significant ($p \leq 0.05$)
**Statistically significant ($p \leq 0.01$)

Table 2.13 (continued)

Source	Athlete status	Strength measure	Acceleration performance measure	Pearson correlation coefficient	Strength performance values reported
Bracic et al. (2011)	36 physical education students (participant status not provided; 78.9 ± 7.3 kg)	Time to peak concentric torque relative to body mass of the hamstrings at 240°/s on an isokinetic dynamometer	5 m and 10 m sprint time	-0.55** (hamstrings, 5 m) -0.44** (hamstrings, 10 m)	105.7 ± 1.83 Nm (time to peak torque = 0.21 ± 0.08 s) 1.34 ± 0.25 Nm/kg
		Time to peak concentric torque relative to body mass of the quadriceps at 240°/s on an isokinetic dynamometer		Values not reported and were non-significant	135.7 ± 2.26 Nm (time to peak torque = 0.16 ± 0.07 s) 1.72 ± 0.31 Nm/kg
Baker and Nance (1999)	20 elite (Tier 4) rugby league players (93.4 ± 11.7 kg)	3RM hang power clean	10 m sprint time	-0.36 (absolute) -0.56* (relative to body mass)	102.2 ± 13.4 kg 1.09 ± 0.14 kg/kg
		40 kg jump squat average power		-0.02 (absolute) -0.52* (relative to body mass)	1626 ± 238 W 17.41 ± 2.55 W/kg
		60 kg jump squat average power		-0.03 (absolute) -0.57* (relative to body mass)	1739 ± 209 W 18.62 ± 2.24 W/kg
		80 kg jump squat average power		-0.07 (absolute) -0.53* (relative to body mass)	1842 ± 221 W 19.72 ± 2.37 W/kg
		100 kg jump squat average power		-0.08 (absolute) -0.61* (relative to body mass)	1856 ± 252 W 19.87 ± 2.70 W/kg
		Jump squat max power		-0.07 (absolute) --0.56* (relative to body mass)	1894 ± 226 W 20.28 ± 2.42 W/kg
Wisloff et al. (2004)	17 elite (Tier 4) soccer players (76.5 ± 7.6 kg)	Countermovement jump height	10 m sprint time	-0.72** (10 m)	0.56 ± 0.04 m
Cunningham et al. (2013)	20 elite (Tier 4) rugby players (105.5 ± 11.9 kg)	Peak power during countermovement jump	10 m sprint time	-0.14 (absolute) -0.82** (relative to body mass)	5476 ± 616.4 W 51.91 ± 5.84 W/kg
		Countermovement jump height		-0.88**	-

*Statistically significant ($p \leq 0.05$)
**Statistically significant ($p \leq 0.01$)

2.7.3 Stiffness and reactive strength

Regardless of an athlete's maximum or power capabilities, the potential of their powerful lower limb actions to generate large amounts of energy and produce high propulsive GRF is unlikely to be fully realised unless a suitably 'stiff' leg is adopted during stance. Stiffness refers to the amount of deformation of an object under a given unit of force and is calculated at the CM and leg levels through the division of the peak GRF by CM (vertical stiffness) or whole leg (leg stiffness) displacement, or at the joint level by the ratio of the change in joint moment and the change in joint angle. Commonly stiffness is measured during 'rebounding' activities such as hopping and sprinting (e.g., Arampatzis et al., 1999; Charalambous et al., 2012; Chelly & Denis, 2001). Powerful hip extension and knee flexion of the swing leg just prior to touchdown will result in rapid thigh and shank segment rotations and thus rapid foot translation into ground contact (Clark et al., 2020). To overcome the downwards velocity of the leg and the negative vertical velocity of the body during ground contact quickly, the ability to resist leg deformation – thus stiffness - would appear important. Leg stiffness during the ground contact phase of running has been reported to increase when velocity increases (Arampatzis et al., 1999; Luhtanen & Komi, 1980) and it is thought that a stiffer system allows for more efficient elastic energy contribution, thus potentially enhancing force production (Farley & Morgenroth, 1999).

Vertical and leg stiffness during stance would seem more important during the maximum velocity phase of sprinting compared with the initial steps of a sprint. For example, Chelly and Denis (2001) measured accelerations and maximum velocities of 11 developmental (Tier 2) handball players (body mass 68 ± 7 kg) during a 40 m sprint by radar. They also measured vertical stiffness during a hopping test (vertical jump rebounds from a standing position for 10 s on a force platform). Vertical stiffness was significantly positively correlated with maximum velocity ($r = 0.68$, $p < 0.05$), but not the initial acceleration magnitude of participants (Chelly & Denis, 2001). Bret et al. (2002) found developmental and trained (Tier 2) sprinters (mean 100 m time reported 11.40 s; body mass 72.8 ± 7.6 kg) who had the greatest leg stiffness (obtained during a repeated hopping test) produced the highest mean velocity between 30 m and 60 m, but leg stiffness was not related to the mean velocities achieved over the first 30 m (Bret et al., 2002). Instead, the countermovement jump was found to be the main predictor of sprint performance to 30 m ($r = 0.66$, $p < 0.01$).

Similar findings were evident in 20 elite (Tier 4) rugby players where a moderate statistically significant negative relationship was found between their 20 to 30 m split time during a sprint and vertical stiffness measured during a two-legged hopping test (r = - 0.46, p = < 0.05), although only a small statistically non-significant negative relationship (r = -0.28) was observed between vertical stiffness and 10 m sprint time (Cunningham et al., 2013). Interestingly a large statistically significant negative relationship (r = -0.60, p = < 0.01) *was* observed between the reactive strength index (RSI) of participants measured during drop jumps from a 40 cm high box (flight time [s] divided by contact time [s]) and their 10 m sprint time (Cunningham et al., 2013). However, when contact time alone during the drop jumps was analysed, only a moderate statistically non-significant positive relationship (r = 0.38) was found between this variable and 10 m sprint time (Cunningham et al., 2013). This would seem logical given that contact time can be used in the estimation of vertical stiffness during hopping tasks (e.g., Dalleau et al., 2004), whereby a shorter ground contact time is reflective of reduced CM displacement during ground contact. This suggests that reactive strength may be of importance to the early acceleration phase, but the ability to generate a higher jump height, rather than reducing contact time in a drop jump is more related to initial acceleration performance. Therefore, the reasons why leg stiffness appears to be correlated to maximum velocity, but not initial acceleration performance may in part be explained by the longer contact times during the initial steps alongside the greater emphasis on power generation compared with the maximum velocity phase where there is a greater power absorption emphasis (e.g., Bezodis et al., 2008).

Although vertical or leg stiffness may not be related to performance during the initial steps of a sprint, research demonstrates that attenuating the degree of ankle dorsiflexion (Bezodis et al., 2015), and that higher levels of ankle joint stiffness during the negative phase of the ground contact (Charalambous et al., 2012), may be advantageous to initial sprint acceleration performance. This is likely because, unlike the hip and knee joints during early acceleration, the ankle shows a clear pattern of dorsi-flexion followed by plantarflexion, and thus energy absorption then generation (e.g., Bezodis, et al., 2014; Charalambous et al., 2012; Debaere et al., 2013a). A stable ankle joint during the first quarter of the stance is therefore necessary so that the hip extensor moments can effectively accelerate the CM horizontally (see Section 2.3.4). Therefore, since leg stiffness has been shown to primarily depend on ankle joint stiffness during hopping tasks (Farley & Morgenroth, 1999), leg or vertical stiffness assessments may still provide useful in establishing the strength qualities of an athlete necessary to optimise sprint performance during the initial steps. As highlighted earlier, multiple regression analyses may also provide further insight into the combined relationships of multiple strength qualities (i.e., given the likely synergy between the hip and ankle joints during acceleration) with initial sprint performance and technique.

2.8 Training intervention studies

The number of studies which have investigated the efficacy of training interventions on the short sprint performance of team sport players is vast. Despite the importance of initial acceleration in team sports, the best training methods to enhance sprinting performance in this phase is unclear (Nicholson et al., 2021). Sport only training which does not include elements specifically aimed at enhancing speed has shown to be insufficient for significantly improving the sprint performance of a range of team sport players over the first 5 or 10 m (e.g., Alves et al., 2010; Brito et al., 2014; Coratella et al., 2019; Faude et al., 2013; Hammami et al., 2019; Ishøi et al., 2018; Krommes et al., 2017; Mendiguchia et al., 2015; Rimmer & Sleivert, 2000; Rodríguez-Rosell et al., 2017; Rodríguez-Rosell et al., 2016; Ronnestad et al., 2008; Spinks et al., 2007; Suarez-Arrones et al., 2019; Torres-Torrelo et al., 2017; Wong et al., 2010). Whilst rugby backs will undertake training for multiple reasons and not solely for the development of speed (e.g., for technical, tactical, strength, power and endurance purposes), these findings suggest that, in addition to rugby training, to enhance the initial acceleration of rugby backs, training methods with the specific intention of enhancing sprinting performance are needed to enhance the initial acceleration of rugby backs.

Due to the need for the concurrent training of multiple physical qualities in team sport players, like rugby backs, understanding the most effective training methods for enhancing their initial acceleration is difficult to determine from the existing literature. For instance, although studies may categorise a specific intervention based on a single training method (e.g., plyometrics), the additional training that is routinely conducted as part of the athletes' training week is rarely taken into consideration, even in most reviews and meta-analyses (e.g., Alcaraz et al., 2018; Garcia-Ramos et al., 2018; Rumpf et al., 2016). Differences in playing standard, age, training background, sport and seasonal training phase also provide challenges in trying to ascertain what the most effective interventions are for enhancing initial acceleration performance. As already discussed, differences in the constraints between athletes (see Section 2.5) will likely alter their system behaviour (Newell, 1986) and thus the same response of an intervention may not be elicited across all team sport players. Therefore, interventions ought to be considered on an individual-specific basis in the context of a particular individual's constraints.

Nicholson et al. (2021) provided the largest systematic review and meta-analysis comparing multiple training methods for developing the acceleration performance of team sport players whilst also considering the routine training of groups alongside the specified interventions being applied as well as different 'moderator' effects (e.g., playing standard, age, gender, training background, sport, and seasonal training phase). Nicholson et al. (2021) reported moderate to large significant improvements in sprint performance (standardised mean differences [SMD] range = 0.52 to 1.33; *p* 0.04 to < 0.001) over 5 or 10 m following methods which individually employed strength-based interventions, resistance (e.g., sled) or assistance (e.g., pulley) sprint training interventions and combined training interventions which included different combinations of specific sprint training ('free' sprinting and sprint-technique drills), strength-based training and resisted/assisted sprinting. Specifically, in rugby sport players (i.e., rugby union, rugby league, rugby sevens; Comfort et al., 2012; Harrison & Bourke, 2009; Winwood et al., 2015) or in groups of team sport players including those who compete in rugby sports (Lockie et al., 2014; Lockie et al., 2014; Spinks et al., 2007), changes in their sprinting performance over the first 5 m has been shown to improve by small to very large magnitudes (mean ± SD, range: $d = 1.28 \pm 0.92$, 0.36 to 3.45) following interventions employing either strength-based, resisted/assisted sprinting or combined training methods. However, no studies directly assessed the efficacy of sprint specific training ('free' sprinting and sprint-technique drills) on the initial acceleration performance of rugby players, and it is not known therefore how sprint specific training can impact the sprinting performance of rugby backs during the initial steps of a sprint.

Interestingly, the findings reported in the Nicholson et al. (2021) review and meta-analysis showed sprint specific training to be the least effective of all methods analysed for improving initial acceleration performance (SMD range = -0.13 [5 m sprint performance], -0.04 [10 m sprint performance]. However, only 11 out of 121 studies met the inclusion criteria of their research and thus relative to the number of studies which have investigated the efficacy of other training methods to enhance acceleration performance, the research on this specific area is lacking. Furthermore, no study to date has attempted to conduct sprint acceleration training interventions for athletes based on their individual technical needs, which have been identified during prior analysis. Given the emphasis which is placed on understanding how the dynamics of each *individual* affect the way they self-organise to satisfy the specific constraints of a task (e.g., sprinting) when interacting with their environment (Davids et al., 2014), research in this area is needed to advance the knowledge of practitioners working with rugby backs and to inform their sprint acceleration training practices.

2.9 Literature review summary

From the research reviewed it is evident that the production of large horizontal propulsive GRFs in short timeframes and the ability to orient the resultant GRF vector more horizontally are key determinants for initial acceleration performance. These GRF characteristics are produced while large amounts of energy are generated by the lower limb. The contribution of the hip extensor and plantarflexor moments and the power generated at the hip and ankle during the stance phase appear to be particularly important for the achievement of high acceleration performance in the initial steps.

Whilst the GRF characteristics and joint kinetic associations with initial acceleration performance are relatively well established, how the kinematic aspects of athletes' technique relate to their performance in this sprint phase is less clear and conflicting perspectives exist on which, if any, technical features are more important for initial acceleration performance. Furthermore, the majority of the current understanding of sprint acceleration technique is primarily based on the data from sprinters and whether this information is transferable to rugby backs is unclear, due to differing ecological constraints between sprinters and rugby players. Whilst the literature demonstrates in some cases that performer constraints, in the way of strength qualities, are related to, and can be trained to enhance, the initial acceleration performance of team sport players, it is not known how the strength qualities of rugby backs interact with their technique to produce high acceleration performance during the initial steps. Research in this area is ultimately needed to determine how the initial acceleration performance of rugby backs competing in a truly high-performance sporting environment can be enhanced.

CHAPTER 3: DIFFERENCES IN SPATIOTEMPORAL AND LINEAR KINEMATICS BETWEEN RUGBY PLAYERS AND SPRINTERS DURING SPRINT ACCELERATION

A version of the study reported in this chapter was published in the European Journal of Sport Science as Wild et al. (2018) - doi.org/10.1080/17461391.2018.1490459. The study presented here has been updated and revised to take account of research published since the study's publication and to integrate fully within the thesis narrative.

3.1 Introduction

The ability to achieve high acceleration during the initial steps is an important aspect of a rugby back's performance in during a rugby match. However, as discussed in the previous chapter much of the current understanding of acceleration technique is from studies of track and field sprinters (e.g., Bezodis, et al., 2014; Bezodis et al., 2015; Debaere et al., 2013a; Ettema et al., 2016; Jacobs & van Ingen Schenau, 1992; Mero et al.,1983; Morin et al., 2015a; Nagahara et al., 2014a; Rabita et al., 2015). This information is potentially attractive to coaches of rugby backs since it is based on the fastest of all athletes and may be used to help inform their players' sprint training practices. However, this approach implies that an ideal movement template exists for all athletes and does not take into account the differing movement strategies which may emerge from the interaction of divergent constraints imposed (Newell, 1986).

Considering that task, environmental and performer constraints are thought to influence movement (Newell, 1986), variations in technique and movement patterns can emerge (Davids et al., 2008; Newell, 1986) as a function of differing interacting constraints between rugby players and sprinters. The block exit (sprinters) and standing (rugby players) start conditions (task constraints), for instance, require different body segment orientations which are likely to influence techniques adopted in the subsequent steps. The environment in which each group performs also differs. For example, rugby is typically played on a grass surface, whereas sprinters compete on a running track. Rugby players are also required to sprint as one of many match demands in their training and competition environments. Differences in such demands are also further evident across playing position in rugby (i.e., backs vs. forwards). Regarding performer constraints, movement strategies adopted between athlete groups are also likely to be affected by physical and anatomical constraints (Holt, 1998). Different performer constraints between sprinters and rugby players, such as physical stature and body mass, musculoskeletal structure (Lee & Piazza, 2009) and strength qualities may therefore result in different patterns of movement. It is therefore important to understand which, if any, of the technical features identified as important for sprint acceleration performance in sprinters may inform the practices of coaches in attempts to enhance the acceleration abilities of rugby players, given the differing constraints imposed.

There are likely many technical factors which influence initial sprint acceleration performance. However, ‘higher order’ spatiotemporal variables, including step length and step rate (the product of which determines step velocity) and contact and flight times have received substantial attention in the literature (e.g., Debaere et al., 2013b; Lockie et al., 2013; Mackala et al., 2015; Mann & Murphy, 2015; Mero et al., 1983; Murphy, et al., 2003; Nagahara et al., 2014b; Rabita et al., 2015). Despite this coverage, there remain conflicting perspectives on the importance of these higher order spatiotemporal variables during the initial acceleration (i.e., the first three of four steps; Nagahara et al., 2014a; von Lieres Und Wilkau et al., 2020b) and the information available on the linear kinematics which determine these factors (Hay, 1994; Hunter et al., 2004) is sparse. The difficulty in establishing the importance of such technical features for acceleration performance is further compounded by different measures used (e.g., absolute or relative), study designs adopted (e.g., correlations or group comparisons) and disparities between how acceleration performance is quantified, which may explain some of the contradictions (Bezodis et al., 2010).

Therefore, the aim of this chapter was to undertake a direct comparison between groups of rugby players and sprinters, with start conditions representative of their respective environments and standardised measures of the technical features of interest and sprint performance in the initial steps. Research question I - ‘*What are the difference in spatiotemporal variables and linear kinematics between professional rugby players and sprinters during the initial steps or a sprint, and how do they relate to performance?’* - was developed to address this aim. By doing so, practitioners applying technical interventions would be better informed on how well the kinematic aspects of a sprinter’s technique can translate to rugby backs.

3.2 Methods

3.2.1 Participants

Eighteen male trained to elite (Tiers 2 to 4) sprinters (mean ± *SD*: age 21 ± 4 years; stature 1.80 ± 0.10 m; body mass 75.7 ± 5.2 kg; 100 m personal best (PB) 10.60 ± 0.40 s, range 9.96 - 11.33 s) and 30 male professional (Tiers 4 to 5) rugby union players competing in the English Premiership Rugby division, separated into forwards (n = 15; mean ± *SD*: age 25 ± 4 years; stature 1.88 ± 0.06 m; body mass 111.6 ± 8.9 kg) and backs (n = 15; mean ± *SD*: age 26 ± 4 years; stature 1.81 ± 0.06 m; body mass 88.6 ± 7.1 kg) volunteered to participate. All participants provided written informed consent and the study protocols were submitted to, and approved by, the Local Research Ethics Committee (see Appendix B for ethics approvals for all studies in the chapters of this thesis). At the time of testing, participants were injury free and completed maximal effort sprint accelerations on a weekly basis as part of their routine training. For the rugby players, data were collected during pre-season following 48 hours of abstinence from running, sprinting, and lower body strength training. For the sprinters, data were collected during track training sessions just prior to the competition phase of the outdoor season on days where the emphasis of training was to sprint maximally over distances between 30 and 60 m from starting blocks set up to their preferred positioning.

3.2.2 Procedures

The rugby players completed a 20-minute standardised warm-up (see Appendix C), and then performed three maximal effort 10 m sprints from a standing start (preferred foot forward), on an outdoor acrylic surface, wearing a t-shirt, shorts and trainers. Rest periods between each sprint were approximately 3-4 minutes. On an outdoor running track, the sprinters completed their regular warm-up routine overseen by their technical coach, and then completed three maximal effort sprints from blocks wearing spikes, shorts and either a vest or no top. Rest periods between each sprint were between 7-12 minutes. For all sprints, video images (448 × 336 pixels) were obtained at 240 Hz (Sanyo Xacti VPC-HD2000). The camera was positioned 20 m from, and perpendicular to, the running lane to capture sagittal plane images from touchdown and toe-off across the first three steps for each athlete within an approximately 6 m wide field of view. A 5.00 m horizontal video calibration was recorded at each data collection session.

The kinematic variables of interest were determined from the video frames identified as the instants of touchdown (first frame the foot was visibly in contact with the ground) and toe-off (first frame the foot had visibly left the ground) across the first three steps of each sprint using Kinovea (v.0.8.15). The human body was modelled as 14 rigid segments: feet, shanks, thighs, hands, lower arms, upper arms, trunk, and head. This required manual digitisation of the following: vertex of the head, halfway between the supra-sternal notch and the 7th cervical vertebra, shoulder, elbow and wrist joint centres, head of third metacarpal, hip, knee and ankle joint centres, the most posterior part of the heel, and the tip of the toe.

The scaled digitised coordinates were exported to Excel (Microsoft Office 2013), where the following spatiotemporal step characteristics were determined: contact time (s), flight time (s), step length (m; horizontal displacement between the toe tips at adjacent touchdowns), step rate (Hz; the reciprocal of step duration, which was determined as the sum of contact time and the subsequent flight time), and step velocity (m/s; the product of step length and step rate). Whole body centre of mass (CM) location was calculated using de Leva's (1996) segmental inertia data. This enabled the calculation of touchdown and toe-off distances (m; horizontal distance between the toe and whole-body CM, with positive values representing the toe ahead of the CM), contact length (m; horizontal distance the CM travelled during stance) and flight length (m; horizontal distance the CM travelled during flight). All lengths and distances were normalised to stature. Finally, average horizontal external power was calculated from the instant of the first touchdown until the end of the third contact phase, and used as an objective measure of sprint acceleration performance (Bezodis et al., 2010). To facilitate between-group comparisons, this was normalised according to a modification of the equation presented by Hof (1996) as used by Bezodis et al. (2010).

3.2.3 Statistical analyses

Test-retest intra-rater reliability of manual digitisation was determined (Hopkins, 2015) using an intraclass correlation coefficient (ICC 3,1) with 90% confidence intervals. ICC values less than 0.50, between 0.50 and 0.75, between 0.75 and 0.90, and greater than 0.90 were used to indicate poor, moderate, good, and excellent reliability (Portney & Watkins, 2000). The segment endpoints at the instant of touchdown and toe-off, for ten participants selected at random, were digitised on two separate occasions, one week apart.

The data obtained for each kinematic variable in each step individually were averaged across the three sprint trials of each participant. Independent Samples t-tests were used to compare the means between each independent group to determine whether they were statistically different. The magnitudes of the differences between group means (sprinters, backs, and forwards) for all spatiotemporal and kinematic variables were also determined using effect sizes (Cohen, 2013), with an effect size of 0.20 used to define the smallest meaningful difference (Hopkins, 2002; Winter et al. 2014). The magnitudes of these standardised differences were expressed as follows: <0.2, trivial; 0.20, small; 0.60, moderate; 1.2, large; 2.0, very large and 4.0, extremely large (Hopkins et al., 2009). Confidence intervals (90%) were calculated to measure the uncertainty of the effect sizes. Differences were considered practically meaningful when the effect size was equal to or greater than 0.20 and confidence intervals did not include positive and negative values greater than smallest meaningful difference (where the chances of positive and negative value differences are both < 5%). Each spatiotemporal and kinematic variable was then averaged over the first three steps for each participant. These values were used to determine the relationships of each technique variable with performance (NAHEP) within each group using Pearson's product moment correlation coefficient, with an r value of ± 0.10 used to define the smallest clinically important correlation (Hopkins, 2002). The strength of relationships were defined as: (±) < 0.1, trivial; 0.1 to 0.3, small; 0.3 to 0.5 moderate, 0.5 to 0.7 large, 0.7 to 0.9 very large and > 0.9, practically perfect (Hopkins, 2002). Confidence intervals (90%) for the observed relationships were calculated to measure the uncertainty of relationship magnitudes. Relationships were deemed meaningful when the relationship magnitude was equal to or greater than the smallest clinically important correlation and confidence limits did not include positive and negative values greater than the smallest clinically important correlation. To determine the statistical significance of the group differences and relationships observed, alpha was set at $p < 0.05$.

3.3 Results

The results of the intra-rater reliability analysis can be found in Appendix D (Table D.1).

3.3.1 Between group differences in acceleration performance

Regarding acceleration performance over the first three steps (Figure 3.1), backs produced significantly (i.e., $p < 0.05$) greater NAHEP than forwards by large meaningful magnitudes, and the NAHEP of sprinters was significantly greater than the forwards and backs by extremely large and large meaningful magnitudes, respectively.

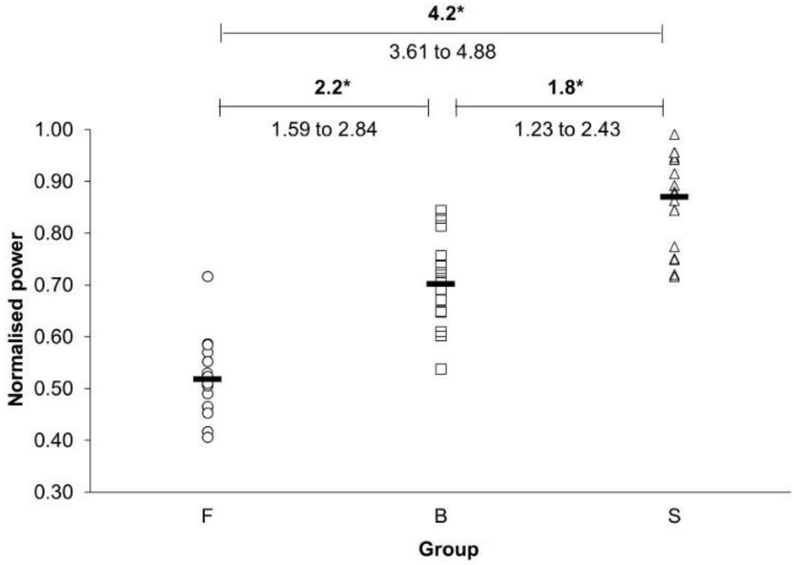

Figure 3.1. Normalised average horizontal external power (NAHEP) for forwards (F), backs (B) and sprinters (S) from first touchdown until the end of the third contact phase of a sprint, and the effect sizes[a] (and their 90% confidence limits[b]) between each group. Individual participant means are plotted, and the black bars represent group means.

[a]Above the horizontal lines. A positive/negative effect size depicts a greater/lesser magnitude of NAHEP produced by the second group in their respective group comparison (e.g., a positive effect size under 'F vs. B' would indicate that backs produced higher NAHEP compared with forwards). Effect sizes in bold depict ‘meaningful’ differences.

[b]Below the horizontal lines. *Statistically significant ($p < 0.05$)

3.3.2 Between group differences in spatiotemporal variables

Regarding spatiotemporal variables, backs achieved significantly greater step velocities (Figure 3.2a) compared with forwards by moderate and meaningful magnitudes (d = 0.76 to 1.08). Sprinters produced significantly and moderately greater step velocities than forwards (d = 0.95 to 1.18), which were meaningful, although compared with backs the differences (in the same direction) were only trivial to small (d = 0.06 to 0.49) and not significant (only meaningful in step three). The step rates (Figure 3.2c) of backs were significantly greater than those of the forwards by moderate and meaningful magnitudes (d = 0.64 to 1.16). Sprinters achieved greater step rates than the forwards by small (step one) and moderate magnitudes (steps two and three), respectively (d = 0.28 to 0.77). These differences were meaningful in steps two and three and significant in step three. However, the sprinters’ step rates were lower than those of the backs, with non-significant small differences evident across all three steps that were meaningful in steps one and two (d = -0.46 to -0.32).

The contact times (Figure 3.2d) of backs were significantly shorter compared with forwards by moderate (step one), large (step two) and very large (step three) meaningful magnitudes (*d* = -2.67 to -1.00). Sprinters' contact times were consistently shorter than forwards and longer than backs. The difference between sprinters' and forwards' contact times in the first step was not significant, but they were small and meaningful, and by the second and third steps it was significant, large and meaningful (*d* = -1.89 to -0.47). The difference between sprinters' and backs' contact times were not significant, but they were moderate (step one), small (steps two and three) and meaningful (*d* = 0.50 to 0.63). The flight times (Figure 3.2e) of backs were greater than forwards by a non-significant, small and not meaningful magnitude in the first step and by non-significant and significant, moderate and meaningful magnitudes in the second and third steps, respectively (*d* = 0.37 to 0.81). Differences in flight times between sprinters and forwards were not significant, small and not meaningful for step one and significant, moderate and meaningful (sprinters producing greater flight times) for steps two and three (*d* = 0.13 to 0.76).

Backs produced significantly greater step lengths (Figure 3.2b) compared with forwards by moderate and meaningful magnitudes in steps one and two and by step three the difference was non-significant, small and meaningful (*d* = 0.51 to 0.75). Sprinters produced significantly longer step lengths than forwards and backs across each step. Compared with forwards these differences were significant, large and meaningful (*d* = 1.36 to 1.46) and compared with backs they were non-significant, small and meaningful in step one, and significant, moderate and meaningful in steps two and three (*d* = 0.52 to 0.92).

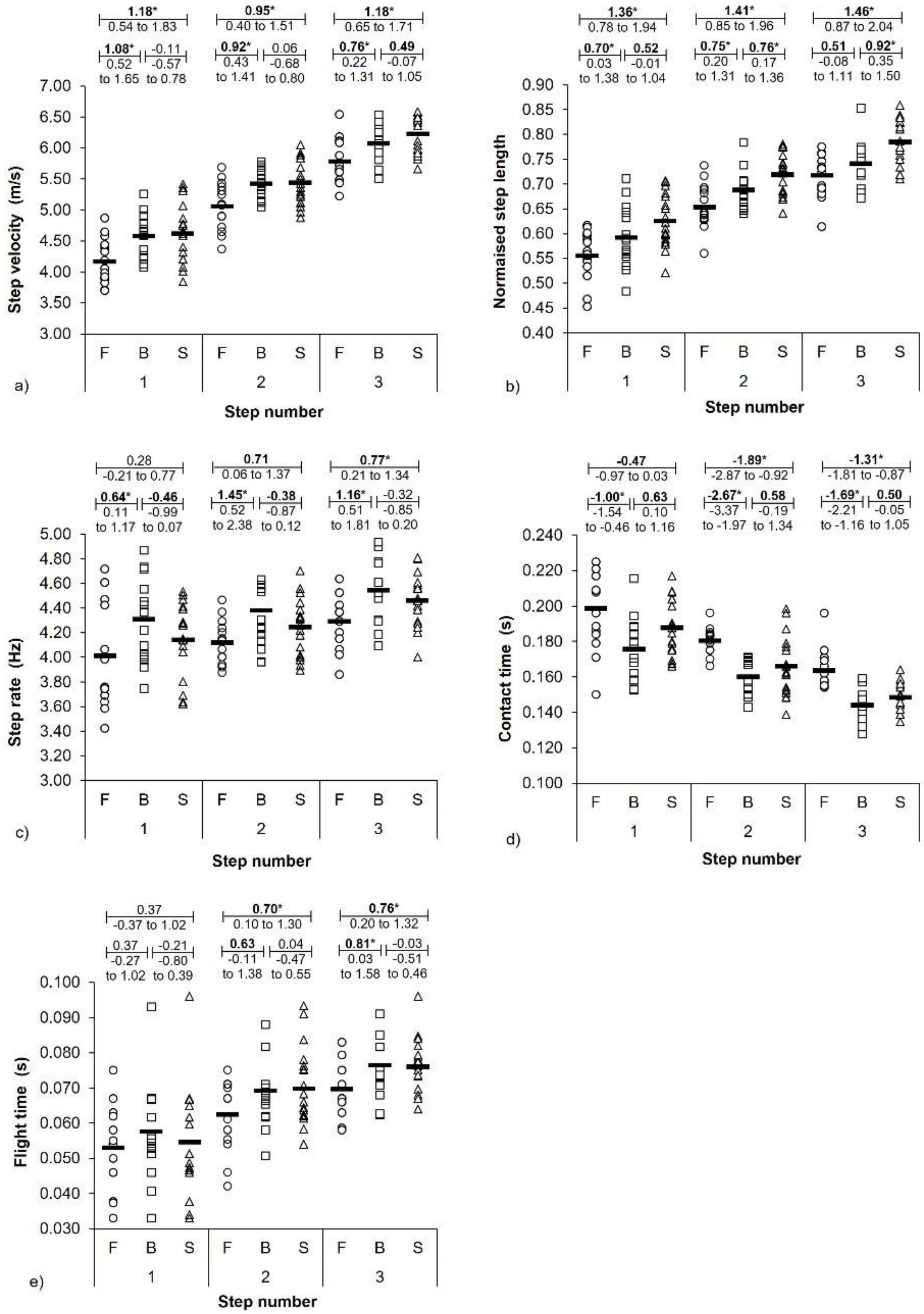

Figure 3.2. Spatiotemporal variables for rugby forwards (F) and backs (B), and sprinters (S) during the first three steps of a sprint and the effect sizes[a] (and their 90% confidence limits[b]) between each group. Individual participant means are plotted, and the black bars represent group means. Each participant within each group is represented as an individual data point.

[a]Above the horizontal lines. A positive/negative effect size depicts a greater/lesser magnitude of the variable produced by the second group in their respective group comparison (e.g., a positive effect size under 'F vs. B' for step rate would indicate that backs produced higher step rates compared with forwards). Effect sizes in bold depict ‘meaningful’ differences.

[b]Below the horizontal lines. * Statistically significant ($p < 0.05$)

3.3.3 Between group differences in linear kinematic variables

Non-significant trivial to small differences between the contact lengths of backs and forwards (Figure 3.3a), which were only meaningful in the third step (shorter in backs), were observed (*d* = -0.25 and -0.33). Sprinters achieved non-significant shorter contact lengths of small meaningful magnitudes compared with forwards in step one, and non-significant greater contact lengths of moderate and meaningful magnitudes compared with backs in step three (*d* = -0.40 and 0.59). Backs achieved significantly greater flight lengths compared with forwards (Figure 3.3b) by moderate (steps one and two) to large (step three) and meaningful magnitudes (d = 0.87 to 1.63). The flight lengths of sprinters were significantly greater compared with forwards across all steps by large to very large and meaningful magnitudes (*d* = 1.41 to 2.45). Sprinters' flight length was also greater compared with backs where non-significant, small and meaningful differences were evident (*d* = 0.38 to 0.48).

Backs touched down with their toe more posterior relative to their CM compared with forwards across each step (Figure 3.3c). During step one the differences in their touchdown distances were not significant, but were moderate and meaningful, and by steps two and three the differences were significant, moderate and meaningful (*d* = -1.19 to -0.57). Sprinters' touchdown distances were consistently more negative across all steps relative to forwards and backs. The difference was significantly greater by large (step one), and very large (steps two and three) meaningful magnitudes compared with forwards (*d* = -2.64 to -1.92). Compared with backs the differences were significantly greater by large (step one) and moderate (steps two and three) meaningful magnitudes (*d* = -0.89 to -1.69).

Backs achieved a CM position which was further ahead of their toe at toe-off (i.e., toe-off distance was more negative, Figure 3.2d) compared with forwards (d = -1.22 to -0.42). A non-significant, small and meaningful difference was observed in step one, whereas significant differences of moderate and meaningful magnitude were evident in steps two and three. Sprinters positioned their CM significantly further forward of their toe at toe-off compared with forwards and backs by very large meaningful magnitudes in each step (*d* = -2.62 to -2.05).

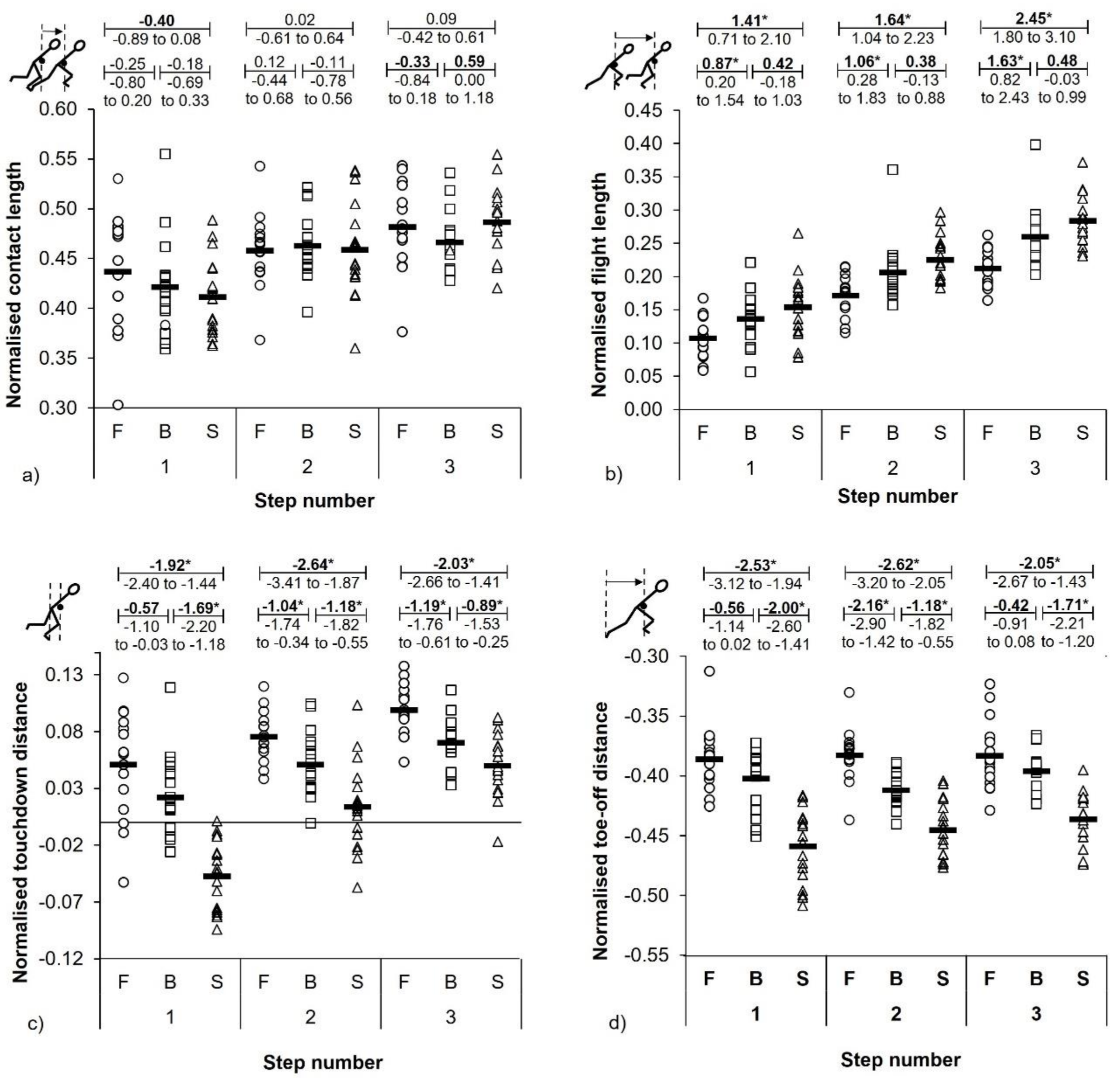

Figure 3.3. Linear kinematic variables for rugby forwards (F) and backs (B), and sprinters (S) during the first three steps of a sprint and the effect sizes[a] (and their 90% confidence limits[b]) between each group. Individual participant means are plotted, and the black bars represent group means. Each participant within each group is represented as an individual data point.

[a]Above the horizontal lines. A positive/negative effect size depicts a greater/lesser magnitude of the variable produced by the second group in their respective group comparison (e.g., a positive effect size under 'F vs. B' for toe-off distance would indicate that backs produced greater toe-off distances compared with forwards). Effect sizes in bold depict ‘meaningful’ differences.

[b]Below the horizontal lines. * Statistically significant ($p < 0.05$)

3.3.4 Relationships between kinematic variables and acceleration performance

Regarding correlation coefficients, only toe-off distance consistently demonstrated a meaningful relationship with NAHEP in each group (Figure 3.4h). These relationships were non-significant and moderate for backs and large and significant for forwards and sprinters (r = -0.58 to -0.44). Meaningful and moderate, but non-significant, relationships were also observed between step length and NAHEP (Figure 3.4a) in both forwards and sprinters (r = 0.39 and 0.45, respectively). In the same two groups non-significant small and meaningful negative relationships between contact time and NAHEP (Figure 3.4c) were observed (r = - 0.39 and r = - 0.35, respectively). The step rate of sprinters was moderately positively correlated to NAHEP (Figure 3b), as was the contact length (Figure 3.4c) of forwards (all meaningful, but not significant).

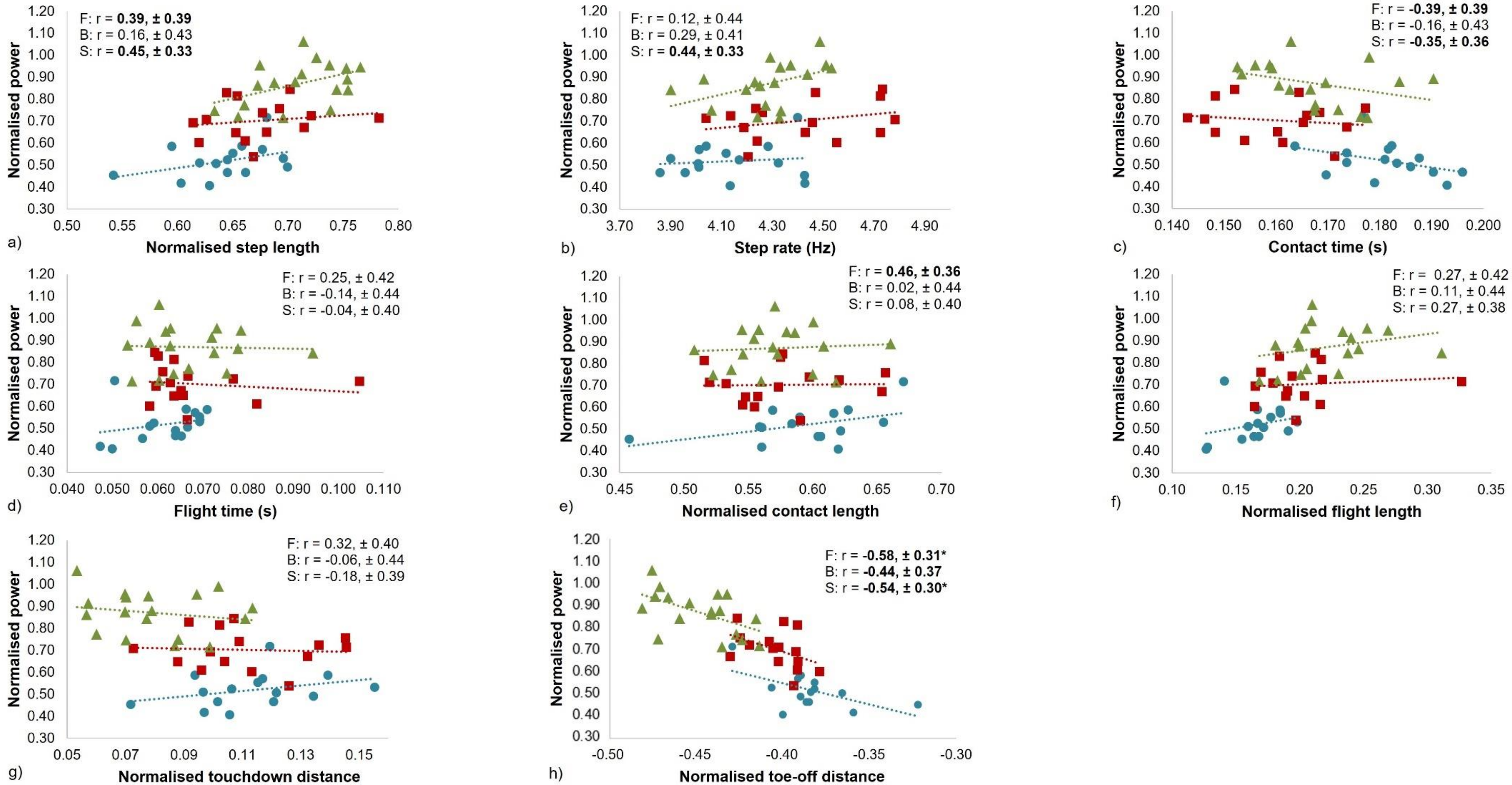

Figure 3.4. Relationships (Pearson's correlation coefficients and their 90% confidence limits) of spatiotemporal and linear kinematic variables with NAHEP for forwards (F), backs (B), and sprinters (S) from first touchdown until the end of the third contact phase of a sprint. Blue circles = rugby forwards; red squares = rugby backs, and green triangles = sprinters. Where correlation magnitudes are in bold font, the relationship is deemed meaningful (where CLs do not overlap substantial positive and negative values [i.e., r = ±0.1; Hopkins, 2002]). *Statistically significant ($p < 0.05$)

3.4 Discussion

The purpose of this chapter was to investigate the differences in spatiotemporal and linear kinematics between professional rugby players and sprinters during the initial steps of acceleration, and how each of these variables relates to initial sprint performance. This provides information to enhance the understanding of how knowledge of sprinters' acceleration techniques may be transferred to inform training practices aimed at enhancing the acceleration abilities of rugby backs. The main finding of this chapter was that there were multiple differences in the touchdown and toe-off kinematics evident between sprinters and rugby groups, but only one technical feature (toe-off distance) was consistently related to sprinting performance in all groups. There may therefore be limitations in how the available information concerning the touchdown and toe-off kinematics and step characteristics of sprinters can be used by coaches tasked with enhancing the acceleration abilities of rugby backs, possibly due to the different constraints imposed (Newell, 1986).

3.4.1 Starting conditions and acceleration performance

Sprinters achieved substantially greater levels of performance (NAHEP) compared with forwards and backs, by 40% and 19%, respectively. This can be explained by differences in the change in velocity from the beginning of the first contact phase to the end of the third (sprinters = 3.26 ± 0.28 m/s; backs = 2.60 ± 0.26 m/s; forwards = 2.48 ± 0.28 m/s), since less than 0.03 s separated the groups with respect to the time taken to achieve this change. No meaningful differences in absolute step velocity, however, were found between sprinters and backs until step three where sprinters reached a meaningfully higher step velocity (d = 0.49), because the backs entered the first step with a higher velocity than the sprinters (3.61 ± 0.16 vs. 3.36 ± 0.31 m/s; forwards = 3.38 ± 0.26 m/s). This is likely reflective of the differences in start conditions, where a longer distance between the feet in the standing start may lead to a longer push-off phase (Salo & Bezodis, 2004), thus affording the opportunity to produce higher impulse where the rapid initiation of a sprint in response to an external stimulus (e.g., starter's gun) is not required.

3.4.2 Spatiotemporal variables and touchdown technique

Sprinters consistently produced longer step lengths than backs, who also achieved longer step lengths than forwards (Figure 3.2b), whereas backs achieved the highest step rates in each step, followed by sprinters and then forwards (Figure 3.2c).The inconsistent findings of previous research as to the relative contribution of step length and step rate to initial acceleration performance of sprinters and team sport players (e.g., Debaere, et al., 2013b; Mackala et al., 2015; Murphy et al., 2003) as discussed in section 2.4 of Chapter 2, is further compounded by the results of the current study where positive moderate and meaningful relationships of step length and step rate with NAHEP in sprinters were found (r = 0.45 and 0.44), whereas only step length was correlated meaningfully to the NAHEP of forwards (r = 0.39) and no meaningful relationships of step length or step rate with the NAHEP of backs were found (Figures 3.4a; 3.4b).

The differences in step length between groups were achieved primarily through different flight lengths, but not contact lengths (Figure 3.3a; 3.3b). However, the location of the foot relative to the CM position was more posterior at both touchdown and toe-off for sprinters compared with both rugby groups, and for backs compared with forwards (Figures 3.3c; 3.3d). Smaller touchdown distances have been shown to be related to a more forward-orientated ground reaction force (GRF) vector (Bezodis et al. 2015; Kugler & Janshen, 2010), which has been identified as a key determinant of acceleration performance (Kawamori et al., 2013; Kugler & Janshen, 2010; Morin et al., 2011; Morin et al., 2012). However, no meaningful relationships between touchdown distance and NAHEP were evident in any group in the current study.

The lack of meaningful relationships between touchdown distance and initial acceleration performance may be explained by a number of factors. For example, Bezodis et al. (2015) demonstrated the existence of a within-individual curvilinear relationship between touchdown distance and horizontal power in the first stance phase for a trained sprinter, whilst vertical impulse production was found to increase linearly as the foot was placed further forward relative to the CM. Limiting how far posteriorly the foot makes contact relative to the CM may therefore be important in producing sufficient vertical GRF to maintain balance. Consequently, an optimal touchdown distance is likely to exist for each individual influenced by varying constraints. For instance, greater vertical GRF will need to be produced with increased body mass, therefore potentially requiring a greater touchdown distance (i.e., foot positioned further forward of the CM). Additionally, the block start already positions the sprinter’s CM ahead of their feet (Mero et al., 1983) and the effect of both running shoe worn and surface may also provide different opportunities for a sprinter’s maintenance of balance. The range of different constraints imposed on rugby players (e.g., greater mass [performer constraint], standing start [task constraint], grass surface [environmental constraint]) suggest that expecting them to touch down posterior to their CM in the same manner as sprinters during the initial steps may not be feasible. It may also be possible to manipulate GRF orientation through other technical means which do not affect the overall touchdown distance (Bezodis et al., 2017). Further investigations into the touchdown technique characteristics and constraints which influence a rugby back's initial acceleration performance is therefore warranted to help inform their sprint training practice.

3.4.3 Toe-off distance and the unique acceleration strategy of rugby backs

Whilst touchdown distance was not related meaningfully to sprint performance for any of the groups, toe-off distance consistently was (r = -0.44 to -0.58). Having the stance toe further behind the CM at toe-off was meaningfully associated with increased NAHEP in all three groups (relationships were also significant in forwards and sprinters), and therefore appeared to be reflective of an effective push-off. A more negative toe-off distance was also evident in sprinters compared with backs, who in turn achieved more negative toe-off distances compared with forwards. This technical feature does appear to transfer between sprinters and rugby players and a CM further forward relative to the point of contact at toe-off during the first step has previously been associated with higher propulsive impulse and GRF vector orientation, where a practically perfect significant relationship ($r = 0.93$, $p \leq 0.001$) between the GRF vector angle at maximum GRF application and CM angle at toe-off in physical education students was observed (Kugler & Janshen, 2010). Whilst a small non-significant relationship between toe-off distance and the first stance magnitude of NAHEP produced by the world class (Tier 5) sprinters was observed by Walker et al. (2021), their absolute toe-off distances (-0.87 ± 0.03 m) were notably more negative than those in the first steps of the trained to elite (Tiers 2 to 4) sprinters (-0.82 ± 0.06 m) and professional (Tiers 4 to 5) rugby backs (-0.73 ± 0.05 m) and forwards (-0.73 ± 0.06 m). It is possible that they had already reached close to a limit of their toe-off distance beyond which any positive effects of a more negative toe-off distance may begin to diminish.

Toe-off distance, and the body segment rotations used to achieve a greater toe-off distance may be a function of GRF orientation characteristics, therefore warranting further investigation. In this chapter, sprinters produced longer contact times relative to backs and may have used this to achieve a greater toe-off distance as a result (Kugler & Janshen, 2010). While start position and footwear may again play roles in the ability to achieve such a forward lean position, performer constraints may also be an important consideration. For example, Lee and Piazza (2009) demonstrated, through computer simulation, that the longer toes of sprinters (compared with non-sprinters) prolonged the time of contact during a 'push-off' giving greater time for forward acceleration by producing greater propulsive forces. However, it is possible to have a high impulse by pushing-off for longer, but low acceleration if the magnitude of the impulse (and thus change in velocity) is achieved primarily through spending a longer time generating GRF rather than by generating greater GRF magnitudes. This may account for the strategy of backs to produce higher step rates through shorter contact times whilst still achieving superior sprint performance compared with forwards.

3.5 Chapter summary

This chapter sought to answer research question I - '*What are the differences in spatiotemporal variables and linear kinematics between professional rugby players and sprinters during the initial steps or a sprint, and how do they relate to performance?* By quantifying the differences in these technical features between groups and their associations with initial acceleration performance, the unique kinematic aspects of rugby backs' technique were identified, and a foundation for further lines of inquiry to determine the technical variables of importance to their initial acceleration performance have been provided. Backs produced notably higher step rates and shorter contact times compared with both forwards and sprinters. These kinematic aspects of technique were the only two technique-based variables in backs to differ meaningfully compared with forwards and sprinters in the same direction which 'set them apart' in terms of their sprinting strategy from these other groups. These along with other clear differences in touchdown and toe-off kinematics between groups are likely to have emerged at least in part as a result of inherent differences in task, environment and performer constraints. Further investigation of the specific influence of performer constraints of rugby backs such as physical qualities (e.g., strength, anthropometrics) may offer greater insight into aspects which influence their sprint acceleration performance and are explored in the ensuing chapters of this thesis.

Toe-off distance was the only technical feature to differ between the groups which was consistently and meaningfully related to sprint performance within each group, and thus may be an important consideration of the sprint training practices of rugby backs. The other features of technique identified as potentially important for sprint acceleration performance from the existing literature on track & field sprint athletes investigated in this chapter may not transfer directly to rugby backs.

Although toe-off distance was identified as a potentially important technical feature of interest, which may be a function of the GRF orientation characteristics, it represents the outcome of everything which takes place during the contact phase prior to toe-off and is determined by the body and lower limb segment orientations at the end of the stance phase. Therefore, to understand which technical features may be manipulated to achieve a more negative toe-off distance and how they may associate to initial acceleration performance further investigation of selected kinematic aspects of technique was required, which was conducted in Chapter 4.

CHAPTER 4: THE ASSOCIATIONS OF ANGULAR KINEMATICS AND NORMALISED SPATIOTEMPORAL VARIABLES WITH THE TOE-OFF DISTANCE AND INITIAL ACCELERATION PERFORMANCE OF PROFESSIONAL RUGBY BACKS

4.1 Introduction

Chapter 3 presented evidence to suggest that toe-off distance was the most important kinematic feature to the initial acceleration performance of backs, since it was the only variable to differ between groups of backs, forwards and sprinters, and was also meaningfully related to the NAHEP produced during the initial steps in each group. Toe-off distance determines the CM angle at toe-off (angle of line between the stance foot and the CM, with respect to the vertical), which characterises the 'forward lean' adopted at the end of the stance phase. As discussed in Chapter 2 (see section 2.2.4), achieving a large CM angle at toe-off (a more negative toe-off distance), is possibly a function of a more horizontally orientated GRF vector (Kugler & Janshen, 2010) – a determinant of initial acceleration performance (e.g., Bezodis et al. 2020). Since toe-off distance is likely influenced by trunk and lower limb segment orientations at the end of the stance phase, it was decided that the toe-off angular kinematics of rugby backs and their relationships with toe-off distance was important to investigate in the current chapter since it would provide practitioners with information on *how* greater toe-off distances are achieved to inform their technique-based sprinting interventions.

Understanding how toe-off angular kinematics relate to the toe-off distance of rugby backs may be useful but understanding how these angular kinematics relate to acceleration performance in their own right was also important. For example, although Walker et al. (2021) did not find a significant relationship between absolute toe-off distance and the magnitude of NAHEP produced by world class sprinters during the first stance, they did find strong significant relationships of NAHEP with thigh separation and trunk angle at toe-off (r = 0.62 and -0.59 respectively, both $p < 0.05$). Furthermore, the toe-off distance and angular kinematics achieved at toe-off, and the magnitude of NAHEP achieved during a step, are a result of everything which takes place prior to the end of the stance phase. Therefore, the associations of toe-off *and* touchdown angular kinematics with the toe-off distance and initial acceleration performance of rugby backs are both important to consider.

Touchdown angular kinematic factors have previously been shown to be important to acceleration performance. Morin et al. (2015b) suggested that the 'intense' backwards movement of the lower limb during the late swing and early stance phases is necessary to produce high amounts of horizontal GRF and impulse. This premise was supported by Bezodis et al. (2017) where greater RF of team sport players at the 5 m mark was preceded by greater hip extension angular velocities at touchdown, in addition to a more dorsiflexed ankle and a more flexed knee. The segment orientations associated with these joint angular positions at touchdown may therefore have acted to influence the direction of the CM acceleration (Jacobs & van Ingen Schenau, 1992; Nagahara et al., 2014a), resulting in the observed increase in RF. Reduced dorsiflexion during the early stance phase has been significantly correlated to horizontal external power during the first step (Bezodis et al., 2015) and, as discussed in Chapter 2 (section 2.3), the ability of the plantarflexor moment to attenuate the amount of dorsiflexion during the early stance phase may assist with a stable foot segment so that the hip extensor moments can better contribute to forwards CM acceleration (Veloso et al., 2015). Therefore, knowledge of the combined associations of hip and ankle angular kinematics representing the outcome of this synergistic interplay during the initial stance phase with acceleration performance would also prove useful for practitioners undertaking technique-based sprint training.

Regarding spatiotemporal variables in Chapter 3, no meaningful relationships were observed between these variables and NAHEP within the backs who were found to accelerate 'differently' through the production of greater step rates and shorter contact times compared with forwards and sprinters, demonstrating that degeneracy exists at the inter-group level during acceleration, likely owing to inherent differences in their performer constraints (Newell, 1986). Since the longer legs of athletes with greater stature represent a performer constraint likely to result in longer step lengths (Hunter et al., 2004; Nagahara et al., 2018a), stature was controlled to provide an objective measure of step length in Chapter 3. However, the step rate, contact time and flight time of participants were not controlled for the effects of leg length, and using dimensionless units for these aspects of technique would also allow for an objective measure of these temporal-based variables. Therefore, information on how the angular kinematics *and* normalised spatiotemporal variables of rugby backs associate with their toe-off distance and acceleration performance was deemed important since questions remain as to which, if any, of these variables are important for the acceleration performance of backs. Accordingly, this chapter sought to answer research question II - *How do angular kinematics and normalised spatiotemporal variables relate to the toe-off distance and initial acceleration performance of professional rugby backs?* This information would provide coaches and other practitioners with a more in-depth understanding of the potentially key technical markers which are important for the acceleration performance of rugby backs, and thus their development of technical-based sprint interventions.

4.2 Methods

4.2.1 Participants

Twenty-five male professional backs (mean ± SD: age 25 ± 3 years; stature 1.82 ± 0.06 m; leg length 1.01 ± 0.05 m; body mass 94.0 ± 9.2 kg) competing in the English Premiership completed a battery of physical assessments. Study protocols were submitted to, and approved by, the local Research Ethics Committee, and at the time of testing all participants were injury-free and completed maximal effort sprint accelerations on a weekly basis as part of their habitual training. Data were collected during the pre-season on one occasion following 48 hours of abstinence from running, sprinting and lower body strength training.

4.2.2. Procedures

Participants completed a 20-minute standardised warm-up, and then performed three maximal effort 30 m sprints from a standing 2-point split-stance start, on an outdoor 3G artificial grass pitch, wearing a t-shirt, shorts and moulded stud boots. These are the conditions in which speed and rugby training would take place during the training phase when the data were collected. Rest periods between each sprint effort were approximately 4-5 minutes. Two smart phone high-speed video cameras (iPhone8, Apple Inc, Cupertino, Ca) were used to capture sagittal plane video images (1920 × 1080 pixels) of the first four steps at 240 Hz. The cameras were positioned perpendicular to, and 12 m from, the running lane to capture sagittal plane images from both sides of the body within a 7.5 m wide field of view. A 5.00 m horizontal video calibration was recorded. Spatiotemporal variables, toe-off distance and NAHEP were determined from the video images captured from one camera (to the left side of the body) as per the approach in Chapter 3, and the left and right side angular kinematic variables of participants were determined from the video images captured using the camera either on the left or right side of participants, respectively.

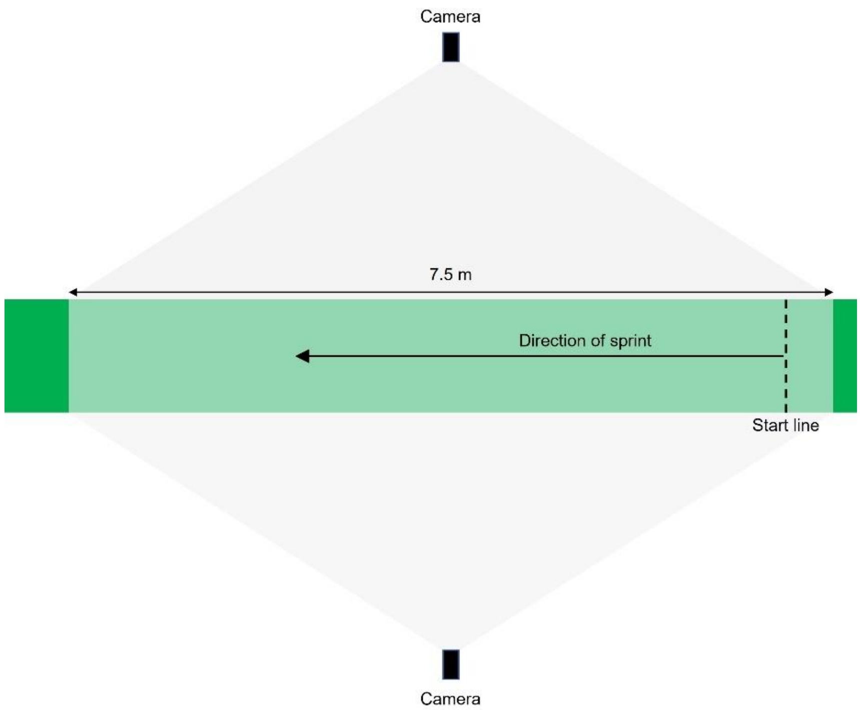

Figure 4.1 Camera set up for sprint testing session.

The kinematic variables were determined from the video images during the first four steps at touchdown and toe-off and several frames during the late swing phase and during ground contact (explained later in this section) using ×6 zoom in Kinovea (v.0.8.27) motion analysis software. Manual digitisation was carried out to model the human body as 14 rigid segments as outlined in Chapter 3 (Section 3.2.2). Scaled coordinates were exported to Excel (Microsoft 2013) to calculate angular orientations (°) at touchdown and toe-off of the stance foot, shank, and thigh, and trunk, segments (with respect to the horizontal; Figure 4.2) and of the stance ankle, knee and hip joints, and the thigh separation angle (the difference between the segment angles of the thighs of the swing and ground contact legs at toe-off; Figure 4.2). Ankle dorsiflexion range of motion (°) during stance was determined by subtracting the peak ankle dorsiflexion angle measured in from the ankle angle at touchdown. To determine peak dorsiflexion angle, ankle angle was determined for ten frames either side of the frame in which it was visually estimated to occur, and the smallest value over this period was used. Mean hip angular velocity (°/s) during stance was determined from the hip angles at touchdown and toe-off, and ground contact time. Hip angles were determined for ten frames prior to and following touchdown in order to obtain hip angular velocity at touchdown by applying second central difference calculations (Miller & Nelson, 1973) to these joint angle data which had been low-pass filtered using a fourth order Butterworth filter with cut-off frequencies determined based on the procedures of Challis (1999).

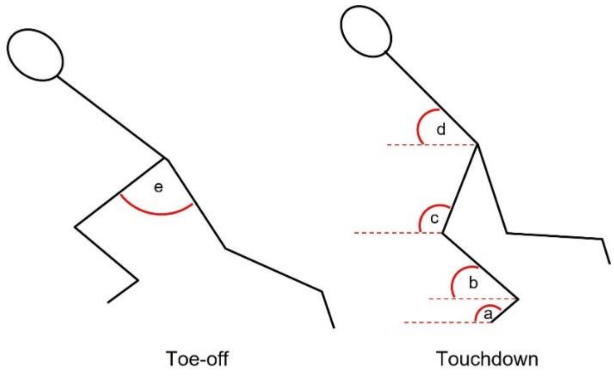

Figure 4.2. Segment angle conventions and thigh separation angle

Foot, a; shank, b; thigh, c; trunk, d; thigh separation, e

The location of the whole-body CM at toe-off was calculated using de Leva's (1996) segmental inertia data and the summation of moments approach in order to determine toe-off distance (m). The following step characteristics were also obtained: contact time (s), flight time (s), step length (m; horizontal displacement between the toe tips at adjacent touchdowns), step rate (Hz; the reciprocal of step duration, which was determined as the sum of contact time and the subsequent flight time). To minimise the confounding influence of inter-individual differences, toe-off distance was normalised to leg length (m; distance from the greater trochanter of the right leg to the bottom of the ipsilateral heel whilst lying supine), as was step length. Dimensionless forms for angular velocities and temporal step characteristics were calculated using the equations from Hof (1996) as follows:

normalised angular velocity = $\frac{\omega}{\sqrt{g/l_0}}$,

normalised contact and flight times = $\frac{t}{\sqrt{l_0/g}}$ and

normalised step rate = $\frac{f}{\sqrt{g/l_0}}$;

where ω = angular velocity, g = gravity, l_0 = leg length, t = time and f = step rate.

Finally, as a measure of initial sprint acceleration performance, NAHEP was calculated based on the change in kinetic energy from the instant of the first touchdown until the end of the fourth contact phase, and through a modification of the equation presented by Hof (1996) as used by Bezodis et al. (2010). This was the same approach used to measure NAHEP in Chapter 3, except over four steps, rather than three. Four steps were selected for the investigation in the current chapter to remove any potential biased findings towards one limb when an odd number of steps is selected for analysis. This was made possible due to the increase in camera resolution used in the current Chapter compared with the camera used in Chapter 3, enabling a wider field of view to be captured whilst maintaining the accuracy with which variables could be obtained.

4.2.3 Statistical analyses

Using the same approach as in Chapter 3 (Section 3.2.3) test-retest intra-rater reliability of manual digitisation to calculate all angular kinematics was determined using an intraclass correlation coefficient (ICC 3,1) with 90% confidence intervals. ICC values less than 0.50, between 0.50 and 0.75, between 0.75 and 0.90, and greater than 0.90 were used to indicate poor, moderate, good, and excellent reliability, respectively (Portney & Watkins, 2000). The angular kinematic variables for 10 backs selected at random were digitised during one of their sprint trials on two separate occasions.

Mean data for kinematic variables were obtained over four steps and averaged across all sprint trials for each back. Group-wide descriptive statistics (mean ± SD) were calculated for all variables of interest. Normal distribution of the data was checked by the Shapiro-Wilk normality test. The relationships of all angular and spatiotemporal kinematic variables with toe-off distance and/or NAHEP were determined by controlling for both leg length and body mass, as follows. The dimensionless values determined for spatiotemporal variables, angular velocities and toe-off distance (which account for inter-individual difference in leg length; Hof, 1996) and their relationships with toe-off distance and/or NAHEP, were determined using semi-partial correlation coefficients (r), controlling for body mass. Semi-partial correlations, controlling for both leg length and body mass were used to determine the relationships of all segment and joint angular positions and dorsiflexion range of motion with toe-off distance and NAHEP. Body mass was deemed an important performer constraint to control for across all kinematic variables in addition to leg length, since it is likely to influence the kinematic variables measured during maximal sprinting. For instance, as discussed in Chapter 3, a less negative touchdown distance has been associated with a greater vertical GRF impulse during the first stance (Bezodis et al., 2015). Greater vertical GRF is needed with increased mass to support body weight, therefore potentially requiring a greater touchdown distance. If touchdown distance differs in relation to body mass, then this will have to be achieved through changes in segment and joint angular positions at touchdown.

Selected kinematic variables were then paired (1: hip angular velocity at touchdown with ankle dorsiflexion range of motion; 2: hip angular velocity at touchdown with peak ankle dorsiflexion angle) as independent variables and included within linear multiple regression models using the 'enter' method for variable selection (Morin et al., 2015b) to assess their combined relationships with NAHEP (dependent variable). These independent variables were selected based on a prior rationale of the potentially important hip and ankle interaction needed for CM horizontal acceleration (see introductory section of this chapter and Chapter 2, Section 2.3.6). Body mass was also entered into the regression models as an independent variable to control for its potential influence on the variation in NAHEP.

As a result of the findings from the correlation analyses, further associations were investigated. This involved an additional multiple linear regression analysis (model 3) which explored normalised toe-off distance and normalised contact time (and body mass) as independent variables with NAHEP (dependent variable). Autocorrelations for all regression analyses conducted (i.e., models 1 to 3) were minimal (Durbin-Watson 2.2 to 2.5) and multicollinearity were within acceptable thresholds (1.1 to 2.5; Hair et al., 2019). In addition, the relationship between participants' toe-off distance averaged over the first three steps, normalised to stature, and NAHEP across the same steps was determined using bivariate Pearson's correlation coefficients using the same approach as used in Chapter 3.

For semi-partial, bivariate and multiple correlation coefficients, the strength of observed relationships were defined as: (±) < 0.1, trivial; 0.1 to 0.3, small; 0.3 to 0.5 moderate, 0.5 to 0.7 large, 0.7 to 0.9 very large and > 0.9, practically perfect (Hopkins, 2002). Confidence intervals (90%) for all observed relationships were calculated to detect the smallest clinically important correlation coefficient ($r = \pm 0.10$). Relationships were deemed meaningful when their magnitudes were equal to or greater than the smallest clinically important correlation and confidence limits did not include positive and negative values greater than the smallest clinically important correlation. For the regression analyses conducted, to reduce the possibility of the estimated explained variation of NAHEP being overstated by the coefficient of determination, owing to the relatively small sample size used in the analysis, adjusted *r* squared (r^2) was calculated to interpret the effect size with thresholds set as: < 0.02, trivial; 0.02 to 0.13, small; 0.13 to 0.26, large (Cohen, 2013). Semi-partial correlation and multiple regression analyses were performed using SPSS (v26.0) with alpha set at $p < 0.05$.

4.3 Results

Descriptive statistics and intra-rater reliability for variables investigated within this chapter can be found in Table 4.1 and Table D.1 (Appendix D), respectively.

Table 4.1. Descriptive statistics for variables

Variables		**Mean**	**SD**
Spatiotemporal variables[a]	NAHEP[a]	0.56	0.07
	Step length	1.31	0.10
	Step rate	1.38	0.09
	Contact time	0.515	0.041
	Flight time	0.211	0.032
Kinematics at touchdown	Hip touchdown angular velocity[a]	174	28
	Foot angle (°)	161	5
	Shank angle (°)	64	4
	Thigh angle (°)	124	4
	Trunk angle (°)	50	4
	Ankle angle (°)	94	4
	Knee angle (°)	120	4
	Hip angle (°)	106	5
Kinematics during stance	Peak ankle dorsiflexion angle (°)	79	4
	Peak ankle dorsiflexion ROM (°)	16	3
	Stance hip mean angular velocity[a]	139	9
Kinematics at toe-off	Foot angle (°)	92	3
	Shank angle (°)	35	3
	Thigh angle (°)	55	3
	Trunk angle (°)	52	4
	Ankle angle (°)	134	4
	Knee angle (°)	160	4
	Hip angle (°)	177	6
	Thigh separation angle (°)	96	6
	Normalised toe-off distance[a]	-0.73	0.03

[a]Dimensionless variables which have been normalised according to the equations of Hof (1996) with a modification to the calculation of NAHEP as used by Bezodis et al. (2010)

4.3.1 Relationships of spatiotemporal variables and angular kinematics with toe-off distance

Step length and step rate demonstrated significantly large negative and moderately positive meaningful relationships with toe-off distance respectively (Figure 4.3). Contact time exhibited the strongest (very large) significant, negative, and meaningful relationship with toe-off distance (Figure 4.3). A non-significant positive moderate and meaningful relationship was found between flight time and toe-off distance.

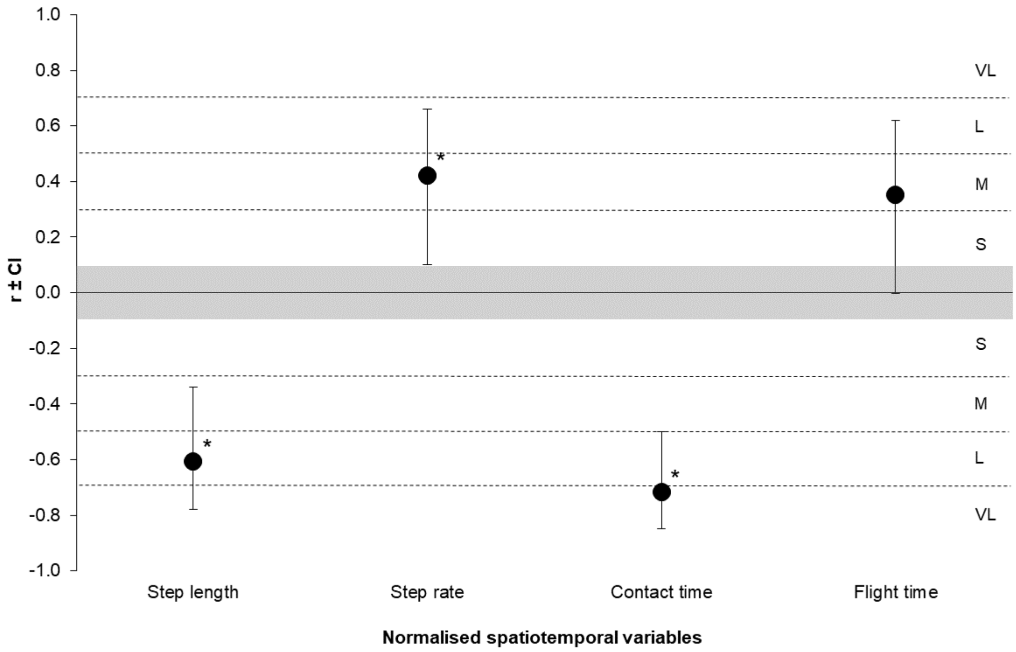

Figure 4.3. Semi-partial correlation coefficients (± 90% CI) between normalised spatiotemporal variables and toe-off distance. A trivial relationship ($r = \pm 0.1$) is indicated by the central grey shaded area. Horizontal dotted lines represent thresholds for the magnitude of relationships (S, small; M, moderate; L, large; VL, very large). Black shaded markers indicate that the relationship is deemed greater than the smallest clinically important correlation coefficient, and therefore 'meaningful'. Asterisks denote relationships that are statistically significant ($p < 0.05$)

At touchdown (Figure 4.4) significantly large negative and meaningful relationships between foot, shank, thigh and hip angles, and toe-off distance were found. Non-significant, but moderately positive and meaningful relationships were evident for touchdown trunk and ankle angles, and ankle dorsiflexion range of motion with toe-off distance. All other relationships between touchdown angular kinematics and toe-off distance were not significant, trivial to small in magnitude and not meaningful. At toe-off, significant moderately positive and meaningful relationships between shank and thigh angles, and toe-off distance, were observed. Non-significant, but moderate and meaningful relationships were found for foot angle and thigh separation angle with toe-off distance.

All other relationships between toe-off angular kinematics and toe-off distance were not significant, trivial to small in magnitude and not meaningful.

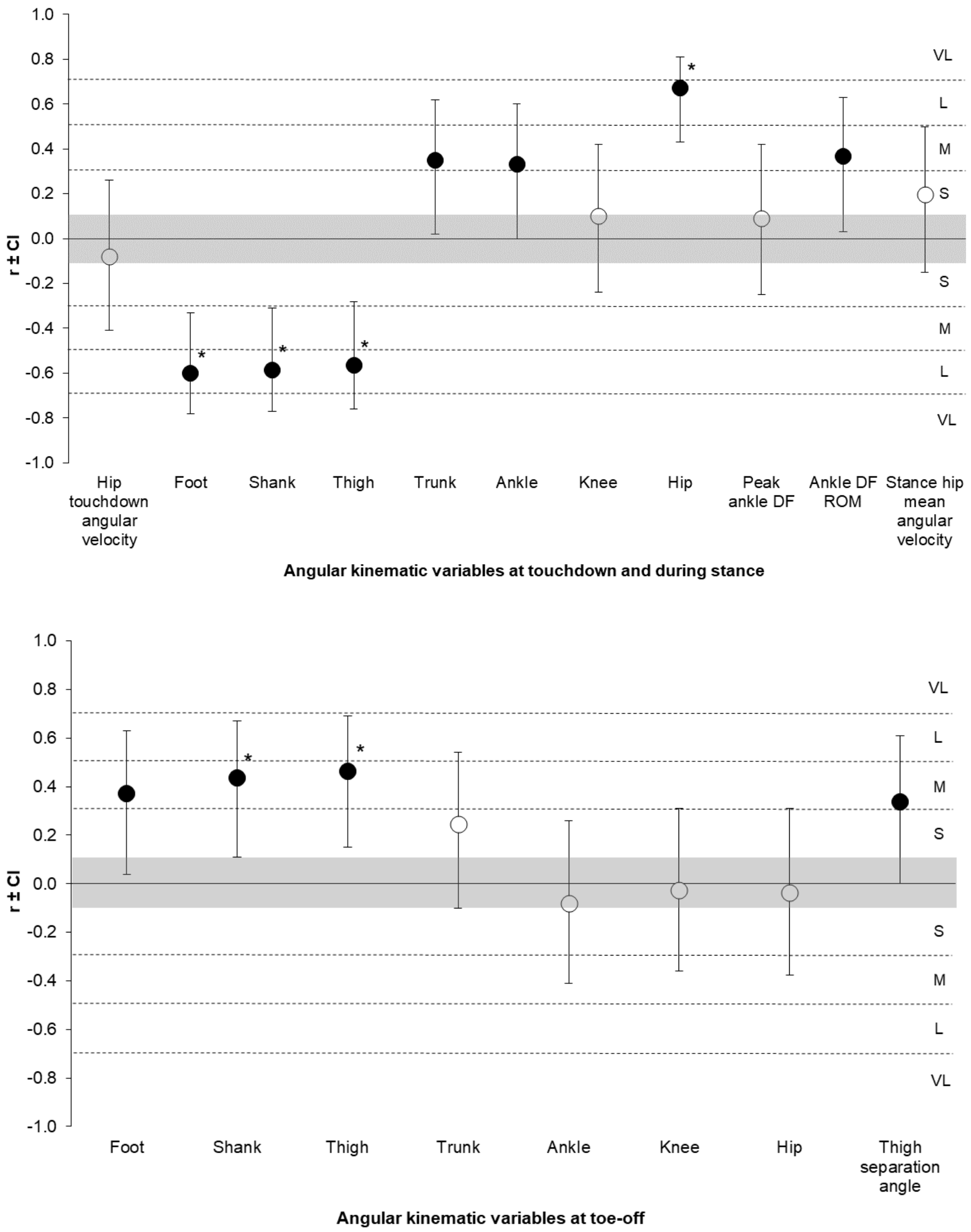

Figure 4.4. Semi-partial correlation coefficients (± 90% CI) of touchdown and stance phase (top figure) and toe-off (bottom figure) angular kinematic variables with toe-off distance. A trivial relationship ($r = \pm 0.1$) is indicated by the central grey shaded area. Horizontal dotted lines represent thresholds for the magnitude of relationships (S, small; M, moderate; L, large; VL, very large). Black shaded markers indicate that the relationship is deemed greater than the smallest clinically important correlation coefficient, and therefore 'meaningful'. Asterisks denote relationships that are statistically significant ($p < 0.05$)

4.3.2 Relationships of spatiotemporal variables and angular kinematics with NAHEP

Of the normalised spatiotemporal variables (Figure 4.5), only step rate was moderately and meaningfully correlated with NAHEP, although the relationship was not significant. All other relationships between normalised spatiotemporal variables and NAHEP were not significant, trivial to small in magnitude and not meaningful.

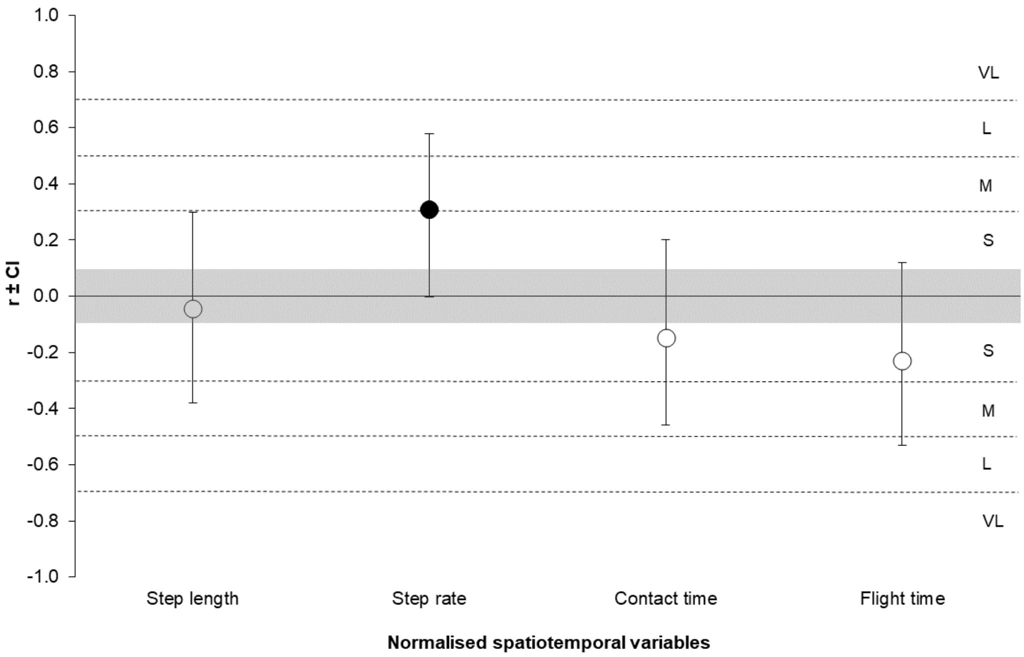

Figure 4.5. Semi-partial correlation coefficients (± 90% CI) between normalised spatiotemporal variables and NAHEP. A trivial relationship (r = ± 0.1) is indicated by the central grey shaded area. Horizontal dotted lines represent thresholds for the magnitude of relationships (S, small; M, moderate; L, large; VL, very large). Black shaded markers indicate that the relationship is deemed greater than the smallest clinically important correlation coefficient, and therefore 'meaningful'. Asterisks denote relationships that are statistically significant ($p < 0.05$)

At touchdown and toe-off (Figure 4.6), significantly moderate negative and meaningful relationships (hip angle at toe-off and trunk angles at touchdown and toe-off) were observed, with NAHEP. Non-significant small (ankle angle at touchdown) and moderate (hip angle at touchdown) negative and meaningful relationships with NAHEP were also observed, whereas all other relationships between touchdown and toe-off angular kinematics and NAHEP were non-significant, trivial to small in magnitude and not meaningful.

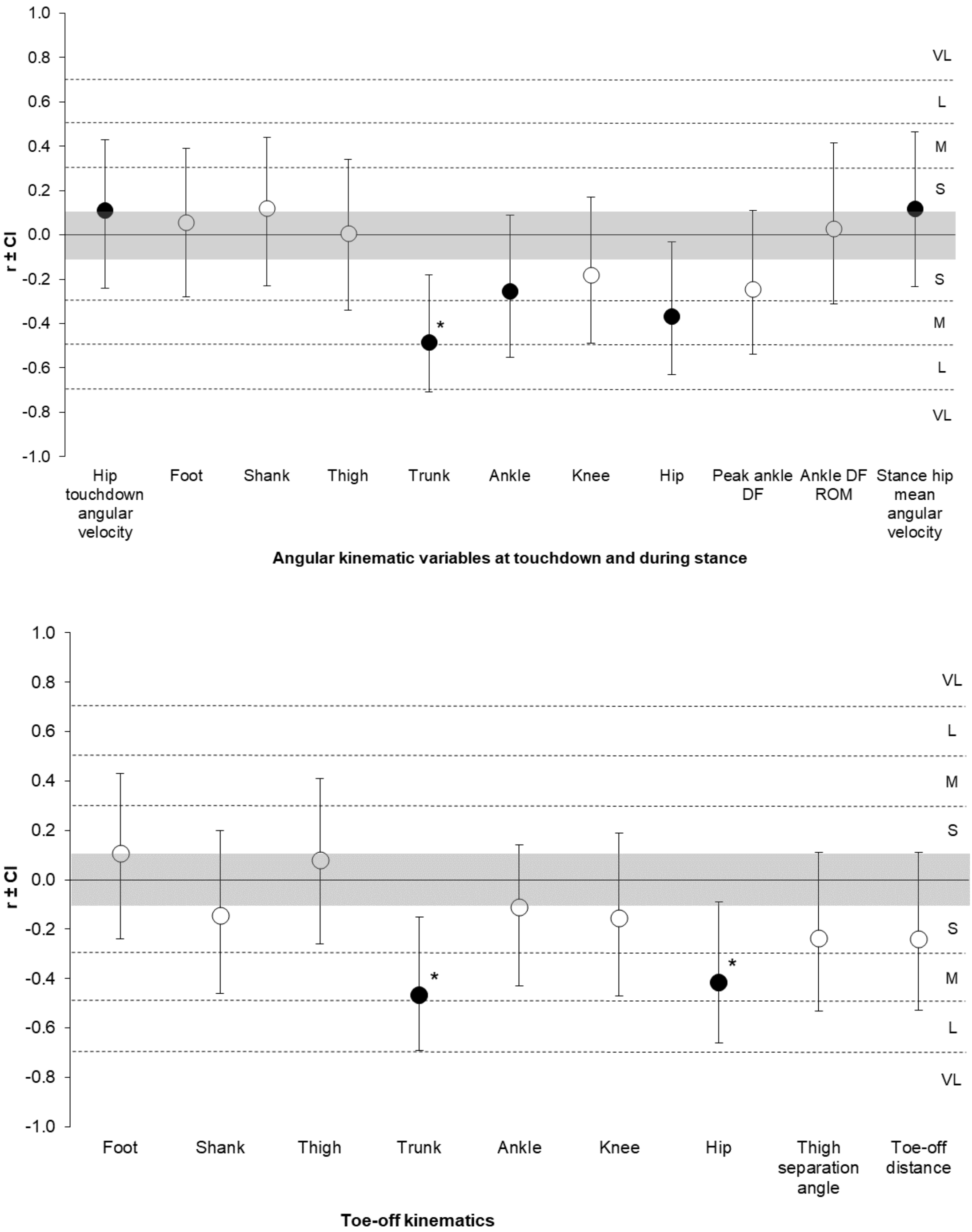

Figure 4.6. Semi-partial correlation coefficients (± 90% CI) of touchdown and stance phase (top figure) and toe-off (bottom figure) kinematic variables with NAHEP. A trivial relationship (*r* = ± 0.1) is indicated by the central grey shaded area. Horizontal dotted lines represent thresholds for the magnitude of relationships (S, small; M, moderate; L, large; VL, very large). Black shaded markers indicate that the relationship is deemed greater than the smallest clinically important correlation coefficient, and therefore 'meaningful'. Asterisks denote relationships that are statistically significant ($p < 0.05$)

4.3.3 Multiple regression analyses

In model 1, a non-significant small and meaningful relationship was evident for the combination of hip touchdown angular velocity, ankle dorsiflexion range of motion and body mass with NAHEP (Table 4.2). In addition, the independent variables were not able to predict the variance in NAHEP (trivial effect). In model 2, hip touchdown angular velocity, peak ankle dorsiflexion angle and body mass combined to demonstrate a non-significant moderate and meaningful relationship with NAHEP (adjusted $r^2 = 0.09$, small effect). Toe-off distance, contact time and body mass combined in a significant regression model (model 3) to predict NAHEP (adjusted $r^2 = 0.28$, large effect) and the multiple correlation coefficient was large and meaningful.

Table 4.2. Multiple linear regression analysis with NAHEP as the dependent variable

Model	Independent variables	*r* (90% CL)	r^2	SEE	*p*	Standardised coefficients
1	Normalised hip touchdown angular velocity	0.32 (-0.02 to 0.59)	-0.03	0.07	0.50	0.13
	Ankle dorsiflexion range of motion					0.04
	Body mass					-0.25
2	Normalised hip touchdown angular velocity	0.45 (0.13 to 0.68)	0.09	0.07	0.19	0.30
	Peak ankle dorsiflexion angle					-0.36
	Body mass					-0.19
3	Normalised toe-off distance	0.61 (0.34 to 0.79)	0.28	0.05	0.02	-0.75
	Normalised contact time					-0.76
	Body mass					0.00

r, multiple correlation coefficient; CL, confidence limits; r^2, adjusted coefficient of determination; SEE, standard error of estimate

4.4 Discussion

The overall aim of this chapter was to investigate the associations of normalised spatiotemporal variables and angular kinematics with the toe-off distance and initial acceleration performance of rugby backs over the first four steps of maximal sprinting. These relationships are summarised in Figures 4.3 to 4.6 and Tables 4.2 to 4.3 and build on the understanding gained from Chapter 3 to provide further information on the biomechanical factors that contribute to the initial acceleration performance of these participants. Sixteen normalised spatiotemporal or angular kinematic variables were meaningfully correlated to toe-off distance, where moderate to very large relationships were observed, of which nine were significant. However, only six from 23 normalised spatiotemporal or angular kinematic variables were meaningfully related to NAHEP. These relationships were small to moderate with only three being significant. Contrary to the findings reported in Chapter 3, toe-off distance was not meaningfully related to NAHEP over the first four steps (r = -0.24; Figure 4.6) – potential reasons for this are discussed in Section 4.4.4. However, when combined with contact time and body mass it predicted a meaningful amount of the variation of NAHEP in a regression model (large effect; Table 4.2, model 3). This finding casts some doubt on the consideration of technical features in isolation and their relationships with initial sprint acceleration performance. Furthermore, different combinations of toe-off distance and contact time were utilised to achieve similar magnitudes of NAHEP (Figure 4.7). Therefore, whilst Chapter 3 demonstrated that degeneracy exists at the inter-group level whereby backs produced an acceleration strategy which set them apart from other groups (see Section 3.4.3), the findings reported in the current chapter suggest that degeneracy may also exist at the inter-individual level in the context of acceleration performance. That is, different technique-based strategies may be present within a group of rugby backs, each of which may result in similar acceleration performance.

4.4.1 Technical features which underpin toe-off distance

In Chapter 3, toe-off distance was highlighted as potentially important to initial acceleration performance. Not only were more negative toe-off distances achieved by the faster athlete groups (i.e., sprinters compared with backs, and backs compared with forwards), it was the only variable to show meaningful correlations with NAHEP in each of the three groups, although the magnitude of this relationship within the backs (r = -0.44, moderate and not significant) was less compared with the forwards and sprinters (r = -0.58 and -0.54, both large and significant). The current results showed that a more negative toe-off distance was achieved (Figure 4.5) by players adopting a body position likely requiring a low CM position at touchdown (i.e., a more flexed hip and ankle; a more horizontal trunk [i.e., when the proximal end of the trunk segment was further forward relative to its distal end in the direction of the sprint] and less horizontally rotated foot, shank and thigh segments [i.e., when their proximal ends were more posterior relative to their distal ends in the direction of the sprint). During stance, smaller ankle dorsiflexion range of motion and foot, shank and thigh angles that were more forward rotated at toe-off (i.e., the proximal ends of their segments were further forward relative to their distal ends in the direction of the sprint) were associated with a more negative toe-off distance. These relationships suggest that the increases in leg segment ranges of motion during the stance phase accompany more negative toe-off distances and horizontal forward displacement of the CM.

4.4.2 The contribution of spatiotemporal variables and angular kinematics to NAHEP

As previously indicated in the introduction (Section 4.1; see also Chapter 2, Section 2.4; Chapter 3, Section 3.4.2), there are contrasting findings within the literature as to which spatiotemporal variables are associated with better initial sprint acceleration performance of team sport players (Bezodis et al., 2017; Lockie et al., 2011; Lockie et al., 2012; Lockie et al., 2013; Lockie et al., 2014a; Lockie et al., 2014b; Lockie et al., 2015; Murata et al., 2018; Murphy et al., 2003; Nagahara et al., 2018a; Nagahara et al., 2019; Spinks et al., 2007; Standing & Maulder, 2017). Within Chapter 3 this uncertainty was further amplified where no meaningful correlations were found between NAHEP and step characteristics (r = -0.16 to 0.29). One of the methodological issues that could account for these mixed findings is the lack of consideration for physical quantities (e.g., leg length/stature and body mass) which may partly explain the differences in the results observed. In this study, to correct for some of these differences between backs, step characteristics were normalised (Hof, 1996) and semi-partial correlations were used to control for leg length and body mass of the kinematic variables investigated. The results showed only step rate to be meaningfully correlated with NAHEP, but the magnitude of the relationship just cleared the threshold to be considered moderate (by 0.10; Figure 4.5) and was not statistically significant. Although step rate is likely important, this finding alone does not provide sufficient evidence to justify a considerable focus on developing step rate over other step characteristics when 91% of variance in NAHEP was uniquely contributed to by other factors.

The product of step rate and step length equates to the step velocity of an athlete. Although NAHEP was used as the performance measure in the present research, its equation requires the calculation of CM velocity at two discrete points and includes the duration of step cycles. Therefore, the velocity produced during initial acceleration is likely to be strongly related to NAHEP (e.g., Bezodis et al., 2010). Since a decrease in either step rate or step length, without a proportional increase in the other, will compromise step velocity, and that different combinations of each variable can be utilised to achieve similar sprint performance, it is logical that there is no strong consensus on whether one variable is more important to initial acceleration performance. In track sprinting over the course of multiple 100 m sprints, elite sprinters' competition performances were shown to be individually reliant on step rate or step length, whilst some were shown to have no reliance on either (Salo et al., 2011). Although these findings may not translate to the initial steps of sprinting in rugby backs, they provide a potential explanation for the lack of consistency observed between the relationships of spatiotemporal variables with sprint performance during the initial steps. To date, no researchers have investigated whether team sport players' initial acceleration performances rely on step rate or step length at the intra-individual level, and this may be an important consideration given the absence of meaningful group-wide correlations. This may enable coaches to individualise sprint training interventions to maintain or enhance the step characteristics that backs are reliant on for better performance in this sprint phase.

One strategy by which increases in step rate could be achieved is to reduce contact times by limiting the amount of leg extension at the point of toe-off (i.e., terminating the stance phase earlier in preparation for the next step). The correlation analysis in this chapter showed less hip extension at toe-off and touchdown to be moderately associated with higher NAHEP (Figure 4.6), with the former relationship being statistically significant. During the stance phase the hip joint moment changes from extensor to flexor dominance to absorb energy and reduce the rate of hip extension before the end of the ground contact (e.g., Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013a; Jacobs & van Ingen Schenau, 1992; Schache et al., 2019). However, the time of this switch from an extensor to a flexor moment varies between athletes (Table 2.4, Chapter 2). This may be due to methodological differences between studies, but also due to performer constraints between athletes. For example, backs who are able to produce greater hip extensor moments sooner in the stance phase due to enhanced strength-based qualities may need to achieve the switch to flexor dominance earlier to prevent contact times from increasing. This suggestion is supported by evidence from Bezodis et al. (2014) who showed the changeover from net extensor to flexor moment took place sooner in the two better performing sprinters (~75%) compared with the worse performing sprinter (~85%) during the first step. The athlete who produced the highest average horizontal external power also completed greater negative work at the hip joint (Bezodis et al., 2014), thus suggesting that limiting the rate of hip extension to reduce contact time may be important to initial acceleration performance. However, caution ought to be applied when drawing conclusions from these findings of a limited number of case studies based on sprinters to the context of rugby backs.

Whilst strategies to increase step rate may be worth considering, deliberately abbreviating contact time may come at the sacrifice of step velocity due to the negative interaction between step rate and step length (Hunter et al., 2004). As contact times decrease, the need for higher average stance GRF increases in order to maintain the impulse needed for CM horizontal acceleration. Should any subsequent increase in GRF be produced more vertically in each step to 'rebound' off the ground sooner, the RF will likely decrease, and initial sprint acceleration will also decrease as more time is spent airborne, resulting in less relative time during the step accruing horizontal impulse. One way to counter these potentially negative effects may be to achieve a greater amount of forward 'trunk lean'. For the 14 active (Tier 1) adults studied by Nagahara et al. (2019), an intentional forward lean resulted in a simultaneous increase in step rate through a decrease in contact times and flight times during the initial steps of a sprint without affecting the mean velocity of participants although smaller braking and vertical impulses were observed. In the present analyses, backs' trunk angles at touchdown and toe-off demonstrated the highest relationships (significant, moderate and meaningful, Figure 4.6) with NAHEP, whereby a more horizontal trunk position was associated with better initial sprint acceleration performance. This orientation of the trunk positions the net GRF vector anterior to the hip joint for longer during the stance phase (Schache et al., 2019), which in turn means the hip has an increased capacity to assist with horizontal propulsion.

4.4.3 Hip and ankle synergy

The magnitude of horizontal CM acceleration during the initial steps of sprinting has previously been shown to be positively related to hip (extensor) and ankle (plantarflexor) joint impulse (e.g., Schache et al., 2019). However, the results of the present analyses indicate that the magnitude of NAHEP (which has been shown to be related to average velocity during the block phase; Bezodis et al., 2010) could not be explained by some of the isolated kinematic technical features of the hip and ankle which might relate to these joint kinetics. Regarding the hip, for instance, a greater hip touchdown velocity (with a view to produce a more 'forceful' backwards action of the leg to maximise horizontal GRF and impulse) has been theorised to be of benefit to sprinting performance (e.g., Mann & Sprague, 1983; Mann et al., 1984; Wiemann & Tidow, 1995). Some experimental data supports this hypothesis where greater hip touchdown velocities were produced by team sport players who also achieved a more horizontally oriented GRF vector at 5 m (Bezodis et al., 2017), and higher mean hip extension angular velocities during stance were observed in the trials which produced greater horizontal propulsive impulse at 16 m (Hunter et al., 2005). Conversely, the touchdown and stance averaged hip extension angular velocities achieved by backs in this chapter were not associated with initial sprint acceleration performance. Possible reasons for why this might be different to previous research are due to differences in participant status and their constraints, the sprint phase studied (i.e., initial acceleration versus the 16 m mark; Hunter et al., 2005) and/or differences in the sprinting performance variable used.

Although the hip joint has been shown to contribute significantly to CM horizontal acceleration (e.g., Schache et al., 2019; Veloso et al., 2015), the ankle has been observed to be the main contributor during the initial steps, predominantly during the final two thirds of the stance phase where it generates high amounts of energy (Debaere et al., 2013a; Schache et al., 2019). However, its function and associated angular kinematics for approximately the first third of the stance phase, whilst absorbing energy, have also been identified as playing an important role. For example, Bezodis et al. (2015) observed, through simulation, that when the amount of ankle dorsiflexion was reduced during the early stance phase of the first step, average horizontal power increased exponentially. The increased power was shown to derive from both a shorter contact time and an increase in net horizontal impulse (Bezodis et al., 2015). Furthermore, during the early stance phase, maintaining a 'stiff' ankle during dorsiflexion has been empirically shown to increase as the resultant GRF and horizontal CM velocity at take-off increases (Charalambous et al., 2012). Despite the importance of ankle joint stiffness and potentially the ability to attenuate ankle dorsiflexion during the negative power phase during early stance, neither ankle dorsiflexion range of motion nor the peak ankle dorsiflexion angle attained during the stance phase were meaningfully related to the NAHEP of backs reported in this chapter.

In isolation the hip and ankle kinematic variables investigated in this chapter were not significantly or meaningfully related to acceleration performance, despite some evidence within the literature to partially support these correlations. However, when combined, touchdown hip angular velocity and peak ankle dorsiflexion angle were moderately meaningfully related to NAHEP. The adjusted r^2 demonstrated a small effect (Table 4.2), although the model was not statistically significant. The meaningful multiple relationship may in part be explained by the synergistic action of the hip and ankle, whereby a relatively stable foot with regards to the foot-ground interface during the first third of the stance phase as the ankle dorsiflexes helps to provide a foundation from which the hip extensors can contribute mostly to CM horizontal acceleration (Schache et al., 2019; Veloso et al., 2015). However, even though the combination of hip and ankle joint angular kinematics could theoretically be important for initial acceleration performance, the regression model testing this theory was not significant and the effect was only small. Further investigations are needed to ascertain whether ankle and hip kinematics during early stance are influential to initial sprint performance. For example, it is feasible that the strength-related qualities of the muscles spanning the hip and ankle joint are likely to contribute to the high hip extensor and ankle plantarflexor moments required for high initial acceleration performance (see Sections 2.3.4 and 2.3.6, Chapter 2). Therefore, exploring how hip and ankle angular kinematics combine with the strength-related qualities of the muscles spanning these joints interact with NAHEP produced during the initial steps is explored in Chapter 5 to provide a more complete understanding on the contributory factors to the initial acceleration performance of rugby backs.

4.4.4 Is toe-off distance consistently related to initial acceleration performance?

Despite a number of variables relating to a more negative toe-off distance, the results of the study presented in this chapter show confidence limits for the relationship between toe-off distance and NAHEP to overlap substantial negative and positive values and thus the correlation (r = -0.24) is not deemed meaningful, or statistically significant. This was an unexpected result given the findings in Chapter 3 where toe-off distance was consistently and meaningfully related to the NAHEP magnitude produced in backs, forwards and sprinters. The magnitude of the relationship between toe-off distance and NAHEP in the current chapter was within the expected range of values for the estimate of the same relationship in Chapter 3 (90% CI: = -0.74 to 0.00). However, despite this and the use of a comparatively homogenous population, the difference in correlation magnitude between chapters (Δ r = 0.20) was sufficient to result in different inferences. The potential reasons for this are discussed next.

Previous research has shown statistically significant and very strong associations between toe-off distance (in the form of centre of mass angle at toe-off) of physical education students and propulsive forces and orientation of the GRF vector during the first step (Kugler & Janshen, 2010).

However, the toe-off distances of world class (Tier 5) sprinters were not related to the magnitude of NAHEP during the first stance phase (Walker et al., 2021). It is feasible that the differences in athlete status (i.e., Tier 1 vs. Tier 5) or acceleration performance measure (i.e., GRF impulse measures vs. NAHEP) may have explained the inconsistency in the findings between Kugler and Janshen (2010) and Walker et al. (2021). However, this cannot explain the inconsistency in the relationship of toe-off distance and acceleration performance observed between Chapters 3 and 4 in this thesis since participants were of the same status (i.e., professional rugby backs, Tiers 4 to 5; 5 participants in Chapter 3 were also included in the current chapter) and the same acceleration performance measure was used. Following the analysis, to check that the difference observed in the relationship between toe-off distance and NAHEP in the current chapter and Chapter 3 was not due to methodological differences, participants' toe-off distances in the current chapter were also normalised to stature and averaged over the first three steps and the relationship of the values obtained with NAHEP over the same steps was determined (i.e., to enable a direct comparison with the same approach used in Chapter 3). The results of this analysis can be found in Table E.1 (Appendix E). The relationship found was also not statistically significant or meaningful and toe-off distance does not, therefore, seem to consistently relate to NAHEP in rugby backs.

One possible reason for the mixed findings between Chapters 3 and 4 in regard to the different relationships observed between toe-off distances and NAHEP can be explained by the different technique-based strategies observed within participants in the current chapter that were used to achieve similar NAHEP magnitudes. That is, inter-individual degeneracy may exist within backs in the context of performance, and it is still seemingly possible to achieve high NAHEP magnitudes relative to other backs without a large negative toe-off distance. However, whilst it may be possible to do so, other technical features may become more important, such as contact time. As evidenced by the strongest relationship of all correlations in this chapter (Figure 4.3 and 4.7), producing a more negative toe-off distance is reliant on a longer contact time. This is logical since the CM will be required to travel a greater horizontal distance during the stance phase to achieve a more negative toe-off distance. This increased contact time may offset the benefits of an increase in propulsive GRF if the magnitude of the increased impulse achieved is primarily through spending a longer time generating GRF rather than substantially increasing GRF magnitude. In such circumstances horizontal CM acceleration will likely be lower. This defines part of an optimisation dilemma for the rugby player to resolve in finding the 'favourable' combination of contact time and toe-off distance to achieve their ideal initial sprint acceleration performance.

The importance of the combination of contact time and propulsive force have been investigated at the third step of male sprinters where the combination of average propulsive force and propulsive time contributed 61% of the variance in NAHEP (von Lieres Und Wilkau et al., 2020a). The results in Table 4.2 (model 3) somewhat echo this finding where the combination of toe-off distance (having been shown to be representative of propulsive GRF magnitude) and contact time accounted for the largest percentage (37%) of the variance in NAHEP explained by any of the regression models. It would also appear that no single combination of toe-off distance and contact time is optimal for initial acceleration performance across all individuals since different combinations of these variables were used as part of individual strategies to achieve similar magnitudes of NAHEP. For instance, as shown in Figure 4.7 the fastest back produced the second shortest contact time but achieved a toe-off distance which was less (i.e., foot more posterior relative to the CM) than 16 out of 25 other players. In contrast, the participant who achieved the second highest magnitude of NAHEP (only 0.026 less than the highest produced within the group) produced the most posterior foot position relative to their CM at toe-off in the group, but their normalised contact times were longer than 20 of the players. Although not at the same extreme ends of the spectrum, similar combinations for the backs ranked third (6^{th} shortest contact time, 12^{th} most negative toe-off distance) and fourth (19^{th} shortest contact time, 19^{th} most negative toe-off distance) in terms of NAHEP were observed.

Of the different combinations in toe-off distance and contact time, backs who produced short contact times and less negative toe-off distances produced higher step rates. Conversely, backs who produced more negative toe-off distances and longer contact times achieved longer step lengths. These patterns are also reinforced by the relationships (Figure 4.3) showing longer step lengths and slower step rates accompanied more negative toe-off distances, and also indicate that different combinations of step rate and step length may also be achieved to produce similar initial sprint acceleration performance. For instance, Figure 4.7 shows the fastest and third fastest back achieved relatively high step rates and short step lengths, whereas the second and fourth fastest backs achieved relatively low step rates and long step lengths. This explains further why there is a lack of consensus, as discussed earlier in this chapter and in Chapter 2, on which of these higher-level step characteristics are more important to sprinting performance.

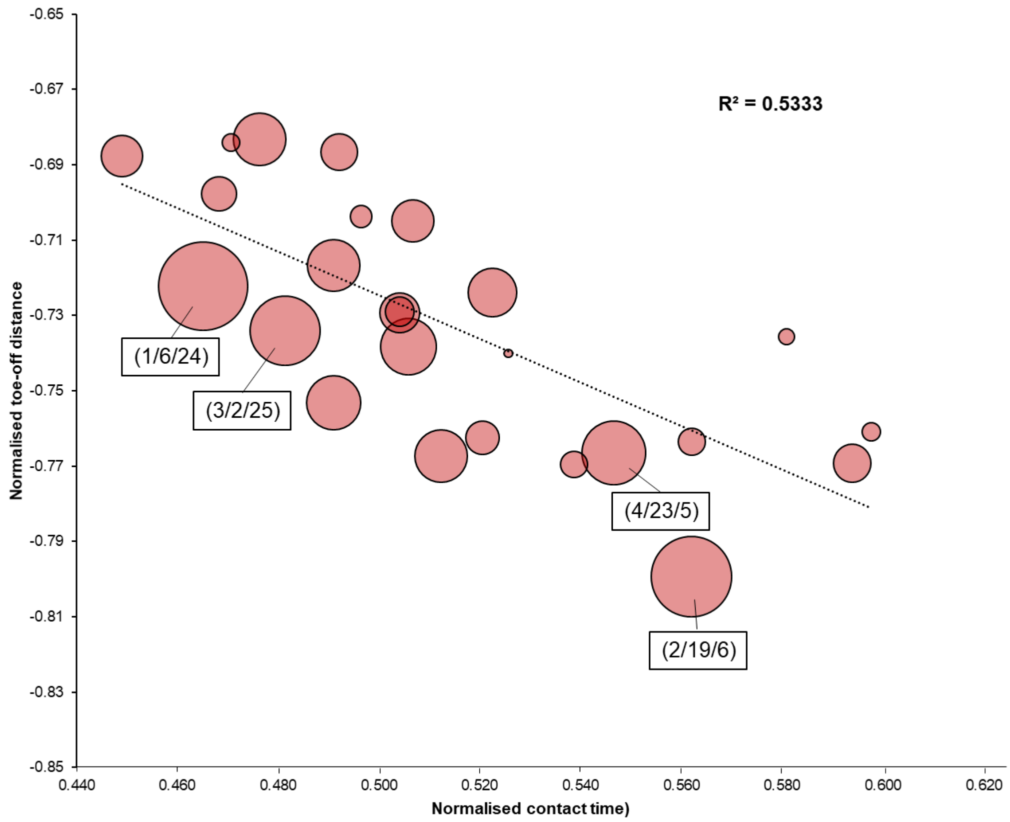

Figure 4.7. Scatterplot showing the relationship between toe-off distance and contact time. Data points have been scaled according to NAHEP magnitude, where the size of each marker is reflective of initial acceleration performance, with a larger marker equating to a greater magnitude of NAHEP. The numbers in brackets represent the rank order for that participant with regards to their observed NAHEP/step length/step rate, respectively. A lower number equates to a higher rank order. For example, '(1/25/2)' would indicate that a back achieved the best sprint performance (highest NAHEP), the shortest (25th) step length and the 2nd highest step rate.

Investigations into the step rate and step length as 'whole-body' gross kinematics and their different combinations leading to enhanced sprinting performance at the individual level, as discussed earlier in this chapter has previously been conducted across the full 100 m sprint in elite sprinters (Salo et al., 2011). A similar approach undertaken during the initial acceleration phase of backs may prove useful in assisting the decision-making process of coaches responsible for enhancing the initial sprint performance of these team sport players. Using a 'whole-body' approach in this way encompasses a backs' individual sprinting strategy which reflects the outcome of the combination of multiple kinematic and kinetic variables. This approach has been adopted in Chapter 6.

Although the laws of motion which govern sprinting are reflected by the external kinetic determinants of acceleration performance (Section 2.2, Chapter 2), and are relatively well established, the way individuals utilise the multiple degrees of freedom available to them when sprinting to solve these mechanical constraints during initial acceleration are more complex and less well known (Sections 2.3 to 2.6, Chapter 2). Consequently, looking at the whole-body gross kinematics (spatiotemporal variables) as a way to encapsulate the multiple possibilities to 'utilise the degrees of freedom' within the mechanical constraints in initial sprint acceleration for backs may capture individual kinematic strategies. Identifying whether backs are individually reliant on certain strategies for better initial acceleration performance may then help direct sprint training practices towards emphasising different strategies for the individualised enhancement of the sprint acceleration capabilities of rugby backs. If, through this process, a different strategy is identified for an individual as being favourable compared with their existing preference then barriers preventing their ability to achieve this new strategy would need to be removed. In consideration of this, understanding the performer constraints which underpin these different strategies is required for further understanding. For instance, if progressing a rugby back to a different strategy is not possible for an individual to consistently do (without sacrificing sprinting performance), because of unmodifiable physical constraints such as leg length, then the thought-to-be new "favourable" strategy for an individual is not achievable. If the physical constraint is a modifiable one (e.g., strength-related qualities) then a 'path' towards the required change in initial sprint strategy will likely require modifications to the underlying physical qualities which underpin the new strategy.

4.5 Chapter summary

This chapter sought to provide an advance in knowledge of the technique-based variables which are associated with the initial acceleration performance of rugby backs by answering research question II - *How do angular kinematics and normalised spatiotemporal variables relate to the toe-off distance and initial acceleration performance of professional rugby backs?* The observed results showed six variables to be meaningfully related to the initial sprint acceleration performance of backs during the first four steps. However, the relationships were only small to moderate and only three were statistically significant. The combination of hip touchdown angular velocity and peak ankle dorsiflexion angle was moderately related to the NAHEP of participants, although the regression analysis model was not significant and other contributory factors explain substantially more of the variation in initial sprint acceleration performance. Perhaps the most surprising finding was that no meaningful relationships were evident between toe-off distance and NAHEP, in contrast with the findings reported in Chapter 3 in which this variable was highlighted as a potentially important technical feature for the initial acceleration performance of backs. When toe-off distance and contact time were combined within a regression model, however, a large multiple correlation was observed, and these variables explained a significantly large variation in NAHEP. Different combinations of contact time and toe-off distances were shown to result in similar initial sprint acceleration performance, however, without a single combination likely resulting in optimisation of performance. Differences in related step characteristics also demonstrated that varying combinations of spatiotemporal variables can also accompany similar initial sprint acceleration performance.

The findings of this chapter, particularly when combined with the findings of Chapter 3, support the premise that a motor task such as sprinting can be accomplished through numerous solutions (Bernstein, 1967). Therefore, the findings of group study designs aiming to establish optimum sports techniques may be misrepresentative due to inter-individual differences in movement preferences which can result in similar performance outcomes. At worst, attempts to alter a single, or select number of, technical features in an individual (based on the findings of group study correlational analysis) may result in decreased initial sprint performance especially if the athlete does not possess the physical qualities required to successfully execute the new strategy. Therefore, an understanding of how physical qualities, in the way of strength-based characteristics, may act as performer constraints (Newell, 1986) to influence the technical features of backs during the initial steps of sprinting, and how they relate to their acceleration performance, is needed alongside a way to identify the kinematic aspects of technique important for backs at the intra-individual level.

CHAPTER 5: THE RELATIONSHIPS OF STRENGTH QUALITIES WITH THE KINEMATICS AND INITIAL SPRINT ACCELERATION PERFORMANCE OF PROFESSIONAL RUGBY BACKS

5.1 Introduction

The previous two studies within this thesis (Chapters 3 and 4) have shown there is inconsistency in the relationships between technical features of professional rugby backs' initial sprint acceleration and their corresponding performance (NAHEP). It was also evident that participants were able to achieve similar magnitudes of NAHEP through different movement tendencies, supporting the premise that motor tasks can be accomplished through numerous movement solutions (Bernstein, 1967). Where relationships have been observed in these studies (Chapters 3 and 4), they were only small to moderate, and other contributory (unknown) factors explained substantially more of the variation in NAHEP. Given that ecological dynamics and constraints led approaches view behaviour as emerging through a function of performer-environment interactions and the interactions between task, environmental, and performer constraints (Newell, 1986), it was prudent to investigate how strength-qualities of rugby backs may relate to NAHEP and how they interact with technical features adopted in this sprint phase. This is important to gain a more complete understanding of the contributory factors to initial sprint acceleration performance in rugby backs,

Owing to the high force and velocity requirements during sprinting, relationships between the lower limb strength and power strength qualities of team sport players and sprint acceleration performance have been researched extensively (e.g., Baker & Nance, 1999; Brechue, et al., 2010; Chelly et al., 2010; Cronin & Hansen, 2005; Cunningham et al., 2013; Dowson et al., 1998; Lockie et al., 2011; Lockie et al., 2015; Loturco et al., 2015; McBride et al., 2009; Sleivert & Taingahue, 2004; Wisloff et al., 2004; Zabaloy et al., 2020). However, during the initial steps of a sprint (approximately ≤ 5 m) these studies have typically focussed on participants from team sports outside of rugby union, or on rugby union players competing at an amateur level. Given that differences exist in the sprinting performances, anthropometrics and strength capabilities between athletes in different team sports, and between competitive standards within rugby union (Brazier et al., 2020), the relationships between these performer constraints may differ in full-time professional rugby union backs, which form the focus of this thesis, compared with those already observed in team sport players in the available literature. Accordingly, one of the aims of this chapter was to answer research question III - *How are lower limb strength qualities related to the performance of professional rugby backs during initial acceleration?*

In addition to the previous research investigating the relationships between strength qualities and initial acceleration performance not being conducted on professional rugby backs, the strength qualities investigated in these studies are considered in isolation from the technical features used by participants, providing a limited perspective and amount of information with which to understand how acceleration performance is achieved. Whilst the strength training of rugby backs is typically undertaken for multiple purposes as part of their physical training to enhance their match-play performance (e.g., to increase muscle mass, cope with contact demands, reduce risk of injury), identifying the lower limb strength qualities of rugby backs, their interactions with technical features, and how these are associated with more effective sprint acceleration can inform the development of strength-based interventions to elicit training adaptations, which are relevant to the initial acceleration of these team sport players. Given that changes in these performer constraints will affect the way individuals interact with their environment (Fajen et al., 2008), knowledge of the way that strength-based qualities relate to technical features adopted during the initial steps of a sprint would also provide further insight into how the different movement strategies observed in this sprint phase may be influenced. Accordingly, this chapter also aimed to answer research question IV - *What are the relationships between lower limb strength qualities and technical features, and how do their interactions associate with initial acceleration performance in professional rugby backs?* By answering research questions III and IV, the information obtained in doing so would inform the training of professional rugby union backs aimed at directly enhancing their lower limb strength capacities and / or movement strategies to improve initial sprint acceleration performance.

5.2 Methods

5.2.1 Participants

The same 25 male professional rugby union backs who were studied in Chapter 4 also participated in this study and were tested as part of a routine battery of physical assessments which take place at several time points across the season. Since these data were pre-existing from the testing conducted as part of the rugby players' usual training schedule, and were anonymised, informed consent was not required (Haugen et al., 2019b; Winter & Maughan, 2009). Study protocols were submitted to, and approved by, the University of Surrey's Research Ethics Committee. At the time of testing, participants were free from injury and frequently completed maximal sprint accelerations and strength and power training within their usual weekly training regime. Data were collected during the pre-season following 48-hours of abstinence from running, sprinting and lower body strength training.

5.2.2. Procedures

Initial sprint acceleration performance (NAHEP) and kinematic variables from participants over the first four steps were obtained from the same data set in Chapter 4 (see section 4.2.2 for full procedures). Additional variables for analyses included in the study reported in this chapter were obtained from three different strength-based assessments which took place on another day in the same week that variables were attained from the sprint trials. Participants were fully familiar with each strength-based assessment, having completed these tests on multiple occasions previously.

5.2.3 Repeated jump assessment

Firstly, participants completed repeated unilateral in-place jumps testing (hereafter referred to as repeated jumps). This involved performing two series of 10 continuous vertical jumps with hands on hips aiming to achieve maximum height whilst spending the smallest possible time in contact with the ground. The hip and knee of the non-test side were flexed to approximately 90° throughout the jumps. Participants performed two warm-up efforts separated by two minutes rest. Following a further two minutes rest, participants completed the first series of 10 repeated jumps (left side, followed by right side) and rested for three minutes before completing a second series. Jump heights (m; determined from flight times) and contact times (s) were collected for each jump, using an infrared timing system (Optojump, Microgate), from which the reactive strength index (RSI) was determined by the ratio of jump height to contact time (Flanagan et al., 2008; Flanagan & Comyns, 2008). Using a modified approach from Comyns et al. (2019), the average of the best three RSI scores within the series of 10 jumps was used to establish an overall RSI value for that series. Contact times and jump heights for each of the three jumps which produced the highest overall RSI within the 10 jumps on the left side were averaged and retained for analysis, as were the equivalent values on the right side. The left and right-side jump heights, contact times and RSI were then averaged and used within the statistical analyses. Vertical stiffness relative to body mass

(K_{vert}/kg) was an additional variable initially calculated from the contact and flight times achieved during repeated jumps using the equations from Dalleau et al. (2004). However, this measure shared a practically perfect negative relationship (r = -0.97) with repeated jump contact time (hereafter referred to as repeated contact time) and thus these variables are synonymous within this assessment. For this reason, vertical stiffness was omitted from any analysis to avoid duplication and reduce the number of variables analysed.

5.2.2 Squat jump force-velocity profiling

Secondly, participants completed squat jumps under different loaded conditions based on procedures modified from Samozino et al. (2013). Participants performed two maximal effort squat jumps under five different loading conditions (0, 20, 40, 60 and 80 kg) as a variety of loads have been shown to produce valid and reliable results for the main output measures of interest (García-Ramos et al., 2021). The maximum load equated to, on average, 85% of participants' body mass (range 75 to 100%). Initially, the vertical distance the CM travelled for each participant during the push off (h_{po}) in each squat jump was estimated. To obtain this, extended leg length was first measured to simulate the take-off position of a squat jump. This was determined as the distance (m) from the centre of the right greater trochanter to the tip of the toe on the same side when lying supine with ankles maximally plantarflexed. Squat jump depth (m) was then measured (to simulate the bottom position of a squat jump) as the distance from the centre of the right greater trochanter to the floor in the bottom of the squat jump position. Squat depth was self-selected by participants according to the depth they felt would achieve the highest jump height based on their experience of performing squat jumps across a number of loads, which has also been shown to be valid and reliable (Janicijevic et al., 2020). By subtracting squat jump depth from extended leg length, h_{po} was estimated (Samozino et al., 2013). To ensure h_{po} was consistent in each jump during testing, a box was set at the height of each participant's squat depth to be in contact with their buttocks when their self-selected squat jump depth was met.

Three measures were determined from the loaded squat jumps (Samozino et al., 2013): 1) theoretical maximal force production of the lower limbs (F_0 [N/kg]); 2) theoretical maximal extension velocity of the lower limbs (V_0 [m/s]); 3) maximal mechanical power output (P_{max} [W/kg]).

For each jump, participants descended to the height at which their buttocks touched the box set to the height of their self-selected depth and held this position for approximately 2 seconds before jumping vertically, on the cue of the tester, with maximal intent. Jump heights (m) were recorded using an infrared timing system (Optojump, Microgate) and each jump was carefully observed to check for any prior countermovement before jumping and that approximately the same leg joint configurations were met upon touchdown as that at the point of take-off (i.e., ankles plantarflexed and knees extended). Participants rested for approximately two and four minutes between each trial of the same and different load, respectively. Using vertical push-off height (h_{po}), jump height (h), the acceleration due to gravity (g; 9.81) and system mass (m; body mass + mass of external mass), averaged leg extension force and CM vertical velocity over the push-off was determined using the previously validated equations (Samozino et al., 2008):

$$\text{Mean force} = mg((h/h_{po}) + 1)$$

$$\text{Mean velocity} = \sqrt{\frac{gh}{2}}$$

The theoretical maximal force production (F_0 [N/kg]) and maximal extension velocity of the lower limbs (V_0 [m/s]) were then extrapolated as the intercept of the force and velocity axes, respectively, from the FV relationship (Samozino et al., 2013). Maximal mechanical power output (P_{max} [W/kg]) was then calculated through the following equation (Samozino et al., 2013):

$$P_{max} = F_0 \times V_0/4$$

5.2.3 Isometric hip extensor torque assessment

Thirdly, the peak isometric torque (Nm/kg) of the hip extensors (hereafter referred to as hip torque) was assessed using adapted protocols from Goodwin and Bull (2021) and Czache et al. (2018). Participants were supine with hips (just below ASIS) positioned beneath an immoveable bar where hard, dense matting was placed between the hips and the bar to prevent gapping and provide comfort (Figure 5.1). The foot of the testing side was strapped to a wooden wedge attached to a linear bearing rail permitting vertical movement only, while the heel of each participant was positioned in the centre of a force plate (PASCO, PS-2141; 1000Hz), with the foot of the non-testing side lifted off the ground. Using a hand-held goniometer, the hip angle of the testing side was set at ~120° to be broadly representative of the mean hip joint angle of participants at touchdown during their first four steps during sprint trials (106°), where peak hip extensor moments are observed during the initial steps (e.g., Bezodis et al., 2014; Schache et al., 2019). The difference between the hip angle in testing and the mean touchdown hip angles of participants during the first four steps was within the previously observed crossover range of joint angle-specific peak isometric torque (Lanza et al., 1995). The knee joint angle (also using a handheld goniometer) was set to 75° to reduce knee flexor involvement within the test (Kwon & Lee, 2013; Sakamoto et al., 2009). The moment arm (m) was measured using a tape measure as the distance from the lateral aspect of the greater trochanter to the point where the heel was in contact with the force plate.

After establishing a baseline vertical force for approximately 5 seconds, participants were instructed to "push their heel down into the force plate as fast and as hard as they can, as if pressing the bar with their hips up towards the ceiling" until the vertical force had visibly plateaued (≤ 5 s). After three minutes rest, participants completed a second trial. This sequence took place three times on both left and right sides, with the peak force achieved averaged across all trials for each side after removal of the baseline force. These forces were then multiplied by the respective moment arm and normalised to body mass before being averaged across both sides to determine an overall peak hip torque (Nm/kg; hereafter referred to as hip torque) for each participant.

Quantitative analysis of sagittal plane videos captured during the testing confirmed that hip and knee angles ranged between 119-122° and 73-77°, respectively. To obtain these angular measures, one trial for ten participants was filmed (240 Hz; iPhoneXS, Apple Inc, Cupertino, Ca). The participants moved towards the left end of the immoveable bar (Figure 5.1) and the camera was positioned perpendicular to participants' hip joint centres, to the right end of the immoveable bar using a ×0.5 zoom wide angle lens setting, permitting a field of view wide enough to obtain the relevant measures. Video files were imported to Kinovea (v.0.8.27) motion analysis software where hip and knee joint angles were checked for deviation from their pre-set angles. Given the low CV values for hip torque (see results section), it is unlikely that the deviations in these joint angles during the hip torque assessment biased any outcomes.

One additional variable was also calculated which combined measures from across two of the above tests: hip torque/repeated jump contact time. This was selected based on stance kinetics during acceleration where hip extensor power generation and ankle stiffness qualities are observed as the ankle absorbs energy and are thought to act synergistically to facilitate horizontal CM acceleration (e.g., Schache et al., 2019; Veloso et al., 2015). This ratio allowed for the evaluation of the combination of hip extensor and vertical stiffness measures, with a higher or lower value indicative of a relatively greater inclination towards hip extensor or vertical stiffness respectively.

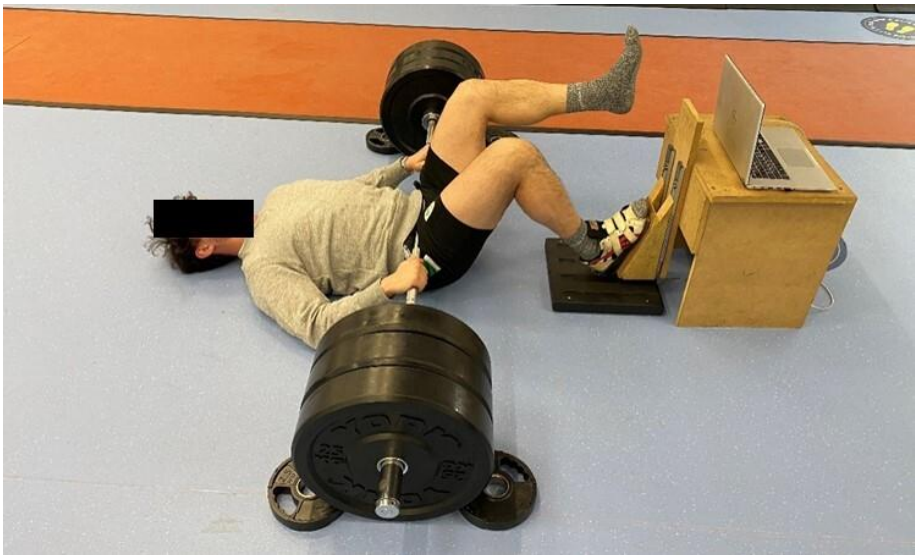

Figure 5.1. Set up for the isometric hip extensor torque assessment

5.2.4 Statistical analyses

Descriptive statistics (mean ± SD) were calculated for all variables. Normal distribution of the data was checked by the Shapiro-Wilk normality test. The within-individual coefficient of variation (CV) was calculated for each individual across their respective trials in each strength-based assessment and the average of these across the entire group was then determined as a measure of relative reliability for each measure, representing the typical error as a percentage of the mean for each measurement (Atkinson & Nevill, 1998). As detailed in Chapter 4 (section 4.3.1), good to excellent reliability for the manual digitisation process for all kinematic variables during the first four steps (ICC = 0.78 to > 0.90) was observed. Relationships between strength-based variables and NAHEP were determined using either multiple, bivariate or semi-partial correlation coefficients (*r*) – the latter to control repeated jump measures for body mass. Relationships of all strength-based variables in their absolute form with normalised spatiotemporal variables, as well as linear and angular kinematics, were determined using partial correlations to control dependent and independent variables for body mass. Confidence intervals (90%) for all observed relationships were calculated to detect the smallest clinically important correlation coefficient ($r = \pm 0.1$). Relationships were deemed meaningful when their magnitudes were equal to or greater than the smallest clinically important correlation and confidence limits did not include positive and negative values greater than the smallest clinically important correlation

Hip torque and body mass were then combined with either repeated contact time, normalised hip extension touchdown angular velocity, or peak ankle dorsiflexion angle within three separate linear multiple regression models, using the 'enter' method for variable selection, to assess their combined associations with NAHEP (dependent variable). Repeated contact time, body mass and normalised hip touchdown angular velocity were also included within a linear multiple regression model to assess their combined associations with NAHEP (dependent variable). The independent variables were selected based on the lower limb joint kinetics during the early portion of the stance phase where hip extensor power generation and lower limb reactive strength and stiffness-like qualities are observed as the ankle absorbs energy (Charalambous et al., 2012; Debaere et al., 2013a; Schache et al., 2019), and are thought to act synergistically to facilitate horizontal CM acceleration (e.g., Veloso et al., 2015). Autocorrelations for regression analyses were minimal (Durbin-Watson 2.0 to 2.5) and multicollinearity was within acceptable thresholds of 1.1 to 1.5 (Hair et al., 2019). Five separate Cartesian plane quadrants were formed to provide a visual representation of the relative magnitudes of hip torque and repeated contact time, hip torque and RSI, and repeated jump height and repeated contact time in relation to the magnitudes of NAHEP achieved by participants.

For all correlation coefficients, the strength of observed relationships were defined as: (±) < 0.1, trivial; 0.1 to < 0.3, small; 0.3 to 0.5 moderate, 0.5 to 0.7 large, 0.7 to 0.9 very large and > 0.9, practically perfect (Hopkins, 2002). To reduce the possibility of the estimated explained variation of NAHEP being overstated by the coefficient of determination, owing to the sample size used in the analysis, adjusted *r* squared (r^2) was calculated to interpret the effect size with thresholds set as: < 0.02, trivial; 0.02 to 0.13, small; 0.13 to 0.26, large (Cohen, 2013). All analyses were performed using SPSS (v26.0) with alpha set at $p < 0.05$.

5.3 Results

Descriptive statistics for the strength-based variables are detailed in Table 5.1. The group mean CVs for all strength variables were < 10%, indicating these data were reliable (Atkinson & Nevill, 1998). The descriptive statistics for NAHEP and sprint technique-based kinematic variables were reported in Chapter 4 (Table 4.1).

Table 5.1. Descriptive statistics for strength-based variables of participants

Variables	Mean	SD	Min.	Max.	CV (%)
F_0 (N/kg)	37.15	4.77	29.00	47.09	4.7
V_0 (m/s)	3.13	0.46	2.32	4.07	5.9
P_{max} (W/kg)	28.94	4.74	18.00	38.67	4.2
Hip torque (Nm/kg)	5.81	0.79	4.46	7.77	2.4
Repeated CT (s)	0.276	0.025	0.240	0.316	4.4
Repeated jump height (m)	0.18	0.02	0.13	0.21	4.7
Repeated RSI (height / CT)	0.64	0.09	0.44	0.82	5.4
Hip torque / repeated CT ratio	21.22	3.69	14.46	30.06	5.2

5.3.1 Relationships of NAHEP with strength-based variables

For strength-based measures in isolation, hip torque, P_{max}, repeated jump height and RSI and the hip torque / repeated CT ratio were all meaningfully and moderately related (r = 0.35 to 0.39) with NAHEP (Figure 5.2). Repeated jump height, when controlled for body mass, however, was the only variable demonstrating a statistically significant relationship with NAHEP, uniquely contributing to 16% of the variance in the independent variable.

When combined in a multiple linear regression model, a meaningful multiple relationship of hip torque, repeated contact time and body mass with NAHEP (small effect) was found, though the model was not statistically significant (Figure 5.3).

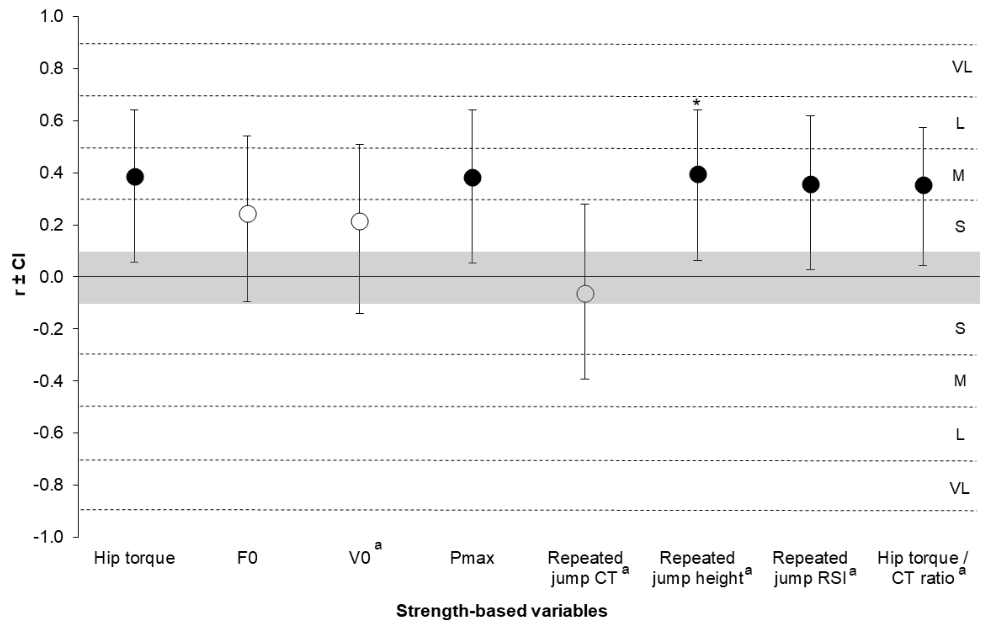

Figure 5.2. Correlation coefficients (± 90% CI) between strength-based variables and NAHEP over the initial four steps of a sprint. A trivial relationship (r = ± 0.1) is indicated by the central grey shaded area. Horizontal dotted lines represent thresholds for the magnitude of relationships (S, small; M, moderate; L, large; VL, very large). Black shaded markers indicate that the relationship is deemed greater than the smallest clinically important correlation coefficient, and therefore meaningful. Asterisks indicate relationships that are statistically significant ($p < 0.05$).

[a]Semi-partial correlations with strength-based measures controlled for body mass (all other relationships were determined using bivariate correlations with strength-based variables normalised to body mass).

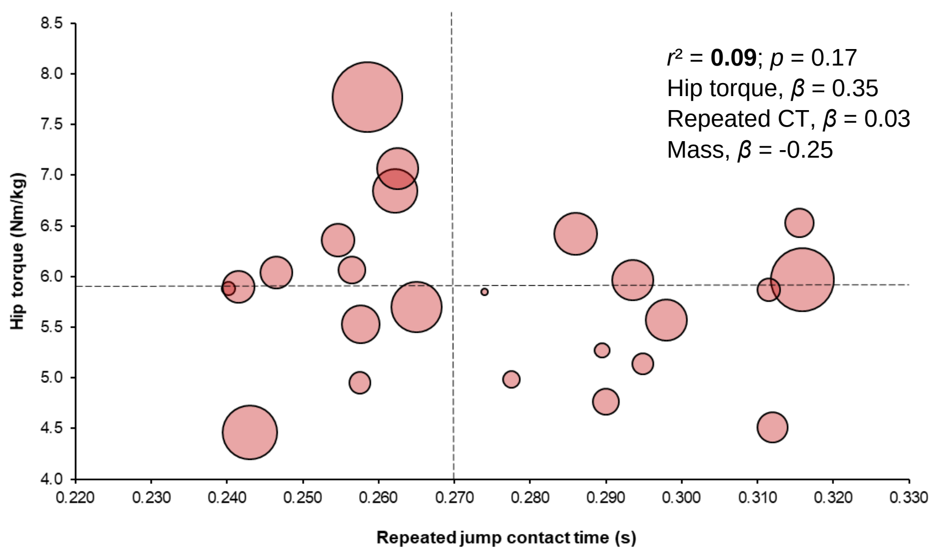

Figure 5.3. Interaction between hip torque, repeated contact time and NAHEP during the first four steps of professional rugby union backs. The centre of each data point represents the mean of these strength measures for an individual. Dotted lines divide axes according to a median split to form quadrants. The size of the marker depicts the relative sprinting performance (NAHEP) of each participant over the first four steps, with marker sizes increasing in proportion to the magnitude of a given participant's performance (i.e., largest marker size = highest NAHEP). Results for the multiple regression analysis in which hip torque, repeated contact time and body mass were entered as independent variables and NAHEP as the dependent variable are also shown. For adjusted r^2 values, bold font depicts an effect size considered meaningful (> 0.09). β = standardised coefficients for independent variables.

5.3.2 Relationships of strength-based characteristics with sprinting kinematics

Several strength-based variables were meaningfully related with normalised spatiotemporal variables (Table 5.2). Five statistically significant relationships were observed involving contact time and step rate. Of these statistically significant correlations, shorter contact times were associated with higher hip torques, hip torque/repeated contact time ratio, RSI and lower repeated contact time (moderate to large relationships). A statistically significant, moderate negative relationship was also observed between repeated contact time and step rate.

Regarding linear kinematics (Table 5.3), participants with more negative touchdown distances produced greater magnitudes of hip torque and shorter repeated contact time (and therefore their hip torque/contact time ratio was also higher) as depicted by the moderate to large and statistically significant relationships of these strength variables with touchdown distance. The strength and direction of these correlations were almost identical to the relationship of these strength variables with contact length, whereas toe-off distance was significantly related only to hip torque/contact time ratio (moderate relationship). That is, participants tended to position their foot less posterior relative to the CM at toe-off when hip torque/contact time ratio was higher. No strength-based variables were meaningfully related to flight length.

Hip torque and hip torque/repeated contact time ratio were more related to leg segment angles at touchdown (i.e., the proximal ends of these segments were more oriented towards the direction of travel) when controlling for body mass, compared with other strength-based variables. This was evident by the statistically significant correlations ranging from r = -0.55 to -0.41 (Table 5.4) showing the relationships of strength-based variables with touchdown and stance phase angular kinematics (note that the 90% CI have been removed from Table 5.4 to help with the clarity of viewing results, but these can be seen in Table F.1 in Appendix F). A higher P_{max} was associated with a more dorsiflexed ankle at touchdown and the peak dorsiflexion angle of this joint during ground contact (significant moderate to large relationships). Peak ankle dorsiflexion also exhibited statistically significant negative relationships of a moderate magnitude with V_0 and repeated contact time. Higher P_{max} and F_0 were strongly and moderately associated with a more flexed knee angle at touchdown, respectively, where statistically significant relationships were observed. P_{max} was negatively and positively associated with hip touchdown angular velocity and stance mean hip angular velocity, respectively, where statistically significant moderate and large relationships were found. Stance mean hip angular velocity was the only touchdown kinematic variable which repeated jump height was significantly correlated to (moderate positive relationship).

The strength-based variable relationships with toe-off angular kinematics (Table 5.5) were typically weaker than their relationships with touchdown angular kinematics (note that the 90% CI have been removed from Table 5.5 to help with the clarity of viewing results, but these can be seen in Table F.2 in Appendix F). Four statistically significant relationships were found, all involving shank, foot or ankle angular positions at toe-off. Of these relationships, hip torque and hip torque/repeated contact time ratio were moderately and positively related to shank angle. Foot angle at toe-off positively and moderately correlated to F_0, whereas the ankle joint angle at toe-off was found to moderately, and negatively, relate to repeated jump height.

5.3.3 Interaction of strength-based variables and sprinting kinematics with NAHEP

The multiple linear regression models investigating the interaction of hip torque and body mass with either hip touchdown velocity or peak ankle dorsiflexion with NAHEP were found to be meaningfully associated with acceleration performance (large effect, Figures 5.4 - 5.5). Trivial relationships with NAHEP were found when repeated contact time and hip touchdown velocity were combined with body mass (Figures 5.6). No linear regression model was found to be statistically significant.

Table 5.2. Partial correlation coefficients (90% CL) between strength-based variables in their absolute form and normalised spatiotemporal variables (Hof, 1996) over the initial four steps, controlling for body mass.

Strength-based variables	**Normalised spatiotemporal variables**							
	Step length		Step rate		Contact time		Flight time	
Hip torque	**-0.28**	(-0.56 to 0.06)	0.17	(-0.18 to 0.48)	**-0.42***	(-0.66 to -0.10)	0.27	(-0.07 to 0.56)
F_0	-0.01	(-0.35 to 0.33)	0.11	(-0.24 to 0.43)	-0.21	(-0.51 to 0.14)	0.17	(-0.18 to 0.48)
V_0	0.10	(-0.25 to 0.42)	-0.19	(-0.50 to 0.16)	0.14	(-0.21 to 0.46)	0.17	(-0.18 to 0.48)
P_{max}	0.05	(-0.29 to 0.38)	-0.06	(-0.39 to 0.28)	-0.17	(-0.48 to 0.18)	0.26	(-0.08 to 0.55)
Repeated CT	**0.34**	(0.00 to 0.61)	**-0.47***	(0.16 to 0.70)	**0.43***	(0.11 to 0.67)	-0.03	(-0.36 to 0.31)
Repeated jump height	0.09	(-0.25 to 0.41)	-0.11	(-0.43 to 0.24)	-0.20	(-0.50 to 0.15)	**0.39**	(0.06 to 0.64)
RSI	-0.11	(-0.43 to 0.24)	0.16	(-0.19 to 0.47)	**-0.42***	(-0.66 to -0.10)	**0.35**	(0.01 to 0.61)
Hip torque/CT ratio	**-0.39**	(-0.64 to -0.06)	**0.34**	(0.00 to 0.61)	**-0.55***	(-0.75 to -0.26)	0.23	(-0.12 to 0.53)

Bold font indicates that the relationship is deemed greater than the smallest clinically important correlation coefficient (r = ± 0.26)
Asterisks indicate statistical significance (p = < 0.05)

Table 5.3. Partial correlation coefficients (90% CL) between strength-based variables in their absolute form and normalised linear kinematic variables (Hof, 1996) over the initial four steps, controlling for body mass.

Strength-based variables	**Normalised linear kinematic variables**							
	Touchdown distance		Toe-off distance		Contact length		Flight length	
Hip torque	**-0.51***	(-0.73 to -0.21)	**0.36**	(0.02 to 0.62)	**-0.49***	(-0.71 to -0.18)	0.17	(-0.17 to 0.48)
F_0	-0.01	(-0.35 to 0.33)	0.09	(-0.26 to 0.41)	-0.05	(-0.38 to 0.29)	0.03	(-0.31 to 0.36)
V_0	0.20	(-0.15 to 0.50)	0.06	(-0.28 to 0.39)	0.11	(-0.24 to 0.43)	0.04	(-0.31 to 0.37)
P_{max}	0.15	(-0.19 to 0.47)	0.14	(-0.21 to 0.45)	0.04	(-0.3 to 0.37)	0.02	(-0.31 to 0.36)
Repeated CT	**0.45***	(0.13 to 0.68)	**-0.37**	(-0.63 to -0.03)	**0.46***	(0.14 to 0.69)	-0.04	(-0.37 to 0.30)
Repeated jump height	-0.13	(-0.45 to 0.21)	0.01	(-0.32 to 0.35)	-0.09	(-0.42 to 0.25)	0.24	(-0.11 to 0.53)
RSI	**-0.37**	(-0.63 to -0.04)	0.23	(-0.12 to 0.52)	**-0.34**	(-0.61 to -0.01)	0.24	(-0.11 to 0.53)
Hip torque/CT ratio	**-0.64***	(-0.80 to -0.39)	**0.48***	(0.17 to 0.70)	**-0.63***	(-0.80 to -0.37)	0.17	(-0.18 to 0.48)

Bold font indicates that the relationship is deemed greater than the smallest clinically important correlation coefficient (r = ± 0.26)
Asterisks indicate statistical significance (p = < 0.05)

Table 5.4. Partial correlation coefficients of strength-based variables in their absolute form with touchdown and stance phase angular kinematics over the initial four steps, controlling for body mass. Hip angular velocity measures have been normalised (Hof 1996)

	Touchdown angular kinematics										
Strength-based variables	Foot angle	Shank angle	Thigh angle	Trunk angle	Ankle angle	Peak ankle dorsiflexion angle	Ankle dorsiflexion ROM	Knee angle	Hip angle	Hip touchdown angular velocity	Stance mean hip angular velocity
Hip torque	**-0.32**	**-0.46***	**-0.37**	-0.03	-0.07	-0.14	0.04	0.02	0.24	-0.09	**0.31**
F_0	-0.02	**-0.35**	0.18	-0.07	**-0.31**	-0.15	0.30	**-0.45***	-0.20	-0.27	**0.34**
V_0	0.10	-0.09	0.15	-0.09	-0.28	**-0.48***	0.04	-0.20	-0.18	-0.33	**0.35**
P_{max}	0.07	**-0.34**	0.25	-0.14	**-0.46***	**-0.56***	0.26	**-0.50***	**-0.31**	**-0.47***	**0.57***
Repeated CT	**0.30**	**0.29**	**0.35**	-0.16	-0.13	**-0.40***	-0.04	-0.16	**-0.37**	-0.15	**0.27**
Repeated jump height	-0.10	-0.18	0.03	-0.06	-0.10	-0.06	-0.06	-0.19	-0.08	-0.14	**0.49***
RSI	**-0.27**	**-0.33**	-0.18	0.04	-0.01	0.20	-0.02	-0.08	0.15	-0.04	0.24
Hip torque/CT ratio	**-0.41***	**-0.55***	**-0.48***	0.07	-0.01	0.09	0.04	0.08	**0.39**	-0.01	0.11

Bold font indicates that the relationship is deemed greater than the smallest clinically important correlation coefficient

Asterisks indicate statistical significance (*p* = < 0.05)

Note that the 90% CI for these relationships can be found in Table F.1 in Appendix F

Table 5.5. Partial correlation coefficients between strength-based variables in their absolute form and toe-off angular kinematics over the initial four steps, controlling for body mass.

	Toe-off angular kinematics							
Strength-based variables	Foot angle	Shank angle	Thigh angle	Trunk angle	Ankle angle	Knee angle	Hip angle	Thigh separation angle
Hip torque	**0.40**	**0.42***	-0.01	0.09	-0.16	**0.27**	0.09	-0.12
F_0	**0.43***	-0.12	**0.31**	0.14	**-0.30**	**-0.34**	-0.07	-0.08
V_0	0.05	-0.14	-0.14	0.05	-0.07	0.05	0.11	0.11
P_{max}	**0.35**	-0.20	0.12	0.14	-0.29	-0.20	0.03	0.05
Repeated CT	-0.11	-0.17	**-0.40**	0.00	-0.12	0.18	0.22	**0.37**
Repeated jump height	**0.30**	-0.13	-0.24	0.04	**-0.43***	0.09	0.18	0.09
RSI	**0.32**	-0.03	0.05	0.02	**-0.29**	-0.05	0.01	-0.16
Hip torque/CT ratio	**0.39**	**0.44***	0.20	0.09	-0.06	0.13	-0.03	**-0.27**

Bold font indicates that the relationship is deemed greater than the smallest clinically important correlation coefficient (r = ± 0.26)

Asterisks indicate statistical significance (*p* = < 0.05)

Note that the 90% CI for these relationships can be found in Table F.2 in Appendix F

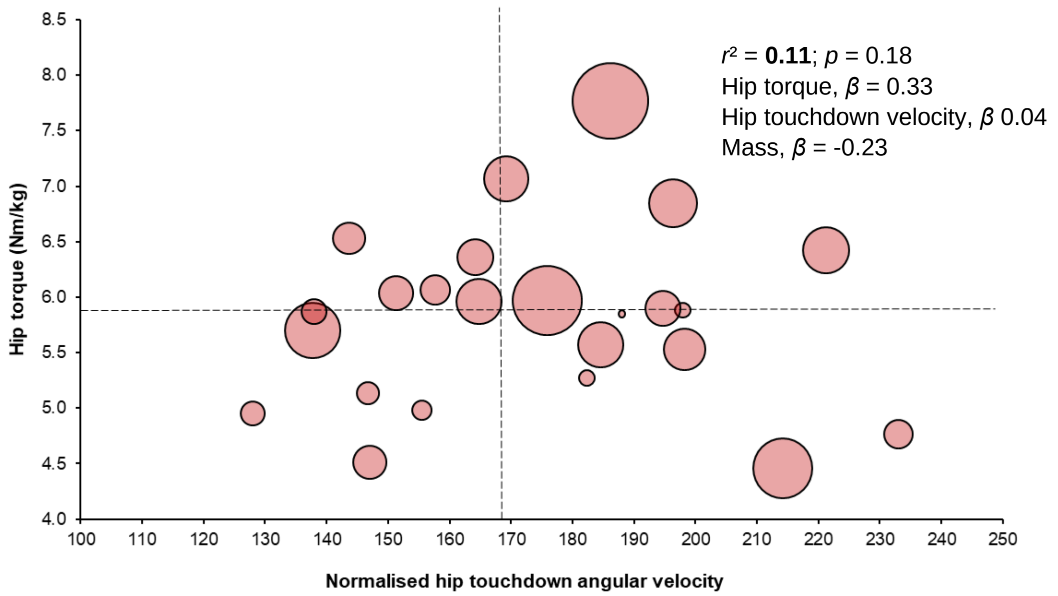

Figure 5.4. Interaction between hip torque and normalised hip touchdown angular velocity and NAHEP during the first four steps of professional rugby union backs. Each marker represents the mean of these strength measures for an individual. Dotted lines divide axes according to a median split to form quadrants. The size of the marker depicts the relative sprinting performance (NAHEP) of each participant over the first four steps, with marker sizes increasing in proportion to the magnitude of a given participant's performance (i.e., largest marker size = highest NAHEP). Results for the multiple regression analysis in which hip torque, normalised hip touchdown angular velocity and body mass were entered as independent variables and NAHEP as the dependent variable are also shown. For adjusted r^2 values, bold font depicts an effect size considered meaningful (> 0.09). β = standardised coefficients for independent variables.

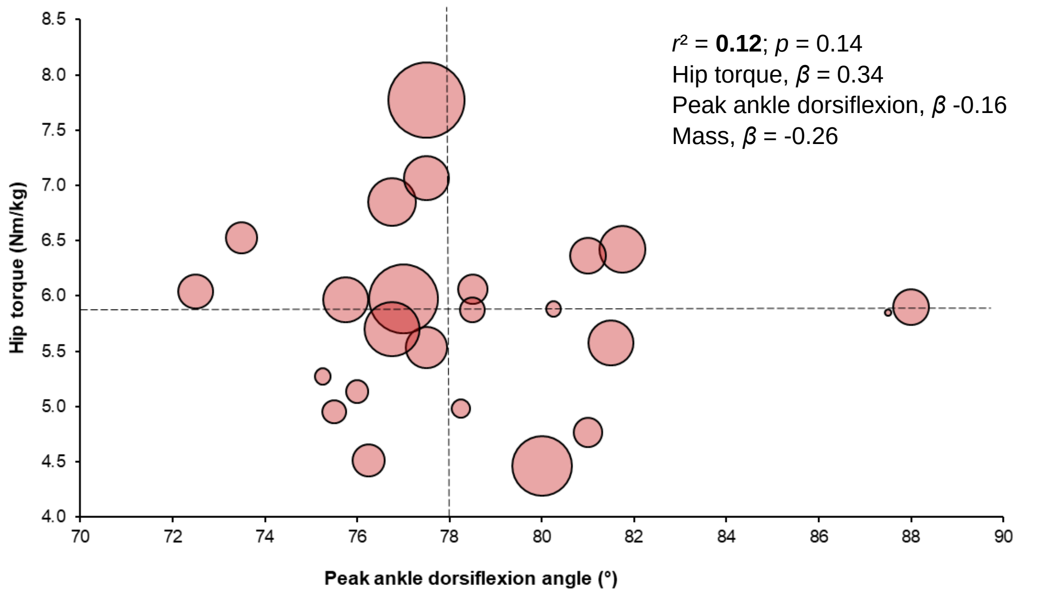

Figure 5.5. Interaction between hip torque and peak ankle dorsiflexion angle and NAHEP during the first four steps of professional rugby union backs. Each marker represents the mean of these strength measures for an individual. Dotted lines divide axes according to a median split to form quadrants. The size of the marker depicts the relative sprinting performance (NAHEP) of each participant over the first four steps, with marker sizes increasing in proportion to the magnitude of a given participant's performance (i.e., largest marker size = highest NAHEP). Results for the multiple regression analysis in which hip torque, peak ankle dorsiflexion and body mass were entered as independent variables and NAHEP as the dependent variable are also shown. For adjusted r^2 values, bold font depicts an effect size considered meaningful (> 0.09). β = standardised coefficients for independent variables.

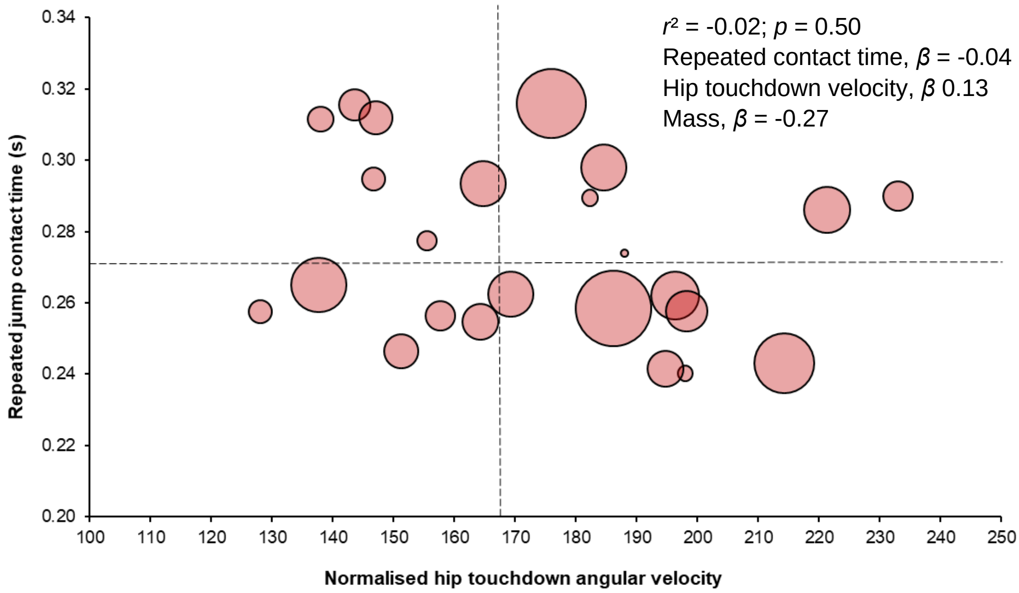

Figure 5.6. Interaction between repeated contact time and normalised hip touchdown angular velocity and NAHEP during the first four steps of professional rugby union backs. Each marker represents the mean of these strength measures for an individual. Dotted lines divide axes according to a median split to form quadrants. The size of the marker depicts the relative sprinting performance (NAHEP) of each participant over the first four steps, with marker sizes increasing in proportion to the magnitude of a given participant's performance (i.e., largest marker size = highest NAHEP). Results for the multiple regression analysis in which repeated contact time, normalised hip touchdown angular velocity and body mass were entered as independent variables and NAHEP as the dependent variable are also shown. For adjusted r^2 values, bold font depicts an effect size considered meaningful (> 0.09). β = standardised coefficients for independent variables.

5.4 Discussion

The results of the study reported in this chapter showed several strength qualities to meaningfully relate to the NAHEP of professional rugby backs during the first four steps of sprinting. However, only one of these relationships was statistically significant, and for all associations only a small percentage of variation in NAHEP could uniquely be attributed to the variation in any single strength-based variable. Furthermore, several multiple linear regression models used to investigate the combination of hip torque and vertical stiffness or the combination of either of these strength variables with hip and ankle joint angular kinematics during initial acceleration could not explain a statistically significant amount of variation in NAHEP. However, a number of large and statistically significant relationships were observed between strength-based variables and sprinting kinematics, providing support for the premise that although they may not combine to directly influence performance outcome, physical constraints do interact with the movement strategies adopted by individuals (Fajen et al., 2008; Newell, 1986).

5.4.1 Squat jump FV profiling measures and NAHEP

Given the high levels of lower limb extensor/plantar flexor energy generation necessary during the initial steps of sprinting to achieve high CM horizontal acceleration (e.g., Bezodis et al., 2014; Brazil et al., 2017; Debaere et al., 2013a), it is logical to deduce that performance during strength-based assessments, such as the squat jump, which also require high extensor/plantar flexor energy generation, would be meaningfully correlated to sprint performances over distances in which these initial steps are taken (Cronin & Hansen, 2005; Sleivert & Taingahue, 2004).

P_{max} of participants during squat jump FV profiling was higher (28.94 ± 4.74 vs 25.64 ± 4.47 W/kg) compared with the only study to publish relationships between squat jump FV profiling measures and initial acceleration performance (5 m sprint times) of rugby backs (Zabaloy et al., 2020). This difference in P_{max} was underpinned by higher V_0 (3.13 ± 0.46 vs 2.77 ± 0.48 m/s), since F_0 was comparable between participant groups (37.15 ± 4.77 vs 36.96 ± 6.21 N/kg) and was possibly due to the differences in playing standard (i.e., the participants studied by Zabaloy et al. (2020) competed at an amateur level). The findings across both sets of analyses were similar to the relationships between both F_0 and V_0 and acceleration performance, where small statistically non-significant relationships were found. Whilst relationships between P_{max} and acceleration performance were also found to be statistically non-significant across both participant groups, the magnitude of this relationship in the current study was moderate (r = 0.38, p = 0.06), and larger than the small magnitude of the P_{max} and acceleration performance relationships (r = 0.18, p > 0.05) of the participants studied by Zabaloy et al. (2020). Whilst P_{max} may play a relatively small role in the production of NAHEP, and despite the squat jump sharing a similar lower limb net energy generation emphasis with the initial steps of a sprint, collectively, these results suggest that other factors contribute a larger extent to the initial acceleration performance of rugby union backs.

One reason why a stronger relationship was not observed between P_{max} and NAHEP could be due to differences in the mechanical specificity between the squat jump and initial steps of sprinting in the relative contributions of the lower limb joint moments and powers to the external power generated in these tasks. For instance, the squat jump has been shown to produce substantially larger peak extensor joint moments and powers at the knee compared with the hip and ankle joints

(Jandacka et al., 2014). However, the initial steps of a sprint require greater hip and ankle joint peak moments and powers compared with those at the knee (Bezodis et al., 2014; Brazil et al., 2017; Charalambous et al., 2012; Debaere et al., 2013a; Jacobs & van Ingen Schenau, 1992; Schache et al., 2019). Hip extensor and ankle plantarflexor joint kinetics have also been shown to be of greater importance, than those at the knee, to sprint acceleration performance by some researchers (Charalambous et al., 2012; Schache et al., 2019; Veloso et al., 2015), outlining the importance of considering relationships of strength qualities focusing more on the hip extensors and ankle plantarflexors with initial acceleration performance.

5.4.2 Hip torque measures and NAHEP

The hip is in an advantageous position to accelerate the CM forwards early in the stance phase, owing to its distance from the GRF vector, where extensor moments are at their peak (Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013a; Jacobs & van Ingen Schenau, 1992; Schache et al., 2019; Veloso et al., 2015). This, to an extent, may explain previous findings which have demonstrated a greater contribution of hip, compared with knee, extensor moments to acceleration performance (e.g., Schache, et al., 2019; Veloso et al., 2015), and a stronger association between mean propulsive power in the hip thrust and 10 m sprint time, than mean propulsive power in the squat jump and 10 m sprint time (Loturco et al., 2018). However, the relationship observed between hip torque and NAHEP in the current study ($r = 0.39$, $p = 0.056$) was near identical to that between P_{max} and NAHEP. Therefore, although in isolation hip torque may play a relatively small role in initial acceleration performance, a greater variation in the NAHEP of participants could also be explained by other factors than their hip torque capacity.

These findings highlight potential issues with only assessing lower limb power and force generating capacities during concentric and/or isometric strength-based assessments, such as the squat jump and hip torque test, respectively, since any benefits derived from lower limb strength qualities relevant to when the ankle absorbs energy during the early stance phase are disregarded. Unlike the hip and knee joints during early acceleration, the ankle shows a clear pattern of dorsiflexion followed by plantarflexion, and thus energy absorption then generation due to the plantarflexor moment dominance throughout stance (e.g., Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013a), justifying the inclusion of the repeated jump assessment in this study.

5.4.3 Repeated jump measures and NAHEP

When rounded to two decimal places, the magnitude of the relationship between repeated jump height and NAHEP was the same as that between hip torque and NAHEP ($r = 0.39$; meaningful, moderate). However, an r value difference of just 0.007 between the two (repeated jump height, $r = 0.394$, $p = 0.045$; hip torque, $r = 0.387$, $p = 0.056$) was enough for the relationship between repeated jump height and NAHEP to be statistically significant. RSI was also correlated to NAHEP by a similar magnitude ($r = 0.36$, $p = 0.07$), although this was not statistically significant. When considered in combination with the trivial relationship between repeated contact time and NAHEP, the pattern of these relationships was similar to previous research. For instance, the relationships of RSI and contact time during bilateral drop jumps with the 10 m sprint times of professional rugby union backs decreased across these strength-based variables (reactive strength, $r = -0.60$, $p < 0.01$; contact time, $r = 0.38$; $p > 0.05$) in Cunningham et al. (2013). Collectively, these findings suggest reactive strength may be of some importance to early acceleration performance in professional rugby union backs, but that the ability to generate a higher jump height for a given contact time, rather than to reduce contact time for a given jump height, in repeated jumping or drop jumps is more related to initial sprint performance. This highlights the importance of considering not only the RSI scores achieved by backs during testing for reactive strength, but also each component of RSI individually (i.e., jump height and contact time) to provide a more complete understanding of their acceleration-specific strength qualities.

5.4.4 Hip and ankle interaction with NAHEP

Leg stiffness during bilateral hopping tasks and vertical stiffness during single leg drop jumps has been shown to primarily depend on ankle joint stiffness during hopping tasks (Farley & Morgenroth, 1999; Kuitunen et al., 2011; Maloney et al., 2017), and therefore, the ankle joint stiffness capacity of participants would likely have contributed substantially to the vertical stiffness (repeated contact times) achieved in the repeated jumps. This is of interest since attenuating the degree of ankle dorsiflexion and achieving higher levels of ankle joint stiffness during the negative power phase of the ground contact in the initial steps, have been shown to be advantageous to initial acceleration performance (Bezodis et al., 2015; Charalambous et al., 2012). Despite the trivial relationship between repeated contact time and NAHEP in the current study, considering the interaction between this strength measure and hip extensor torque, and the interaction of these strength-based variables with hip and ankle kinematics during initial acceleration is relevant owing to the synergy between the hip and ankle in this sprint phase, as discussed in detail in the literature review in Chapter 2 (see Sections 2.3.4, 2.3.6 and 2.6.3). In brief, sufficient ankle stiffness will be needed in early acceleration to help facilitate a stable foot position with regards to the foot-ground interface. In turn this will enable the hip extensors to generate effective horizontal CM acceleration without their energy being dissipated by a relatively weak ankle joint (Veloso et al., 2015). On the basis of such findings in the initial steps, researchers have advocated the development of reactive strength and stiffness qualities of the plantarflexors through plyometric hopping-based activities to enhance initial sprint acceleration performance (Bezodis et al., 2015; Charalambous et al., 2012). Equally though, without the ability to produce large hip extensor moments, the advantages of a stable foot position will decrease since the forwards CM acceleration induced by the hip extensors would be lower.

Findings from multiple linear regression analyses in this chapter exploring the interaction of hip torque and repeated contact time with NAHEP and these strength qualities with hip and ankle kinematic features build on the results in Chapter 4 (Section 4.4.2). In Chapter 4, when peak ankle dorsiflexion angle was combined with hip touchdown velocity and body mass a meaningful relationship with NAHEP was evident (adjusted $r^2 = 0.09$, small effect). Similarly, across the multiple linear regression models within this chapter, combinations of hip torque and repeated contact time and combinations of hip torque and ankle kinematics demonstrated meaningful relationships (adjusted $r^2 = 0.09$ to 0.12, small effects) with NAHEP. Although smaller and trivial effects in the regression models involving repeated contact time and body mass with either hip touchdown angular velocity or peak ankle dorsiflexion angle were observed, the division of the axes in Figures 5.3 and 5.6 using a median split provides some insight of the interaction of these variables with NAHEP. For instance, in Figure 5.3 eight of the nine participants in the quadrant where hip torque was low and repeated contact time was high were among the eleven lowest NAHEP magnitudes observed in participants (bottom right quadrant). In Figure 5.6, of the seven participants contained within the quadrant where longer repeated contact time and lower hip touchdown angular velocity was observed (top left quadrant), six of the 13 slowest participants were also found. Collectively, these descriptive findings provide some evidence that coaches might want to consider hip torque and vertical stiffness strength-based qualities of rugby backs along with their hip and ankle kinematics during the initial steps (i.e., touchdown angular velocity and peak ankle dorsiflexion angle) in the context of their early acceleration performance. However, the regression analyses were not statistically significant and could only explain a small amount in the variation of NAHEP. It was apparent that rugby backs could achieve similar NAHEP with different combinations in the variables investigated. Therefore, even when variables are considered in combination, fundamentally different technical approaches can be used between different sub-groups, which explains why there are no strong relationships at the whole-group level. The effects of the regression models were also mostly explained by the magnitude of hip torque, as shown by the higher standardised beta-coefficients for this independent variable (Figures 5.3 – 5.5), which is consistent with the relationship of this variable in isolation with NAHEP (Figure 5.2).

5.4.5 Strength-based measures and sprinting kinematics

Little is known about how strength qualities and technical features of athletes during sprinting are related. Given that movement patterns adopted by individuals are influenced by their organismic constraints (Newell, 1986), the strength qualities that rugby backs possess may, in part, shape their movement preferences during the initial steps of a sprint. There were a number of moderate to large statistically significant relationships between strength qualities and sprinting kinematics in the current study, suggesting that the movement strategies adopted by rugby backs during the initial steps of sprinting may be associated with their leg strength capacities.

Higher hip torque and lower repeated contact time, and therefore a higher hip torque/repeated contact time ratio, correlated significantly to shorter contact time during the initial steps, shown by the statistically significant moderate to large relationships between these variables (Table 5.2). There appeared to be a pattern to the relationships of hip torque, repeated contact time and hip torque/repeated contact time ratio with other sprinting kinematics, which explains their association with contact time during sprinting. For instance, these strength-based variables demonstrated relationships of a similar magnitude and the same direction with touchdown distance and contact length as they did with contact time. This is logical since a smaller touchdown distance and contact length will likely result in a shorter contact time, since less time is required for the CM to rotate forward of the stance foot before producing rapid leg extension (Jacobs & van Ingen Schenau, 1992).

Higher vertical stiffness should enable energy to be released more quickly during the ground contact phase, whereas greater hip extensor strength capabilities may have resulted in increased forward acceleration of the CM, especially during the early stance phase owing to the hip's mechanically advantageous position at this point (Schache et al., 2019; Veloso et al., 2015), thus contributing to a reduced contact time. Given the moderate to large statistically significant negative relationships of hip torque/repeated contact time ratio with foot, shank and thigh angle at touchdown, participants with higher levels of these strength qualities may have self-organised to produce the smaller touchdown distances by orienting their lower limb segments more horizontally (i.e., with their proximal ends more forward rotated towards the direction of travel), although this requires further investigation.

P_{max} was the only other strength-based variable to be statistically significantly related to several technical features of participants during initial acceleration. Higher P_{max} was negatively associated the knee flexion angle of participants at touchdown (relationship was large and statistically significant) during the initial steps of acceleration. The smaller knee angles adopted at touchdown may have enabled participants with greater P_{max} during the squat jump FV profiling to produce greater knee extensor resultant moments when sprinting, thus taking advantage of their greater explosive knee extensor capabilities demonstrated during the squat jump (Jandacka et al., 2014). Although caution ought to be given when drawing conclusions from case-study approaches with low participant numbers (n = 3), the kinetic investigation undertaken by Bezodis et al. (2014) revealed that the sprinter in their study who produced greater peak knee extensor moments (by a factor of approximately 1.5 to 2.5) and greater peak positive power at the knee (by 1.7 to three times higher) compared with the other sprinters also produced a more flexed knee angle. Collectively, from the results reported in the current chapter, there a number of meaningful relationships between strength-based qualities and technique-based features of rugby backs, and interactions of both strength and technique variables with their acceleration performance which, when considered in relation to existing biomechanics research on initial sprint acceleration, may provide insight into the way in which rugby backs may self-organise in part due to their strength-based qualities, although again this requires further investigation and to be tested through intervention-based research.

In summary, with reference to the research questions posed in this chapter, four strength-based variables in isolation (hip torque, P_{max}, repeated jump height and RSI) were meaningfully related to NAHEP. The largest of these relationships, which was the only statistically significant relationship observed between the strength variables in isolation and acceleration performance, involved repeated jump height. However, only 16% of the variance in NAHEP was uniquely accounted for by this strength-based variable when it was controlled for body mass. Whilst combinations of multiple strength qualities and strength-based variables with technical features focussed on the hip and ankle were meaningfully related with NAHEP (small effect), the multiple linear regression models were not statistically significant and only a small variance in acceleration performance could be predicted by the variation of the independent variables. These findings, combined with those in Chapters 3 and 4, highlight the challenges in finding technical or strength variables in isolation, or even in combination, that are significantly and consistently related to the initial acceleration of rugby union backs when considered cross-sectionally across a whole group. This is likely owing to the complex adaptive nature of humans (Davids et al., 2014) and the multiple degrees of freedom during sprinting, which interact to produce different patterns of emergent movement (Tononi et al., 1999).

Several strength qualities – namely hip torque, repeated contact time, hip torque/repeated contact time ratio and P_{max} – were associated with a range of sprinting kinematic variables where moderate to large statistically significant relationships between strength capacities and a number of spatiotemporal, linear and angular kinematics were observed. This information builds on a strong body of evidence which highlights that changes to an individual's performer properties directly influences their emergent behavioural patterns (Davids et al., 2008; Newell, 1986; Newel 1976; Saltzman & Kelso, 1987). However, whilst there is some experimental evidence that changes in joint kinematics can be made through specific strength training (Rajic et al., 2020), kinematic changes are yet to be demonstrated during initial sprint acceleration following a strength-based intervention. The results of the current study therefore provide preliminary groundwork on which this concept is explored during the initial steps of maximal sprinting in professional rugby backs in Chapters 6 and 7.

5.5 Chapter summary

By answering research question III – *How are lower limb strength qualities related to the performance of professional rugby backs during initial acceleration?* – the current study is the first to provide insight into the relationships between a range of strength qualities and acceleration performance of professional rugby union backs and how these strength-based variables combine with technical features to interact with NAHEP. By answering research question IV - *What are the relationships between lower limb strength qualities and technical features, and how do their interactions associate with initial acceleration performance in professional rugby backs?* – it is also the first to investigate how strength qualities associate with selected spatiotemporal variables and linear and angular kinematics in this population during the first four steps of maximal sprinting. The findings suggest that some strength qualities in isolation and combination may be important to initial acceleration performance, but only to a relatively small extent given the relatively low correlation magnitudes and lack of statistically significant relationships. When strength-based variables were combined with technical features relating to hip and ankle kinematics, they were only able to predict a small amount of the variation in participants' initial acceleration performance that was not statistically significant. In contrast, there were several moderate to large statistically significant relationships between strength qualities and a range of technical features.

Collectively these results, in conjunction with the findings in Chapters 3 and 4, indicate that generalised, whole-group, patterns in the relationships of technical features and strength qualities with acceleration performance across a group of rugby backs may not exist, and that similar performance can be achieved with varying combinations in the magnitudes of these variables. Therefore, to provide actionable information for the training interventions of coaches aiming to enhance the early acceleration performance of rugby backs, the characteristics of these athletes at the intra-individual level ought to be investigated, since group level findings clearly cannot be applied with a high degree of confidence to any single individual.

CHAPTER 6: CHARACTERISING INITIAL SPRINT ACCELERATION STRATEGIES USING A WHOLE-BODY KINEMATICS APPROACH

A version of the study reported in this chapter was published in the Journal of Sports Sciences as Wild et al. (2022) - doi.org/10.1080/02640414.2021.1985759.The study presented here has been updated and revised to take account of research published since the study's publication and to integrate fully within the thesis narrative.

6.1 Introduction

As observed by the findings reported in Chapters 3 to 5, there is variation in the technique strategies used during the initial steps of sprinting by rugby backs. From an ecological dynamics perspective, this can be explained by the different interacting environmental, task and performer constraints for each individual (Newell, 1986) which will result in different patterns of emergent motor behaviour during initial acceleration. Thus far in this thesis, no definitive conclusions can be drawn from the findings of the research undertaken at a whole-group level on which, if any, technique-based strategies are more important for any given individual back to achieve high acceleration performance. The approach taken so far has been to investigate how the technical features of rugby backs associate with their initial acceleration performance in terms of the motor system's individual, constituent parts. Although a system is composed of its constituent parts, proponents of ecological dynamics would suggest that a system will have characteristics which cannot be found by studying these individual parts alone (Button et al., 2020). Therefore, a way to encapsulate the motor system behaviours of rugby backs as a 'whole' during the initial steps may provide more useful information on the strategies they adopt to achieve high levels of acceleration performance.

Due to the multi-articular nature of sprinting, portraying an acceleration strategy is complex owing to the multiple degrees of freedom that coordinate to achieve the task goal (Bernstein, 1967). Consequently, the data required to provide a full description of an athlete's movement coordination during sprinting is highly challenging to assimilate and would lead to a vast amount of information which is of limited value to coaches pursuing an actionable basis for their technical interventions. Determining an individual's acceleration strategy through higher-level spatiotemporal characteristics may therefore be a more viable ‘whole-body’ approach. Such an approach is consistent with ecological dynamics where, as already alluded to, information on system behaviour at a holistic level is deemed richer than information on individual constituent parts (Button et al., 2020). From an applied perspective this is beneficial as spatiotemporal measures can be obtained promptly. Measures such as step length, step rate, contact time and flight time are the outcome of a complex interaction between linear and angular kinematic and kinetic factors underpinning this motor skill, and they provide rich holistic level information regarding system behaviour during acceleration.

If acceleration strategies can be identified using a whole-body approach, it is important to establish whether a discrete number, or a widespread continuum, of strategies exists, even within a relatively homogeneous cohort of individuals from the same sport who are typically subjected to similar task and environmental constraints. If a given cluster of individuals, defined by a discrete strategy, is shown to achieve better acceleration performance than other clusters, then a training approach targeting the more successful strategy may be warranted across the entire group. If clusters cannot be identified, but performance is associated with a given strategy on a continuum, then this may also signify that all individuals might benefit from interventions aimed at facilitating a shift towards that strategy. Alternatively, if there is no clear indication that the strategy of a given cluster, or on a continuum if clear clusters do not exist, is superior in performance terms, then each individual’s needs ought to be considered with regards to the enhancement of acceleration performance.

To provide more granular information to inform the training practices of coaches where a shift in sprinting strategy is deemed necessary, an understanding of the linear and angular kinematic technical features and strength qualities that underpin the different strategies adopted is necessary. Accordingly, this chapter sought to answer research question V - *To what extent do whole-body kinematic strategies differ within a group of professional rugby backs according to the combination of their normalised spatiotemporal variables during the first four steps, and what are the differences in technical features and strength qualities between these strategies?* An additional factor which needs to be considered is the consistency of a given individual’s strategy, since high levels of variability (i.e., a less stable strategy) would undermine training interventions if a representative strategy for an individual cannot be identified. Therefore, determining levels of intra-individual variability is important so that meaningful changes in strategies can be identified with confidence and so research question VI - *How stable are intra-individual whole-body kinematic strategies during initial acceleration in professional rugby backs?* - was also addressed in this chapter.

6.2 Methods

6.2.1 Participants

Twenty-nine male professional rugby union backs (mean ± SD: age 25 ± 3 years; stature 1.81 ± 0.06 m; leg length 1.00 ± 0.05 m; body mass 93.7 ± 9.1 kg) competing in the English Premiership were analysed in this study. Since these data were pre-existing from the testing conducted during the players' usual training schedule, and were anonymised, informed consent was not required (Haugen et al., 2019b; Winter & Maughan, 2009). As explained later in this section, data from Chapters 4 and 5 were used in this chapter and thus study protocols relating to the collection of these data were already approved by the University of Surrey Ethics Committee. For new data obtained in this chapter, ethical and/or governance review was not deemed as required after completing the University of Surrey Self-Assessment Governance and Ethics form for Humans and Data Research (SAGE-HDR). At the time of testing, participants were injury free and frequently completed maximal sprint accelerations within their usual weekly training regime.

6.2.2 Procedures

Firstly, to determine how acceleration strategies differ within participants, the acceleration performance and spatiotemporal data based on the 25 participants in Chapter 4 were used along with acceleration performance and spatiotemporal data which were obtained from four additional participants. These variables included: acceleration performance (NAHEP) and normalised spatiotemporal variables (step length, step rate, contact time and flight time) over the first four steps. From the spatiotemporal variables, two additional variables – normalised step length/normalised step rate and contact time/flight time ratios (hereafter referred to as length/rate and contact/flight ratios) – were calculated as a measure of each participant's whole-body kinematic strategy. The former ratio allows for the evaluation of the combination of step length and step rate (Nagahara et al., 2018a), whilst the latter allows for the evaluation of the combination of contact time and flight time (Coh & Tomazin, 2006). These ratios provide additional useful information to step length and step rate alone and have been used to categorise distinctive running styles to guide future measurement and interpretation (van Oeveren et al., 2021), although whether this approach can be applied to initial acceleration is not known.

Secondly, to determine how the technical features and strength-based qualities differed between acceleration strategies, the data used were based on the technical features and strength-based qualities determined for the 25 participants in Chapter 4 (technical features) and Chapter 5 (strength-based qualities) respectively (i.e., the same 25 participants indicated in the opening paragraph of this section). In addition to measures of NAHEP, normalised spatiotemporal variables and their ratios as mentioned above, the other technical features of interest in this chapter included: linear kinematics (touchdown distance, toe-off distance, contact length and flight length), angular orientations (°) of the stance foot, shank, and thigh, and trunk, segments (with respect to the horizontal) and of the stance ankle, knee and hip joints at touchdown and toe-off, peak dorsiflexion angle, ankle range of motion and mean stance hip angular velocity during the stance phase, and hip angular velocity at touchdown and thigh separation angle at toe-off. Spatiotemporal variables, linear kinematics and angular velocities were all normalised using the equations of Hof (1996). For more detail on how NAHEP and all sprint-technique kinematic variables were obtained, see Section 4.2.2 (Chapter 4). The strength-based variables of interest in this chapter included: hip torque (Nm/kg), P_{max} (W/kg), repeated jump height (m), repeated jump CT (contact time, s), RSI (height/contact time) and the hip torque/CT ratio. For information on how these data were obtained, see Section 5.2.3 to 5.2.5 (Chapter 5).

Thirdly, to address the aim of this chapter regarding the stability of whole-body kinematic strategies, 13 of the 29 participants completed the sprint testing protocol on three additional occasions. At all three sessions, NAHEP and normalised spatiotemporal variables were obtained, resulting in data being collected for 12 sprints for 13 participants (i.e., three sprints on four separate occasions) over the course of six to eight weeks during pre-season.

6.2.3 Statistical analyses

Mean data for kinematic variables were obtained over four steps and averaged across the three sprint trials for each participant. Group descriptive data (mean ± SD) were calculated for all variables and checked for normal distribution using the Shapiro-Wilk statistic. The within individual coefficient of variation (CV) was calculated for each individual and the average of these across the entire group was then determined as a measure of relative reliability representing the typical error as a percentage of the mean for each measurement (Atkinson & Nevill, 1998). To examine the relationships of normalised spatiotemporal variables and strength qualities with NAHEP, semi-partial correlation coefficients controlling the independent variables for body mass or bivariate correlations were used. Therefore, the direct effects of inter-individual differences in both body mass and leg length on the results of this analysis were minimised. Confidence intervals (90%) for all observed relationships were calculated to detect the smallest clinically important correlation coefficient ($r = \pm 0.1$). Relationships were deemed meaningful when their magnitudes were equal to or greater than the smallest clinically important correlation and confidence limits did not include positive and negative values greater than the smallest clinically important correlation. The strength of relationships were defined as: (±) < 0.1, trivial; 0.1 to < 0.3, small; 0.3 to < 0.5 moderate, 0.5 to < 0.7 large, 0.7 to < 0.9 very large and ≥ 0.9, practically perfect (Hopkins, 2002).

The length/rate and contact/flight ratios were standardised as z-scores across the group. Cartesian plane quadrants were formed with these standardised length/rate and contact/flight ratios on the vertical and horizontal axes, respectively, to provide a novel single visual representation of each individual's whole-body kinematic strategy. A hierarchical agglomerative cluster analysis (Everitt et al., 2011) was then conducted to determine homogenous participant groups according to the combination of their normalised spatiotemporal variables. The complete linkage approach (Gordon, 1999; Lance & Williams, 1967) was used and the final number of clusters was determined by visual inspection of the scree plot (Hair et al., 2019; Jauhiainen et al., 2020), with the dendrogram also visually inspected to confirm the number of clusters identified (Phinyomark et al., 2015; Watari et al., 2018). To identify any differences in normalised spatiotemporal variables, linear and angular kinematics and strength qualities between clusters, a one-way ANOVA was conducted and, where significant main effects were observed, post hoc testing (Tukey's HSD) was run. The Kruskal-Wallis test was used where data were not normally distributed. All analyses were performed using SPSS (v26.0) with alpha set at $p < 0.05$.

For the 13 participants who undertook testing on four separate occasions, coefficients of variation and intraclass correlation coefficients (ICC) were calculated to determine the reliability of measured variables across their twelve sprint efforts. To determine the within-session consistency on each of the four testing occasions, the CV over three sprint efforts was calculated for each individual. The

CVs obtained from each testing occasion were then averaged for each individual. These values were averaged across the group to establish the group mean CV. An acceptance threshold of < 10% for CV was used (Atkinson & Nevill, 1998) to indicate whether these strategies were reliable. To determine the consistency of participants' sprinting strategies between testing sessions, for all variables, the mean value for each individual participant from each testing occasion were entered into Hopkins' (2015) spreadsheet to calculate ICC and their 90% confidence intervals based on a single-rater, absolute agreement, 2-way mixed-effects model (Koo & Li, 2016). Intraclass correlation coefficient values were defined as poor (ICC = < 0.50), moderate (ICC = 0.50 to < 0.75), good (ICC = 0.75 to < 0.90) and excellent (ICC = ≥ 0.90) reliability (Koo, & Li, 2016).

The distribution of participants' whole-body kinematic sprinting strategies across their 12 sprints was represented in the form of individual confidence ellipses (90% confidence limits) calculated from the mean and covariance of their standardised length/rate and contact/flight ratios. The variability of normalised spatiotemporal variables and length/rate and contact/flight ratios was determined using the standard deviation and CV across the 12 sprints for each participant. The stability of the variables for each individual relative to the group standard deviation of the 29 participants from the single sprint was calculated as a stability index (Maselli et al., 2019) as follows, where a higher Sj is indicative of a more stable variable for that individual:

$$Sj = 1 - \left(\frac{intra\ individual\ SD}{inter\ individual\ SD}\right)$$

6.3 Results

Group mean CVs for NAHEP, normalised spatiotemporal variables, and length/rate and contact/flight ratios during the single testing session involving 29 participants, and strength-based variable involving 25 participants (Table 6.1) were all ≤ 6%. When controlling independent variables for body mass using semi-partial correlations, a statistically significant moderate relationship between repeated jump height and NAHEP was found (Table 6.1). No other significant relationships were found between NAHEP and strength variables, or between NAHEP and normalised spatiotemporal variables or length/rate and contact/flight ratios.

6.3.1 Acceleration strategies and differences in their technical features and strength qualities

Four homogenous clusters were established based on the combination of participants' length/rate and contact/flight ratios (Figure 6.1a, 6.1b). No significant differences in NAHEP were evident between these clusters (Figure 6.1c). The initial sprint acceleration strategies were achieved through significant differences in a range of linear and angular kinematics between clusters, whilst several strength-based characteristics also differed significantly between clusters (Figures 6.2 to 6.8).

Step lengths were successively greater across clusters A to D, with significant differences between cluster A participants and all other clusters and between clusters B and D (Figure 6.2a). Differences in step length were accounted for primarily through touchdown distance and contact length which were both significantly smaller in clusters A and B compared with clusters C and D (Figure 6.3a,c). Step rates were successively less across clusters A to D, with significant differences evident between cluster A participants and all other clusters and between clusters B and D (Figure 6.2b). These differences in step rate between clusters were accounted for through differences in contact time, flight time, or both (Figure 6.2c,d).

Regarding angular kinematics, significantly smaller foot and thigh segment touchdown angles (i.e., both segments were more vertical) were observed in clusters A and B, compared with clusters C and D (Figures 6.4a,c and 6.8). At toe-off, trunk angles of cluster D participants were significantly greater (more vertical; Figure 6.4d) and they also achieved significantly greater hip extension and thigh separation at toe-off compared with clusters A and B (Figures 6.6c, 6.6e and 6.7). Of the strength characteristics assessed, higher hip torque/contact time ratios were achieved by clusters A and B compared with clusters C and D (Figure 6.8f).

Table 6.1. Mean ± *SD* descriptive statistics for all variables, and relationships between normalised spatiotemporal variables over three sprint trials of participants and NAHEP.

Descriptive statistics		Correlations with NAHEP	Coefficient of variation (%)
Variable	*Mean ± SD*	*r (90% CL)*	*Mean ± SD*
NAHEP	0.562 ± 0.073	-	4.0 ± 2.4
Step length	1.32 ± 0.10	-0.04 (-0.35 to 0.28)[a]	1.9 ± 1.0
Step rate	1.38 ± 0.09	0.31 (0.00 to 0.57)[a]	1.3 ± 0.8
Contact time	0.514 ± 0.041	-0.15 (-0.44 to 0.17)[a]	1.8 ± 1.0
Flight time	0.212 ± 0.032	-0.23 (-0.51 to 0.09)[a]	3.2 ± 2.3
CT/FT ratio	2.48 ± 0.46	0.18 (-0.14 to 0.47)[a]	4.1 ± 2.7
SL/SR ratio	0.96 ± 0.13	-0.18 (-0.47 to 0.18)[a]	3.0 ± 1.7
Hip torque (Nm/kg)	5.81 ± 0.79	0.39 (0.06 to 0.64)[b]	2.4 ± 1.3
P_{max} (W/kg)	28.94 ± 4.74	0.38 (0.05 to 0.64)[b]	4.2 ± 2.4
Repeated jump height (m)	0.18 ± 0.02	0.39 (0.06 to 0.64)*[a]	4.7 ± 2.5
Repeated jump CT (s)	0.276 ± 0.025	-0.06 (-0.39 to 0.28)[a]	4.4 ± 2.3
RSI (height/CT)	0.64 ± 0.09	0.36 (0.03 to 0.62)[a]	5.4 ± 3.0
Hip torque/CT ratio	21.22 ± 3.69	0.35 (0.01 to 0.61)[b]	5.2 ± 2.2

[a]Semi-partial correlations controlling the independent variables for body mass

[b]Bivariate correlations

*Statistically significant (*p* = < 0.05). Note the *r* value for the relationship between repeated jump height and NAHEP was 0.004 greater than the relationship between hip torque and NAHEP (i.e., enough of a difference for the former relationship to be considered statistically significant)

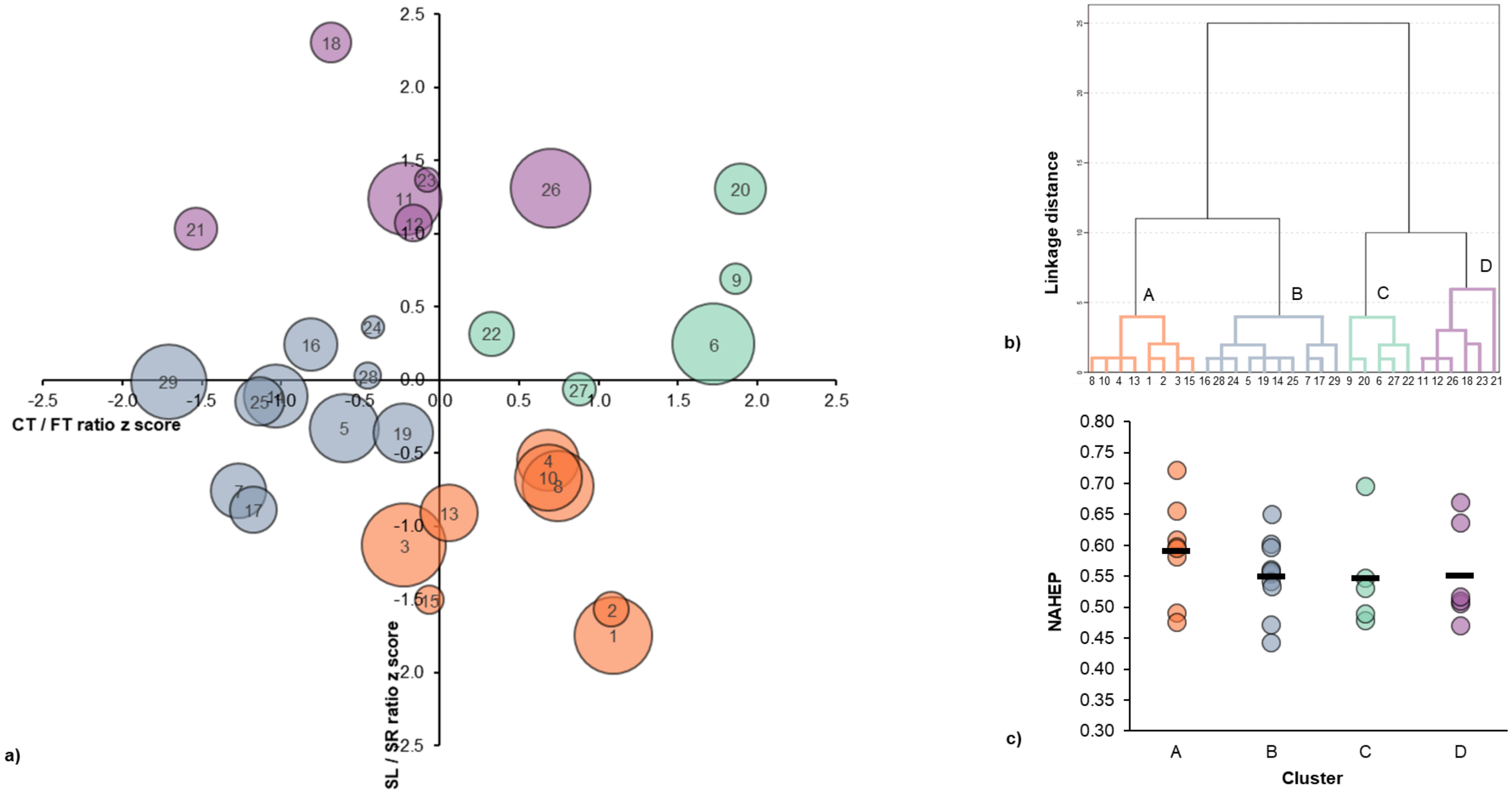

Figure 6.1. Cluster analysis used to establish homogenous groups of rugby backs according to their initial sprint acceleration strategy: a) a quadrant depicting the dispersion of participants according to their contact/flight and normalised length/rate ratios (standardised as z scores). Each marker and their centred number represent an individual. Participants have been grouped according to the four clusters identified during the hierarchical analysis (see Figure b) and the size of each marker is reflective of initial sprint acceleration performance, with a larger marker equating to a greater magnitude of normalised average horizontal external power (NAHEP); b) a dendrogram for the hierarchical cluster analysis of participants' spatiotemporal step characteristics during the first four steps of a sprint. Individuals are represented by numbers on the x-axis**.** Four clusters are identified by colour and letters (A-D); c) NAHEP of each participant (circles) and the mean (black filled rectangles) for each cluster. No significant differences (one-way ANOVA) were evident between the mean NAHEP of clusters.

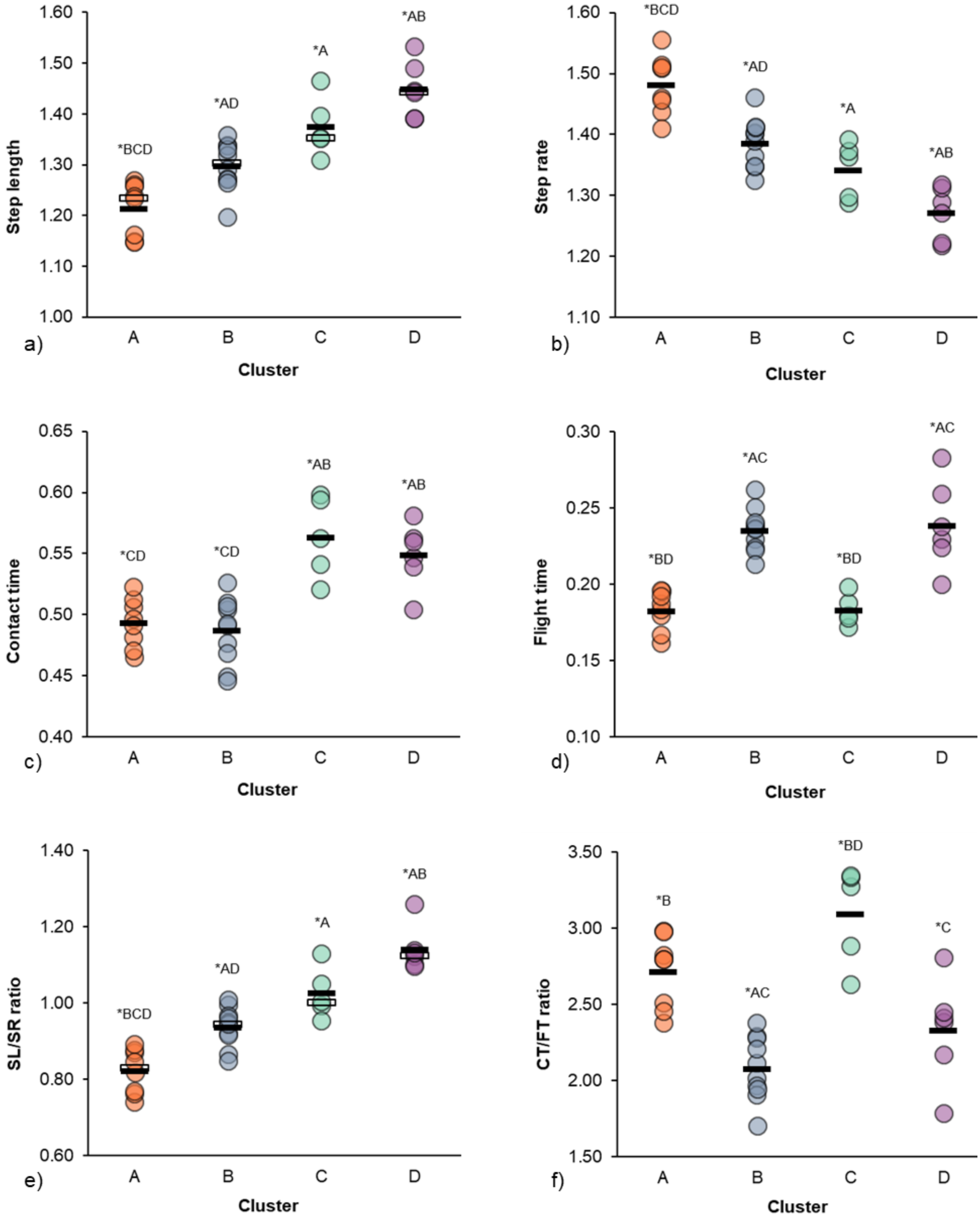

Figure 6.2. Normalised spatiotemporal variables, and step length/step rate and contact time/flight time ratios for clustered participants. Each marker (circle) represents an individual participant. Black filled rectangles indicate the group mean for each cluster. Data show results of the one-way ANOVA analysis conducted to determine differences in normalised spatiotemporal variables between each cluster of participants. The Kruskal-Wallis test was used as the non-parametric alternative to the one-way ANOVA for determining differences in step length and step length/step rate ratio due to the non-normal distribution of these data for cluster ‘A' (step length) and cluster ‘D' (step length/step rate ratio). The median for each cluster in these cases is shown by the unfilled rectangles.

*ABCD Data are significantly different ($p \leq 0.05$) to clusters A, B, C and D respectively.

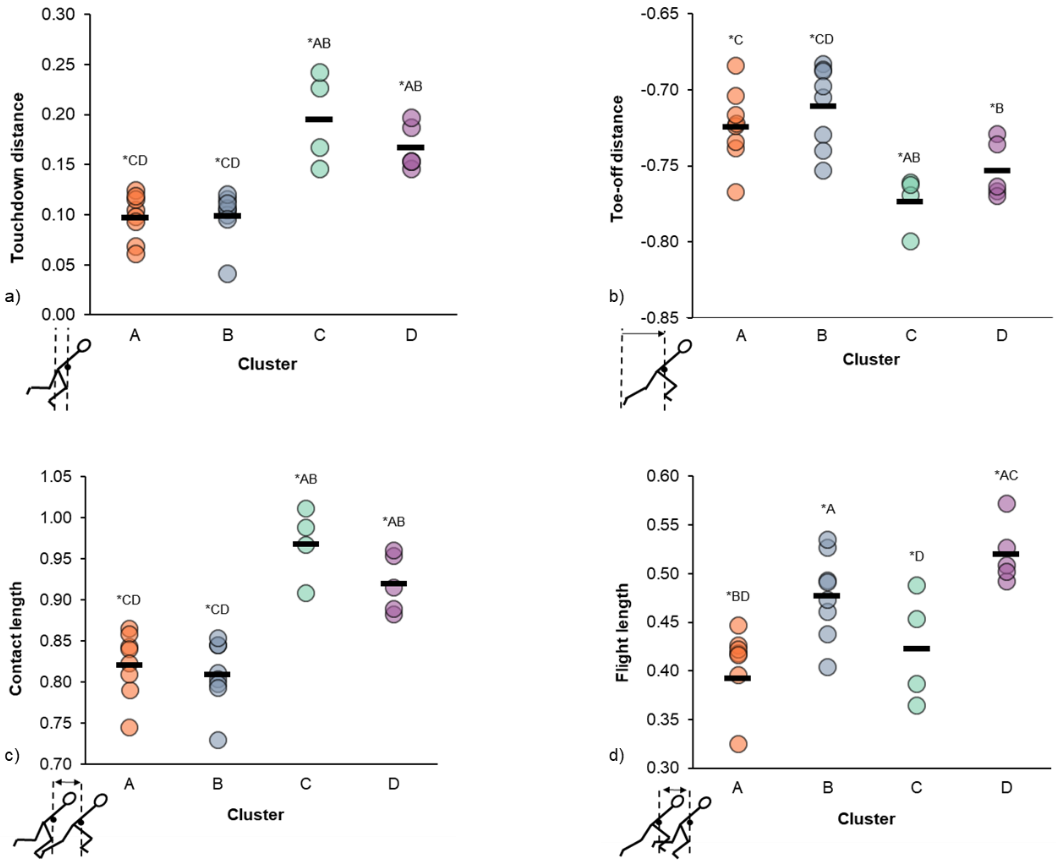

Figure 6.3. Normalised linear kinematics for clustered participants. Each marker (circle) represents an individual. Black filled rectangles indicate the group mean for each cluster. Data show results of the one-way ANOVA analysis conducted to determine differences in normalised linear kinematic variables between each cluster.

*ABCD Data are significantly different ($p \leq 0.05$) to clusters A, B, C and D respectively.

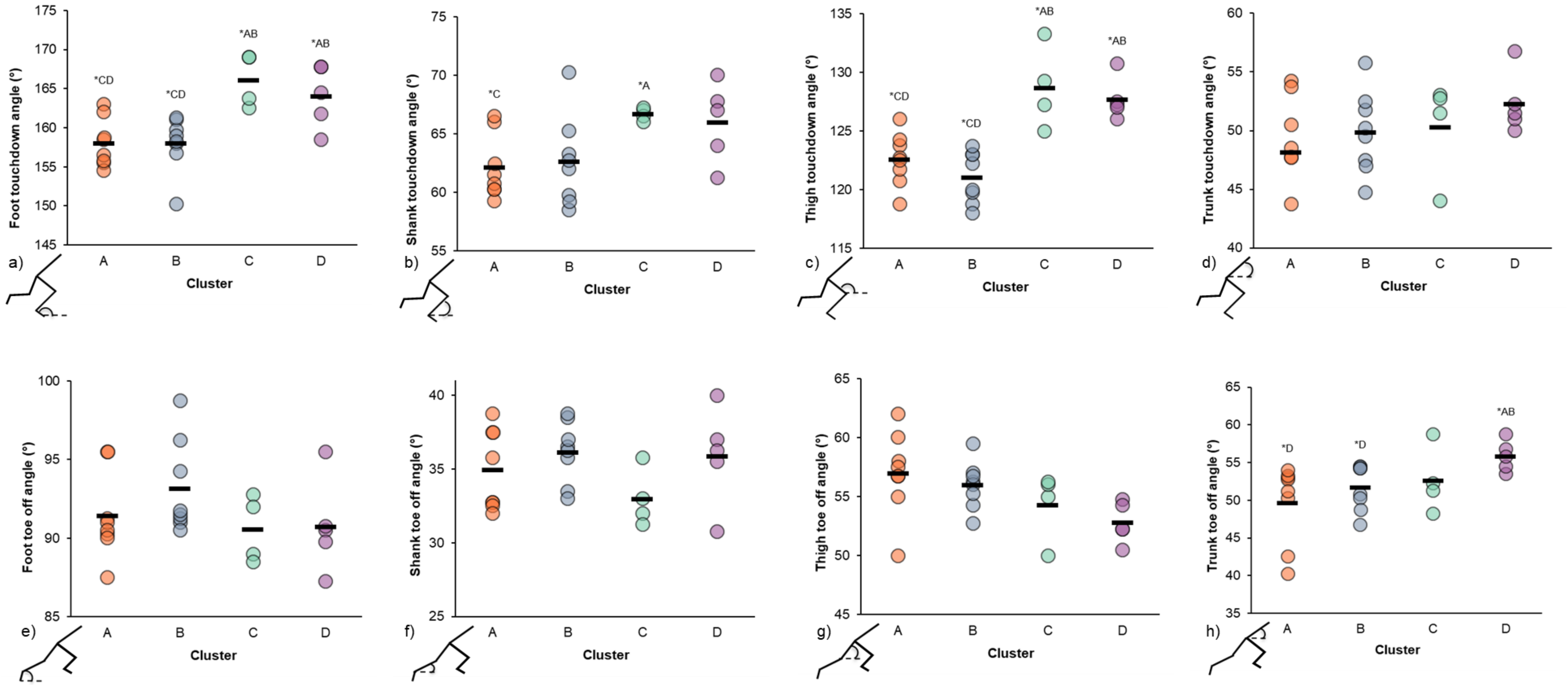

Figure 6.4. Segment touchdown and toe-off angular kinematics for clustered participants. Each marker (circle) represents an individual participant. Black filled rectangles indicate the group mean for each cluster. Data show results of the one-way ANOVA analysis conducted to determine differences in segment angle kinematic variables between each cluster.

^{*ABCD}Data are significantly different ($p \leq 0.05$) to clusters A, B, C and D respectively.

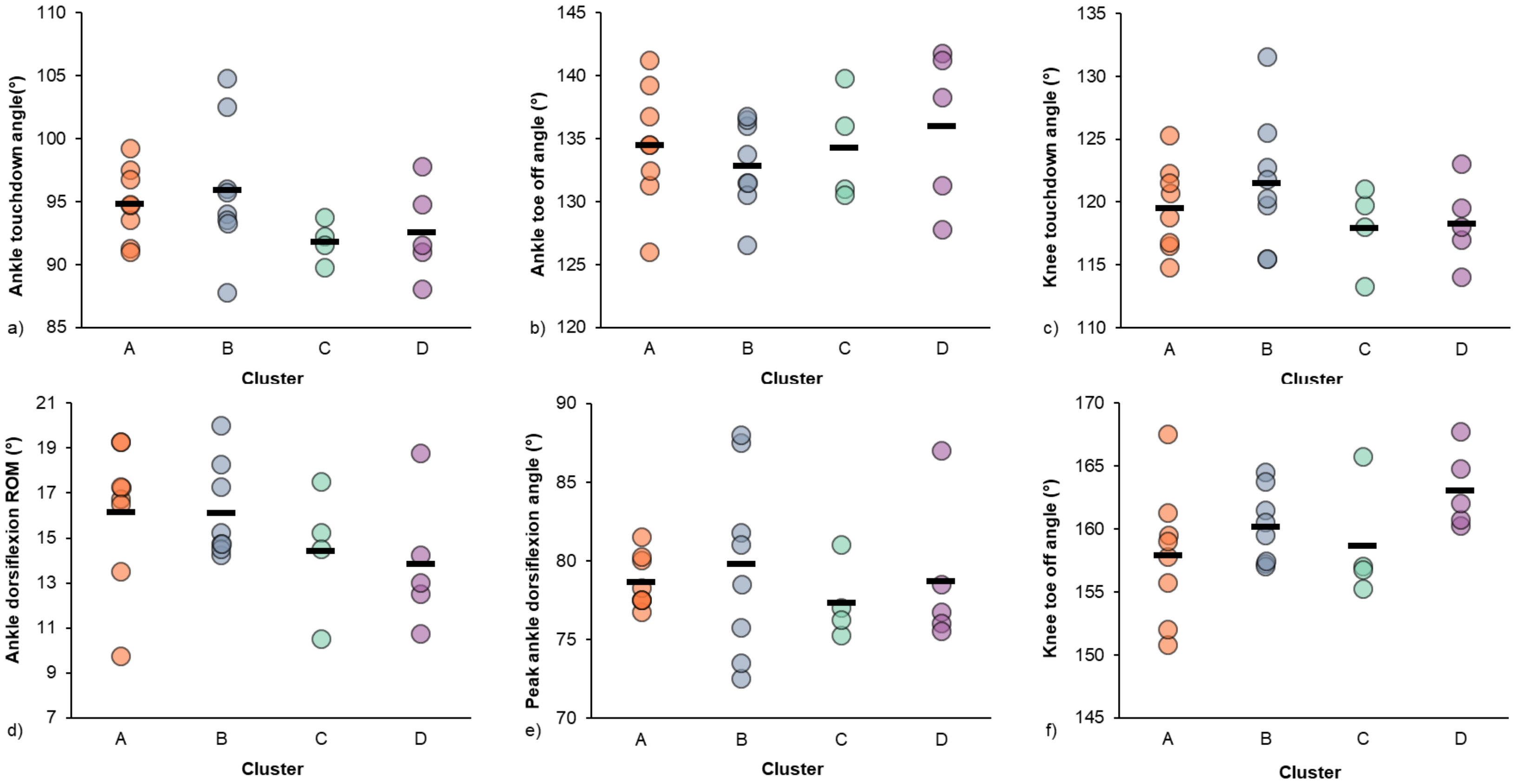

Figure 6.5. Knee and ankle angular kinematics for clustered participants. Each marker (circle) represents an individual participant. Black filled rectangles indicate the group mean for each cluster. Data show results of the one-way ANOVA analysis conducted to determine differences in knee and ankle angular kinematic variables between each cluster.

*ABCDData are significantly different ($p \leq 0.05$) to clusters A, B, C and D respectively.

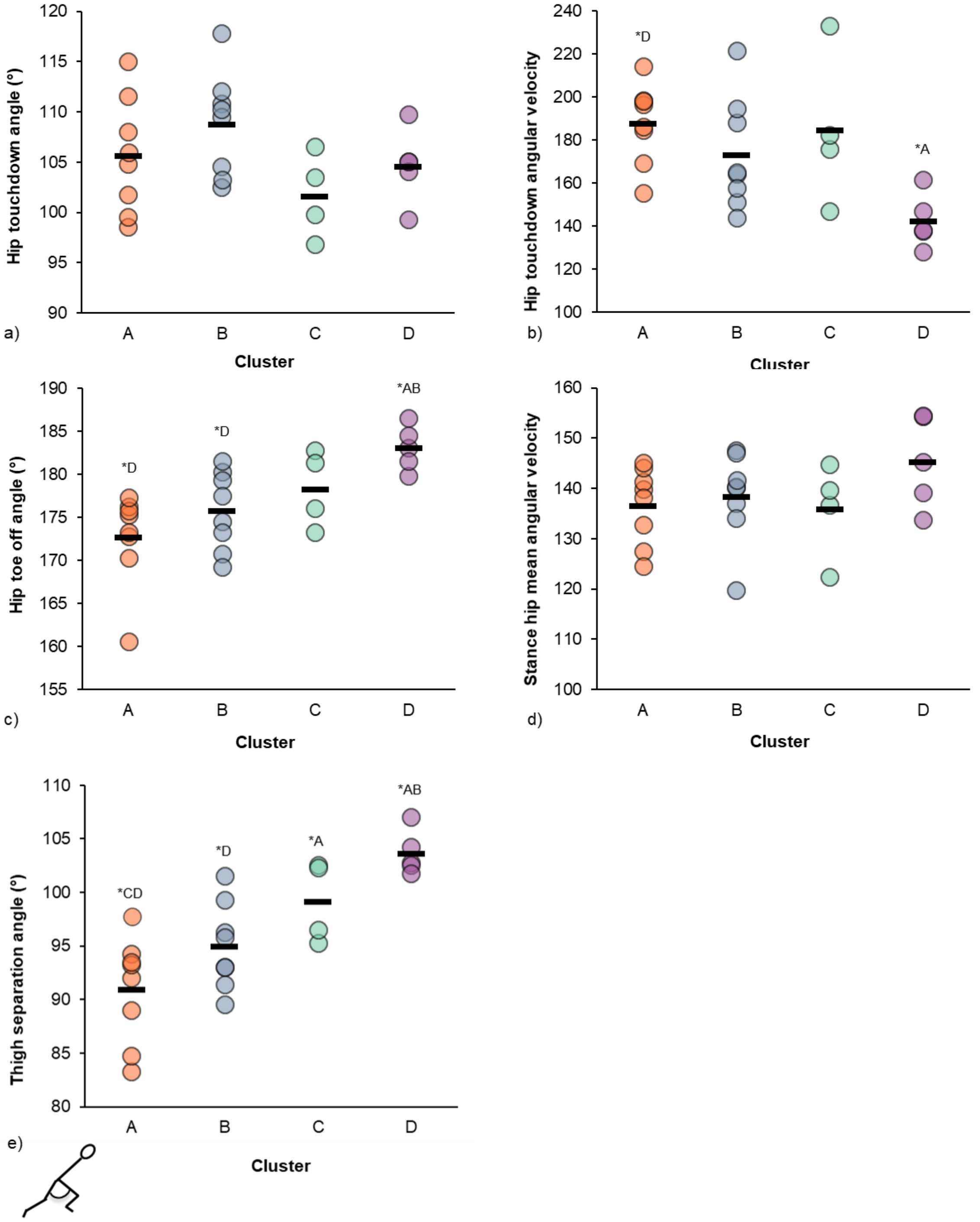

Figure 6.6. Hip joint kinematics and thigh separation angle at toe-off for clustered participants. Each marker (circle) represents an individual. Black filled rectangles indicate the group mean for each cluster. Data show results of the one-way ANOVA analysis conducted to determine differences in hip joint angular kinematics between each cluster at touchdown and toe-off.

*ABCD Data are significantly different ($p \leq 0.05$) to clusters A, B, C and D respectively.

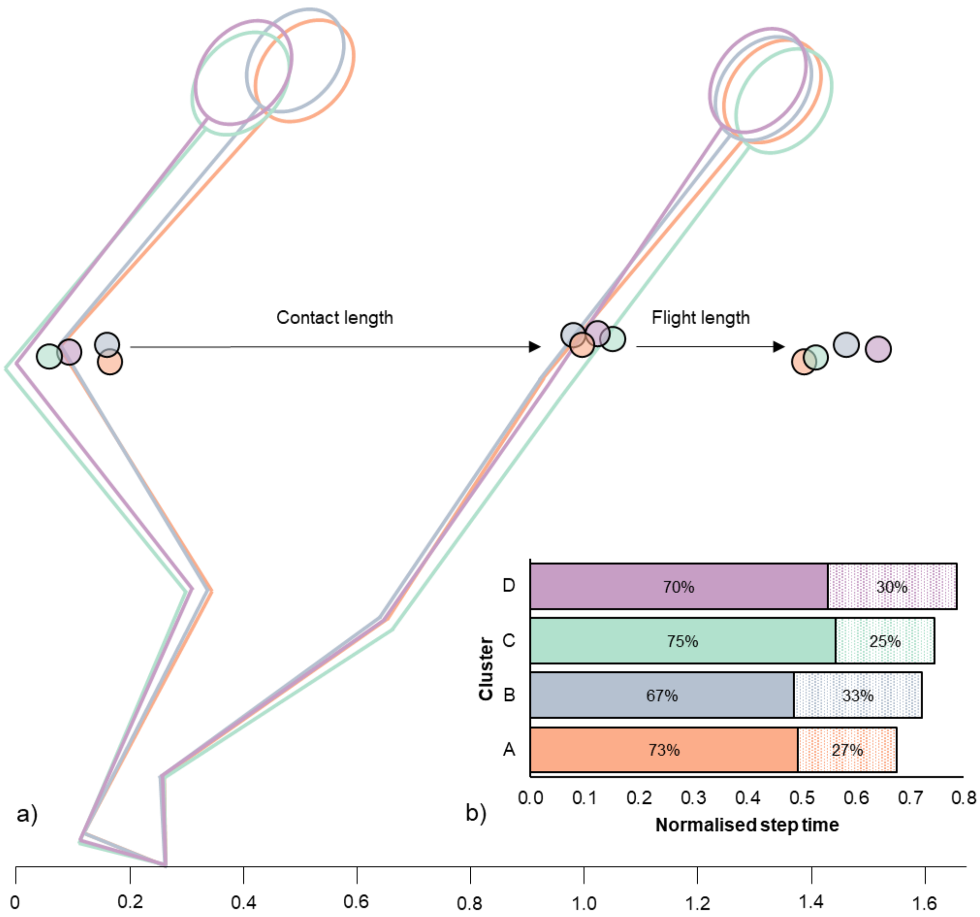

Figure 6.7. a) Scaled spatial model showing the average of the mean orientations of the stance leg (foot, shank, thigh), trunk and head segments across all (four) steps for each cluster at touchdown and toe-off. The mean centre of mass location at touchdown and toe-off positions for clusters across all (four) steps is depicted as markers (circles), showing normalised linear kinematic variables. Horizontal and vertical scales are the same and all normalised linear kinematic variables are referenced to position of the toe of the contact leg; b) average of the mean normalised step times for clusters, divided into contact time (filled bars) and flight time (pattern filled bars). The proportion of time spent during the contact and flight phases relative to step time are shown as percentages.

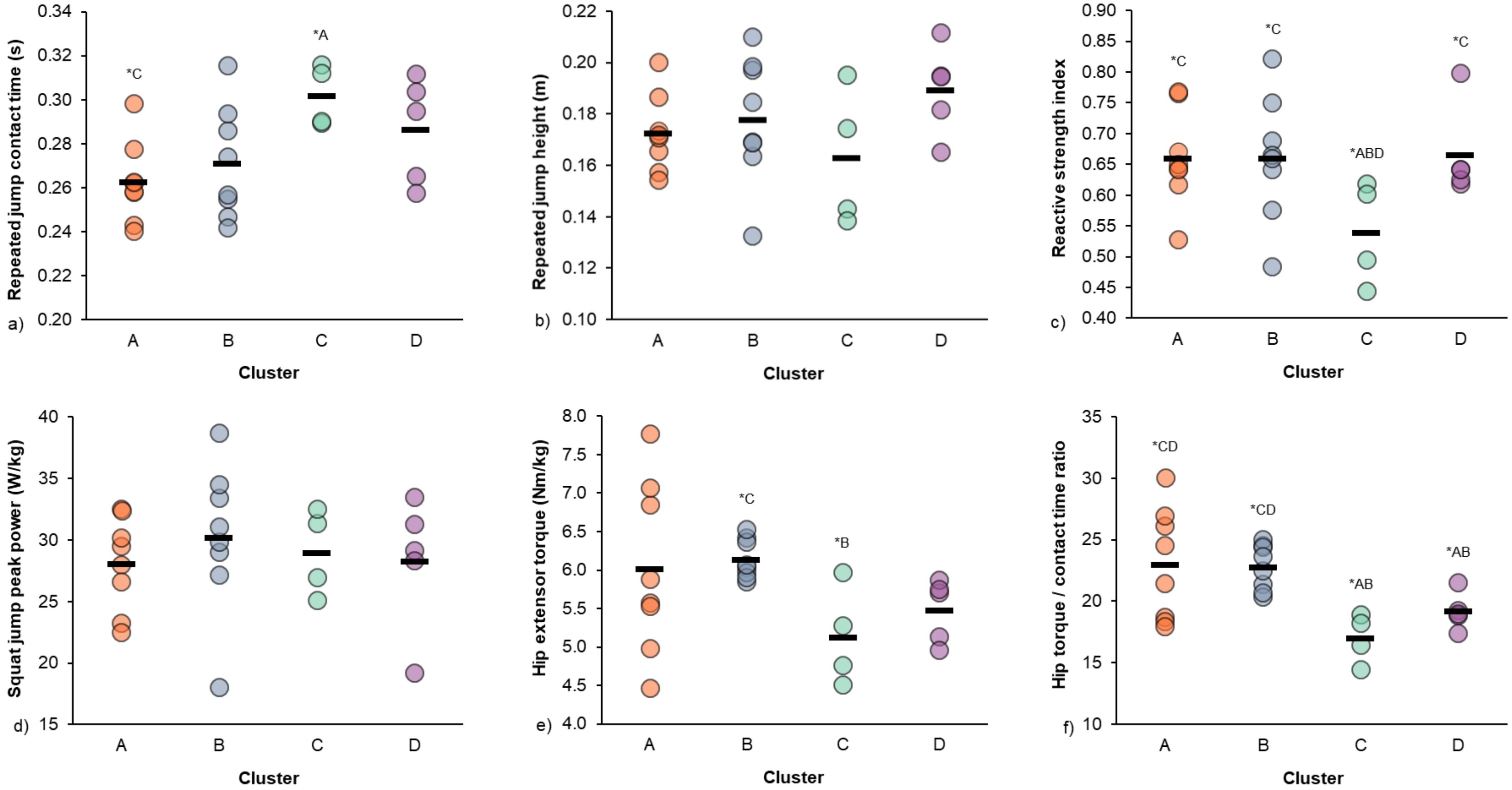

Figure 6.8. Strength qualities for clustered participants. Each marker (circle) represents an individual. Black filled rectangles indicate the group mean for each cluster. Data show results of the one-way ANOVA analysis conducted to determine differences in strength qualities between each cluster.

^{*ABCD}Data are significantly different ($p \leq 0.05$) to clusters A, B, C and D respectively.

6.3.2 Stability of individual acceleration strategies

For the 13 participants who undertook three sprint efforts on four separate occasions, ICCs and CVs (Table 6.2) across mean NAHEP, normalised spatiotemporal variables and length/rate and contact/flight ratios from each of the four testing sessions indicated excellent reliability (ICC > 0.90; mean CI 0.86-0.99, CVs 1.1-4.4%).

Table 6.2. Reliability of normalised average horizontal external power and normalised spatiotemporal variables of rugby backs during initial sprint acceleration over four testing sessions

Variable	Coefficient of variation (%)[a]	Intraclass correlation coefficients[b]
	Mean ± SD	*Mean (90% CL)*
NAHEP	3.9 ± 2.1	0.94 (0.87 to 0.97)
Step length	2.1 ± 1.5	0.93 (0.86 to 0.97)
Step rate	1.1 ± 0.7	0.97 (0.93 to 0.99)
Contact time	1.4 ± 0.9	0.95 (0.91 to 0.98)
Flight time	3.6 ± 1.5	0.95 (0.90 to 0.98)
CT/FT ratio	4.4 ± 1.6	0.95 (0.89 to 0.98)
SL/SR ratio	2.8 ± 1.6	0.97 (0.94 to 0.99)

[a]On four testing occasions the coefficient of variation over three sprint efforts was calculated for each individual participant. Values obtained from each testing session were then averaged for each individual. Coefficients of variation across each individual were then averaged across the group to establish the mean ± *SD* displayed in this table.
[b]ICC estimates and their 90% confidence intervals were calculated based on a single-rater, absolute agreement, 2-way mixed-effects model.

A representative sample of individual acceleration strategies were observed in the 13 participants studied over four sessions in the context of the z-scores of all 29 participants studied on one occasion (Figure 6.9). Greater intra-individual variability in contact/flight ratios than length/rate ratios was evident (Figure 6.9), with a mean CV of 4.3 to 9.9% and SD of 0.117 to 0.244 in the contact/flight ratio across individuals compared with 2.7 to 5.4% and an SD of ≤ 0.052 in the length-rate ratios (Table 6.3). Even with greater intra-individual variability for the contact/flight ratio, only two participants (participants 2 and 3) exhibited SDs considered greater than the smallest worthwhile differences (*d* ≤ 0.20; Hopkins, 2002; Winter et al., 2014).

Table 6.3. Stability of the individual strategy of backs over the initial four steps of maximal sprinting across 12 sprint trials (3 sprints conducted on 4 separate testing occasions)

Participants	Stability index (%)[b]		Variability											
	Ratios[c]	Spatiotemporal variables[d]	CT/FT		SL/SR		SL		SR		CT		FT	
			CV	*SD*	*CV*	*SD*	*CV*	*SD*	*CV*	*SD*	*CV*	*SD*	*CV*	*SD*
1	75	85	7.0	0.208	4.3	0.032	4.1	0.048	1.9	0.030	1.8	0.008	6.4	0.010
2	74	89	7.6	0.222	3.7	0.028	2.4	0.027	2.5	0.038	3.8	0.019	4.8	0.008
3	71	82	9.9	0.244	5.4	0.046	4.8	0.061	1.7	0.025	2.0	0.009	8.9	0.017
14	80	86	6.8	0.160	4.7	0.044	3.7	0.049	1.3	0.018	<0.1	0.006	5.7	0.012
16	82	89	5.9	0.136	4.3	0.046	2.0	0.028	2.7	0.035	3.5	0.018	4.4	0.010
17	85	87	5.9	0.117	4.2	0.036	3.5	0.042	1.7	0.024	3.0	0.014	3.8	0.009
19	83	91	6.3	0.136	2.9	0.028	1.8	0.023	1.9	0.026	2.3	0.011	5.4	0.012
20	81	87	4.3	0.148	5.0	0.052	2.7	0.038	2.5	0.034	2.6	0.015	4.5	0.007
27	83	91	4.7	0.142	2.7	0.026	2.0	0.026	1.2	0.017	1.6	0.009	4.0	0.007
11	77	90	8.2	0.194	2.6	0.029	1.7	0.025	1.7	0.022	1.5	0.008	7.0	0.016
12	80	89	7.6	0.161	3.7	0.039	2.1	0.029	1.8	0.024	2.8	0.014	5.7	0.014
21	83	89	7.8	0.143	2.8	0.030	2.2	0.031	1.6	0.021	2.2	0.011	6.2	0.017
26	84	91	4.7	0.134	2.7	0.030	1.7	0.025	1.7	0.022	1.9	0.011	4.1	0.008
Mean	80	88	6.7	0.165	3.8	0.036	2.7	0.035	1.9	0.026	2.4	0.012	5.5	0.011

[a]Stability of the variables for each individual relative to the group standard deviation of the participants, calculated (Maselli et al., 2019) as follows, Sj = 1 - (intra-individual SD / inter - individual SD)

CV, coefficient of variation (%); SD, standard deviation for normalised spatiotemporal variables; CT/FT, contact/flight ratio; SL/SR, length/rate ratio; SL, step length; SR, step rate; CT, contact time; FT, flight time

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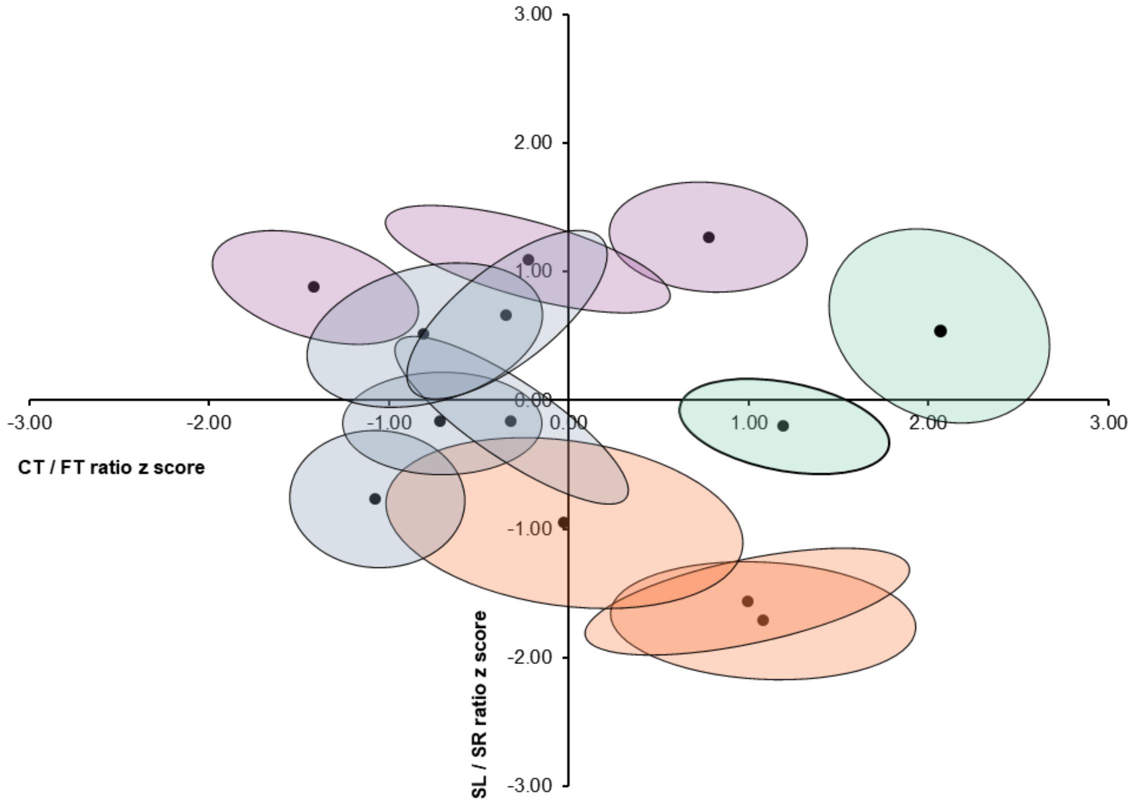


Figure 6.9. Covariance ellipses (90% confidence level) for the 13 participants who completed testing on four separate occasions, depicting the within- and between-participant distribution of their individual sprinting strategies. The centre of each ellipse (black markers) represents the mean of a given individuals' contact/flight and length/rate ratios. Each ellipse is colour coded according to the clusters of sprinting strategies identified. Z-scores are taken from the original data (Figure 6.2a) based on all 29 participants within this study.

The length/rate and contact/length ratios were stable at the intra-individual level with the stability index of participants ranging between 75 and 85% (Table 6.3), where 0% would represent the same variation in intra-individual SD across the 12 sprints for the 13 participants as that observed at the inter-individual level for the group of 29 participants during the single testing session. On average, the normalised spatiotemporal variables were 8% 'more stable' compared with the length/rate and contact/flight ratios, where the stability index for participants ranged between 82 and 91% (Table 6.3). This was also reflected in less intra-individual variability of the normalised spatiotemporal variables where the CV ranged between 0.0 and 8.9%, and SD between 0.006 and 0.061 across individuals. The mean CV for normalised spatiotemporal variables, in order of magnitude, were 1.9, 2.2, 2.7 and 5.5% for step rate, contact time, step length, and flight time, respectively.

6.4 Discussion

6.4.1 Different initial acceleration strategies

The aims of the study were firstly to establish whether different acceleration strategies existed between sub-groups of professional rugby union backs based on their combined normalised spatiotemporal variables and, if so, secondly, to determine the technical features and strength qualities that underpin these strategies and how stable they are. With this novel approach, it was found that participants could be grouped into four clusters which were characterised by a range of technical features and, to a lesser extent, strength qualities, although superior sprint performance was not observed in any single cluster during the first four steps. At the intra-individual level, strategies remained relatively stable across sprint efforts and can be considered specific to the individual.

If changing an individual's whole-body kinematic initial sprint acceleration strategy is deemed favourable, then information on features characterising the different clusters will help inform this process. A change in whole-body kinematic strategy does not necessarily refer to a move from one cluster to another (Figure 6.1a). Rather, it is likely indicative of a subtle change in strategy within a given cluster, depending on the stability of the individual's strategy and the proximity of their ellipse centroid (Figure 6.9) to other clusters. Significant differences were evident in step length and step rate between clusters, which determined the magnitude of their length/rate ratio. How these step length and step rates were achieved, though, differed between clusters of similar length/rate ratios. For instance, participants in clusters B and C produced similar step lengths but reached these through greater flight lengths (cluster B) or contact lengths (cluster C). Furthermore, to achieve similar step rates, the participants in cluster B used shorter contact times, whilst those in cluster C produced shorter flight times. These findings outline the different options available for altering step length and step rate through manipulation of their constituent variable.

6.4.2 Consistency in macro, but not micro system behaviour

Although noticeable differences in normalised spatiotemporal variables and linear kinematics between clusters were evident, the differences observed in the angular kinematics at touchdown and toe-off (Figures 6.4 to 6.6) were less clear. This further illustrates the levels of inter-individual degeneracy which exist during the initial sprint acceleration of rugby backs, not only in context of the different whole-body kinematic strategies used in reaching the same performance outcome, but also how different arrangements in angular kinematics are observed with similar normalised spatiotemporal variables. When looking to facilitate changes in whole-body acceleration strategy, attempts to do so by explicitly coaching changes in segmental and joint angular positions to manipulate the desired normalised spatiotemporal variables associated with a given strategy must be considered with caution. There is also a risk that detailed information on limb positioning may result in coaching instructions that draw an athlete's attentional focus internally (Porter et al., 2010) and interfere with self-organisation processes, resulting in a negative performance effect (Wulf, 2013). Consequently, practitioners would be advised to consider using a more externally focussed approach with a view to facilitating changes in acceleration strategy directly or indirectly through manipulating the spatiotemporal variables or linear kinematics.

6.4.3 The potential influence of strength qualities on acceleration strategies

Similar to the lack of differences in the angular kinematics between clusters, strength characteristics were also generally comparable between clusters with the exception of the hip extensor torque/contact time ratio which was significantly higher in clusters A and B than C and D. This combined strength feature may have resulted in participants in clusters A and B self-organising their segment orientations at touchdown (Figure 6.4) and linear kinematics (Figure 6.3) in a favourable way to yield shorter contact times compared with clusters C and D (Figure 6.2c), without sacrificing performance. On this basis, different strength characteristics of the participants in clusters C and D appeared to interact to produce alternative strategies (e.g., greater step length through increased contact length and/or flight length) to the participants in clusters A and B to maintain comparable levels of acceleration performance. Owing to the time-course necessary for eliciting either neuromuscular (Baroni et al., 2013; Brown et al., 2017; Moritani & deVries, 1979; Rasmussen & Phillips, 2003) or technical (Bezodis et al., 2018) adaptations through strength-based interventions, more direct instructional methods to manipulate spatiotemporal variables will likely yield faster acute changes. However, for changes in spatiotemporal variables to emerge without conscious effort, and for the outcome to be effective, the corresponding physical changes which accompany these technical manipulations will likely be necessary so that the desired sprinting action is available to an individual (Fajen et al., 2008; Michaels, 2003).

6.4.4 Acceleration strategies are stable at the intra-individual level

For the participants who completed 12 sprint trials on four separate occasions, the normalised spatiotemporal variables and their ratios were highly reliable within and between testing sessions, (Table 6.2). As a result, the strategies identified for individuals are representative of their actual strategy at the given time of testing. Although intra-individual movement variability is an inherent feature of human movement (Newell & Ranganathan, 2009; Preatoni et al., 2013), the stability indices (Table 6.3), covariance ellipses (Figure 6.9), and CVs (Table 6.3) demonstrate consistent individual spatiotemporal variables with respect to the inter-individual variability. Greater variability was evident in the contact/flight ratio (mean CV, 6.7%; mean SD, 0.165) than the length/rate ratio (mean CV, 3.8%; mean SD, 0.036), as illustrated by the typically greater dimensions of the covariance ellipses in the x-axis (Figure 6.9). The higher contact/flight ratio CV is primarily due to variability in flight time than in contact time. Further work is needed to explore the potential implications of how the variation of these measures associate with changes in acceleration performance of athletes at an individual level. These measures provide a means to determine each individual's inherent variability so that meaningful changes in acceleration strategies can be detected with certainty in response to training interventions. Given the stability of strategies evident across the four separate testing sessions, these data can be collected on separate occasions, rather than during a single session, to eliminate any potential effects of fatigue.

The novel approach used in this study to establish a single measure which represents an individual's whole-body kinematic initial sprint acceleration strategy (Figure 6.1a), can be performed reliably at a given point in time, as indicated by the low CVs observed for the length/rate and contact/flight ratios (Table 6.1). Whilst the hierarchical clustering approach was first required to determine whether discrete clustered strategies or a widespread continuum of strategies existed, the combined length/rate and contact/flight ratios as a whole-body kinematic measure, represented by a single data point on a quadrant, provides a way for practitioners to assess changes in acceleration whole-body kinematic strategies over time. However, deciding on what changes could be used to enhance acceleration performance is not straightforward, as no significant relationships were found between NAHEP and any normalised spatiotemporal variables or their ratios (Table 6.1) and there were no significant differences in NAHEP between clusters of participants (Figure 6.1). These findings suggest that different technical strategies can be adopted to achieve similar performance outcomes during the initial steps, which may explain the inconsistent findings between

Chapters 3 and 4 (i.e., differences in the magnitude of the relationship between toe-off distance and NAHEP) as well as the general lack in meaningful relationships between variables in isolation and NAHEP in Chapters 3 to 5. It may also explain why the findings from previous research investigating the relative importance of isolated spatiotemporal variables to acceleration performance in team sport players has also been inconsistent (e.g., Lockie et al., 2011; Lockie et al., 2013; Murata et al., 2018; Murphy et al., 2003; Nagahara et al., 2018a; Standing & Maulder, 2017).

The findings reported in this study suggest that a single optimum technique does not exist during initial sprint acceleration in rugby backs and so efficacy of technique strategies ought to be considered at the individual level to inform sprint training practices. This would require selected variables to be measured over multiple trials for each individual and considered with the performance outcome measure across each trial (Glazier & Mehdizadeh, 2018). Consequently, practitioners could determine how changes in whole-body kinematic strategies, in addition to athlete's spatiotemporal variables in isolation, are associated with NAHEP to determine which variables an individual may be reliant on for better acceleration performance. For instance, for an individual who is step rate reliant (i.e., they achieve higher NAHEP when their length/rate ratio is typically lower), it would be possible to determine whether their higher step rates are achieved through a reduction in contact or flight time, or a combination of both. This information may provide a more focussed direction for a practitioner's speed training interventions when looking to target the normalised spatiotemporal variables an individual's acceleration performance is reliant on, although experimental research is required to determine the effectiveness of this approach (see Chapter 7).

Reliance on step length or step rate has been shown to be a highly individual occurrence in elite sprinters when considered across the whole 100 m sprint (Salo et al., 2011). Salo et al. (2011) proposed that this individual reliance should be considered in the context of an athlete's training and that the step characteristics they are reliant on for better sprinting performance ought to be prioritised. The added advantage of monitoring an individual's whole-body kinematic strategy, in addition to their normalised spatiotemporal variables in isolation, is that a more holistic view is provided that takes into account how the combination of all normalised spatiotemporal variables collectively change in relation to changes in acceleration performance. Interventions can then be implemented to enhance the variables associated with an individual's reliance to increase their acceleration performance or, at least, to ensure they are able to consistently produce a high performance in this phase relative to their individual capabilities.

6.5 Chapter summary

Collectively, the findings from this study have demonstrated that the normalised spatiotemporal variables and the length/rate and contact/flight ratios can be used to reliably portray acceleration strategies. Using this novel approach, four clusters of professional rugby backs were identified according to the similarity of their normalised spatiotemporal variables, but acceleration performance did not differ significantly between clusters. This implies that a single optimal strategy does not exist during initial sprint acceleration and therefore the efficacy of technique strategies used ought to be considered at the individual level to inform sprint training practices. At the intra-individual level, the variables which portray the individual strategies of participants remained consistent relative to the inter-individual variability observed. The approach employed in this study provides a new solution for longitudinally monitoring changes in an individual's whole-body acceleration strategy to accurately detect any changes in response to influencing factors (e.g., training interventions, fatigue, training load and rehabilitation from injury).

CHAPTER 7: USING INDIVIDUALLY PRESCRIBED TRAINING INTERVENTIONS TO ENHANCE THE SPRINT ACCELERATION PERFORMANCE OF PROFESSIONAL RUGBY UNION BACKS: INSIGHTS FROM MULTIPLE CASE STUDIES

7.1 Introduction

Chapters 3-6 have provided empirical evidence that a single optimum technique does not exist for professional rugby backs during initial acceleration. This was shown through inter-individual differences in movement strategies and the trivial differences in sprint acceleration performance observed between groups of rugby backs who adopted different strategies. Therefore, to inform their sprint practices, it was proposed that practitioners should consider measuring selected technical features over multiple trials, determine how these features are associated with sprint performance within an individual, and use this information to develop individual-specific training programmes. However, no research to date has investigated this approach during initial acceleration or used the resulting information to apply individual-specific interventions aimed at enhancing the sprinting performance of athletes. Consequently, investigating these associations and longitudinally assessing changes in acceleration technique and performance of professional rugby union backs in response to interventions based on their individual needs would clearly be of value to practitioners working in rugby union.

Spatiotemporal variables (step length, step rate, contact time and flight time) were identified in Chapter 6 as appropriate technical features of rugby backs to longitudinally measure during initial acceleration for three principal reasons: 1) they can be obtained promptly, which is important in an applied setting for data to be actionable; 2) they can be obtained reliably for individuals across multiple sprint trials (CV < 6.5%; Table 6.3), thus meaningful changes can be detected with assurance; 3) they represent the movement outcomes of sprinting and can be used to alter technical features from an externally focussed perspective (e.g., Bezodis et al., 2017; Winkelman, 2018). However, despite these potential benefits, spatiotemporal data of athletes during sprinting are seldom reported across multiple timepoints in the literature.

The longitudinal spatiotemporal data which does exist within published research is typically based on the step length and step rate of sprinters during the maximum velocity phase. For instance, across a five-month period, four elite sprinters were found to achieve large and meaningful increases in mean step velocity during the maximum velocity phase, typically when mean step rate, but not mean step length, was higher during training (Bezodis et al., 2018). However, elite sprinters have also been shown to individually rely on either step length or step rate (or neither variable) for better sprinting performance during competition when their step variables were averaged over the entire 100 m of multiple races (Salo et al., 2011). These findings highlight value in determining how step length and step rate are individually associated with sprinting performance and suggest that intentionally attempting to enhance, or, at least, prevent a negative effect on, the variable athletes are individually reliant on for better sprinting performance is important. However, it remains to be seen how interventions which target the variables athletes are individually reliant on would affect their technique and sprinting performance. Furthermore, whilst spatiotemporal variables can be obtained in a timely manner from two-dimensional video images across the initial steps, using the same video-based approach to calculate NAHEP - the measure of initial acceleration performance in this thesis - requires digitising multiple segment endpoints to determine whole-body centre of mass at touchdown and toe-off. A more practical solution to measure initial acceleration performance longitudinally in response to changes in an athlete's spatiotemporal variables may also be of benefit in the applied setting.

In Chapter 6, a framework was developed for practitioners to measure individual whole-body kinematic strategies, depicted by the spatial location of cartesian coordinates for rugby backs formed by the combination of their length/rate and contact/flight ratios (Figure 6.1). Monitoring an individual's whole-body kinematic strategy in this way, which incorporates contact time and flight time variables in addition to step length and step rate, may be used to provide a more detailed view by accounting for how these spatiotemporal variables in their dimensionless form collectively and individually change in relation to changes in initial acceleration performance. This is consistent with ecological dynamics and constraints led approaches where information on human movement behaviour is considered more holistically.

Therefore, the aims of the study reported in this chapter were to, first, investigate within-individual associations between the acceleration performance and technical features of rugby backs and, second, to understand how the technique and sprint performance of these athletes change longitudinally when individual-specific interventions based on this information are applied. There were two main research questions to address the aims of the study: VII - *What are the within-individual relationships of whole-body kinematic strategies and normalised spatiotemporal variables* *with the initial acceleration performance of professional rugby backs during the first four steps?* – and VIII - *How do longitudinal individual-specific training interventions that focus on the variable(s) which specific professional rugby backs are reliant upon for better sprint performance affect their acceleration capabilities?*

To determine whether an alternative acceleration performance measure to NAHEP could be used, thus providing practitioners in the applied setting with timesaving way to obtain information to inform their sprint training interventions, a final research question was proposed: IX: *How closely can the within-individual relationships of whole-body kinematic strategies and normalised spatiotemporal variables with NAHEP, and the within-individual changes of these variables following individual-specific training interventions be replicated using a more practical performance measure than NAHEP?*

7.2 Methods

7.2.1 Participants

Data from 35 professional rugby union backs (mean ± SD: age 25 ± 3 years; stature 1.81 ± 0.06 m; leg length 1.00 ± 0.05 m; body mass 93.0 ± 8.5 kg) competing in the English Premiership were analysed in this study. Since these data were pre-existing from the testing conducted as part of the rugby players' usual training schedule, and were anonymised, informed consent was not required (Haugen et al., 2019b; Winter & Maughan, 2009). As explained later in this section, data from Chapter 6 were used in this chapter. For new data obtained in this chapter, ethical and/or governance review was not deemed as required after completing the University of Surrey Self-Assessment Governance and Ethics form for Humans and Data Research (SAGE-HDR). At the time of testing, participants were free from injury and frequently completed maximal sprint accelerations within their usual weekly training regime.

7.2.2 Procedures

The research in this chapter was conducted in three stages (Table 7.1), which will be referred to hereafter to clarify the different parts of the research. In Stage 1 during the baseline period, normalised spatiotemporal variables, whole-body kinematic strategies (length/rate and contact/flight ratios) and NAHEP were obtained from all participants over the first four steps of three sprints on a single testing occasion. These data were based on the 29 participants in Chapter 6 and six additional participants. To address research question IX, a second acceleration performance measure (5 m time) was also determined, in Kinovea (v.0.8.27) analysis software, for all 35 participants. This was defined as the time from the first frame the toe of participants' back foot visibly lifted off the ground at the start until the frame their mid hips passed the 5 m mark, based on the method used by Healy et al. (2016). The 5 m distance was selected because it is commonly used to measure initial acceleration performance in an applied setting (Bracic et al., 2011; Chelly et al., 2010; Cronin & Hansen, 2005; Marques et al., 2011; Zabaloy et al., 2020) and, in the current study, it represented a large percentage of the distance covered by participants from the start until completion of their fourth steps (mean ± SD: 81 ± 6%).

In Stage 2 during the baseline period (Table 7.1), the same testing was conducted for 19 of the 35 participants on three further occasions. This resulted in all variables being measured for these participants for twelve sprints during a baseline testing period (Stages 1 and 2) in pre-season over six weeks (i.e., 3 sprint trials on 4 separate occasions). This data set was based on 13 of the participants in Chapter 6 and the six participants added to the wider group of 35 participants in this chapter. The data obtained during the baseline period (Stages 1 and 2) were used to determine whether these 19 participants were individually reliant on step length or step rate (Salo et al., 2011) for better sprint performance, and how contact and flight times and whole-body kinematic strategies were also related to acceleration performance.

Thirteen of the 19 participants were then randomly selected to be studied over 18 weeks of training during the in-season (Stage 3, Table 7.1). At the onset of this period, five participants were designated as controls, whilst eight participants were each given an individual-specific intervention based on their own needs as determined from the data obtained during the baseline period (Stages 1 and 2). Due to injury and/or changes to training schedules, five participants were unable to fully complete the training period (Stage 3), reducing the number of control participants and those who completed an individualised intervention to three and five, respectively. All participants had a minimum of three years' professional senior rugby experience and a minimum of five and two years of strength and sprint training experience, respectively. Three participants also had senior international caps.

Table 7.1. An outline of the different stages in the study

Period	Baseline				Intervention
Duration	6 weeks				18 weeks
Stage	1	→	2	→	3
No. participants	35		19		8[a]
Testing undertaken	Sprint testing for all participants on a single testing occasion (3 sprints) Strength-based testing on a single testing session for 25 participants (Chapter 5)		Sprint testing for all participants on 3 further occasions (3 sprints on 3 separate occasions)		Sprint testing for all participants on weeks 7, 10, 13 and 15-18 (3 sprints on each occasion)
Data obtained	Normalised spatiotemporal variables, whole-body kinematic strategies and acceleration performance measures (NAHEP and 5 m time) Touchdown and toe-off angular kinematics and strength-based variables for a single participant (S1)[a]		Normalised spatiotemporal variables, whole-body kinematic strategies and acceleration performance measures (NAHEP and 5 m time)		Normalised spatiotemporal variables, whole-body kinematic strategies and acceleration performance measures (NAHEP and 5 m time) Touchdown and toe-off angular kinematics and strength-based variables for a single participant (S1)[a]

[a]13 participants were originally given an individual-specific intervention (5 controls, 8 intervention). Due to drop out, numbers decreased to 8 participants (3 control,4 technical intervention and 1 strength intervention)

In Stage 3, the control group underwent their usual training regime over the 18-week period (Stage 3, Table 7.1). Four participants who were given a technical intervention completed the same training as the control participants. However, when completing sprint efforts during speed training sessions and warm-ups for rugby training and matches, they focussed on technical features found to individually relate to better sprinting performance (determined from the baseline testing period). They were not given instructions to focus on these technical prompts during matches or in the main component of rugby training sessions. One participant (S1) completed the same sprint training as all other participants (without any technical focus during these sprints), but a different strength programme. The strength programme for this participant was informed by strength scores they achieved in the repeated jump, hip torque and squat jump profiling tests during the baseline testing period (Stage 1, data from Chapter 5) and relationships observed between strength-based measures and sprint technical variables found in Chapters 5 and 6. The strength qualities relating to sprint variables which the participant was identified as being reliant on for better sprinting performance during the baseline period (Stages 1 and 2) formed the focus of their strength programme. Touchdown and toe-off angular and linear kinematics for this participant in the baseline testing phase (Stage 1, data from Chapter 5) were also analysed so that a comparison of these technical features could be made for this participant following the intervention.

The timeline for interventions in Stage 3 and the type and number of training sessions undertaken during the different phases of the intervention period are shown in Figure 7.1. The total number of sprints recorded for each training phase for each individual included those which took place during speed training sessions and during warm-ups prior to rugby training sessions and matches, as well as those completed during rugby training and matches. On average, approximately six maximal sprint efforts were undertaken during speed training sessions and four maximal sprint efforts were completed during warm-ups prior to rugby training sessions and matches over distances of approximately 10 to 40 m. During rugby training and matches a sprint was determined using the GPS (Catapult Sports, 10 Hz) outputs in OpenField Cloud Analytics software when the threshold of 80% of a player’s maximum velocity was exceeded. Although no evidence-based recommendations exist for an appropriate threshold, it is common practice in professional rugby union clubs and therefore provided an appropriate and objective way to measure the number of sprints completed during matches. A full description of the training undertaken by participants is provided in Appendix G (Figures F.1 to F.3).

TIMELINE

	Session type	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Weeks		1, 2, 3, 4	5, 6, 7	8, 9, 10	11, 12, 13, 14	15, 16, 17, 18
C1	Speed training	6	4	4	5	4
C1	Strength training	11	8	6	9	5
C1	Rugby training	12	9	7	11	6
C1	Match	2	1	-	1	1
C1	Total sprints	69 / 25	48 / 35	38 / 22	56 / 33	38 / 22
C2	Speed training	6	3	2	4	4
C2	Strength training	11	9	7	6	5
C2	Rugby training	11	9	9	6	8
C2	Match	4	3	2	3	2
C2	Total sprints	75 / 60	49 / 48	41 / 50	47 / 45	45 / 43
C3	Speed training	6	5	4	3	4
C3	Strength training	9	9	9	6	5
C3	Rugby training	11	9	9	9	7
C3	Match	2	1	-	2	2
C3	Total sprints	67 / 44	52 / 38	42 / 38	45 / 33	42 / 37
S1	Speed training	4	2	2	2	4
S1	Strength training	12	8	9	10	5
S1	Rugby training	12	8	9	11	6
S1	Match	1	-	1	1	1
S1	Total sprints	54 / 46	30 / 34	36 / 37	42 / 45	37 / 27
Focus		Contrasting	Reliance focus	Contrasting	Reliance focus	No focus
T1	Speed training	6	3	3	3	4
T1	Strength training	10	8	5	11	5
T1	Rugby training	12	9	6	12	7
T1	Match	4	3	2	3	3
T1	Total sprints	76 / 61	50 / 42	36 / 32	55 / 57	45 / 40
T2	Speed training	6	3	3	4	3
T2	Strength training	11	6	6	10	5
T2	Rugby training	11	9	7	12	7
T2	Match	4	3	3	3	3
T2	Total sprints	72 / 54	51 / 47	42 / 34	60 / 42	40 / 31
T3	Speed training	7	5	2	4	4
T3	Strength training	11	8	7	8	6
T3	Rugby training	12	9	9	11	7
T3	Match	1	-	1	1	2
T3	Total sprints	71 / 50	47 / 33	38 / 50	52 / 51	42 / 45
T4	Speed training	6	5	4	4	4
T4	Strength training	11	9	6	12	5
T4	Rugby training	12	8	7	11	8
T4	Match	1	-	2	1	-
T4	Total sprints	64 / 25	45 / 30	46 / 32	52 / 33	38 / 22

Baseline data collection over 6 weeks

Exploratory session

Figure 7.1. Stage 3 (intervention) timeline and the type and number of sessions completed by participants. The total number of sprints shown for each participant include those completed during speed sessions and warm-ups before rugby training and matches (left side of the forward slash) and those completed during rugby training and matches, considered when participant's velocity was above 80% of their maximum velocity capability, derived from GPS outputs (right side of the forward slash). Individuals (in grey) above the dashed line formed the control participants. Participants underneath the dashed line underwent strength (orange) and technical (blue) based interventions. Red shaded weeks represent the baseline period and weeks in which sprint testing occasions took place during the intervention and final testing periods.

Following the initial baseline period in which data from 12 sprints were collected across a six-week period for all participants (Table 7.1, Stages 1 and 2), normalised spatiotemporal variables, whole-body kinematic strategies, NAHEP and 5 m time were obtained from all participants during three sprint trials on three separate occasions (weeks seven, 10 and 13 during Stage 3 (intervention period) – see red weeks in Figure 7.1). The same data for all participants were collected on a further three to four occasions (10 to 12 sprint trials in total) across the final four weeks of the intervention in Stage 3 (Phase 5, Figure 7.1) so that any changes in these variables could be compared appropriately to baseline testing. The angular and linear kinematics and strength-based variables were also obtained on a single occasion for participant S1 (strength intervention) during the final phase (Phase 5) of the intervention in Stage 3. The methods and conditions under which sprint and strength data were collected were the same across all testing sessions.

To provide a focus for the participants given an individualised technical intervention, holistic cues or analogies were self-generated by participants during an exploratory session prior to the intervention period in Stage 3, resulting in technical prompts to use in the ensuing intervention (Figure 7.1). During this exploratory session, the results of the initial baseline testing (Stages 1 and 2), and their implications, were first explained individually to participants by the coach leading this session. The coach was also the lead researcher who was an accredited strength and conditioning coach (UKSCA), an athletics coach (level 2, British Athletics) and had > 20 years' experience coaching athletes. The concept of using holistic cues or analogies as technical prompts to help direct attention during sprinting was also explained to participants (Abedanzadeh et al., 2021; Winkelman, 2018; Winkelman & Coyle, 2020).

Following a warm-up, participants were asked to spend five to ten minutes by themselves practicing 10 m sprint efforts (n = 3-4) in which they focussed on targeting the variable(s) they were primarily and secondarily (Table 7.2) found to individually rely on for better sprinting performance during the first four steps, which also underpinned the association between a change in Cartesian plane spatial location of their whole-body kinematic strategy and acceleration performance (this process is described later in this section). They were also asked to reflect on how this technical change felt (physically) to them and to try and verbalise this feeling through the use of a holistic cue or analogy as a technical prompt when sprinting. Participants then reported back to the coach with their self-generated holistic cue or analogy and completed six 10 m sprints alternating between no focus of attention and using their technical prompts. Normalised spatiotemporal variables were collected during each of these sprints to compare these variables independently and collectively (whole-body strategies) between the no focus and technical focussed efforts to check that the desired changes in participants' technical features were being achieved.

Table 7.2 Self-generated technical prompts, for participants given a technical intervention, during initial acceleration according to the variables underpinning the changes in whole-body strategy associated individually with better sprinting performance in this phase

Participant	Primary reliance[a]	Secondary reliance[b]	Intended Cartesian plane direction shift[c]	Technical prompt	Prompt context for intended direction shift in whole-body strategy
T1	↑Step rate	↓Flight time	SE	"Skate"	Participant explained the feeling of increasing their step rate primarily through a reduction in flight time as "fast skating". That is, it felt like they were skating over the ground with each step.
T2	↑Contact/flight	↑Step length	NE	"Glide"	Participant explained the feeling of increasing their step length whilst increasing contact/flight ratio as "gliding". The typical flat trajectory of a hang-glider was used to describe the feeling the participant had with a flatter centre of mass trajectory in sprinting likely resulting from the combination of longer contact times and shorter flight times in a step (i.e., a higher contact/flight ratio)
T3	↑Length/rate	↑Step length	N	"Float"	Participant explained the feeling of increasing their step length as "floating".
T4	↑Step rate	↓Contact time	SW	"Ra-ta-ta-ta"	Participant explained the feeling of increasing their step rate primarily through a reduction in contact time audibly with a noise reflecting the sound of a machine gun.

[a]Variable most related to acceleration performance (up and down arrows represent whether an increase or decrease in the variable is associated with acceleration performance)

[b]Variable second most related to acceleration performance

[c]The Cartesian plane shift depicts the intended Cartesian plane spatial location change in the whole-body strategy of participants related to their initial acceleration performance (see explanation below, also Figure 7.2 and Appendix H)

SE = south-east; NE = north-east; N = north; SW = south-west

The self-generated technical prompts for participants are shown in Table 7.2. The intended changes in Cartesian plane spatial location of their whole-body kinematic strategies were expressed as directions on a 16-point compass, determined according to the magnitudes of the relationships observed between each ratio (length/rate and contact/flight) and NAHEP during Stages 1 and 2 of the baseline period (see Figure 7.2 showing the results of this analysis for a single participant). For instance, a meaningfully positive relationship (defined in section 7.2.3) between the length/rate ratio and NAHEP for an individual would denote a favourable shift northward on the Cartesian plane (i.e., higher NAHEP is achieved with a larger length/rate ratio). This is evident in the example of participant 33 in Figure 7.2 where larger marker sizes representing higher magnitudes of NAHEP are typically larger more northwards on the Cartesian plane. A meaningfully positive relationship between the contact/flight ratio and NAHEP would denote a favourable shift eastward on the Cartesian plane (i.e., higher NAHEP achieved with a larger contact/flight ratio). This is evident in Figure 7.2 where marker sizes are typically larger more eastwards on the Cartesian plane. If the difference between the magnitude of these relationships is trivial ($r < 0.1$), then collectively the intended favourable direction shift would be represented by an intercardinal direction (north-east in this example).

If both ratios are meaningfully related to NAHEP, but the difference between the magnitudes of the relationships is considered at least small ($r \geq 0.1$) then the cardinal direction signifying the intended shift in strategy would result in a 'half-wind' (i.e., direction points obtained by bisecting intercardinal directions yielding 16 direction categories each 22.5° from its nearest neighbours) oriented more towards the relationship of a higher magnitude. For example, for participant 33 (Figure 7.2) the within-participant relationships of the length/rate and contact/flight ratios with NAHEP were $r = 0.45$ and 0.77, respectively (i.e., both relationships are meaningful, but the difference between the magnitudes of these relationships is $r > 0.1$), thus the resultant intended direction shift for this individual would be the half-wind ENE. For participant S1 (strength intervention), the intended technical change was informed by the relationships between normalised spatiotemporal variables in isolation and NAHEP, since a meaningful relationship between their whole-body kinematic strategy and NAHEP was not found.

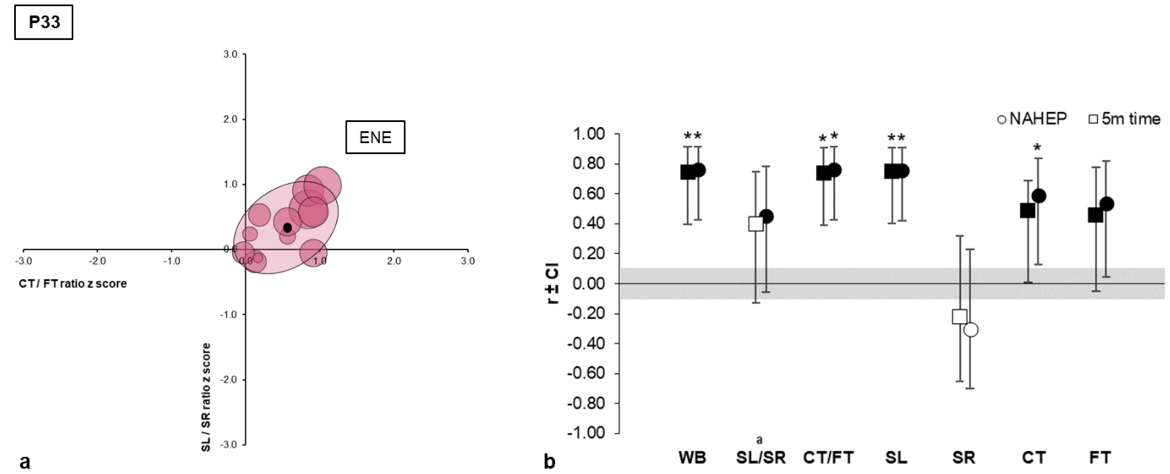


Figure 7.2. An example whole-body kinematic strategy (a) for a random participant (P33). Each marker depicts a single sprint, with marker sizes reflecting acceleration performance (a larger marker size equates to greater NAHEP). Where whole-body kinematics are meaningfully related to NAHEP, the theoretical favourable Cartesian plane spatial location change in strategy for better sprint performance is included as a compass bearing. Relationships (with 90% confidence intervals) of their whole-body kinematic strategy, normalised spatiotemporal variables and length/rate and contact/flight ratios with NAHEP and 5 m time are also shown (b). For clarity, to aid comparisons between relationships of NAHEP and 5 m time with variables, the direction of relationships between 5 m time and variables has been inverted. Black filled makers depict relationships $r \geq 0.43$ and asterisks indicate that relationships are statistically significant ($p = < 0.05$)

WB = whole-body kinematic strategy; SL/SR = length/rate ratio; CT/FT = contact/flight ratio; SL = step length; SR = step rate; CT = contact time; FT = flight time

The technical prompts were used by the participants undertaking the technical intervention throughout Stage 3 during the intervention period, apart from the final phase of testing (Phase 5, Figure 7.1). During phases 1 and 3 of the intervention during Stage 3 (Figure 7.1), contrasting technical training was undertaken. That is, during speed training sessions or warm-ups before rugby training and matches, participants alternated between sprinting with no focus and sprinting by focussing on their technical prompts during the first four steps. This is similar to the “old way/new way” proposed by Lyndon (1989) in the non-sport school learning environment as a way of practising that reduces the mental interference from established habit patterns and consequently accelerates learning and improves performance. This approach has since been reported as successful in a case study investigation with an Olympic sprinter and a javelin thrower where the athletes’ habitual techniques were contrasted with new more favourable ones (Hanin et al., 2002). During phases 2 and 4 of the intervention period in Stage 3, participants were asked to focus only on their technical prompts and shift in sprinting strategy over the first four steps, thus attempting to remove the interference of their existing habitual technique altogether. During the final phase (5) in Stage 3 (and during any data collection sessions throughout the intervention) participants were asked not to focus on anything and to try and cover the sprint distances in as fast a time as possible. The control participants and participant S1 (strength intervention) were asked to focus only on covering sprint distances in as fast a time as possible throughout the intervention period in Stage 3 during training and testing.

Control participants and those who were given an individualised technical intervention followed the same strength-based training across the intervention period during Stage 3 (see Figure G.2, Appendix G). During baseline testing (Stage 1), participant S1 (strength intervention) was found to be reliant on higher step rate for better sprinting performance, which was underpinned primarily by achieving shorter contact times (Figure H.2, Appendix H). Meaningful and statistically significant relationships were observed between these technical features and several strength qualities in Chapter 5 (Table 5.2). In Chapter 5 shorter contact times in sprinting were achieved by participants who produced shorter repeated jump contact time, greater hip torque and repeated RSI, and larger torque/contact time ratios (r = -0.55 to -0.42; $p \leq 0.05$). Shorter repeated contact times (higher vertical stiffness) during strength testing were also associated with shorter contact times (r = 0.43; $p \leq 0.05$) and higher step rate (r = -0.43; $p \leq 0.05$) during the first four steps of acceleration. The strength-based scores participant S1 achieved in Stage 1 of the baseline period (Table 7.1) suggested they were limited in these physical capacities and therefore that there was scope for meaningful changes in these features. For instance, they achieved the second lowest repeated jump height and second longest repeated jump contact times, which combined to produce the lowest repeated RSI. They also achieved the second lowest hip torque score and lowest torque/contact time ratio of the 25 participants who undertook strength-based testing in Chapter 5. Collectively, this reflected comparatively poor hip extensor maximum strength, vertical stiffness and lower limb reactive strength capabilities. Therefore, participant S1’s strength-based programme was designed to address these strength deficiencies to facilitate a technical strategy resulting in shorter contact times and higher step rates during initial acceleration.

The strength programme for participant S1 (detailed in Figure G.2, Appendix G) during intervention (Stage 3, Figure 7.1) aimed to enhance their vertical stiffness and lower limb reactive strength by incorporating specific isometric-based training and a higher volume of plyometric training, since training approaches adopting these exercises have been shown to enhance muscle-tendon stiffness qualities and stretch-shortening cycle performance (e.g., Foure et al., 2010; Kubo et al., 2017, Lum et al., 2021; Moran et al., 2021; Yata et al., 2006). The programme also aimed to enhance participant S1's hip extensor maximum strength ability by using exercises in which a greater extensor demand is placed on the hip compared with the knee and ankle (e.g., Brazil et al., 2021) and loading protocols recommended for maximum strength development (Androulakis-Korakakis et al., 2020).

7.2.3 Statistical analyses

In Stage 1 of the baseline period (Table 7.1) data for normalised spatiotemporal variables and NAHEP were averaged over four steps and then averaged again over the three sprint trials for each of the 35 participants, consistent with the approaches used in Chapters 4-6. This approach was also taken for 5 m time. The mean ± SD 5 m time, NAHEP, normalised spatiotemporal variables and the length/rate and contact/flight ratios for the 12 sprints completed by each of the 19 participants who completed sprint trials on four separate occasions during Stages 1 and 2 of the baseline period (Table 7.1) were reported individually. All group and intra-individual descriptive data (mean ± SD) were calculated for all variables and checked for normal distribution using the Shapiro-Wilk statistic.

To assess the consistency of 5 m time, group and intra-individual coefficients of variation (CV) were measured. In Stage 1 of the baseline period the 5 m time within-participant CV for each of the 35 participants across their three sprint trials were calculated and the average of these across the entire group was then determined to provide the group level CV, using the same approach as Chapters 5 and 6. For the 19 participants who completed sprint trials on four different occasions during Stages 1 and 2 of the baseline period (Table 7.1), the 5 m time CVs for each participant across their twelve sprint efforts were reported individually. The same approach was taken to determine the intra-individual CVs for NAHEP, normalised spatiotemporal variables and the length/rate and contact/flight ratios.

The strength of group and within-individual relationships between NAHEP and 5 m time, and their confidence intervals (90%), were determined using Pearson coefficient correlations. A group level correlation was based on the mean NAHEP and 5 m time achieved by each of the 35 participants (Table 7.1, Stage 1) in their initial three sprint trials. The intra-individual correlations were also determined individually for the 19 participants across their 12 sprint trials during baseline testing

(Table 7.1, stages 1 and 2), and these relationships were then averaged across those participants to provide the mean intra-individual correlation for this sub-group.

The whole-body kinematic strategies and distribution of these strategies for the 19 participants in the sub-group (stages 1 and 2) were determined using the same approaches as used in Chapter 6, although participant z-scores were calculated based on the larger group ($n = 35$) from Stage 1 (Table 7.1) in the current analysis. Pearson's or Spearman rank (non-parametric data) correlation coefficients were used to measure the strength of intra-individual relationships (90% confidence intervals) of normalised spatiotemporal variables and the length/rate and contact/flight ratios with initial acceleration performance across their 12 sprints. Correlations were also used to determine the intra-individual relationship between participants' whole-body kinematic strategies (combination of the length/rate and contact/flight ratios) and sprint performance. Relationships were deemed meaningful where the magnitude of the observed relationship was greater than the smallest clinically important correlation (Hopkins, 2007), equating to a value of $r \pm 0.43$. Relationships were deemed unclear if their magnitude was within this threshold ($-0.43 < r < 0.43$). The strength of relationships was defined as: (±) < 0.1, trivial; 0.1 to < 0.3, small; 0.3 to < 0.5 moderate, 0.5 to < 0.7 large, 0.7 to < 0.9 very large and ≥ 0.9, practically perfect (Hopkins, 2002).

To check the technical prompts used by participants undergoing an intervention in Stage 3 (Figure 7.1) were facilitating the intended technical changes, effect size differences (Cohen's *d*) between relevant variables obtained during sprints completed with and without a technical focus were determined. Differences between variables were deemed meaningful when effect sizes were larger than 0.2 (smallest worthwhile difference; Hopkins, 2002) and when the absolute differences (%) were greater than intra-individual CVs obtained for the selected variable, as identified during the initial baseline testing period. The magnitude of changes in whole-body strategies were measured by the Euclidean distance between the spatial locations of their centroid cartesian coordinates as follows:

$$d(x, y) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

During the intervention (Stage 3, Figure 7.1), effect size differences (Cohen's *d*) were used to determine the magnitude of the pairwise differences in mean ± SD NAHEP, 5 m time, normalised spatiotemporal variables and the length/rate and contact/flight ratios between all testing occasions.

A sequential estimation technique was applied during the baseline period (stages 1 and 2) to identify the minimum number of sprint trials necessary to establish a stable mean for each kinematic variable and participant. This was deemed necessary to provide confidence in any meaningful changes observed between variables obtained during initial baseline testing and during the final testing phase. This involved calculating the cumulative mean of each variable, adding one trial at a time (Clarkson et al., 1980; Preatoni et al., 2013). Stability was assumed to have been reached for each variable when the cumulative mean remained constant within an acceptance bandwidth of ±0.25 SD of the mean, which has commonly been used previously (Chen et al., 2019; Hamill & McNiven, 1990; Preatoni et al., 2010; Rodano & Squadrone, 2002). The minimum number of trials necessary to establish stable means for kinematic variables and participants ranged between 4 and 10. An example of this approach is shown in Figure 7.3.

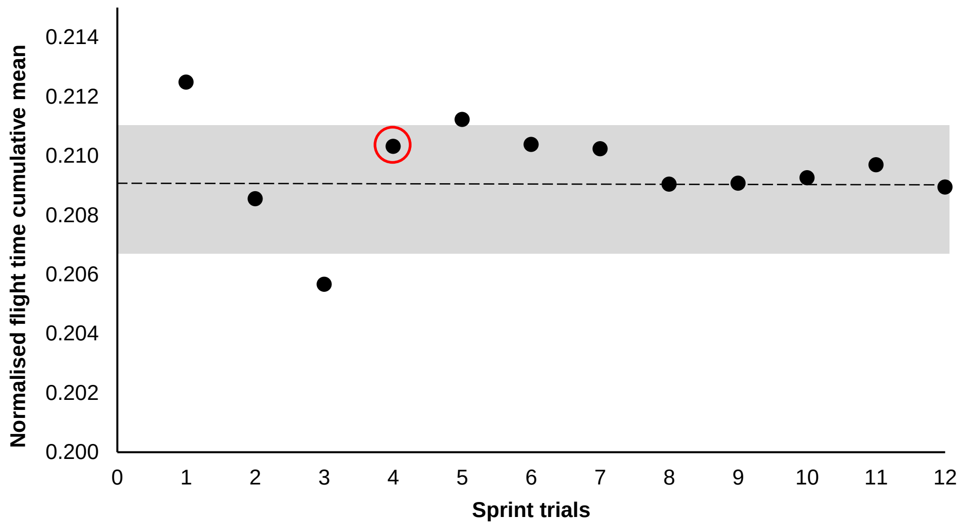


Figure 7.3. An example of the sequential estimation technique used to identify the minimum number of trials necessary to establish a stable mean for the variables of interest. This figure shows that a minimum of four trials were needed to identify the stable mean for the normalised flight time of participant 33.

Paired samples *t*-tests or Wilcoxon signed-rank (nonparametric data) were used to determine the changes in the mean ± SD normalised spatiotemporal variables, length/rate and contact/flight ratios, NAHEP and 5 m time between baseline testing in stages 1 and 2 (12 sprint trials, Table 7.1) and the final testing period during (10 to 12 sprint trials; Phase 5, Figure 7.1) within each participant observed during the intervention period in Stage 3. Changes were deemed meaningful for each individual when all three of the following criteria were met: 1) effect sizes were larger than 0.2

(smallest worthwhile difference; Hopkins, 2002); 2) the absolute differences (%) were greater than intra-individual CVs obtained for the selected variable (Turner et al., 2021); 3) differences were statistically significant (*p* ≤ 0.05). For participant S1 (strength intervention), differences in their linear and angular kinematics and strength qualities between baseline testing (Stages 1) and the final testing session (Phase 5 of Stage 3 intervention period) were also analysed with meaningful changes deemed to have taken place when the first two criteria outlined above were met.

Magnitudes of the changes in the whole-body kinematics between baseline (Stages 1 and 2) and final testing (Phase 5 of Stage 3, Figure 7.1) were determined using the Euclidean distance between the spatial locations of their centroid cartesian coordinates. The direction change in whole-body strategy for each individual was also quantified by first calculating the angle between a vertical line and the vector represented by the x and y coordinates of the centroids from baseline (Stages 1 and 2, Table 7.1) and the final testing period (Phase 5 of Stage 3, Figure 7.1). These angles were then expressed as compass bearings, where north, east, south and west were depicted by angles of 0°, 90°, 180° and 270°, respectively. Angles were round to the nearest 22.5° to determine cardinal, intercardinal or half-wind directions.

To determine whether whole-body kinematic strategies were from different distributions, thus reflecting a change in strategy from one cluster to another in the context of a given individual, rather than a shift in strategy within the same cluster, a two-dimensional Kolmogorov-Smirnov test as defined by Friedman and Rafsky (1979) was employed. A statistic in the range [0,1] was calculated by scaling the statistic by the quantity:

$$\sqrt{\frac{n1n2}{n1 + n2}}$$

where $n1$ is the sample size of the pre data set and $n2$ is the sample size of the post data set. The closer the statistic is to 1, the more different the distributions of the whole-body kinematic strategies are (Friedman & Rafsky, 1979). Statistical significance was determined using a permutation test in which the observed data are resampled multiple times to obtain a *p*-value for the test. The Kolmogorov-Smirnov statistic and permutated p-values were determined using an open-source package in R (Rahmatallah et al., 2017).

7.3 Results

Group and within individual descriptive statistics for acceleration performance obtained in Stages 1 and 2 during baseline testing can be found in Tables 7.3 and 7.4, respectively.

Table 7.3. Initial sprint acceleration performance of 35 professional rugby union backs and their normalised spatiotemporal variables over the first four steps during a single testing session in the baseline period (Stage 1) involving three sprint trials

Variable	Mean ± SD
NAHEP	0.559 ± 0.074
5 m time (s)	1.029 ± 0.035
Step length	1.31 ± 0.10
Step rate	1.38 ± 0.09
Contact time	0.51 ± 0.04
Flight time	0.21 ± 0.03
CT/FT ratio	2.48 ± 0.46
SL/SR ratio	0.96 ± 0.13

Practically perfect and statistically significant group and mean within individual relationships were found between NAHEP and 5 m time (Table 7.4) following stages 1 and 2 of baseline testing. Group (Table 7.4) and within individual (Table 7.5) CV for acceleration performance measures, normalised spatiotemporal variables and the length/rate and contact/flight ratios were all less than 10%, indicating acceptable relative reliability (Atkinson & Nevill, 1998).

Table 7.4. Group (n = 35) and mean within individual (n = 19) level relationships between NAHEP and 5 m time, and group coefficient of variation for the measurement of 5 m time

r (90% CI)		**5 m time CV ± SD (%)**
Group	*Within individual*	*Group*
-0.90* (0.83 to 0.95)	-0.91* (-0.97 to -0.75)	1.40 ± 1.02

*$p < 0.05$

Table 7.5. Descriptive statistics and variability of acceleration performance and normalised spatiotemporal variables of individual participants across twelve sprint trials, obtained in the Stage 1 and 2 of baseline testing.

Participant	**Mean ± SD (CV; %)** NAHEP	5 m time (s)	CT/FT	SL/SR	SL	SR	CT	FT
1	0.628 ± 0.027 (4.2)	1.015 ± 0.018 (1.8)	2.97 ± 0.21 (7.0)	0.74 ± 0.03 (4.3)	1.17 ± 0.05 (4.1)	1.57 ± 0.03 (1.9)	0.48 ± 0.01 (1.8)	0.16 ± 0.01 (6.4)
2	0.409 ± 0.045 (9.6)	1.109 ± 0.027 (2.4)	2.94 ± 0.22 (7.6)	0.76 ± 0.03 (3.7)	1.14 ± 0.03 (2.4)	1.50 ± 0.04 (2.5)	0.50 ± 0.02 (3.8)	0.16 ± 0.07 (4.8)
3	0.644 ± 0.035 (5.4)	1.013 ± 0.035 (2.5)	2.47 ± 0.24 (9.9)	0.84 ± 0.05 (5.4)	1.26 ± 0.06 (4.8)	1.50 ± 0.03 (1.7)	0.47 ± 0.01 (2.0)	0.19 ± 0.02 (8.9)
11 (T1)	0.631 ± 0.028 (4.5)	1.017 ± 0.023 (2.3)	2.38 ± 0.19 (8.2)	1.10 ± 0.03 (2.6)	1.42 ± 0.02 (1.7)	1.29 ± 0.02 (1.7)	0.55 ± 0.01 (1.5)	0.23 ± 0.02 (7.0)
12 (C1)	0.505 ± 0.021 (4.2)	1.064 ± 0.013 (1.2)	2.11 ± 0.16 (7.6)	1.03 ± 0.04 (3.7)	1.37 ± 0.03 (2.1)	1.33 ± 0.02 (1.8)	0.51 ± 0.01 (2.8)	0.24 ± 0.01 (5.7)
13 (T2)	0.651 ± 0.027 (4.1)	1.004 ± 0.009 (0.9)	2.79 ± 0.19 (7.0)	0.91 ± 0.04 (4.7)	1.30 ± 0.03 (2.6)	1.43 ± 0.04 (2.5)	0.51 ± 0.02 (3.9)	0.19 ± 0.01 (3.8)
14	0.626 ± 0.032 (5.1)	1.025 ± 0.027 (2.6)	2.34 ± 0.16 (6.8)	0.94 ± 0.04 (4.7)	1.32 ± 0.05 (3.7)	1.40 ± 0.02 (1.3)	0.50 ± 0.01 (1.7)	0.21 ± 0.01 (5.7)
16 (C2)	0.553 ± 0.042 (7.5)	1.058 ± 0.029 (2.8)	2.32 ± 0.14 (5.9)	1.07 ± 0.05 (4.3)	1.40 ± 0.03 (2.0)	1.32 ± 0.04 (2.7)	0.53 ± 0.02 (3.5)	0.23 ± 0.01 (4.4)
17	0.610 ± 0.026 (4.2)	1.023 ± 0.014 (1.4)	1.99 ± 0.12 (5.9)	0.86 ± 0.04 (4.2)	1.21 ± 0.04 (3.5)	1.40 ± 0.02 (1.7)	0.48 ± 0.01 (3.0)	0.24 ± 0.01 (3.8)
18	0.546 ± 0.022 (4.0)	1.048 ± 0.012 (1.1)	2.65 ± 0.19 (7.1)	1.09 ± 0.04 (3.3)	1.42 ± 0.03 (2.3)	1.27 ± 0.02 (1.4)	0.56 ± 0.01 (2.2)	0.23 ± 0.01 (4.4)
19	0.539 ± 0.032 (5.9)	1.063 ± 0.019 (1.8)	2.16 ± 0.14 (6.3)	0.94 ± 0.03 (2.9)	1.29 ± 0.02 (1.8)	1.37 ± 0.03 (1.9)	0.50 ± 0.01 (2.3)	0.23 ± 0.01 (5.4)
20	0.483 ± 0.037 (7.6)	1.079 ± 0.024 (2.2)	3.42 ± 0.15 (4.3)	1.04 ± 0.05 (5.0)	1.40 ± 0.04 (2.7)	1.35 ± 0.03 (2.5)	0.57 ± 0.01 (2.6)	0.17 ± 0.01 (4.5)
21 (C3)	0.517 ± 0.017 (7.8)	1.068 ± 0.008 (2.8)	1.84 ± 0.14 (2.2)	1.07 ± 0.03 (1.6)	1.40 ± 0.03 (2.2)	1.30 ± 0.02 (6.2)	0.50 ± 0.01 (3.3)	0.27 ± 0.02 (0.8)
25	0.544 ± 0.025 (4.5)	1.057 ± 0.025 (2.3)	2.37 ± 0.20 (8.6)	0.93 ± 0.06 (6.8)	1.37 ± 0.06 (4.7)	1.39 ± 0.04 (2.5)	0.51 ± 0.01 (2.1)	0.22 ± 0.02 (7.8)
26 (S1)	0.635 ± 0.025 (3.9)	1.001 ± 0.015 (1.5)	2.84 ± 0.13 (4.7)	1.12 ± 0.03 (2.7)	1.47 ± 0.03 (1.7)	1.31 ± 0.02 (1.7)	0.57 ± 0.01 (1.9)	0.20 ± 0.01 (4.1)
27 (T3)	0.450 ± 0.022 (5.0)	1.072 ± 0.011 (1.1)	3.03 ± 0.14 (4.7)	0.94 ± 0.03 (2.7)	1.29 ± 0.03 (2.0)	1.38 ± 0.02 (1.2)	0.54 ± 0.01 (1.6)	0.18 ± 0.01 (4.0)
31 (T4)	0.535 ± 0.025 (4.6)	1.061 ± 0.022 (2.1)	2.72 ± 0.18 (6.5)	0.89 ± 0.05 (6.0)	1.28 ± 0.05 (3.9)	1.41 ± 0.03 (2.4)	0.52 ± 0.02 (4.0)	0.20 ± 0.01 (2.9)
32	0.468 ± 0.026 (5.6)	1.079 ± 0.017 (1.6)	2.36 ± 0.22 (9.2)	1.10 ± 0.04 (3.5)	1.33 ± 0.03 (1.9)	1.30 ± 0.04 (3.2)	0.54 ± 0.02 (3.5)	0.24 ± 0.02 (8.0)
33	0.627 ± 0.030 (6.1)	1.036 ± 0.022 (4.7)	2.74 ± 0.17 (3.6)	1.01 ± 0.05 (1.4)	1.34 ± 0.05 (2.3)	1.34 ± 0.02 (3.4)	0.54 ± 0.01 (4.7)	0.21 ± 0.01 (2.1)
Group mean CV ± SD (%)	5.5 ± 1.8	2.1 ± 0.9	6.5 ± 1.9	3.9 ± 1.4	2.8 ± 1.0	2.3 ± 1.1	2.7 ± 1.0	5.0 ± 2.1

Individuals in grey (control), orange (strength) and blue (technical) underwent the intervention in Stage 3. Original participant numbers (from Chapter 6 and Stage 2 of this research) and those (in brackets) used for participants who also underwent an intervention in Stage 3 are shown for these individuals.
Where units are not provided, variables are in their dimensionless form using the equations of Hof (1996)

7.3.1 Within individual relationships between acceleration performance and sprint variables

Trivial to very large within individual relationships of NAHEP with whole-body kinematic strategy, length/rate and contact/flight ratios and each normalised spatiotemporal variable of the 19 participants (stages 1 and 2 in the baseline period) were observed (see Figure 7.2 and Figures F.1 to F.6 [Appendix G] for all participants' individual Figures). Within individual relationships (r = 0.14 to 0.88) between whole-body kinematic strategy and NAHEP were meaningful ($r \geq 0.43$) in 12 participants and statistically significant for six. Within individual relationships of NAHEP with length/rate and contact/flight ratios (r = -0.74 to 0.75 and r = -0.42 to 0.80) were meaningful in eleven (in four, $p \leq 0.05$) and seven (in two, $p \leq 0.05$) participants, respectively. Within individual relationships between NAHEP and normalised step length (r = -0.29 to 0.76) were meaningful in seven participants (in six, $p \leq 0.05$). Within individual relationships between NAHEP and normalised step rate (r = -0.64 to 0.88) were meaningful in 13 participants (in seven, $p \leq 0.05$). Within individual relationships of NAHEP with normalised contact time and normalised flight time (r = -0.63 to 0.78 and r = -0.79 to 0.54) were meaningful in six (in three, $p \leq 0.05$) and nine (in five, $p \leq 0.05$) participants, respectively.

Differences in magnitude between the within individual relationships of 5 m time and NAHEP with whole-body kinematic strategy, length/rate and contact/flight ratios and each normalised spatiotemporal variable were trivial to small (mean ± SD difference: whole-body kinematic strategy, $\Delta r = 0.08 \pm 0.06$; length/rate ratio, $\Delta r = 0.08 \pm 0.06$; contact/length ratio, $\Delta r = 0.10 \pm 0.07$; normalised step length, $\Delta r = 0.08 \pm 0.06$; normalised step rate, $\Delta r = 0.09 \pm 0.06$; normalised contact time, $\Delta r = 0.12 \pm 0.07$; normalised flight time, $\Delta r = 0.10 \pm 0.06$). Of the number of meaningful within-individual relationships (n = 64) across participants between NAHEP and sprint technique variables, 89% (n = 57) of the same relationships were also found to be meaningful when NAHEP was replaced by 5 m time (Figure 7.3 and Appendix G). In three participants, meaningful relationships of sprint technique variables observed with 5 m time were not observed with NAHEP (participant 12 [C1], whole-body strategy $\Delta r = 0.01$; participant 2, whole-body strategy $\Delta r = 0.14$, contact/flight ratio $\Delta r = 0.16$, flight time $\Delta r = 0.09$; participant 20, whole-body strategy $\Delta r = 0.15$, length/rate ratio $\Delta r = 0.14$, step length $\Delta r = 0.14$, step rate $\Delta r = 0.13$). Of the number of statistically significant within individual relationships (n = 33) across participants between NAHEP and sprint technique variables, 79% (n = 26) of the same relationships were also found to be statistically significant when NAHEP was replaced by 5 m time. A breakdown of results is shown in Table 7.6.

Table 7.6. Number of meaningful and statistically significant within-individual relationships between initial acceleration performance and normalised sprint kinematic variables

Variable	WB		SL/SR		CT/FT		SL		SR		CT		FT	
	a	b	a	b	a	b	a	b	a	b	a	b	a	b
NAHEP	12	6	9	3	7	2	7	6	10	5	5	2	7	3
5 m time	12	5	11	4	7	2	7	6	12	7	6	3	9	5

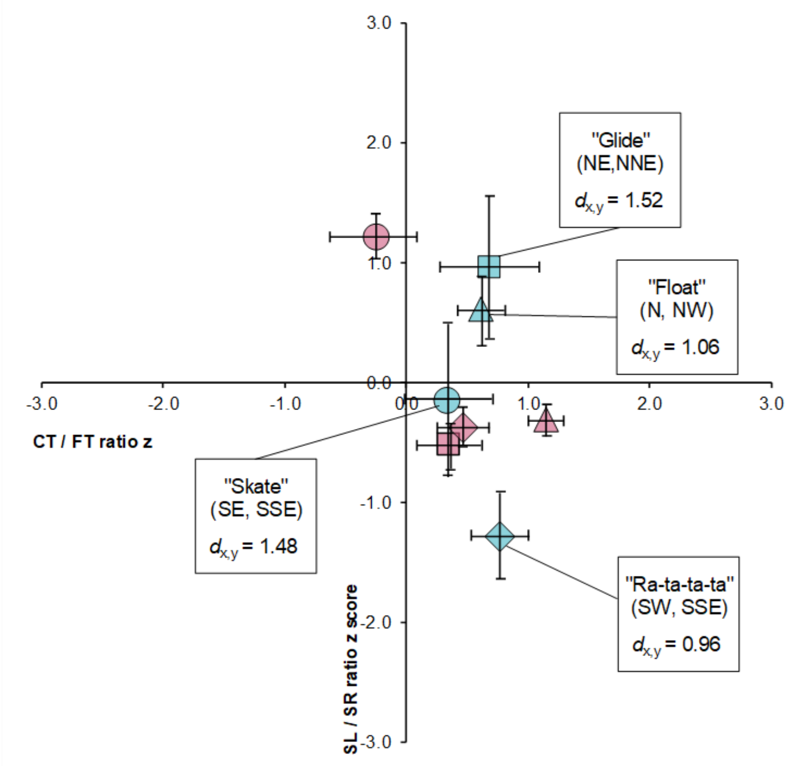
WB = whole-body strategy, SL/SR = length/rate ratio, CT/FT = contact/flight ratio, SL = step length, SR = step rate, CT = contact time, FT = flight time

[a] number of meaningful relationships
[b] number of statistically significant relationships

7.3.2 Exploratory session for technique intervention participants

Moderate to extremely large differences (Cohen's *d* = 1.08 to 5.75) were observed (Figure 7.4) when comparing all variables between no focus and technical focus (prompt) conditions during the exploratory session (Stage 1, Table 7.1) prior to the start of the intervention period (Stage 3, Figure 7.1) for participants who were given a technical intervention. Acceleration performance (NAHEP and 5 m time) was acutely negatively affected by large to extremely large magnitudes during the sprints undertaken with the technical focus provided (Figure 7.4).

The direction of the changes in magnitude of variables were aligned with those variables individuals were primarily and secondarily reliant on for better acceleration performance (Table 7.2) during the baseline period in stages 1 and 2, according to the associations of their whole-body kinematic strategy, length/rate and contact/flight ratios and normalised spatiotemporal variables with acceleration performance (Figures G.1, G.2; Appendix H). Changes in sprint variables were moderate to extremely large and the collective changes in these variables for each individual resulted in a directional change of their whole-body kinematic strategies to within one (participants T1 and T2), two (participant T3) and three (participant T4) half-winds of the intended Cartesian plane direction shift (Figure 7.4).



T1	Mean ± SD No focus (pink circle)	Mean ± SD Prompt (blue circle)	Effect sizes
NAHEP	0.621 ± 0.004	0.598 ± 0.047	**-5.75**
5m	1.021 ± 0.018	1.074 ± 0.036	**2.94**
CT/FT	2.41 ± 0.15	2.65 ± 0.21	**1.64**
SL/SR	1.11 ± 0.06	0.97 ± 0.14	**-2.31**
SL	1.43 ± 0.03	1.35 ± 0.09	**-2.67**
SR	1.29 ± 0.03	1.39 ± 0.07	**3.33**
CT	0.549 ± 0.006	0.523 ± 0.013	**-4.33**
FT	0.228 ± 0.007	0.197 ± 0.020	**-4.43**

T3	Mean ± SD No focus (pink triangle)	Mean ± SD Prompt (blue triangle)	Effect sizes
NAHEP	0.496 ± 0.010	0.464 ± 0.014	**-3.20**
5m	1.067 ± 0.013	1.105 ± 0.015	**2.92**
CT/FT	3.01 ± 0.09	2.78 ± 0.12	**-2.56**
SL/SR	0.93 ± 0.04	1.04 ± 0.09	**2.75**
SL	1.31 ± 0.03	1.40 ± 0.07	**3.00**
SR	1.41 ± 0.02	1.33 ± 0.05	**-4.00**
CT	0.532 ± 0.007	0.552 ± 0.016	**2.86**
FT	0.177 ± 0.006	0.191 ± 0.008	**2.33**

T2	Mean ± SD No focus (pink square)	Mean ± SD Prompt (blue square)	Effect sizes
NAHEP	0.637 ± 0.017	0.591 ± 0.031	**-2.71**
5m	1.017 ± 0.006	1.046 ± 0.023	**4.83**
CT/FT	2.67 ± 0.13	2.81 ± 0.19	**1.08**
SL/SR	0.91 ± 0.06	1.08 ± 0.14	**2.83**
SL	1.30 ± 0.04	1.41 ± 0.08	**2.75**
SR	1.43 ± 0.05	1.33 ± 0.08	**-2.00**
CT	0.508 ± 0.010	0.564 ± 0.012	**5.60**
FT	0.191 ± 0.005	0.201 ± 0.014	**2.00**

T4	Mean ± SD No focus (pink diamond)	Mean ± SD Prompt (blue diamond)	Effect sizes
NAHEP	0.522 ± 0.015	0.499 ± 0.028	**-1.53**
5m	1.061 ± 0.014	1.098 ± 0.029	**2.64**
CT/FT	2.72 ± 0.12	2.85 ± 0.15	**1.08**
SL/SR	0.92 ± 0.05	0.82 ± 0.11	**-2.00**
SL	1.30 ± 0.04	1.21 ± 0.08	**-2.25**
SR	1.41 ± 0.03	1.48 ± 0.06	**2.33**
CT	0.520 ± 0.010	0.499 ± 0.018	**-2.10**
FT	0.532 ± 0.007	0.502 ± 0.009	**-4.29**

Figure 7.4. Differences in whole-body kinematic strategies, normalised spatiotemporal variables and initial acceleration performance for participants under no focus and technical focus (prompt) conditions during an exploratory session. Self-generated technical prompts are shown in the speech marks for each participant, with the direction changes in strategy indicated in brackets (intended, actual) as compass bearings calculated to the nearest 22.5°. Euclidean distance ($d_{x,y}$) depicts the magnitude of change in participant whole-body kinematic strategies.

7.3.3 Pre and post changes following intervention

Pre (baseline testing; Stages 1 and 2) to post (final testing phase of the intervention; Phase 5 – the final phase of Stage 3) changes in the whole-body kinematic strategies of participants given a technical intervention are shown in Figure 7.5. The directional change of whole-body centroids for these participants were the same (participant T2) or within one (participants T1 and T3) or three (participant T4) half-winds of the intended Cartesian plane direction shift. The Euclidean distance between pre and post whole-body kinematic centroids of participants given a technical or strength intervention were greater than all control participants (Figure 7.6). A change in strategy from one cluster to another was evident for participant T1 (technical intervention, Figure 7.5) although the magnitude of this change was not as great as the change in strategy of participant S1 (strength intervention, Figure 7.6) as indicated by the statistically significant different distributions of their pre and post whole-body kinematic strategies, the magnitudes of which were determined by the two-dimensional Kolmogorov-Smirnov test.

Acceleration performance of participants undergoing a technical intervention in Stage 3 was enhanced where statistically significant differences between pre and post NAHEP and 5 m times were greater than the within-individual CV for each participant (Figures 7.7 to 7.10). The magnitude of change in NAHEP were positive and large for participants T1 to T4 (d = 1.29 to 1.46), and the magnitude of change in 5 m times (d = 1.11 to 2.82) were negative and moderate (participant T4), large (participants T1 and T2) and very large (participant T3). Acceleration performance remained unchanged (pre to post changes were less than the within individual CV for participants and no statistically significant differences were evident) for strength and control participants (Figures 7.11 to 7.14). For control participants no changes in length/rate and contact/flight ratios or normalised spatiotemporal variables were evident, although the magnitude of change in contact/flight ratio for participant C3 (Figure 7.14) exceeded their within individual CV for this variable. For participants who were given an intervention, statistically significant differences were evident and exceeded within individual CV for at least two variables for each individual (d = 1.11 to 3.99).

For participant S1 (strength intervention) very to extremely large (d = 3.13 to 9.15) meaningful differences (Figure 7.15) in all but one strength-based measure (squat jump P_{max}) were observed when comparing the baseline period (Stage 1) and final testing phase (Phase 5 of Stage 3, Figure 7.1). The proximal endpoints of their shank and thigh at touchdown were rotated more towards the direction of travel during testing on a single occasion in Phase 5 (Stage 3, Figure 7.1), whilst the proximal end of their foot segment was less rotated towards the direction of travel at toe-off. Meaningful differences were also observed for ankle dorsiflexion range of motion during stance (less in post compared with baseline testing), peak ankle dorsiflexion angle during stance (greater dorsiflexion in post compared with baseline testing). The largest pre to post change of a technical feature was evident in the participant's touchdown distance (extremely large magnitude), where the foot was more posterior relative to the CM at touchdown, which also resulted in a smaller contact length.

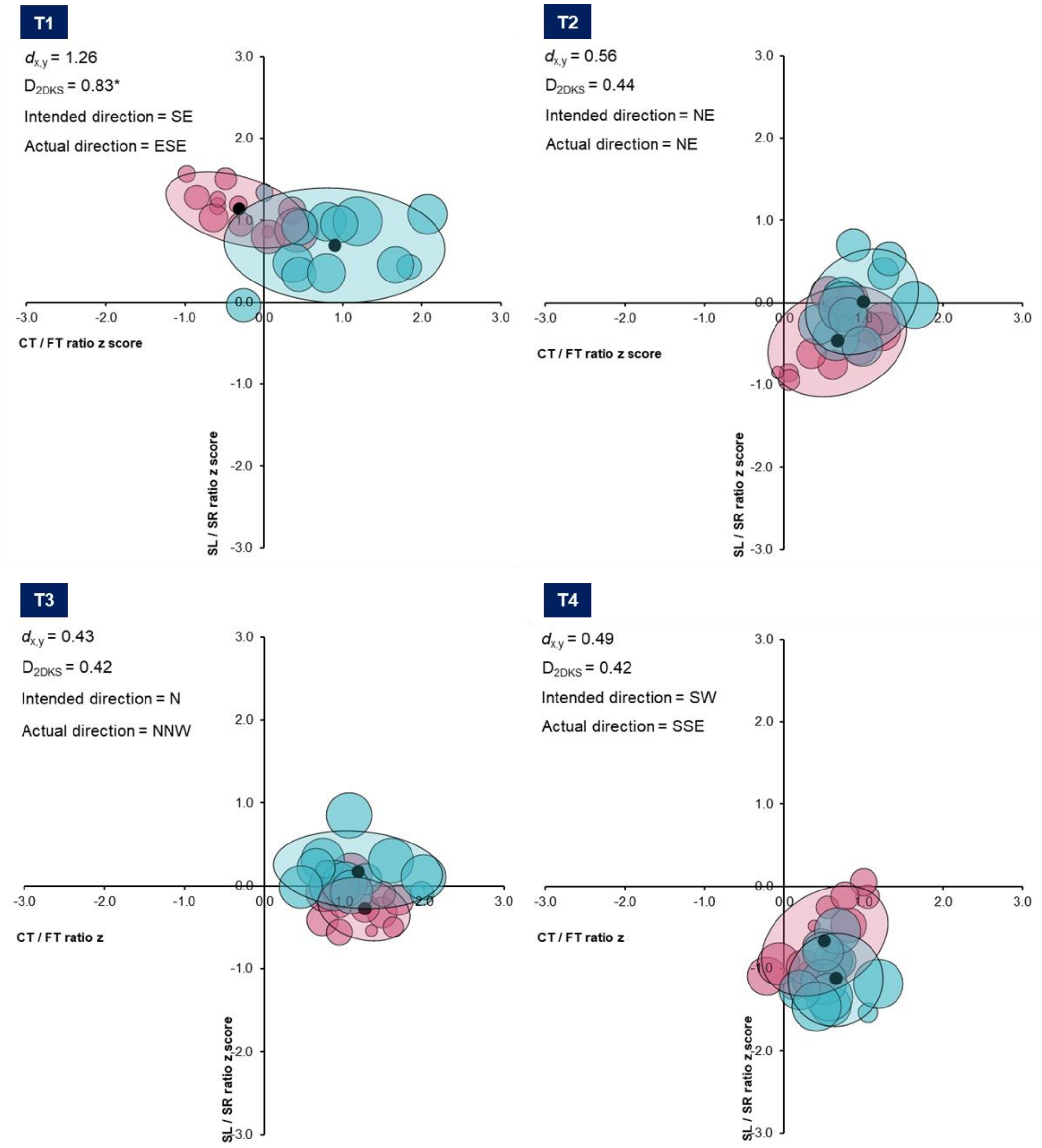


Figure 7.5. Change in whole-body kinematic strategies of participants who were given a technical intervention between initial baseline (pink ellipse) and final testing phases (blue ellipse).

$d_{x,y}$ = Euclidean distance between the whole-body kinematic strategies

D_{2DKS} = two-dimensional Kolmogorov-Smirnov statistic to determine the extent to which whole-body kinematic strategies are from the same distribution. Asterisks indicate whether the differences in distribution are statistically significant ($p < 0.05$)

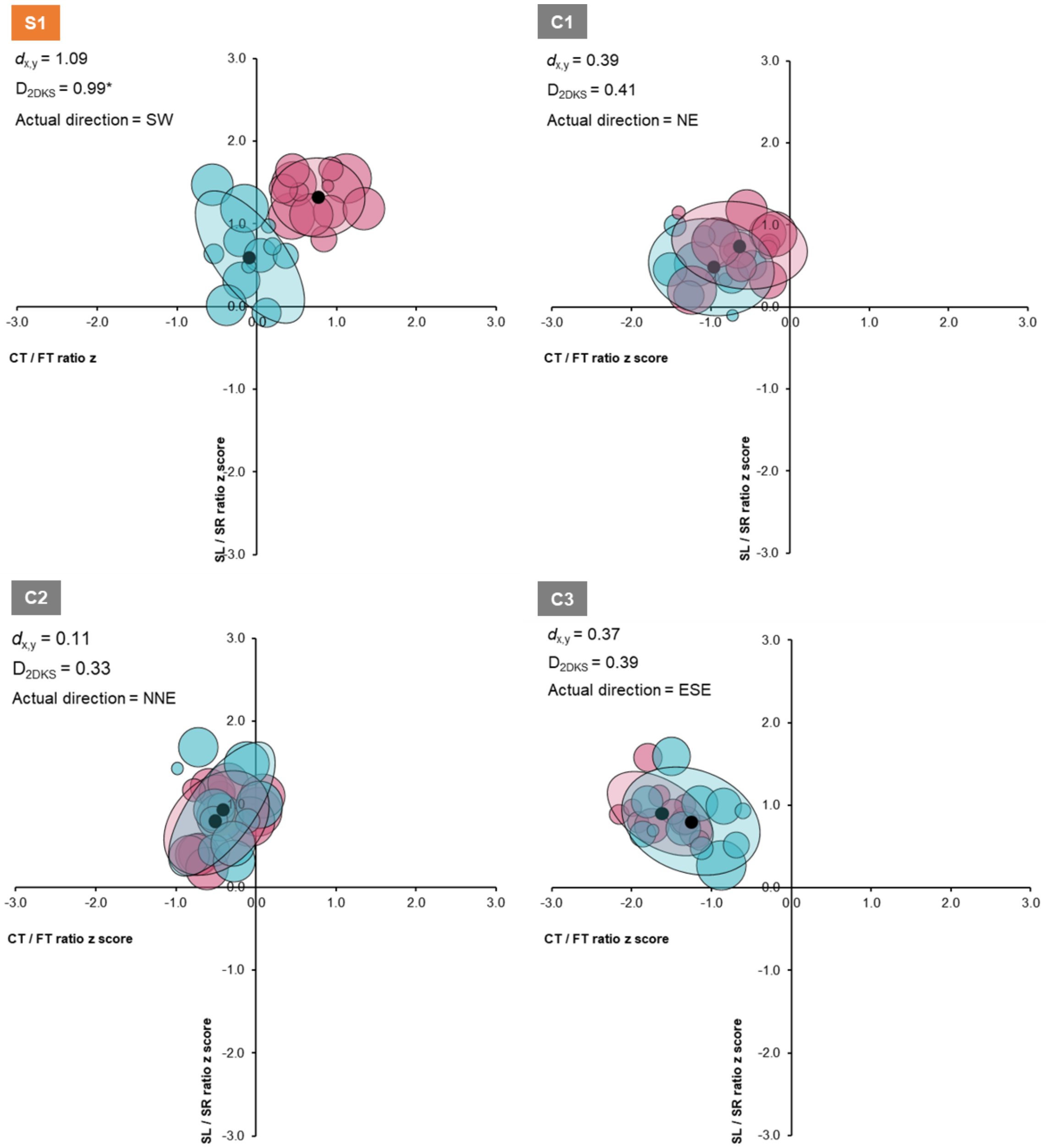


Figure 7.6. Change in whole-body kinematic strategies of control participants and participant S1 (strength intervention, orange filled participant number box) between initial baseline (pink ellipse) and final testing phases (blue ellipse).

$d_{x,y}$ = Euclidean distance between the whole-body kinematic strategies

D_{2DKS} = two-dimensional Kolmogorov-Smirnov statistic to determine the extent to which whole-body kinematic strategies are from the same distribution. Asterisks indicate whether the differences in distribution are statistically significant ($p < 0.05$)

Note that an intended direction was not included for participants S1 because their whole-body strategy was not meaningfully related to their acceleration performance (see Figure H.2, Appendix H). The strength intervention was intended increase their step rate, primarily through reducing their contact time, which would result in their whole-body spatial location moving towards south-west on the Cartesian plane

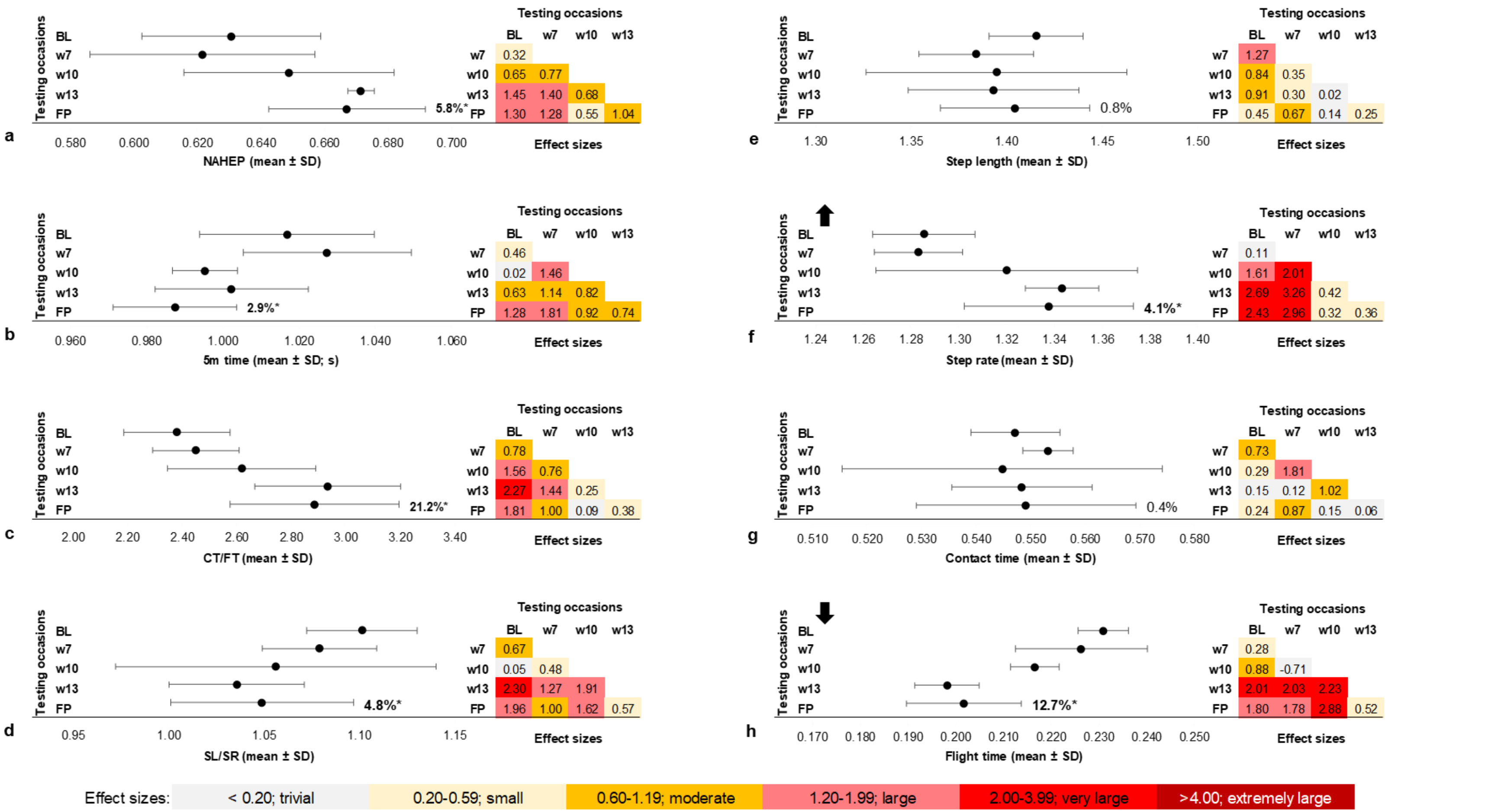


Figure 7.7 Mean ± SD of NAHEP, 5 m time, normalised spatiotemporal variables and the length/rate and contact/flight ratios for **participant T1** (technical intervention). Between testing occasion effect sizes (absolute) are shown (BL = baseline testing phase, w7 = week 7, w10 = week 10, w13 = week 13, FP = final testing phase). Black arrows indicate the direction of the intended changes in magnitude of the variables most underpinning the associations between participant whole-body kinematic strategy and acceleration performance observed during baseline testing. The absolute percentage change between initial baseline testing (session number 1) and the final testing phase (session 5) is shown. If this value is bold, the magnitude of the change is greater than the smallest worthwhile difference (Hopkins, 2002) and asterisks indicate whether the difference is statistically significant ($p \leq 0.05$), according to Paired samples *t*-tests or [a]Wilcoxon singed-rank (nonparametric data) tests.

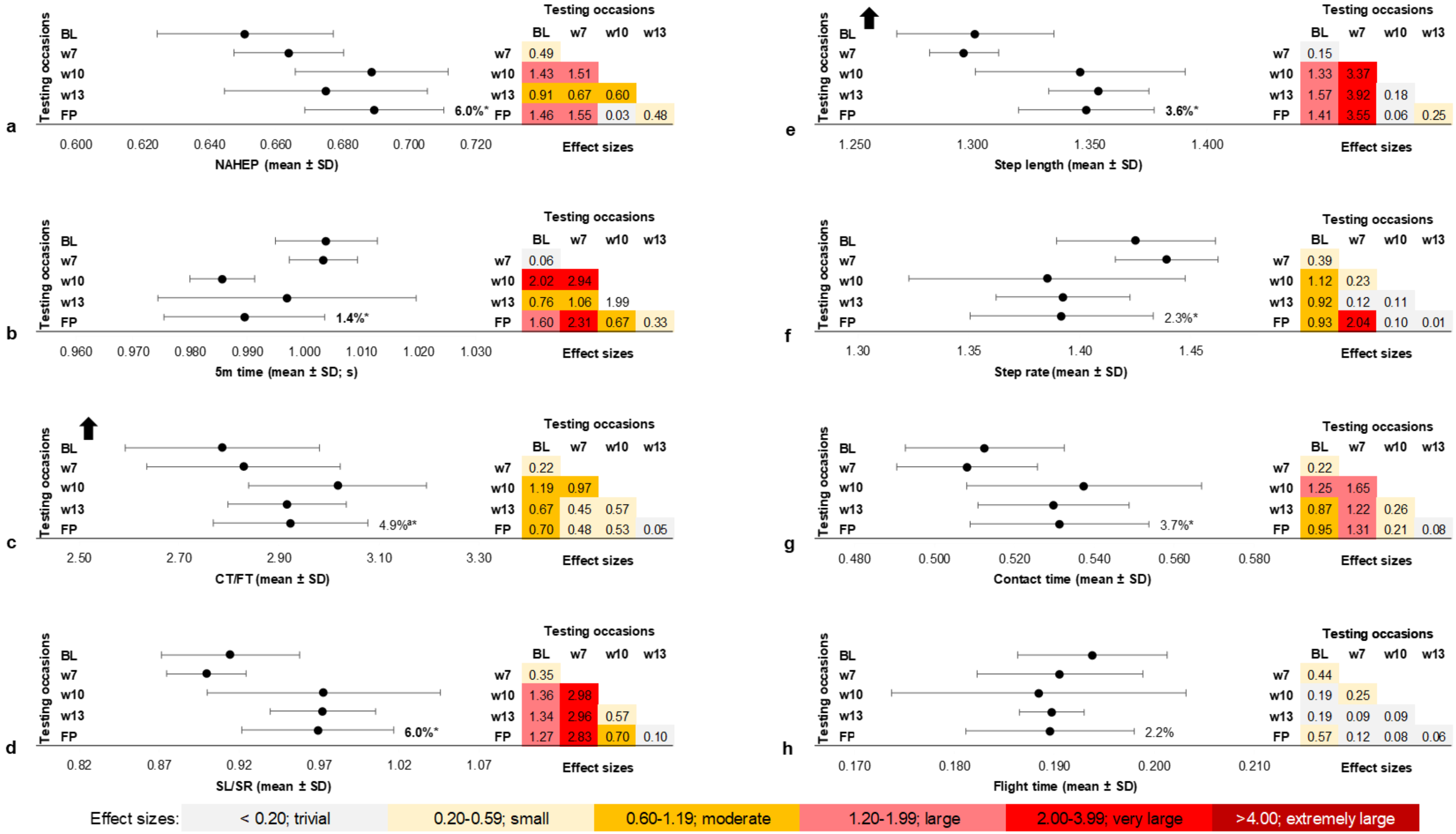


Figure 7.8 Mean ± SD of NAHEP, 5 m time, normalised spatiotemporal variables and the length/rate and contact/flight ratios for **participant T2** (technical intervention). Between testing occasion effect sizes (asbsolute) are shown (BL = baseline testing phase, w7 = week 7, w10 = week 10, w13 = week 13, FP = final testing phase). Black arrows indicate the direction of the intended changes in magnitude of the variables most underpinning the associations between participant whole-body kinematic strategy and acceleration performance observed during baseline testing. The absolute percentage change between initial baseline testing (session number 1) and the final testing phase (session 5) is shown. If this value is bold, the magnitude of the change is greater than the smallest worthwhile difference (Hopkins, 2002) and asterisks indicate whether the difference is statistically significant ($p \leq 0.05$), according to Paired samples *t*-tests or [a]Wilcoxon singed-rank (nonparametric data) tests.

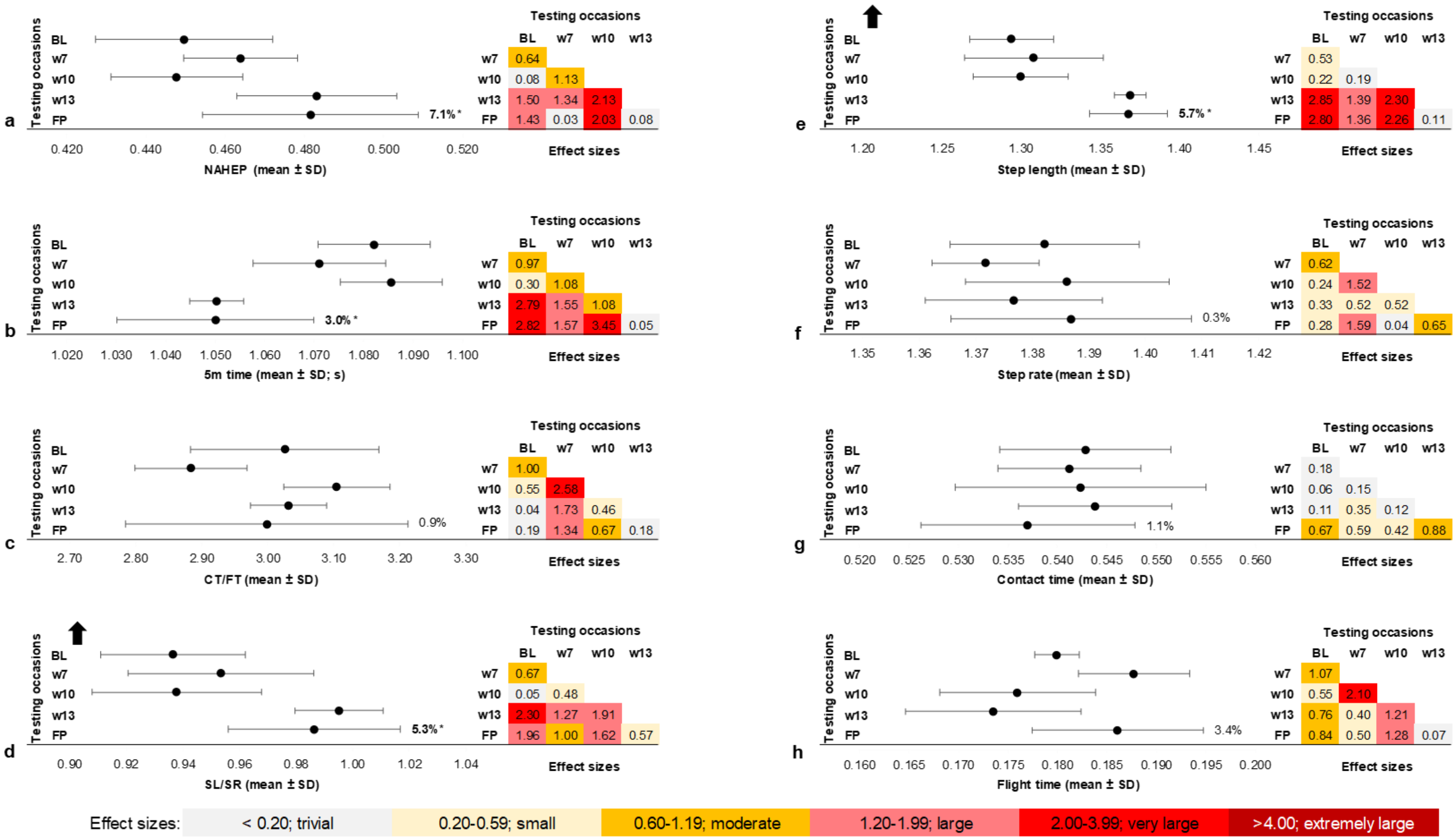


Figure 7.9 Mean ± SD of NAHEP, 5 m time, normalised spatiotemporal variables and the length/rate and contact/flight ratios for **participant T3** (technical intervention). Between testing occasion effect sizes (absolute) are shown (BL = baseline testing phase, w7 = week 7, w10 = week 10, w13 = week 13, FP = final testing phase). Black arrows indicate the direction of the intended changes in magnitude of the variables most underpinning the associations between participant whole-body kinematic strategy and acceleration performance observed during baseline testing. The absolute percentage change between initial baseline testing (session number 1) and the final testing phase (session 5) is shown. If this value is bold, the magnitude of the change is greater than the smallest worthwhile difference (Hopkins, 2002) and asterisks indicate whether the difference is statistically significant ($p \leq 0.05$), according to Paired samples *t*-tests or [a]Wilcoxon singed-rank (nonparametric data) tests.

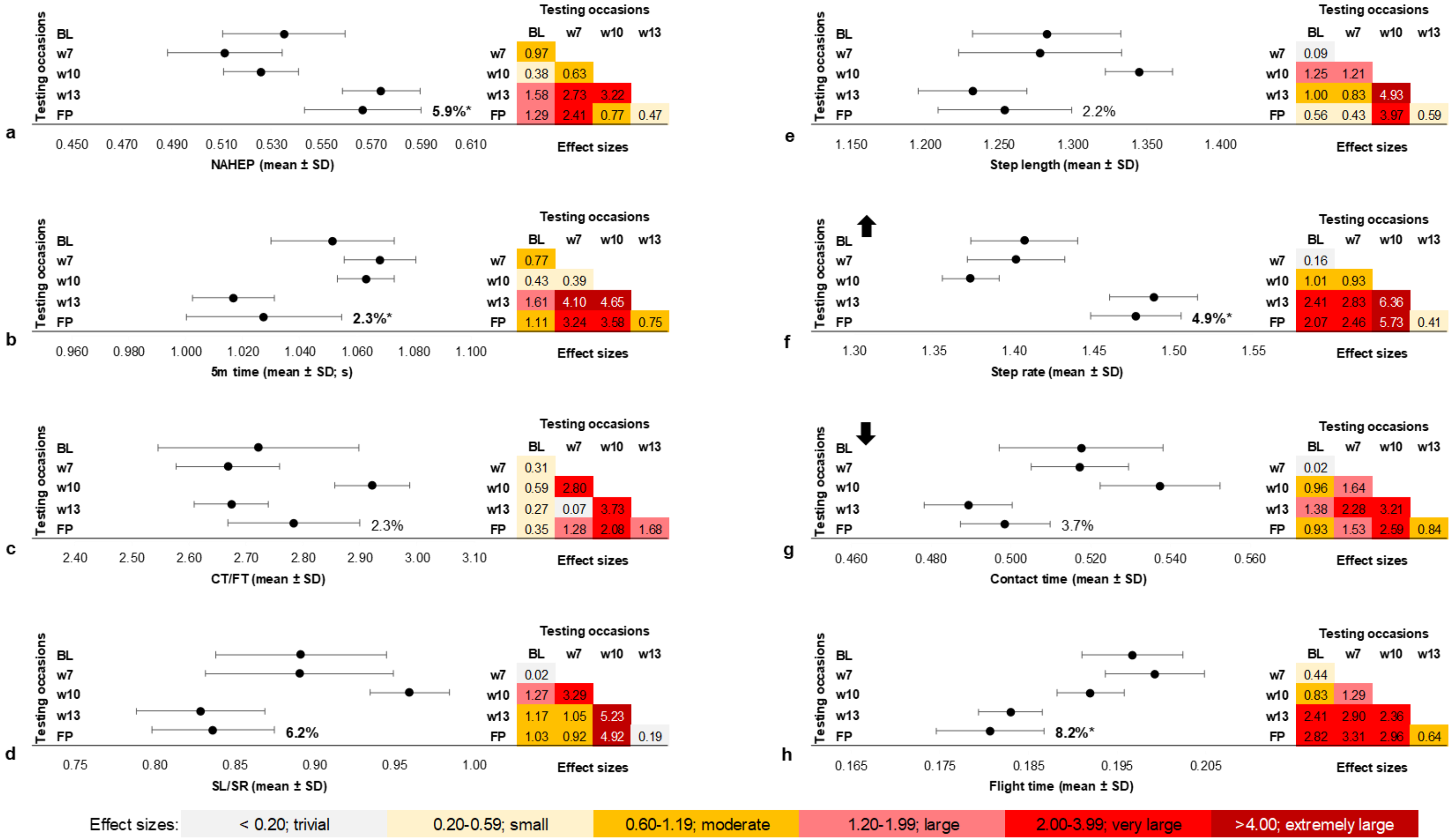


Figure 7.10 Mean ± SD of NAHEP, 5 m time, normalised spatiotemporal variables and the length/rate and contact/flight ratios for **participant T4** (technical intervention). Between testing occasion effect sizes (absolute) are shown (BL = baseline testing phase, w7 = week 7, w10 = week 10, w13 = week 13, FP = final testing phase). Black arrows indicate the direction of the intended changes in magnitude of the variables most underpinning the associations between participant whole-body kinematic strategy and acceleration performance observed during baseline testing. The absolute percentage change between initial baseline testing (session number 1) and the final testing phase (session 5) is shown. If this value is bold, the magnitude of the change is greater than the smallest worthwhile difference (Hopkins, 2002) and asterisks indicate whether the difference is statistically significant ($p \leq 0.05$), according to Paired samples t-tests or [a]Wilcoxon singed-rank (nonparametric data) tests.

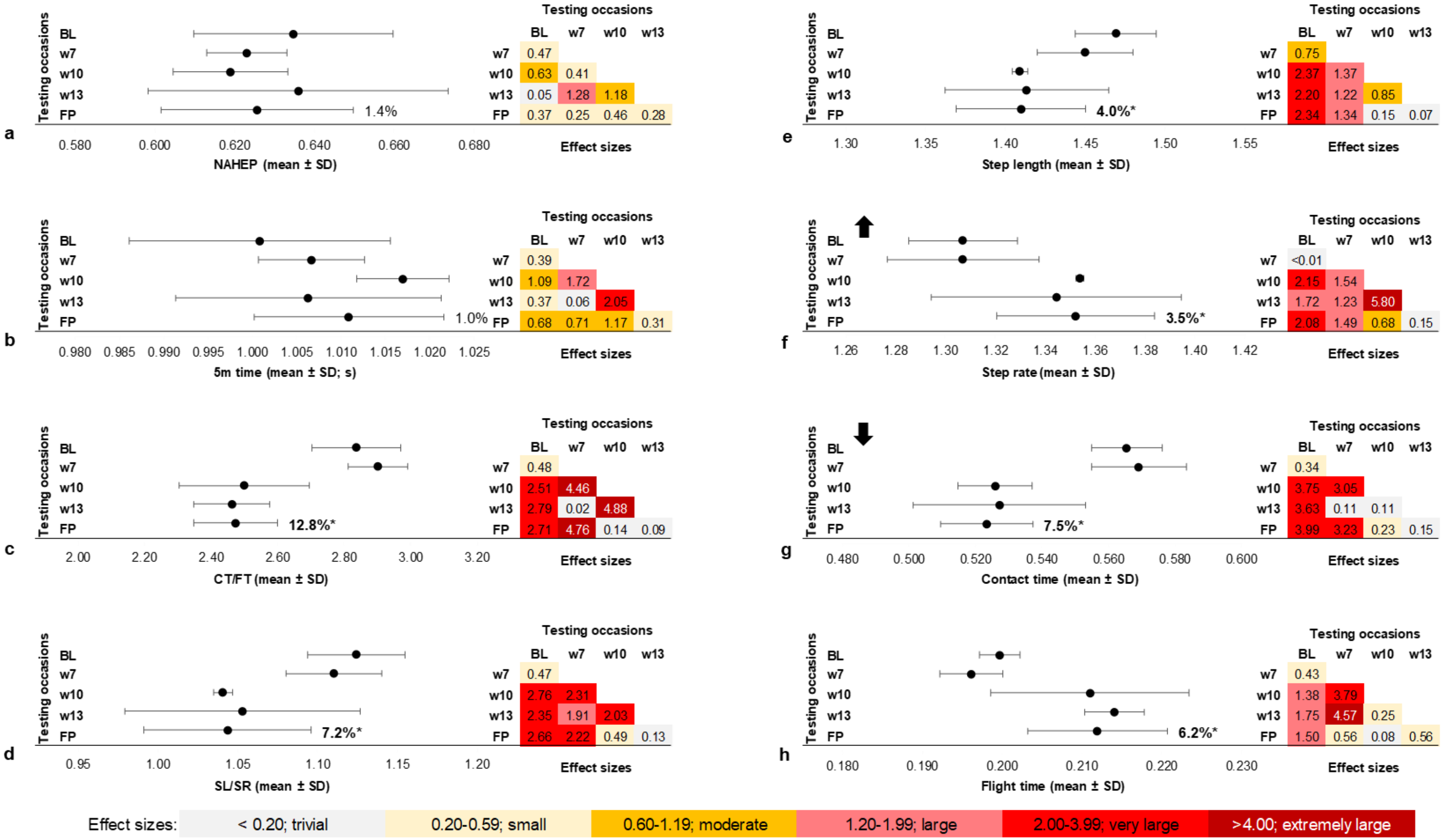


Figure 7.11 Mean ± SD of NAHEP, 5 m time, normalised spatiotemporal variables and the length/rate and contact/flight ratios for **participant S1** (strength intervention). Between testing occasion effect sizes (absolute) are shown (BL = baseline testing phase, w7 = week 7, w10 = week 10, w13 = week 13, FP = final testing phase). Black arrows indicate the direction of the intended changes in magnitude of the variables most underpinning the associations between participant whole-body kinematic strategy and acceleration performance observed during baseline testing. The absolute percentage change between initial baseline testing (session number 1) and the final testing phase (session 5) is shown. If this value is bold, the magnitude of the change is greater than the smallest worthwhile difference (Hopkins, 2002) and asterisks indicate whether the difference is statistically significant ($p \leq 0.05$), according to Paired samples *t*-tests or [a]Wilcoxon singed-rank (nonparametric data) tests.

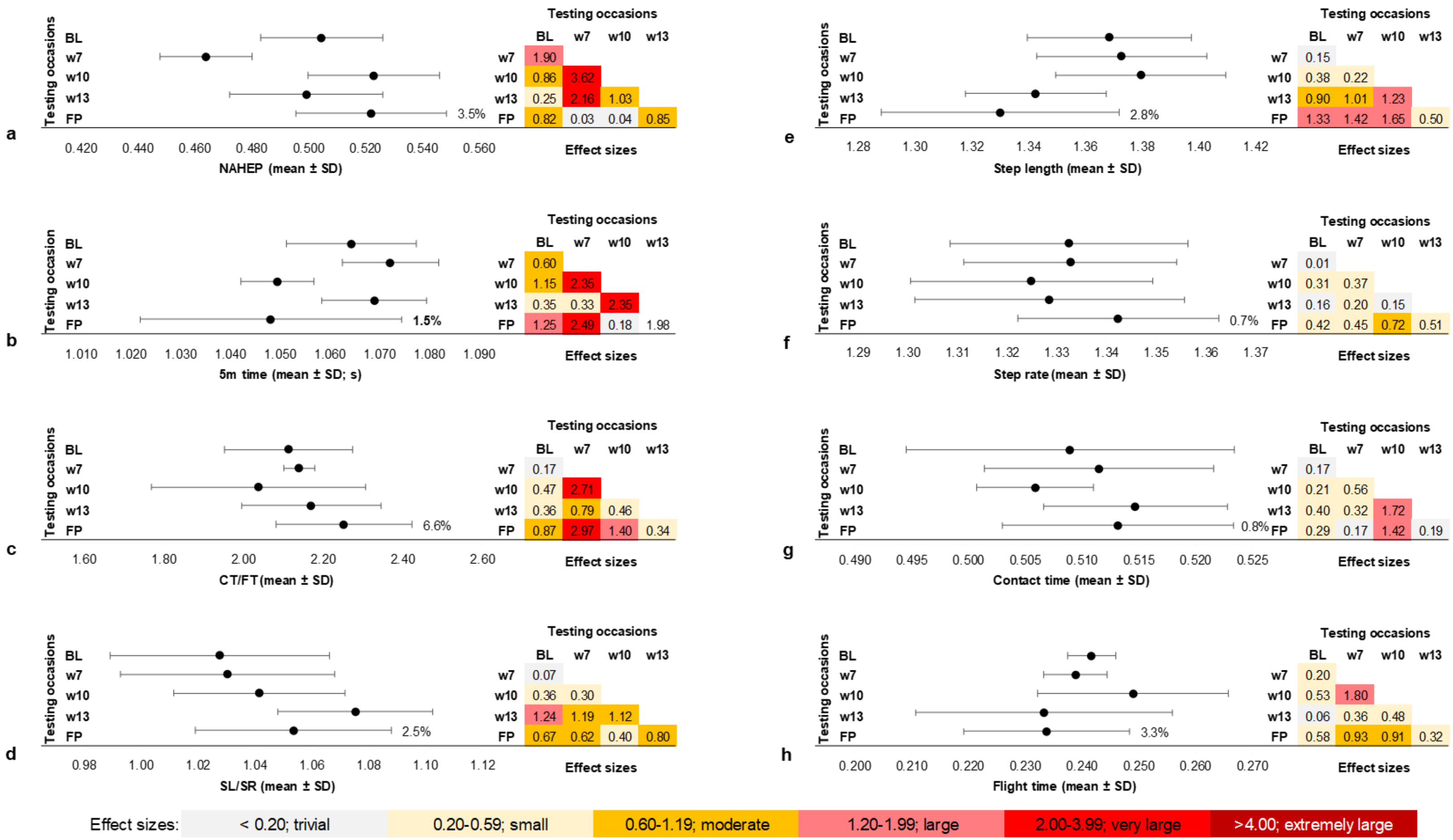


Figure 7.12 Mean ± SD of NAHEP, 5 m time, normalised spatiotemporal variables and the length/rate and contact/flight ratios for **participant C1** (control). Between testing occasion effect sizes (absolute) are shown (BL = baseline testing phase, w7 = week 7, w10 = week 10, w13 = week 13, FP = final testing phase). Black arrows indicate the direction of the intended changes in magnitude of the variables most underpinning the associations between participant whole-body kinematic strategy and acceleration performance observed during baseline testing. The absolute percentage change between initial baseline testing (session number 1) and the final testing phase (session 5) is shown. If this value is bold, the magnitude of the change is greater than the smallest worthwhile difference (Hopkins, 2002) and asterisks indicate whether the difference is statistically significant ($p \leq 0.05$), according to Paired samples *t*-tests or [a]Wilcoxon singed-rank (nonparametric data) tests.

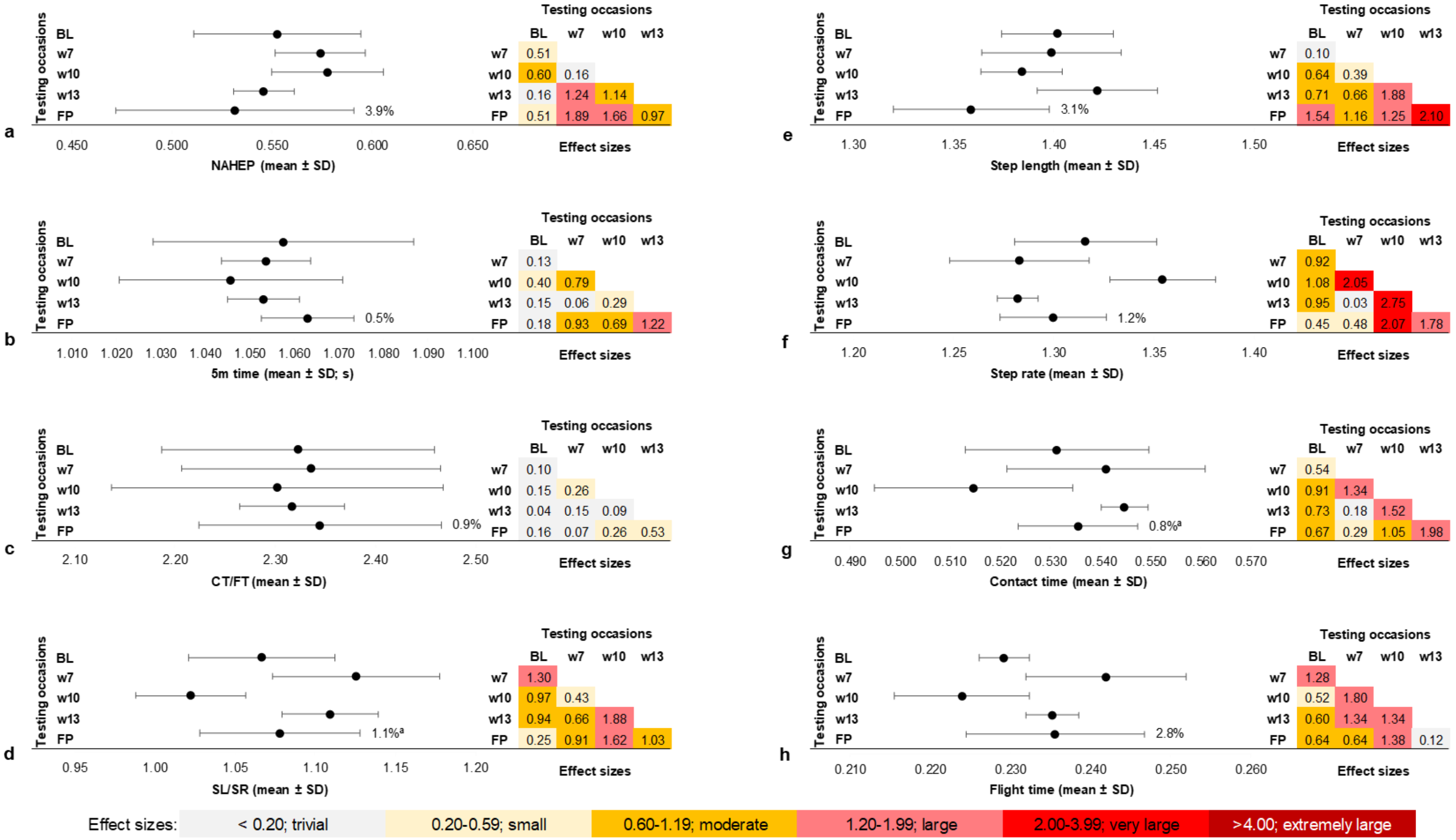


Figure 7.13 Mean ± SD of NAHEP, 5 m time, normalised spatiotemporal variables and the length/rate and contact/flight ratios for **participant C2** (control). Between testing occasion effect sizes (absolute) are shown (BL = baseline testing phase, w7 = week 7, w10 = week 10, w13 = week 13, FP = final testing phase). Black arrows indicate the direction of the intended changes in magnitude of the variables most underpinning the associations between participant whole-body kinematic strategy and acceleration performance observed during baseline testing. The absolute percentage change between initial baseline testing (session number 1) and the final testing phase (session 5) is shown. If this value is bold, the magnitude of the change is greater than the smallest worthwhile difference (Hopkins, 2002) and asterisks indicate whether the difference is statistically significant ($p \leq 0.05$), according to Paired samples t-tests or [a]Wilcoxon singed-rank (nonparametric data) tests.

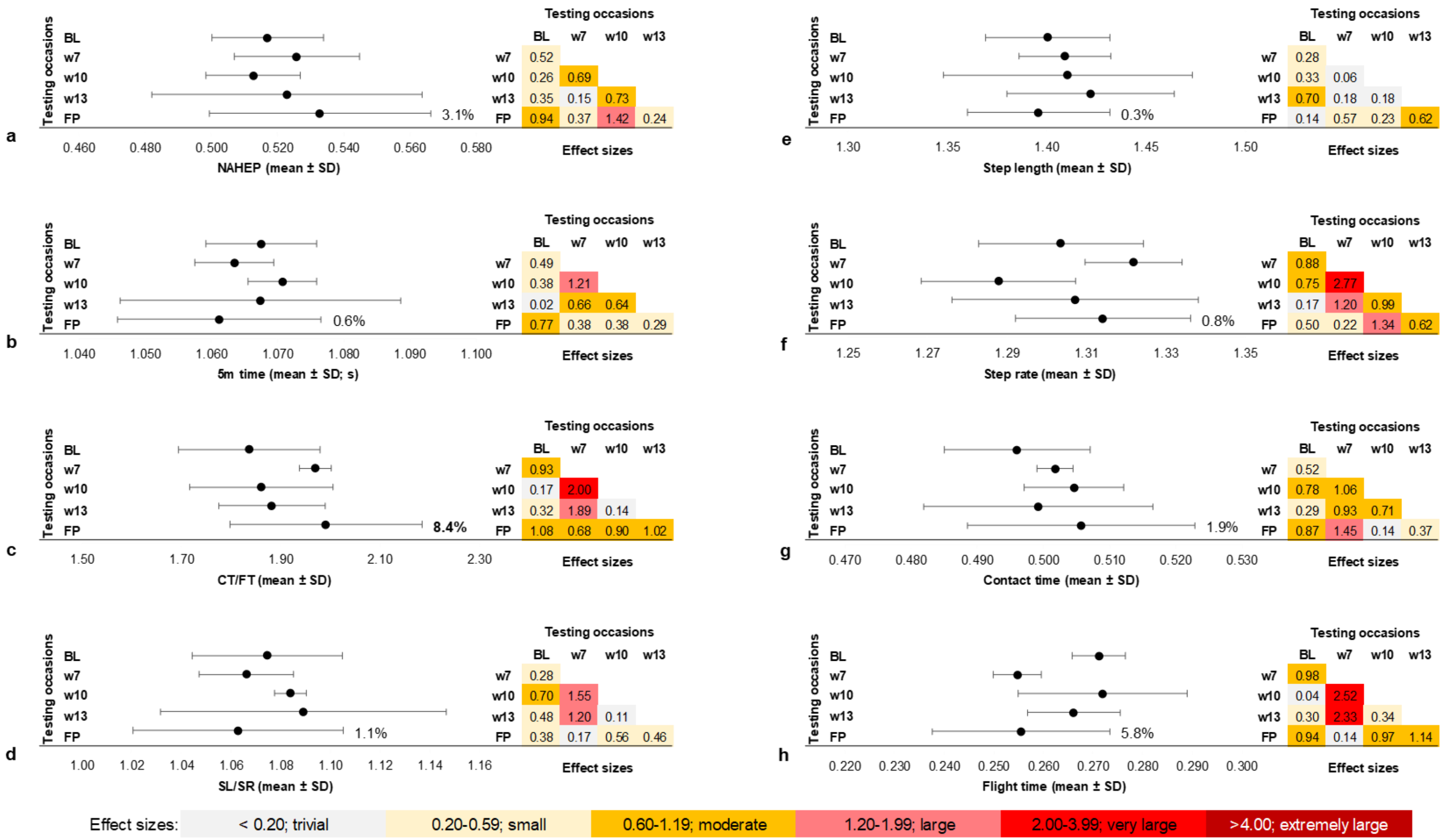
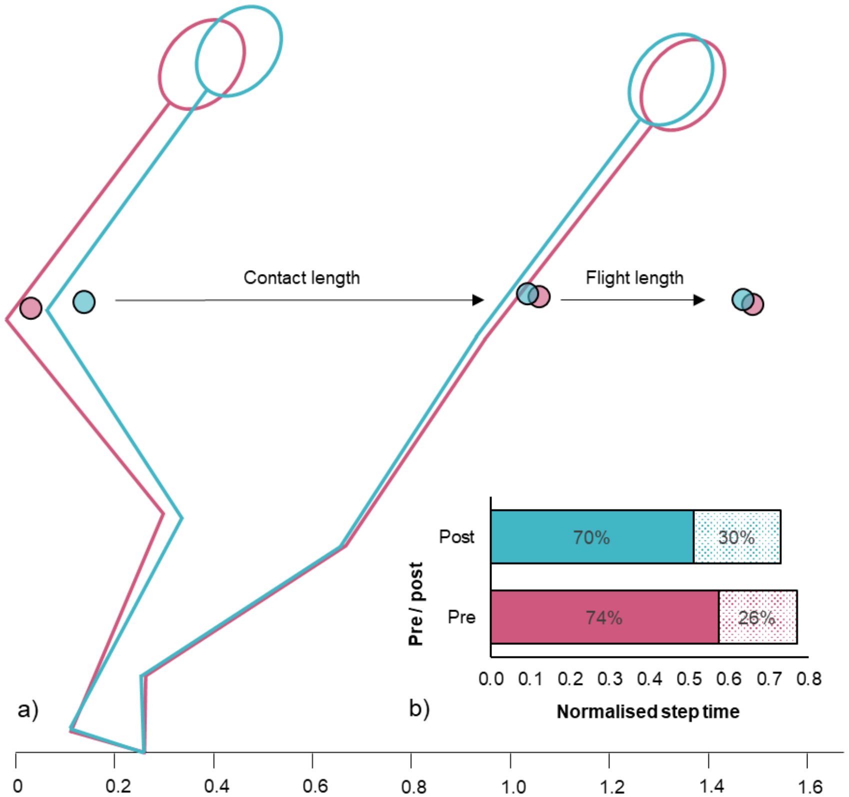


Figure 7.14 Mean ± SD of NAHEP, 5 m time, normalised spatiotemporal variables and the length/rate and contact/flight ratios for **participant C3** (control Between testing occasion effect sizes (absolute) are shown (BL = baseline testing phase, w7 = week 7, w10 = week 10, w13 = week 13, FP = final testing phase). Black arrows indicate the direction of the intended changes in magnitude of the variables most underpinning the associations between participant whole-body kinematic strategy and acceleration performance observed during baseline testing. The absolute percentage change between initial baseline testing (session number 1) and the final testing phase (session 5) is shown. If this value is bold, the magnitude of the change is greater than the smallest worthwhile difference (Hopkins, 2002) and asterisks indicate whether the difference is statistically significant ($p \leq 0.05$), according to Paired samples *t*-tests or [a]Wilcoxon singed-rank (nonparametric data) tests.



c)

Variables	Mean ± SD Pre	Mean ± SD Post	Effect sizes
Foot TD (°)	164 ± 2	162 ± 2	-1.00
Shank TD (°)	67 ± 2	62 ± 3	**-2.50**
Thigh TD (°)	129 ± 2	123 ± 2	**-3.00**
Trunk TD (°)	53 ± 3	54 ± 3	0.33
Foot TO (°)	89 ± 1	92 ± 2	**3.00**
Shank TO (°)	33 ± 2	33 ± 3	0.00
Thigh TO (°)	56 ± 2	57 ± 3	0.50
Trunk TO (°)	52 ± 3	53 ± 3	0.33
Touchdown distance	0.242 ± 0.014	0.134 ± 0.019	**-7.71**
Toe-off distance	-0.769 ± 0.018	-0.760 ± 0.024	0.50
Contact legth	1.011 ± 0.063	0.894 ± 0.071	**-1.86**
Flight length	0.436 ± 0.031	0.441 ± 0.041	0.16
DF ROM (°)	18 ± 2	14 ± 2	**-2.00**
Peak DF (°)	76 ± 3	81 ± 3	**1.67**
Pmax (W/kg)	26.91 ± 1.36	27.99 ± 1.02	0.79
Hip torque (Nm/kg)	4.51 ± 0.11	4.95 ± 0.09	**4.00**
Repeated RSI	0.45 ± 0.02	0.64 ± 0.02	**9.55**
Repeated jump height (m)	0.14 ± 0.01	0.17 ± 0.01	**3.13**
Repeated CT (s)	0.312 ± 0.011	0.258 ± 0.014	**-4.91**
Torque / CT	14.46 ± 0.94	19.24 ± 0.91	**5.09**

Figure 7.15. Scaled spatial model showing the mean segmental orientations across all (four) steps for **participant S1** (strength intervention) at touchdown and toe-off during baseline (purple, pre) and final (turquoise, post) testing phases. The mean centre of mass location at touchdown and toe-off positions is depicted as markers (circles), showing normalised linear kinematic variables. Note that horizontal and vertical scales are the same and all normalised linear kinematic variables are referenced to position of the toe of the contact leg; b) average of the mean normalised step times during baseline and final testing, divided into contact time (filled bars) and flight time (pattern filled bars). The proportion of time spent during the contact and flight phases relative to step time are shown as percentages; c) differences in mean ± SD values for segment and angular kinematics and strength qualities between baseline and final testing stages for participant 26. Effect size differences (Cohen's d) were calculated between all variables and meaningful differences were deemed evident if the magnitude of the difference was greater than the smallest worthwhile difference (Hopkins, 2002) and the absolute difference (%) was greater than the intra-individual CV for these variables determined during baseline testing. If these two criteria have been met, the effect size values appear in bold.

7.4 Discussion

This study sought to determine how sprint technique variables (whole-body kinematic strategies, normalised spatiotemporal variables and length/rate and contact/flight ratios) of professional rugby backs related individually to their initial sprint performance, and how their sprint technique and performance changed longitudinally through individual-specific training interventions that were informed by these relationships. Meaningful within individual relationships were found between sprint technique variables and NAHEP (Figure 7.2 and Appendix H) in all but two (P1 and P12 [C1]) of 19 participants during the baseline period (Stages 1 and 2, Table 7.1). Further, when individual-specific interventions were given to a sub-group of participants during the intervention period in Stage 3 (Figure 7.1), changes in the Cartesian plane spatial locations of their whole-body kinematic strategies were observed towards the direction of the intended change (Figures 7.5 and 7.6). Meaningful and statistically significant improvements in acceleration performance were observed alongside the changes in whole-body spatial locations in participants who underwent individual-specific technical interventions over these 18 weeks (Figures 7.7 - 7.10), whereas no meaningful changes in acceleration performance were evident in the participant who followed a strength-based intervention (Figure 7.11) or in the control participants (Figures 7.12 - 7.14). Although some caution ought to be given when drawing conclusions with relatively low participant numbers, these results based on multiple case-study interventions suggest that the approach adopted in the study to apply individual-specific technical interventions may provide practitioners with a novel way to individualise and enhance the sprint acceleration training of professional rugby union backs.

7.4.1 Within individual relationships between sprint technique and performance

To inform how individual-specific interventions were applied it was first necessary to address research question VII) *what are the within-individual relationships of whole-body kinematic strategies and normalised spatiotemporal variables with the initial acceleration performance of professional rugby backs during the first four steps?* By determining the within-individual relationships, it was possible to identify variables that participants were individually reliant on for better sprint performance. This builds on previous research (Salo et al., 2011) in which sprinters were found to individually rely on either greater step length or step rate (or neither variable) for better sprinting performance across 100 m races. Of the 11 sprinters studied by Salo et al. (2011), three were shown to rely on step length, whilst one was shown to rely on step rate for better sprint performance according to the difference between magnitudes of step length and step rate relationships with 100 m times. Consequently, based on these analyses alone, practitioners could be left without a technical training direction for the majority of sprinters from this cohort. Although Salo et al. (2011) focussed on the maximum velocity phase, in order to overcome potentially similar limitations when analysing the initial acceleration phase, the current study sought to understand how performance was not only related individually to step length and step rate, but also to contact and flight times and the whole-body kinematic strategies of participants. This provided a more in-depth understanding of the spatiotemporal variables which athletes may rely on for better sprint performance.

Eleven of the 19 participants (Figure 7.2 and Appendix H) were found to individually rely on step length or step rate, where a meaningful r value of ≥ 0.43 was evident between step length (n = 6) or step rate (n = 5) and NAHEP, and the difference in correlation magnitude between the relationships of step length and step rate with NAHEP for each of these participants was also $r \geq 0.43$. However, when considering whole-body kinematic strategies and contact and flight times in addition to step length and step rate, 17 of the 19 participants were observed to individually rely on at least one sprint technique variable for better acceleration performance (Figure 7.2 and Appendix H). Given that some athletes appear to be reliant on variables other than step length or step rate, these findings suggest that it is useful for practitioners to consider the relationships of initial acceleration performance with whole-body kinematic strategies and contact and flight times, in addition to just step length and step rate. Determining within-individual relationships between whole-body kinematic strategies and initial acceleration performance would appear particularly important since meaningful relationships were observed in 12 of the 19 participants. Since optimum technique can be considered as the motions yielding maximum performance for a given individual as a function of the constraints at that time (Hatze, 1973), this approach provides valuable direction for practitioners to inform the individualisation of their technical interventions and formed the basis of the individual-specific interventions of participants in Stage 3 (Figure 7.1).

7.4.2 Changes in technique, acceleration performance and strength qualities

To address research question VIII) *How do longitudinal individual-specific training interventions that focus on the variable(s) which specific professional rugby backs are reliant upon for better sprint performance affect their acceleration capabilities?* longitudinal individual-specific interventions were applied which focussed on the variable(s) that five participants were found to be individually reliant upon for better initial acceleration performance. By the final phase of the intervention in Stage 3 (Phase 5, Figure 7.1) the differences in distribution of individual whole-body strategies compared with baseline were greater within intervention participants than controls (Figures 7.5 and 7.6, as indicated by the two-dimensional Kolmogorov-Smirnov statistic (mean D_{2DKS}: intervention participants: 0.62; controls, 0.38). A change in strategy from one cluster to another was observed in participants T1 and S1, as indicated by the statistically significant difference in distributions of their whole-body strategies (T1: D_{2DKS} 0.83, S1: D_{2DKS} 0.99; both $p < 0.05$). Therefore, for all other participants, any changes in whole-body strategy spatial location between baseline (Stages 1 and 2, Table 7.1) and final phase of the intervention in Stage 3 (Phase 5, Figure 7.1), represented a shift in strategy within the same cluster for each individual.

For participants who completed a technical intervention (T1-T4), the technical prompts applied during the exploratory session prior to the intervention phase had an acute negative effect on acceleration performance compared with no focus in that session (Figure 7.4). However, the intention of this session was to use analogies or holistic cues as technical prompts to convey the movements required to move the Cartesian plane spatial location of each individual's whole-body strategy towards the direction of the intended spatial location change, rather than to enhance their acceleration performance acutely. Therefore, given that the specific objective in this session was for participants to adhere to the technical prompt rather than directly enhancing initial acceleration performance, the acute reduction in NAHEP was not of concern. The mean Euclidean distance between the spatial location of whole-body strategy for each participant (T1-T4) during no focus and technical focus conditions during this exploratory session (Figure 7.4, $d_{x,y}$ mean: 1.26; range: 0.96 to 1.52) was greater than the mean Euclidean distance between the spatial location of their whole-body strategy between baseline and the final phase of the intervention period (Figure 7.5, $d_{x,y}$ mean: 0.69; range: 0.43 to 1.26) by a factor of approximately two. This was anticipated since the sprint trials in which whole-body strategies were obtained during the intervention period were carried out by participants without a technical focus and, therefore, they would be expected to regress towards their natural movement preferences identified during the baseline period in Stages 1 and 2 (Table 7.1) owing to each individual's unique intrinsic dynamics. That is, they are likely to have regressed towards their movement preferences shaped by their performer constraints, and experience with the task (i.e., sprinting) prior to the intervention (Kostrubiec et al., 2012; Thelen, 1995). Therefore, to determine how considerable the changes in whole-body strategy spatial locations were for T1-T4 following the intervention, they ought to be considered in the context of the change in whole-body strategy spatial locations of the strength and control participants observed during the intervention period.

The mean change in whole-body strategy spatial location during the final phase of the intervention period for T1-T4 compared with baseline was greater than the mean change observed in control participants ($d_{x,y}$ mean, 0.36; range, 0.11 to 0.39, Figure 7.6) by more than a factor of two. Even the smallest change in technical intervention participants ($d_{x,y}$ = 0.43) was greater than the largest change in controls ($d_{x,y}$ = 0.39). The directional changes of their (T1-T4) whole-body strategy centroids were also the same or within three half-winds of the intended direction change. Therefore, the consistency of technically focussed sprint repetitions completed by participants T1-T4 during the first 14 weeks of the intervention period (Stage 3, Figure 7.1) appeared to be sufficient to bias their movement tendencies in the general direction of the technical focus during the final phase of the intervention period. One possible explanation for the changes evident in whole-body centroid spatial locations for participants T1-T4 is the phenomenon known as 'use-dependent learning' which describes how motor behaviour is shaped in the direction of previous motor actions (Diedrichsen et al., 2010; Mawase et al., 2017), and has been used previously to explain changes in gait following the learning of novel asymmetric stepping patterns (Wood et al., 2020; Wood, 2021).

Not only were the whole-body strategies of T1-T4 likely shaped at the end of the intervention period by their prior motor actions resulting from their individual technical prompts, but statistically significant large (Cohen's *d* = 1.29 to 1.46) and moderate to large (Cohen's *d* = 1.11 to 2.82) increases in NAHEP and decreases in 5 m time were also observed (Figures 7.7 to 7.10). The magnitude of the changes in NAHEP and 5 m time for T1-T4 were also greater than the within individual CV of these acceleration performance variables for each participant (Table 7.5). No meaningful changes in NAHEP or 5 m time were evident for S1 or C1-3 following the intervention period. These findings suggest that individual-specific technical interventions are likely more effective at eliciting larger technical changes and greater enhancements in acceleration performance compared with a generalised 'one-size-fits-all' approach.

The magnitude of change in NAHEP for participants T1-T4 appeared to correspond to the magnitude of their within-individual relationships between whole-body kinematic strategy and NAHEP, in the same direction. For instance, participants (technical intervention) could be ranked in the same order based on their whole-body strategy and NAHEP relationships and the effect size magnitudes of the changes in NAHEP observed between the baseline period and the final phase of the intervention (largest to smallest *r* value: T2 (0.88), T3 (0.77), T1 (0.55), T4 (0.51); largest to smallest *d*: T2 (1.46), T3 (1.43), T1 (1.30), T4 (1.29)). This suggests that the potential performance benefits of a technical intervention based on the within individual relationship between whole-body strategy and NAHEP may be greater for those with a strong reliance in the first instance. This novel approach provides a foundation for future research to investigate whether this pattern is consistent over a greater number of repeat observations for individuals to determine how the magnitude of within-individual relationships between whole-body strategy and NAHEP change with changes in acceleration performance.

The direction of the change in magnitude of the variables which participants T1-T4 were primarily and secondarily reliant on for better acceleration performance (Table 7.2; Figures G.1, G.2, Appendix H) followed a similar direction pattern change in NAHEP over the successive testing sessions during the different phases of the intervention (Figures 7.7 to 7.10). For example, compared to baseline both NAHEP and step rate for T1 (Figure 7.7 a and f) decreased in testing session one (trivial change in step rate), whilst they both increased successively for testing sessions two and three before decreasing during the final testing session (trivial change in NAHEP compared to testing session 4). The largest change in magnitude of the variables that participants were reliant on for better acceleration performance compared with baseline occurred in one of the testing sessions prior to the final testing phase during the intervention period in Stage 3 (Table 7.1). The variable participant T2 was primarily reliant on for better acceleration performance peaked in testing session three (Figure 7.8 c), whereas the variables participants T1 and T3-T4 were primarily and secondarily reliant on for better acceleration performance peaked in testing session 4 (Figures 7.7 to 7.10). Since all sprints undertaken by participants T1-T4 during the final phase of the intervention took place without a focus on their technical prompts, these findings suggest that the use-dependent aftereffects from their prior motor actions may have begun to subside (Diedrichsen et al., 2010; Mawase et al., 2017; Wood et al., 2020; Wood, 2021) when they ceased to apply a technical focus during training. Ultimately, for participants T1-T4 the changes made to the variables they were individually reliant on for better acceleration performance by the end of the intervention were intentional and the aspects of retention discussed above were not a focus of the research (intentionally by the design of the study). However, further research is needed to understand how technical features and acceleration performance are retained across different durations following technical focussed interventions.

Whilst the technical foci individually applied to participants T1-T4 may have biased their motor actions in the same direction during the final phase of the intervention, the same explanation cannot not be used to explain the whole-body spatial location changes (Figure 7.5; $d_{x,y} = 1.09$; $D_{2DKS} = 0.99$, $p < 0.05$) observed for participant S1 (strength intervention) by the end of the intervention period (Figure 7.11). No focus was applied to the sprint training undertaken by S1 in any phase of the intervention. Instead, they underwent an individual-specific strength intervention during this period, which targeted the variables they were primarily (higher step rate) and secondarily (shorter contact time) reliant on for better acceleration performance (Figure H.2, Appendix H). Meaningful and statistically significant differences in all spatiotemporal variables and length/rate and contact/flight ratios were observed during the final phase of the intervention compared with baseline (for comparison, in participants T1-T4, 17% to 83% of effect size differences were meaningful and/or statistically significant). This resulted in different distributions of participant S1's baseline and post intervention whole-body strategies and therefore a change in strategy from one cluster to another. These findings show that a greater change in whole-body strategy was observed following an individual-specific strength intervention, compared with individual-specific technical interventions, and that these changes could possibly be explained by the relationships determined between strength-based qualities and individual spatiotemporal variables in Chapter 5.

In Chapter 5, step rate (the variable S1 was primarily reliant on) was meaningfully related to repeated jump contact time (r = - 0.47; $p < 0.05$) and torque/contact time ratio (r = 0.34, $p > 0.05$) across a larger group of rugby backs. These strength capacities increased in S1 by very large magnitudes (repeated contact time [a proxy measure of vertical stiffness], d = - 4.91; torque/contact time ratio, d = 5.09) and were achieved in tandem with a very large increase in their step rate (Figure 7.14, d = 3.99). Participant S1 also increased their hip torque and repeated RSI by extremely large magnitudes (Figure 7.15 c, d = 4.00 and d = 9.55 respectively), which, in addition to repeated contact time and torque/contact time ratio, were also meaningfully related to normalised contact time (secondary reliant variable for participant S1) in Chapter 5. Alongside these strength-based changes, participant S1's contact time during acceleration decreased by a very large magnitude (Figure 7.14 g, *d* = - 3.99). Unlike in the technical intervention participants where the intended changes in the variables they were reliant on for better acceleration performance generally subsided during the final testing phase (Stage 3, Phase 5), the changes in participant S1's step rate (primary reliance) and contact time (secondary reliance) peaked in the final testing phase. For practitioners, this would imply that individual-specific strength-based may be more effective than individual-specific technical-based interventions for longer term retention of intended technical changes in acceleration. However, more individual-specific strength-based interventions would clearly be needed to provide stronger evidence to support this premise.

The changes in step rate and contact time during acceleration achieved by participant S1 were underpinned by meaningful extremely large decreases in touchdown distance (*d* = - 7.71; absolute difference = 0.099 m) and meaningful large decreases in contact length (*d* = 1.86; absolute difference = 0.108 m). These linear kinematic findings are logical since a more negative touchdown distance will mean the CM has less distance to travel forwards of the stance foot before rapid leg extension (Jacobs & van Ingen Schenau, 1992), and the total horizontal distance travelled by the centre of mass is reflected by a shorter contact length. Given that movement preferences are influenced by performer constraints (Newell, 1986), the changes in participant S1's strength capacities may, in part, have shaped their touchdown kinematics, self-organising to produce a smaller touchdown distance by orienting their lower limb segments more horizontally (i.e., the proximal ends of participant S1's shank and thigh at touchdown were rotated more forwards toward the direction of travel [*d* = 3.00] post intervention). Although, again, further single participant strength-based interventions are required to directly support this assertion, it is underpinned by a strong body of evidence which highlights that changes to an individual's organismic properties directly influence their emergent behavioural patterns (Davids et al., 2008; Newell, 1986; Newell, 1976; Saltzman & Kelso, 1987).

Despite the change in whole-body strategy from one cluster to another, and the changes in magnitude of the variables participant S1 was reliant on for better acceleration performance, no meaningful differences were observed for their acceleration performance (Figure 7.14 a).

Participant S1 completed a noticeably smaller total number of sprints compared with participants T1-T4 during speed sessions and in warm-ups for rugby training and matches (participant S1: 199; participants T1-T4 range = 245 to 265), although this alone cannot explain the differences in acceleration performance since control participants whose acceleration performances were also not meaningfully different following the intervention period completed a similar number of speed training and warm up sprints (mean n = 251) to participants T1-T4. Although the short distance sprint performances of team sport players have been shown to be enhanced by strength-based interventions (see Nicholson et al. (2021) for a review), combined methods including technical-based training with sprint and strength-based training are considered best practice in the field (Haugen et al., 2019c) for the development of speed. Therefore, it is feasible that enhancements in participant S1's acceleration performance may have been observed with an individual-specific technical focus alongside the individual-specific strength intervention applied. However, more research is required to understand how acceleration performance changes with such a combined technical and strength individual-specific intervention targeting the sprint variables individuals are reliant on for better acceleration performance.

7.4.3 5 m time as an alternative measure to NAHEP

The method used to obtain NAHEP in this thesis provides a reliable (CV = 4%, Table 6.1) and objective measure of initial acceleration performance. However, it requires digitisation of 22 segment endpoints twice to define the 14-segment human model used so that the whole-body CM location can be determined (once at the beginning of the first contact phase and once at the end of the fourth contact phase). In an applied setting, a simpler way to measure initial acceleration performance is of interest so that actionable information can be communicated in a timelier manner. A less time-intensive initial acceleration measure (5 m) was used to answer research question VII) *How closely can the within-individual relationships of whole-body kinematic strategies and normalised spatiotemporal variables with NAHEP, and the within-individual changes of these variables following individual-specific training interventions be replicated using a more practical performance measure than NAHEP?* This required timestamping just two occurrences (the instant the back toe lifts off the ground at the start and when the mid-hips pass the 5 m mark) and was obtained to determine whether it could be used as a more practical alternative to the method used in this thesis to obtain NAHEP.

The reliability of 5 m time (CV = 1.4%, Table 7.4) was higher compared with NAHEP and differences in the correlation magnitudes between NAHEP and 5 m time with sprint technique variables were only trivial to small (mean ± SD *r* difference: whole-body strategy 0.07 ± 0.06; length/rate ratio: 0.08 ± 0.05; contact/flight ratio: 0.10 ± 0.07; step length: 0.08 ± 0.06; step rate: 0.09 ± 0.06; contact time: 0.09 ± 0.07; flight time: 0.10 ± 0.06). When correlation coefficients were inverted for 5 m time, the direction of relationships with sprint technique variables were the same as NAHEP for 95% of relationships determined. Although there were six occasions where directions differed, relationships of both 5 m time and NAHEP with sprint technique variables in these cases were trivial and not meaningful (absolute magnitudes were all $r < \pm 0.16$). Given these findings and the similarity in statistically significant and / or meaningful within-individual relationships of sprint technique variables with both NAHEP and 5 m time (Table 7.6), 5 m time appears an appropriate initial acceleration measure to identify variables athletes are reliant on for better initial acceleration performance. The statistically significant and/or meaningful changes observed in NAHEP between baseline testing (Stage 1, Table 7.1) and the final phase of testing (Stage 3, Figure 7.1) were also observed as statistically significant and/or meaningful when comparing change in 5 m time between the same testing occasions. This suggests that worthwhile changes in initial acceleration performance can be identified using either initial acceleration measure and because 5 m time is easier to obtain, it is proposed as a more practical alternative to use within the field than NAHEP to determine acceleration performance.

7.5 Chapter summary

Novel individual-specific technical interventions were effective in enhancing the initial acceleration performance of professional rugby union backs. The collective findings of this study emphasise the importance of considering participants on an individual basis and add to existing literature which identifies that important information on the characteristics of individuals can be lost when using group level cross-sectional analysis (Bates,1989; Bates et al., 2004; Cushion et al., 20201; Dufek et al., 1995; James & Bates, 1997). Five metre time was also identified as an initial acceleration performance variable which was comparable to NAHEP over the first four steps, offering a practical measure to assess performance in response to technical interventions applied during early acceleration. Using the approach developed in Chapter 6 to characterise whole-body kinematic strategies, analyses were undertaken to understand how individual acceleration performance was reliant on changes in the Cartesian plane spatial location of participant-specific whole-body kinematic strategies and the normalised spatiotemporal variables which underpinned these changes. Meaningful and statistically significant enhancements were observed in the acceleration performance of participants who were given an individual-specific technical intervention, in contrast to the lack of meaningful changes in acceleration performance of controls. An individual-specific strength-based intervention for a single participant led to favourable changes in their strength capacities and intended changes in their sprint technique kinematics, but this did not result in better acceleration performance. This is the first study to investigate how sprint acceleration performance and technique change following individual-specific interventions applied to athletes, based on their individual needs from prior analysis. The unique approach used bridges the gap between research and applied practice, using evidence-based individual-specific interventions to provide a way for practitioners working with professional rugby union backs, or other athletes competing in sports where initial acceleration performance is important, to individualise their sprint-based training practices.

CHAPTER 8: GENERAL DISCUSSION

8.1 Introduction

The overarching aim of this thesis was to understand how the technical and strength features of professional rugby backs related to their sprint performance during the initial steps and, informed by this advance in knowledge, to develop and apply an intervention framework to enhance their initial acceleration performance. The focus of the investigations undertaken in the programme of research to address this aim was formed by the research questions presented in Chapter 1. The key findings from the investigations reported in Chapters 3 to 7 to address these research questions are synthesised and discussed in this chapter alongside their practical implications. Finally, this chapter concludes with a reflective evaluation of the work undertaken and suggestions for potential directions of future work.

8.2 Addressing the research questions

Researchers who have previously investigated the initial sprint acceleration technical features of highly trained to world class (Tiers 3 to 5) athletes have typically studied track and field sprinters. Whilst sprint acceleration is an important feature for rugby backs, the extent to which the kinematic aspects of sprinters' technique during the initial steps were transferable to rugby players was unknown. This led to the first research question:

I. **What are the differences in spatiotemporal variables and linear kinematics between professional rugby players and sprinters during the initial steps of a sprint, and how do they relate to performance?**

Two key aspects can be surmised from the investigation in Chapter 3 to address this research question which informed research undertaken in the subsequent chapters of this thesis: 1) meaningful differences were observed in nearly all spatiotemporal and linear kinematic variables between groups which, when combined with the between-group differences in gross performer constraints (e.g., body mass, stature), supported the premise that rugby backs sprint 'differently' to trained track & field sprinters who the majority of the existing knowledge is based upon and therefore ought to be considered in their own right for future study; 2) normalised toe-off distance was the only variable which showed a meaningful relationship with initial acceleration performance

(NAHEP) in each of the three groups (Figure 3.2), thus this technical feature and other kinematic aspects of technique (e.g., angular kinematics) that were not studied in this investigation warranted further investigation. These two aspects of the research are discussed next.

Although multiple differences were observed between the technical features of each group, the only variables observed in backs to differ by a meaningful magnitude in the same direction compared with *both* rugby forwards and sprinters were step rate and contact time. That is, rugby backs produced greater step rates across all three steps compared to rugby forwards and sprinters, which were underpinned by shorter contact times. This showed that different preferential acceleration strategies may be adopted by different athlete groups, likely owing to inherent differences in their performer constraints (Newell, 1986), thus demonstrating that degeneracy exists during initial acceleration at the inter-group level. This provided some of the foundational work which led to research that was reported in later chapters (Chapters 6 and 7), which extended these findings and provided evidence for degeneracy existing at an inter-individual level also.

Regarding normalised toe-off distance, this linear kinematic variable differed meaningfully between rugby backs, rugby forwards and sprinters, and was meaningfully related to NAHEP in each group. The ability to move the CM further forward of the foot at the end of the stance phase has been shown to characterise better accelerators in terms of propulsive impulse and to be strongly associated with a more forward oriented resultant GRF vector in the first step (Kugler & Janshen, 2010; von Lieres Und Wilkau, 2020a). These GRF characteristics are known to be key determinants of acceleration performance (e.g., Morin et al., 2011; Morin et al., 2015a) and, therefore a more negative toe-off distance was identified as a potentially important variable during early acceleration steps.

Further investigation of how the technical features adopted by rugby backs enable a more negative normalised toe-off distance was then required. It was also necessary to determine whether other technical features could explain a greater proportion in the variation of rugby backs' initial acceleration performance. Accordingly, the second research question was proposed:

II. How do angular kinematics and normalised spatiotemporal variables relate to the toe-off distance and initial acceleration performance of professional rugby backs?

In Chapter 4, six out of 23 technical features were meaningfully related to NAHEP, although these relationships were all small to moderate (the largest unique contribution to the variance in NAHEP was 24%), and only three were statistically significant. The results also showed that a more negative toe-off distance was explained mostly by longer normalised step lengths and longer normalised contact times, as well as participants' angular kinematics at touchdown. However, the main finding of this study showed, unexpectedly, that normalised toe-off distance was not meaningfully related to NAHEP over the first four steps. Despite the correlation magnitude of this relationship falling within the expected range of values (90% CI) of the estimate for the same relationship in Chapter 3, this finding conflicted with data from the study presented in Chapter 3 which had shown that toe-off distance was meaningfully related to the magnitude of NAHEP in each group studied.

Two methodological differences between the investigations in Chapters 3 and 4 (toe-off distance was normalised to *stature* and determined with NAHEP over *three* steps in Chapter 3 but normalised to *leg length* and determined with NAHEP over *four* steps in Chapter 4) could not explain the conflicting finding (see Section 4.3.3, Chapter 4 and Table E.1, Appendix E). Furthermore, since the sprint-technique and acceleration performance data obtained throughout this thesis were determined to be reliable, the conflicting finding between Chapters 3 and 4 was not due to the degree of agreement between, or the consistency of, measurements. The smaller sample of rugby backs in Chapter 3 compared with Chapter 4 (Δ n = 10) may have inflated the magnitude of the relationship observed between normalised toe-off distance and NAHEP, since smaller sample sizes can increase the apparent size of an effect (Knudson, 2017), although the confidence limits did not overlap substantial positive and negative *r* values in Chapter 3. Therefore, sample size alone was unable to explain why normalised toe-off distance was meaningfully related to NAHEP in Chapter 3, but not in Chapter 4, despite the very similar populations which formed the samples in these investigations. Accordingly, these findings suggested that a consistent pattern in the relationships between rugby backs' technical features during the initial steps and their initial acceleration performance may not exist across different samples from the same population. This implied that a single exemplar technique for high acceleration performance does not exist for rugby backs and therefore, on this basis, that group-based cross-sectional studies may be of limited value for certain purposes.

In isolation, normalised toe-off distance was not meaningfully related to NAHEP in Chapter 4, but when combined with normalised contact time these variables accounted for 37% of the variance in NAHEP, when controlling for body mass. This indicated that it may be of benefit to practitioners to consider normalised toe-off distance in combination with normalised contact time, rather than an independent technical feature during initial acceleration. The complexity of this relationship was evident through the different combinations of normalised toe-off distance and normalised contact time that were used by individuals to achieve high initial acceleration performance. Therefore, it was suggested that different combinations of normalised toe-off distance and normalised contact time were likely required for rugby backs to achieve their individual optimal initial sprint acceleration performance. These combinations were seemingly adopted by participants who produced longer normalised step lengths (in those with more negative toe-off distances) or higher normalised step rates (in those with shorter contact times) respectively. This level of inter-individual degeneracy in the context of performance during initial acceleration may explain the conflicting findings on the importance of these higher order spatiotemporal kinematic variables (i.e., step length, step rate, contact time and flight time) in this sprint phase (e.g., Debaere et al., 2013b; Murphy et al., 2003; Nagahara et al., 2018a). The different performer constraints between individuals, such as their strength-based characteristics, was theorised to be one explanation for the level of inter-individual degeneracy observed, which subsequently warranted investigation.

As demonstrated by the research reported in Chapters 3 and 4, attempting to understand how individuals achieve high acceleration performance through their technical features is problematic owing to the multiple degrees of freedom available (Bernstein, 1967). When considering the movement solutions adopted by athletes through an ecological dynamics lens, which views behaviour as emerging through the interaction of task, environmental and performer constraints (Newell, 1986), important information can be obtained on how movement preferences may be influenced by their physical characteristics (performer constraints), such as their strength-based qualities. This led to the development of research questions III and IV as follows:

III. **How are lower limb strength qualities related to the performance of professional rugby backs during initial acceleration?**

IV. What are the relationships between lower limb strength qualities and technical features, and how do their interactions associate with initial acceleration performance in professional rugby backs?

Based on the meaningful relationships observed in Chapter 5 between several strength-based variables and NAHEP, some potentially important strength qualities for initial acceleration performance were identified (in isolation: hip torque, peak squat jump power and repeated jump height and RSI; in selected combinations: hip torque with repeated contact time). Whilst several meaningful relationships were identified between strength qualities and acceleration performance, for the strongest relationship determined, repeated jump height could still only uniquely explain 17% of variance in NAHEP when controlling for body mass. Combined with the lack of statistically significant relationships, the importance of these strength qualities was evidently small, and it was still possible for participants to achieve high initial acceleration performance with low strength-related capacities relative to their counterparts within a cohort of professional rugby backs. This is broadly consistent with other research which has investigated the relationships between the strength qualities of rugby backs and their initial acceleration performance, although this research has typically been conducted on rugby backs of a lower playing standard (e.g., Zabaloy et al., 2020). Nonetheless, the findings in Chapter 5 may provide practitioners working with professional rugby union backs with information to develop ‘minimum’ strength-based thresholds to help guide their strength training interventions, where enhancing acceleration performance is the goal.

Although using linear multiple regression models to determine how selected strength qualities combined with either hip or ankle joint angular kinematic technical features during the first four steps could explain the variance in NAHEP, only trivial to small non statistically significant effects were found. Considered alongside the empirical data in Chapters 3 and 4, these findings provided further evidence that, even when non-technical factors such as strength were also considered, multiple technique solutions could be adopted by professional rugby union backs to reach high acceleration performance. However, several stronger relationships were found between strength-based variables and technical features. This suggested that although strength qualities and kinematic aspects of rugby backs’ technique do not collectively explain a meaningful amount of the variation in acceleration performance, performer constraints such as strength qualities are likely to interact with the movement strategies adopted by athletes during the initial steps.

After addressing research questions I to IV, two clear themes emerged. First, it was evident that no one single strategy leads to high acceleration performance. Consequently, when considering relationships across the whole group aggregated data from the cross-sectional investigations in Chapters 3 to 5 important information on the different strategies adopted by individuals during the initial steps of acceleration were overlooked. This is supported by evidence which highlights the need for caution when applying the conclusions drawn from group level data to their constituent individuals, since the former may not be reflective of the latter (e.g., Bates, 1989; Bates et al., 2004; Fisher et al., 2018; James & Bates, 1997). The second theme to emerge was concerned with the limitations of considering how the technical features or strength qualities of rugby backs associate in isolation, or in selected combinations, with acceleration performance. Although some important insights were gleaned, this approach was not sufficient to explain how complex adaptive systems achieve high performance in sprint acceleration, where multiple system degrees of freedom coordinate to satisfy the demands of the task (Bernstein, 1967). Therefore, the remaining studies in this thesis (Chapters 6 and 7) aimed to advance the current research practice in this field by considering the performer as a complex system during the initial steps of sprinting rather than by its individual parts, since the system will organise as a function of ongoing interactions between its constituent parts. Consequently, it was suggested that a whole-body approach focussing on a combination of higher order spatiotemporal variables in their dimensionless form which depict the outcome of an individual's movement coordination in sprinting may provide a more viable 'macro' level portrayal of an acceleration strategy and could be used to better understand the different strategies adopted between individuals. These two themes resulted in the development of the next two research questions:

- **V. To what extent do whole-body kinematic strategies differ within a group of professional rugby backs according to the combination of their normalised spatiotemporal variables during the first four steps, and what are the differences in technical features and strength qualities between these strategies?**
- **VI. How stable are intra-individual whole-body kinematic strategies during initial acceleration in professional rugby backs?**

In the first phase of the research in Chapter 6, using hierarchical agglomerative cluster analysis, four clear participant groups were identified according to their combined normalised spatiotemporal variables during the first four steps of maximal effort sprinting. Significant differences in the technical features and strength qualities existed between clusters, but significant differences in NAHEP were not observed, showing that inter-athlete degeneracy exists in the context of performance during the initial acceleration of rugby backs. This supported the premise that a range of movement solutions can be adopted to satisfy the demands of sprint acceleration, and that the physical constraints of the performer (strength qualities in this instance) affect how they interact with their environment (e.g., Fajen et al., 2008), but that no specific combination of these consistently led to any higher levels of sprint acceleration performance.

Another novel aspect of the research in Chapter 6 was the use of two ratios (length/rate and contact/flight) to provide a more refined depiction of the individual acceleration strategies adopted by participants and their groupings as identified by the cluster analysis. This provided a single visual representation of each individual's whole-body acceleration strategy, characterised by its spatial location on a Cartesian plane. From an applied perspective such an approach will likely prove useful for practitioners since it could provide them with a way to monitor changes in acceleration strategies in response to interventions that they deliver. However, for this whole-body measurement to be used in this way, it was important to assess how stable the whole-body acceleration strategies of the participants were to ensure that any real changes in whole-body acceleration strategy could be detected with confidence by practitioners. In the second phase of the research in Chapter 6, the within-participant reliability of the whole-body measurement was determined to answer research question VI. Intra-individual level whole-body kinematic strategies were shown to be stable, thus individuals were likely self-organising at a more microscopic level (e.g., limb motions) to consistently create ordered patterns of behaviour at a more macroscopic level (e.g., normalised spatiotemporal variables), which is aligned with dynamical systems theory (Kauffman, 1993).

The findings obtained to address the first six research questions pointed strongly to the need to adopt individual-based rather than group-based analyses to identify technical and strength-based factors that contribute meaningfully to individual performance. This premise is supported by growing recognition that the findings of group-based aggregated data do not necessarily reflect any single individual within that group (e.g., Fisher et al., 2018) and an ecological perspective where the demands of a task, like sprinting, are thought to be solved in ways which are specific to individuals according to their task, environmental and performer constraints (Newell, 1986). Therefore, it was proposed that the whole-body kinematic strategies of individuals should be measured over multiple sprint trials, including on separate occasions, to determine how these strategies are associated with their initial acceleration performance. Practitioners can then use this information to develop individual-specific training programmes aimed at enhancing the initial acceleration performance of rugby backs, by identifying how the normalised spatiotemporal variables of individuals alter in relation to changes in their sprinting performance. This was made possible by the novel and rigorous framework developed in Chapter 6 for practitioners to monitor whole-body acceleration strategies, and the effectiveness of this approach was then tested in multiple longitudinal case-study interventions in Chapter 7.

In Chapter 7, within-individual associations of the whole-body kinematic strategies, length/rate and contact/flight ratios and normalised spatiotemporal variables of 19 rugby backs with their acceleration performance during the first four steps were determined over 12 sprint trials (i.e., three sprint trials on four separate occasions), to address research question VII:

VII. What are the within-individual relationships of whole-body kinematic strategies and normalised spatiotemporal variables with the initial acceleration performance of professional rugby backs during the first four steps?

Adopting a similar approach to Salo et al. (2011), 11 out of 19 participants were found to individually rely on step length or step rate, where a meaningful relationship was evident between step length (n = 6) or step rate (n = 5) and NAHEP. However, participants were also shown to be reliant on other variables (whole-body kinematic strategies, length/rate and contact/flight ratios and normalised contact time and normalised flight time). Whole-body strategy was meaningfully related with acceleration performance in 12 of the 19 participants and, on average, was more strongly related to acceleration performance than the other sprint-technique variables analysed in isolation. This further highlights the importance of considering the motor behaviour of rugby backs at a holistic level during sprint acceleration.

The initial period in which within individual relationships were determined for participants was also used to establish baseline measures of initial acceleration performance (NAHEP and 5 m time) and technical features (whole-body strategy, length/rate and contact/flight ratios and normalised spatiotemporal variables in isolation) for eight of the 19 participants who then undertook an intervention or acted as controls during an 18-week period. Additionally, leg strength data, and associated angular and linear kinematics were also collected from one of these eight participants at a single timepoint during this period for a baseline reference of these strength variables. From the information on each individual's 'reliance', a desired change in the Cartesian plane spatial location of each participant's whole-body strategy was determined. Individual-specific interventions were applied to five participants (four sprint technique-based interventions and one strength-based intervention), based on the variable(s) they were found to be individually reliant on for better acceleration performance, whereas control participants (n = 3) underwent their usual training regime over the 18-week period. This enabled the next research question to be addressed:

VIII. How do longitudinal individual-specific training interventions that focus on the variable(s) which specific professional rugby backs are reliant upon for better sprint performance affect their acceleration capabilities?

The findings presented in Chapter 7 demonstrated the applied value of, and built on, the framework developed in Chapter 6 for practitioners to prescribe individual specific interventions and then monitor changes in individual acceleration strategies and performance over several months in response to the individual specific training undertaken. They also showed that desired changes in the kinematic aspects of a professional rugby back's technique could be made through individual-specific technical or strength-based interventions, which target the variables they are reliant on for better acceleration performance.

Substantial changes in the acceleration strategies of intervention participants emerged generally towards the intended direction of change by the end of the intervention period, but not in those in the control condition. For participants T1-T4 (technical intervention), frequent technical focussed sprint repetitions appeared to bias their movement tendencies in the general direction of the intended technical focus during the final testing phase. However, these use-dependent aftereffects

(Diedrichsen et al., 2010; Mawase et al., 2017; Wood et al., 2020; Wood, 2021) appeared to subside between the penultimate and final testing phases (except for the variable participant T2 was primarily reliant on, which remained the same). This suggested that these participants may have started to revert somewhat towards their movement preferences shaped by their intrinsic dynamics (Kostrubiec et al., 2012; Thelen, 1995) when the technical focus was removed during the final testing phase. However, in absolute terms, the magnitude of the changes in these technical features were still greater than the intra-individual CVs determined for the corresponding variables in the baseline period. Meaningfully large and statistically significant enhancements in NAHEP accompanied the changes in the technical features observed for these participants, demonstrating the success of focussing on technical features that individuals are reliant on for better sprint performance and the potential value of this for practitioners working with athletes in sport where sprint acceleration is important.

Despite the largest change in whole-body strategy distribution and individual technical features across all participants being observed in participant S1 (strength intervention), these intended changes did not translate to a meaningful and statistically significant increase in their acceleration performance. However, whilst acceleration performance remained the same for participant S1, the same diminishing use-dependent aftereffects of the variables that participants T1-T4 were reliant on for better acceleration performance were not observed between the penultimate and final testing sessions for participant S1. This suggests more ‘permanent’ adaptations or retention of changes in technical features may be possible when meaningful changes to individual performer constraints (i.e., strength-based qualities) are elicited. It remains to be seen how the combination of a strength-based and technical-based individual-specific intervention which focusses on the technical features an individual is primarily and secondarily reliant on for better acceleration performance affects acceleration performance. It is feasible that, for participant S1, a technical focus was required to transfer the strength-based changes made to better acceleration performance, although further research is also required to determine how other individual strength interventions influence acceleration technique and performance given that only a single participant underwent a strength intervention in the experimental work in this thesis.

Collectively, the findings from this investigation suggested that individual-specific interventions are likely more effective at eliciting larger technical changes and, in the case of technical but not strength interventions, greater enhancements in acceleration performance compared with a generalised ‘one-size-fits-all’ approach. However, individualising the training of a squad of rugby backs is more time consuming than a general group approach and determining the CM location at touchdown and toe-off for individuals when calculating NAHEP is a time-consuming process requiring multiple segment endpoints to be digitised. A more practical solution to measure initial acceleration performance longitudinally in response to changes in an athlete’s spatiotemporal variables may also be of benefit in the applied setting and was sought in Chapter 7. Therefore, to determine whether an alternative initial acceleration performance measure to NAHEP can be used so that actionable information can be obtained in a timelier manner a final research question was addressed:

IX. How closely can the within-individual relationships of whole-body kinematic strategies and normalised spatiotemporal variables with NAHEP, and the within-individual changes of these variables following individual-specific training interventions, be replicated using a more practical performance measure than NAHEP?

Time to 5 m is a more practical alternative than the method used in this thesis to obtain NAHEP, which largely yielded the same insight. The use of time to 5 m as a performance measure was therefore proposed for four principal reasons. First, meaningful practically perfect and statistically significant group and within-individual relationships between NAHEP and 5 m time were observed. Second, the reliability of 5 m time was higher compared with NAHEP. Third, the differences in the correlation magnitudes between 5 m time and NAHEP with sprint technique variables were trivial to small and only differed in their directions on six out of 199 occasions and, even then, the differences in correlation magnitudes were trivial. Lastly, the statistically significant and/or meaningful changes observed in NAHEP between baseline testing and the final phase of testing were also observed as statistically significant and/or meaningful when replacing NAHEP with 5 m time. The outcome from these collective findings was that 5 m time is an appropriate acceleration measure, which can be obtained more quickly compared with NAHEP, to use when identifying variables that athletes are reliant on in the first four steps for better acceleration performance and it can be used to identify worthwhile changes in acceleration performance.

In conclusion, the study in Chapter 7 was the first to investigate how acceleration performance and technique of professional rugby backs change longitudinally following individual-specific interventions based on prior analysis of their individual needs. This evidence-based approach showed the potential value of considering the needs of each individual athlete and provided prospective evidence to demonstrate the theory proposed from the findings of previous chapters which suggested that a single optimal technique does not exist for all professional rugby backs.

8.3 Critical reflections on the programme of research undertaken

In this section, important considerations relating to the methods used in the investigations conducted throughout this thesis will be discussed. This includes the sample studied, the external validity and rigour of research conducted, and the balance struck between this external validity and the internal validity and reliability of the data obtained.

A well-known challenge of research on high performance athletes is that it is usually limited to investigating a relatively small sample size (e.g., Bernards et al., 2017). The participant numbers in the group-based studies (n = 15 to 35) throughout the chapters in this thesis are comparable, if not large, based on the similar biomechanical studies in the literature (e.g., participant numbers in the following studies which focussed on the initial acceleration kinematics of team sport players and sprinters, and were widely cited in this thesis, range from 4 to 24: Bezodis et al., 2018; Bezodis at al., 2017; Bezodis et al., 2010; Debeare et al., 2013b; Ettema et al., 2016; Lockie et al., 2011; Murphy et al., 2003). Not only were these sample sizes at least comparable to previously published sample sizes, but the characteristics of the participants sampled through the studies in this thesis were such that they were all elite to world class (Tiers 4 to 5) rugby players (competing in the English Premiership, and in some cases internationally), whereas the team sport players in the aforementioned research were competing at amateur levels (mostly Tiers 2 to 3). If the sample size through this thesis had been expanded, this would likely have meant diluting the level of participant, which in turn would likely have affected the results. Therefore, on balance it was deemed better to maintain the participant standard rather than increase the sample size with a lower level of participant, particularly given that the numbers studied were on the higher end in the context of comparable literature.

The move to a multiple single participant study design in the final investigation was an important transition to examine how individuals with their own unique characteristics responded to the interventions applied. However, due to the applied nature of the experimental research, the number of participants decreased from 19 to eight (drop out due to injury and/or changes in training schedules). This reduced the number of opportunities to assess the relative effectiveness of individual-specific technique-based interventions (n = 4) and, particularly, strength-based interventions, which was only applied to a single participant (three participants were controls). However, one of the strong aspects of the investigations conducted throughout this thesis is the external validity of the data which was collected within the habitual training environment of professional rugby union backs, rather than as a separate standalone laboratory-based research study which would not reflect their true practise. Accordingly, the findings from these investigations can be generalised to true applied contexts of professional rugby backs. The experimental investigation conducted in which individual specific interventions were applied across an 18-week period was the first study to longitudinally assess changes in kinematic aspects of technique and acceleration performances of rugby backs in response to prior assessment of their individual needs, thus yielding much-needed novel insight regarding effective methods of training to enhance the acceleration performance of athletes.

To ensure the data collected throughout the investigations in this thesis were externally valid, it was important to use a method to collect these data in a non-intrusive manner. Although marker-based laboratory three-dimensional motion capture is considered the ‘gold-standard’ for obtaining kinematic data, this would not have been practical to use within the routine training environment of professional rugby backs. Accordingly, data were obtained using manual two-dimensional video analysis. The reliability of the approach used was demonstrated by the good to excellent intra-rater reliability for variables determined (ICC range = 0.76 to 0.97), and the precision of the consistency of measures that were obtained across multiple sprint trials (for example, mean within individual CVs for kinematic and acceleration performance variables range = 2.1% to 6.5%). Therefore, variables could be collected accurately and reliably, providing assurance when drawing conclusions from results. The robustness of the methods used in this thesis were also demonstrated by considering the variability (combination of biological and test variability) associated with each variable obtained so that clear comparisons between participant groups could be made and to ensure that any changes detected during the analysis were representative of a ‘real’ change during the experimental research. For instance, in Chapter 7 using a sequential estimation technique (Clarkson et al., 1980; Preatoni et al., 2013) six to 10 trials were found to be the minimum number of sprints required across individuals to determine stable means for each variable. This highlighted the importance of using appropriate experimental designs and data processing which account for issues concerning the natural variability of human motion (Preatoni et al., 2013), and suggests that caution should be applied when drawing conclusions from intervention studies where single timepoints are used to measure pre and post changes in sprint technique and performance. This information was then used when detecting differences in acceleration technique and performance pre and post intervention using three criteria to detect changes in these variables: 1) when effect sizes were larger than 0.20 (smallest worthwhile difference, Hopkins, 2002); 2) when the absolute differences (%) were greater than the intra-individual CVs for the selected variable (Turner et al., 2021); 3) when differences were statistically significant ($p \leq 0.05$). Collectively, the methodological approach used was rigorous *and* enabled the collection of externally valid data.

Controlling task and environmental constraints were necessary so that accurate information could be obtained and that appropriate interpretations of findings could be made. Whilst controlling constraints was important for the quality of data obtained, the environmental (e.g., weather), task (e.g., sprint start conditions) and performer constraints (e.g., fatigue) imposed on rugby backs will be subject to change during match-play. Therefore, whilst it was possible to determine the within-individual relationships between participants’ acceleration strategies and acceleration performance to identify their ‘reliance’ during testing, it is feasible that these relationships may differ as the constraints imposed on them change during a match. Therefore, the technical foci applied to participants T1-T4 in Chapter 7 may not always have been ‘optimal’ for those individuals at all times during a rugby match, and they may also change over time due to changes in their physical constraints which result from the training programmes they undertake. Therefore, being ‘adaptable’ with their acceleration strategy is also an important factor to consider in the sprint training of rugby backs. That said, as ideal as it would be to reflect the ‘chaotic’ nature of match-play, it was important to at least have a reliable measurement of the acceleration technical characteristics and performances of rugby backs in a setting where task and environmental constraints were as controlled as they could be.

8.4 Directions for future research

The research studies and their associated findings presented in this thesis have advanced knowledge regarding the factors that contribute to the initial acceleration performance of professional rugby backs and the development of a novel evidence-based framework to enhance their initial acceleration performance. However, it has also highlighted where further insights could continue to be gained though future work.

Although the technical features of participants following individual-specific interventions changed in the direction of the intended technical changes by the end of the intervention in Chapter 7, only the technical-based interventions led to increased acceleration performance. Since only one participant underwent a strength-based intervention due to participant drop out, further single participant strength-based interventions are required to determine whether similar findings can be observed, and the extent to which individual-specific combined technical and strength-based interventions might translate to enhancements in acceleration performance. Other methods of training such as the use of wearable resistance when sprinting, which has been investigated in rugby players previously (Feser et al., 2021) and has shown to cause acute changes in step rate during acceleration (Macadam et al., 2020), could also prove useful in facilitating technical changes during the initial steps.

The technical foci applied to the technical intervention participants in Chapter 7 biased their future motor actions in the direction of the technical focus given, but the extent of these changes subsided somewhat in the final testing phase where no technical focus was applied during their sprint training (although the changes had not returned to baseline levels and were still meaningfully and statistically different). It is feasible that a different practice design may have led to better retention of the changes in technique and performance. For example, increased variability and contextual interference during training are proposed to increase the learning and retention of performance in motor skills (e.g., Hodges & Lohse, 2022; Hodges & Lohse, 2020). Future research is therefore needed to investigate the extent to which changes in the kinematic aspects of rugby backs' technique and their acceleration performance are retained over different durations following interventions of different practice design, length, and density of technically focussed sprint training and different intervention types.

As already alluded to in Section 8.3 the changing constraints imposed on rugby backs during a match will likely require different movement solutions to optimise acceleration performance. Therefore, an advance in knowledge could be gained by investigating how the whole-body acceleration strategies of rugby backs differ when task (e.g., sprinting competitively or whilst carrying a ball or from a rolling start), environmental (e.g., playing surface) or performer (e.g., sprinting when fatigued) constraints are manipulated, and by determining how the variable(s) participants are reliant on for better acceleration performance change in response to the changes in these constraints. Since performer constraints will change over time in response to the training undertaken by rugby backs, and due to other factors such as age, a greater number of repeat observations over longer periods are required to determine whether the within-individual relationships between their whole-body strategies and acceleration performance change over these time periods. This would help practitioners to manipulate their technical interventions in response to changes in these within-individual relationships to continually enhance, or at least prevent a decline in, acceleration performance over time. In Chapter 7 the potential performance enhancements of the technically focussed interventions based on the within individual relationships between whole-body strategy and acceleration performance appeared to be greater in individuals whose whole-body strategies were initially more strongly related to performance. Therefore, it would also be interesting to explore whether the magnitude of the reliance becomes weaker and gains in acceleration performance diminish as the variable(s) an individual is reliant on change towards the intended direction.

Furthermore, whilst targeting the variables participants were reliant on for better acceleration performance during speed training sessions and during warm-ups prior to rugby training and matches led to better acceleration performance in field-based testing (Chapter 7), it is not known how the intervention impacted their acceleration performance during match play. Quantifying acceleration performance accurately during match-play is challenging and only currently possible through wearable technology, like GPS. A recent method to derive sprint acceleration force-velocity profiles from GPS data collected *in-situ* during the sports training of soccer players (Morin et al., 2021) may provide an opportunity to assess how a rugby backs' match-play acceleration performance changes in response to individual-specific interventions. To date, however, the reliability of the method to measure acceleration profiles is yet to be tested during matches and the dynamic nature of match-play means it would be challenging to control.

8.5 Practical implications for coaches

As alluded to within this thesis (Chapters 2 and 3 in particular), most of the information available in the literature on sprint technique, prior to this programme of research, has been conducted on track sprinters. Perhaps in part because of this, it has been commonplace for coaches and practitioners who undertake speed training within team sport settings, like rugby, to convey a single correct technique to the athletes they work with primarily based on the movement patterns apparently observed in track sprinters. Basing the sprinting interventions of team sport players on the movement patterns of the fastest of all athletes in this way would seem sensible. However, from an ecological dynamics perspective this approach does not consider how differences in the environmental, task and performer constraints imposed between team sport players and track sprinters may result in different movement strategies to optimise sprinting performance during the initial steps in their respective sports. Moreover, this approach also discounts the likely differences in performer constraints between athletes within the *same* sport even when the environmental and task constraints (and in-game positional requirements) are the same. The work in this thesis provides evidence to suggest that the approach taken to base the sprint technique training of backs on the movement patterns adopted by track sprinters and to ascribe to a one-size-fits-all ideal movement template during initial acceleration is not as effective as applying interventions based on the individual needs of a given player.

Multiple physical, technical, and tactical qualities are required to compete in team sports at a high level. Consequently, the time for a team sport player to develop any single, but important, physical quality, such as their sprinting speed, is limited. Therefore, the opportunity offered by the framework developed in this thesis to integrate individual-specific sprint technique interventions seamlessly within a team sport player’s habitual training week is likely an attractive prospect for coaches or other practitioners working in team sports (and potentially other non-team sports in which sprint acceleration is also important). Although the initial investigations in this thesis (Chapters 3 to 6) involved a relatively complex undertaking of exploratory research, this was necessary to develop the aforementioned framework, and the steps needed to adopt the approach used to individualise the sprint technique interventions of team sport players is straightforward:

1) Determine the within-individual relationships of whole-body kinematic strategies and normalised spatiotemporal variables with the acceleration performance of each individual during a baseline period to identify which variable(s) they are reliant on for higher performance in this sprint phase.

2) Based on the information obtained in step 1, work with the team sport players to identify the focus of attention which results in a shift in their acceleration strategy towards the direction of the intended technical change.

3) Use opportunities within the training week (e.g., at the end of warm-ups prior to sport training sessions and matches or during sprint efforts during stand-alone speed training sessions) for players to focus on their technical prompts during sprint efforts.

4) After a defined period of time, measure changes in their acceleration strategy and acceleration performance to determine the effectiveness of the intervention applied and to establish whether their individual needs have changed, thus helping to inform their subsequent training requirements.

Steps 1 and 2 can easily be implemented within the pre-season phase of the training year and whilst it is clearly important that the testing being conducted is done so in a robust, standardised and reliable manner, the time it takes to record three sprint trials across a cohort of athletes within testing sessions is minimal whilst an appropriate training stimulus is also being applied at the same time. Once the work to identify the technical focus needed for each individual during a baseline period has been conducted and quality checked to ensure that the prompts used result in a shift in strategy towards the direction of the intended change, even less work is involved when applying the technical-based interventions. Players, under supervision or ‘checked’ where necessary, can focus on their technical prompts without extra coaching input, thus applying the technical intervention does not have to be labour intensive on the coach or practitioner’s behalf. The added benefit here is that an individualised approach to technique-based sprint training can be applied to a large group during the same sprint training session. For instance, provided each individual (or sub-group where relevant) has their own technical prompt to follow, it is not necessary for the team sport players to undertake different sprinting tasks to one another within the speed training session and sprinting volume and frequency can remain the same across the group. In the event where coaches or other practitioners may want to facilitate sprint-technique changes during acceleration towards the direction of an intended change in acceleration strategy, relationships between the strength qualities and technical features of the rugby backs studied in this thesis (Chapter 5) have been presented and preliminary insights on how an individualised strength programme may be used in this context has been detailed in a single-participant case study in Chapter 7. Ultimately, the current framework developed provides a unique approach for coaches and other practitioners to integrate individualised sprint acceleration-based interventions into their field-based training environment, thus offering a valuable service to the athletes they work with and their employers.

8.6 Thesis conclusion

The aim of this thesis was to understand how the technical and strength features of professional rugby backs relate to their sprint performance during the initial steps and, informed by this advance in knowledge, to develop and apply a framework to enhance their initial acceleration performance. To meet this aim, a series of exploratory and experimental investigations were conducted to address nine research questions. Differences in aspects of acceleration technique were first identified between rugby backs, rugby forwards and sprinters. A wider range of technique-based and strength-based data were then collected from rugby backs. The associations of these characteristics independently and in select combinations with acceleration performance were determined, as were the relationships between the strength qualities and technical features obtained. To further the understanding of the motor behaviour adopted by rugby backs during initial acceleration, cluster analysis was used to identify four different sub-groups among a wider group of rugby backs according to the combination of their normalised spatiotemporal variables. Strength-qualities, linear and angular kinematics of participants were compared between each sub-group. Using a method to depict the combination of these variables as whole-body kinematic acceleration strategies, a novel framework was developed to provide practitioners with a way to longitudinally assess the efficacy of their technical sprint-training interventions. The application of this framework was then demonstrated and advanced using an evidence-based approach which applied individual-specific interventions to multiple single participants, enhancing their initial acceleration performance.

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APPENDIX A – PARTICIPANT CLASSIFICATION FRAMEWORK

Table A.1. The framework used to describe participant ability levels[a]

Table 1 Participant Classification Framework

Tier	Criteria for classification
Tier 5: World Class = <0.00006% of the global population = <0.001% of the Australian population	• Olympic and/or world medalists. • World-record holders and athletes achieving within 2% of world-record performance and/or world-leading performance. • Top 3–20 in world rankings and/or top 3–10 at an Olympics/World Championships (ie, finalists in their event), with this number determined based on size and depth of competition in the event. • Top players within top teams (teams which medal or are in the most competitive leagues) or athletes achieving individual accolades (ie, most valuable player, player of the year). • Maximal, or nearly maximal training, within the given sports norms. • Exceptional skill-level achieved (ie, running biomechanics, ball skills, acquired decision-making components).
Tier 4: Elite/International Level = ~0.0025% of the global population = ~0.0055% of the Australian population	• Competing at the international level (individuals or team-sport athletes on a national team). • Team-sport athletes competing in international leagues/tournaments. • Top 4–300 in world rankings, with this number dependant on size and depth of competition in the event. • Achievement of within ~7% of world-record performance and/or world-leading performance. • NCAA Division I athletes. • Maximal, or nearly maximal training, within the given sports norms, with intention to complete at top-level competition. • Highly proficient in skills required to perform sport (ie, biomechanics, ball skills, acquired decision-making components).
Tier 3: Highly Trained/National Level (Provincial/State or Academy Programs) = ~0.014% of the global population = ~0.027% of the Australian population	• Competing at the national level. • Team-sport athletes competing in national and/or state leagues/tournaments. • Achievement of within ~20% of world-record performance and/or world-leading performance. • NCAA Division II and III athletes. • Completing structured and periodized training and developing towards (within 20%) of maximal or nearly maximal norms within the given sport. • Developing proficiency in skills required to perform sport (ie, biomechanics, ball skills, acquired decision-making components).
Tier 2: Trained/Developmental = ~12%–19% of the global population = ~18% of the Australian population	• Local-level representation. • Regularly training ~3 times per week. • Identify with a specific sport. • Training with a purpose to compete. • Limited skill development.
Tier 1: Recreationally Active = ~35%–42% of the global population = ~30% of the Australian population	• Meet World Health Organization minimum activity guidelines: Adults aged 18–64 years old completing at least 150 to 300 min moderate-intensity activity or 75–150 min of vigorous-intensity activity a week, plus muscle-strengthening activities 2 or more days a week.[20] • May participate in multiple sports/forms of activity.
Tier 0: Sedentary = ~46% of the global population = ~52% of the Australian population	• Do not meet minimum activity guidelines. • Occasional and/or incidental physical activity (eg, walking to work, household activities).

[a]This is a direct copy of the table presented by McKay et al., 2022 (Table 1, p.319) to outline their participant classification framework

APPENDIX B – ETHICS APPROVALS FOR STUDIES IN THE CHAPTERS OF THIS THESIS

Ethics approvals for the studies in Chapters 3 to 5 in this appendix. Note for the studies in Chapters 6 and 7, ethical and/or governance review was not deemed as required after completing the University of Surrey Self-Assessment Governance and Ethics form for Humans and Data Research (SAGE-HDR).

Ethics approval for the study in Chapter 3

St Mary's University Twickenham London

19th June 2015

Cc Neil Bezodis/ Jamie North

James Wild (SHAS) Relationships between early sprint acceleration technique and ground reaction force characteristics

Dear James,

University Ethics Sub-Committee

Thank you for re-submitting your ethics application for consideration.

I can confirm that all required amendments have been made and that you therefore have ethical approval to undertake your research.

Yours sincerely

Dr Conor Gissane
Chair of the Ethics Sub-Committee

Ethics approval for the studies in Chapters 4 and 5

UNIVERSITY OF SURREY

FHMS Chair's Action

Reference	FT-1819-83
Name of student	Andrew Stevens
Title of Project	Relationships between strength qualities and the step characteristics of elite rugby union players during the initial sprint acceleration phase.
Supervisor	James Wild
Date of Submission	26/11/2018
Date of outcome	27/11/2018

The above Research Project has been submitted to the Faculty of Health and Medical Sciences Ethics Committee and has received a favourable ethical opinion on the basis described in the protocol and supporting documentation.

The final list of revised documents reviewed by the Committee is as follows:

Ethics Application Form
Detailed Protocol for the project
Participant Information sheet
Consent Form
Risk Assessment (If appropriate)
Insurance Documentation (If appropriate)

All documentation from this project should be retained by the student/trainee in case they are notified and asked to submit their dissertation for an audit.

Professor Bertram Opitz, Co-Chair, FHMS Ethics Committee

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Please note:

If there are any significant changes to your proposal which require further scrutiny, please contact the Faculty of Health and Medical Sciences Ethics Committee before proceeding with your Project

APPENDIX C – STANDARDISED WARM-UP FOR SPRINT TESTING PROTOCOLS FOR RUGBY BACKS

The standardised warm up for the sprint testing protocol for the rugby participants in this thesis can be viewed by using the hyperlink below:

https://youtu.be/EJ-2201tMYY

APPENDIX D – INTRA-RATER RELIABILITY FOR DATA OBTAINED IN CHAPTERS 3 AND 4

Intraclass correlation coefficients between the first and second digitising occasions for the intra-rater reliability analysis conducted in Chapters 3 and 4 can be found in Table D.1. Intra-rater reliability was good for hip touchdown angular velocity, stance mean hip angular velocity, trunk angle and foot angle at touchdown, hip angle at touchdown, knee angle at toe-off and peak ankle dorsiflexion angle and ankle dorsiflexion range of motion (ICC = 0.78-0.87), and excellent for all other variables (ICC ≥ 0.90).

Table D.1. Intraclass coefficients and their 90% confidence intervals for variables

Variables		**ICC (90% CI)**
Spatiotemporal variables[b]	NAHEP[ab]	0.92 (0.81 to 0.97)
	Step velocity (m/s)	0.94 (0.85 to 0.98)
	Step length (m)	0.97 (0.92 to 0.99)
	Step rate (Hz)	0.91 (0.78 to 0.96)
	Contact time (s)	0.94 (0.85 to 0.98)
	Flight time (s)	0.92 (0.81 to 0.97)
Linear kinematics[b]	Contact length (m)	0.91 (0.78 to 0.96)
	Flight length (s)	0.89 (0.74 to 0.95)
	Touchdown distance (m)	0.91 (0.78 to 0.96)
	Toe-off distance (m)	0.90 (0.76 to 0.95)
Angular kinematics at touchdown	Hip touchdown angular velocity (°/s)	0.78 (0.60 to 0.88)
	Foot angle (°)	0.86 (0.74 to 0.93)
	Shank angle (°)	0.95 (0.90 to 0.97)
	Thigh angle (°)	0.90 (0.81 to 0.95)
	Trunk angle (°)	0.84 (0.70 to 0.92)
	Ankle angle (°)	0.92 (0.84 to 0.96)
	Knee angle (°)	0.90 (0.81 to 0.95)
	Hip angle (°)	0.80 (0.63 to 0.90)
Angular kinematics during stance	Peak ankle dorsiflexion angle (°)	0.83 (0.68 to 0.91)
	Peak ankle dorsiflexion ROM (°)	0.79 (0.62 to 0.89)
	Stance hip mean angular velocity (°/s)	0.82 (0.63 to 0.90)
Angular kinematics at toe-off	Foot angle (°)	0.90 (0.81 to 0.95)
	Shank angle (°)	0.96 (0.92 to 0.98)
	Thigh angle (°)	0.92 (0.84 to 0.96)
	Trunk angle (°)	0.90 (0.81 to 0.95)
	Ankle angle (°)	0.94 (0.88 to 0.97)
	Knee angle (°)	0.87 (0.75 to 0.93)
	Hip angle (°)	0.91 (0.83 to 0.95)
	Thigh separation angle (°)	0.95 (0.90 to 0.97)
	Toe-off distance (m)[b]	0.90 (0.76 to 0.96)

[a]Calculated according to the equations of Hof (1996) with a modification to the calculation of NAHEP as used by Bezodis et al. (2010)

[b]Intra-rater reliability results from the ICC determined for these variables in Chapter 3 (all other ICC were determined for variables in Chapter 4)

APPENDIX E – RELATIONSHIPS BETWEEN NAHEP AND TOE-OFF DISTANCE IN CHAPTER 4

In Chapter 4 when using semi-partial correlations controlling for body mass, the relationship between toe-off distance over the first four steps (normalised to leg length) and NAHEP over the first four steps was not meaningful. This finding was unexpected given the moderate and meaningful relationship observed between toe-off distance and NAHEP during Chapter 3. However, in Chapter 3 toe-off distance over the first three steps was normalised to stature and NAHEP was calculated over the first three steps, and a bivariate correlation was used to determine the relationship between these two variables. Therefore, in Chapter 4, toe-off distance normalised to stature and NAHEP over the first three steps were also obtained (i.e., using the same approach as in Chapter 3) so that a direct comparison of the findings between Chapters 3 and 4 could be made with the respect to the relationship between toe-off distance and NAHEP. The results of this analysis can be found in Table E.1.

Table E.1. Bivariate and semi-partial correlations (± 90% CI) between toe-off distance and NAHEP

	NAHEP (over steps one to three)	**NAHEP**[b] (over steps one to four)
Toe-off distance (normalised to stature and averaged over steps one to three)	-0.21 (-0.51 to 0.13)[a]	-
Toe-off distance (normalised to leg length and averaged over steps one to four)	-	-0.24 (-0.53 to 0.11)[b]

[a]Bivariate correlation coefficient, providing a direct comparison of this relationship between Chapters 3 and 4
[b]Semi-partial correlation coefficient, controlling for body mass

APPENDIX F – 90% CI ADDED TO THE PARTIAL CORRELATION COEFFICIENTS OF STRENGTH-BASED VARIABLES WITH TOUCHDOWN, STANCE AND ANGULAR KINEMATICS FROM CHAPTER 5

Table F.1. Partial correlation coefficients (90% CL) of strength-based variables in their absolute form with touchdown and stance phase angular kinematics over the initial four steps, controlling for body mass, observed in Chapter 5. Hip angular velocity measures have been normalised (Hof 1996).

	Touchdown and stance phase angular kinematics										
Strength-based variables	Foot angle	Shank angle	Thigh angle	Trunk angle	Ankle angle	Peak ankle dorsiflexion angle	Ankle dorsiflexion ROM	Knee angle	Hip angle	Hip touchdown angular velocity	Stance mean hip angular velocity
Hip torque	**-0.32** (-0.60 to - 0.01)	**-0.46*** (-0.69 to - 0.15)	**-0.37** (-0.63 to - 0.03)	-0.03 (-0.36 to 0.31)	-0.07 (-0.40 to 0.28)	-0.14 (-0.46 to 0.20)	0.04 (-0.30 to 0.37)	0.02 (-0.32 to 0.36)	0.24 (-0.11 to 0.53)	-0.09 (-0.41 to 0.25)	**0.31** (-0.03 to 0.59)
F0	-0.02 (-0.35 to 0.32)	**-0.35** (-0.61 to - 0.01)	0.18 (-0.17 to 0.49)	-0.07 (-0.40 to 0.27)	**-0.31** (-0.58 to 0.03)	-0.15 (-0.46 to 0.20)	0.30 (-0.04 to 0.58)	**-0.45*** (-0.69 to - 0.14)	-0.20 (-0.50 to 0.15)	-0.27 (-0.56 to 0.07)	**0.34** (0.00 to 0.61)
V0	0.10 (-0.25 to 0.42)	-0.09 (-0.41 to 0.25)	0.15 (-0.20 to 0.46)	-0.09 (-0.42 to 0.25)	-0.28 (-0.56 to 0.06)	**-0.48*** (-0.71 to - 0.18)	0.04 (-0.30 to 0.38)	-0.20 (-0.50 to 0.15)	-0.18 (-0.49 to 0.17)	-0.33 (-0.60 to 0.01)	**0.35** (0.02 to 0.62)
P_{max}	0.07 (-0.27 to 0.40)	**-0.34** (-0.61 to 0.00)	0.25 (-0.09 to 0.54)	-0.14 (-0.46 to 0.20)	**-0.46*** (-0.69 to - 0.14)	**-0.56*** (-0.76 to - 0.28)	0.26 (-0.08 to 0.55)	**-0.50*** (-0.71 to - 0.19)	**-0.31** (-0.59 to 0.03)	**-0.47*** (-0.70 to - 0.16)	**0.57*** (0.29 to 0.76)
Repeated CT	**0.30** (-0.04 to 0.58)	**0.29** (-0.05 to 0.57)	**0.35** (0.02 to 0.62)	-0.16 (-0.47 to 0.19)	-0.13 (-0.45 to 0.21)	**-0.40*** (-0.65 to - 0.08)	-0.04 (-0.37 to 0.30)	-0.16 (-0.47 to 0.19)	**-0.37** (-0.63 to - 0.04)	-0.15 (-0.47 to 0.19)	**0.27** (-0.08 to 0.55)
Repeated jump height	-0.10 (-0.42 to 0.25)	-0.18 (-0.49 to 0.17)	0.03 (-0.31 to 0.36)	-0.06 (-0.39 to 0.28)	-0.10 (-0.42 to 0.25)	-0.06 (-0.39 to 0.28)	-0.06 (-0.39 to 0.28)	-0.19 (-0.50 to 0.15)	-0.08 (-0.40 to 0.27)	-0.14 (-0.46 to 0.20)	**0.49*** (0.19 to 0.71)
RSI	**-0.27** (-0.56 to 0.07)	**-0.33** (-0.60 to - 0.01)	-0.18 (-0.49 to 0.17)	0.04 (-0.30 to 0.37)	-0.01 (-0.34 to 0.33)	0.20 (-0.15 to 0.50)	-0.02 (-0.35 to 0.32)	-0.08 (-0.40 to 0.27)	0.15 (-0.19 to 0.47)	-0.04 (-0.38 to 0.30)	0.24 (-0.10 to 0.54)
Hip torque/CT ratio	**-0.41*** (-0.66 to - 0.08)	**-0.55*** (-0.75 to - 0.26)	**-0.48*** (-0.70 to - 0.16)	0.07 (-0.27 to 0.40)	-0.01 (-0.34 to 0.33)	0.09 (-0.26 to 0.41)	0.04 (-0.30 to 037)	0.08 (-0.26 to 0.41)	**0.39** (0.07 to 0.65)	-0.01 (-0.35 to 0.33)	0.11 (-0.24 to 0.430

Table F.2. Partial correlation coefficients (90% CL) between strength-based variables in their absolute form and toe-off angular kinematics over the initial four steps, controlling for body mass.

Strength-based variables	**Toe-off angular kinematics**							
	Foot angle	Shank angle	Thigh angle	Trunk angle	Ankle angle	Knee angle	Hip angle	Thigh separation angle
Hip torque	**0.40** (0.07 to 0.65)	**0.42*** (0.10 to 0.67)	-0.01 (-0.34 to 0.33)	0.09 (-0.25 to 0.41)	-0.16 (-0.47 to 0.19)	**0.27** (-0.08 to 0.55)	0.09 (-0.26 to 0.41)	-0.12 (-0.44 to 0.23)
F_0	**0.43*** (0.11 to 0.67)	-0.12 (-0.44 to 0.22)	**0.31** (-0.03 to 0.58)	0.14 (-0.20 to 0.46)	**-0.30** (-0.58 to 0.04)	**-0.34** (-0.60 to 0.00)	-0.07 (-0.40 to 0.27)	-0.08 (-0.41 to 0.26)
V_0	0.05 (-0.29 to 0.38)	-0.14 (-0.45 to 0.21)	-0.14 (-0.45 to 0.21)	0.05 (-0.29 to 0.38)	-0.07 (-0.40 to 0.28)	0.05 (-0.29 to 0.38)	0.11 (-0.24 to 0.43)	0.11 (-0.24 to 0.43)
P_{max}	**0.35** (0.02 to 0.62)	-0.20 (-0.51 to 0.14)	0.12 (-0.23 to 0.44)	0.14 (-0.21 to 0.46)	-0.29 (-0.57 to 0.05)	-0.20 (-0.50 to 0.15)	0.03 (-0.31 to 0.36)	0.05 (-0.29 to 0.38)
Repeated CT	-0.11 (-0.43 to 0.24)	-0.17 (-0.48 to 0.16)	**-0.40** (-0.65 to -0.07)	0.00 (-0.34 to 0.34)	-0.12 (-0.50 to 0.16)	0.18 (-0.17 to 0.49)	0.22 (-0.13 to 0.52)	**0.37** (0.04 to 0.63)
Repeated jump height	**0.30** (-0.04 to 0.58)	-0.13 (-0.45 to 0.21)	-0.24 (-0.52 to 0.11)	0.04 (-0.30 to 0.37)	**-0.43*** (-0.67 to -0.11)	0.09 (-0.26 to 0.41)	0.18 (-0.16 to 0.49)	0.09 (-0.25 to 0.41)
RSI	**0.32** (-0.02 to 0.59)	-0.03 (-0.37 to 0.31)	0.05 (-0.30 to 0.38)	0.02 (-0.32 to 0.35)	**-0.29** (-0.57 to 0.05)	-0.05 (-0.38 to 0.29)	0.01 (-0.33 to 0.35)	-0.16 (-0.47 to 0.19)
Hip torque/CT ratio	**0.39** (0.06 to 0.64)	**0.44*** (0.12 to 0.67)	0.20 (-0.14 to 0.50)	0.09 (-0.26 to 0.41)	-0.06 (-0.39 to 0.29)	0.13 (-0.22 to 0.44)	-0.03 (-0.37 to 0.31)	**-0.27** (-0.56 to 0.07)

Bold font indicates that the relationship is deemed greater than the smallest clinically important correlation coefficient (r = ± 0.26)
Asterisks indicate statistical significance (*p* = < 0.05)

APPENDIX G – TRAINING UNDERTAKEN BY PARTICIPANTS IN CHAPTER 7

Figure G.1. Training undertaken by participants T1-T4, S1 and C1-C3 during the baseline phase. A PDF copy of this with video demonstrations of the exercises in speed the training undertaken can be accessed here: https://www.dropbox.com/s/krep69u3r9wykr7/Figure%20D.1.%20Baseline.pdf?dl=0

STRENGTH

Session	Exercise	Week -5	Week -4	Week -3	Exercise	Week -2	Week -1	Week 0
Session 1	SA DB flat press	4 x 8	4 x 8	4 x 6	SA DB flat press	4 x 6	4 x 6	-
	SA DB row	4 x 8	4 x 8	4 x 6	SA DB row	4 x 6	4 x 6	-
	BB javelin press	4 x 10	4 x 10	4 x 10	BB javelin press	4 x 10	4 x 8	-
	Half kneeling cable row	4 x 10	4 x 10	4 x 10	Half kneeling cable row	4 x 10	4 x 8	-
	Chin ups	3 x AP	3 x AP	3 x AP	Chin ups	3 x AP	3 x AP	-
	Press ups	3 x AP	3 x AP	3 x AP	Press ups	3 x AP	3 x AP	-
Session 2	Bulgarian split squat ISOs hold[a]	3 x 5	3 x 5	3 x 5	Squat jump (20kg)	4 x 4	4 x 4	4 x 4
	Supine SL hip ext. ISOs[b]	3 x 5	3 x 5	3 x 5	Back squat	3 x 5	3 x 5	3 x 5
	Seated SL calf raise	2 x 10	2 x 10	2 x 10	DB walking lunge	3 x 5	3 x 5	3 x 5
					Romanian deadlift	3 x 5	3 x 5	3 x 5
Session 3	Squat jump (20kg)	2 x 4	3 x 4	3 x 4	Incline bench press	3 x 4	4 x 3	4 x 3
	Back squat	3 x 5	3 x 5	3 x 5	Weighted chin up	3 x 5	4 x 5	4 x 5
	Romanian deadlift	3 x 5	3 x 5	3 x 5	Prone DB row	3 x 8	4 x 8	4 x 8
	Rollouts	3 x 8	3 x 8	3 x 10	DB reverse fly	3 x 10	4 x 10	4 x 10
					Weighted press ups	4 x 15	4 x 20	4 x 25
					Nordic curl (band assisted)	3 x 5	3 x 5	3 x 5
Session 4	Incline bench press	4 x 5	4 x 5	4 x 5				
	Weighted chin up	4 x 6	4 x 6	4 x 6				
	Prone DB row	4 x 8	4 x 8	4 x 8				
	Close-grip press up	4 x 20	4 x 20	4 x 20				
	Incline DB fly	3 x 10	3 x 10	3 x 10				
	BB curl	3 x 12	3 x 12	3 x 12				
	Nordic curl (band assisted)	3 x 5	3 x 5	3 x 5				

SPEED

Session	Exercise	Week -5	Week -4	Week -3	Exercise	Week -2	Week -1	Week 0
Session 1	Switch (single)	2 x 5m	2 x 8m	2 x 10m	Switch (triple)	2 x 8m	2 x 10m	3 x 15m
	Switch (triple)	2 x 5m	2 x 5m	2 x 8m	Straight leg bound	3 x 10m	3 x 15m	2 x 20m
	Straight leg bound	2 x 8m	2 x 10m	2 x 10m	Jump conditioning 2	x 2 rounds (5 reps)	x 2 rounds (5 reps)	x 2 rounds (5 reps)
	Jump conditioning 1	x 2 rounds (6 reps)	x 2 rounds (6 reps)	x 2 rounds (6 reps)	Medball heave (upwards)	2 x 2 (8kg)	2 x 2 (10kg)	2 x 3 (10kg)
	Medball heave (upwards)	2 x 2 (5kg)	2 x 3 (5kg)	2 x 3 (8kg)	Resisted acceleration bound	2 x 10m	2 x 10m	2 x 10m
	Resisted acceleration bound	2 x 5m	2 x 10m	2 x 10m	Resisted sprint	2 x 10m (40kg)	2 x 10m (60kg)	-
	Resisted sprint	-	-	1 x 10m (40kg)	Sprint (2-point start)	3 x 30m	4 x 20m	3 x 30m
	Sprint (2-point start)	2 x 10m	3 x 30m	2 x 10m				
	Sprint (2-point start)	-	-	2 x 15m				
Session 2	Dribble (shin)	2 x 20m	2 x 20m	2 x 20m	Hop conditioning 2	x 2 rounds (4 reps)	x 2 rounds (4 reps)	x 2 rounds (4 reps)
	Dribble (knee)	2 x 10m	2 x 10m	2 x 10m	Pogo (maximal)	2 x 5m	2 x 8m	2 x 10m
	Hop conditioning 1	x 2 rounds (4 reps)	x 2 rounds (4 reps)	x 2 rounds (4 reps)	Dribble (knee)	2 x 15m	2 x 20m	2 x 20m
	Pogo (rhythmic)	2 x 10m	3 x 10m	3 x 10m	Sprint (2-point start)	1 x 10m	1 x 10m	1 x 20m
	Sprint (upright, rolling start)	-	2 x 10m	2 x 10m	Sprint (2-point start)	1 x 20m	1 x 20m	2 x 40m
	Sprint (2-point start)	-	-	1 x 15m	Sprint (upright, rolling start)	2 x 15m	2 x 20m	-
	Sprint (2-point start)	3 x 30m	2 x 10m	3 x 20m				

Strength key: SA = single arm; SL = single leg; DB = dumbbell; BB = barbell; ISOs = isometrics; AP = as many reps as possible

Speed key: m = metres; red shaded contents = testing sessions during which acceleration technique and performance data were obtained from participants; exercises underlined are linked to video demonstrations which can be accessed through a PDF version of this programme

Strength notes: generally, participants selected a load whereby 1-3 reps were left in reserve for each set. Rest between sets were typically 60-150s, with the lower and higher ends of this rest continuum applied to exercises when intensity was lower and higher respectively. [a]Participants held for 5 s in the bottom position for each rep. [b]Completed in the set up position for the hip torque test, participants attempted to 'push' the immovable bar upwards, gradually increasing their effort (similar to Balshaw et al., 2016) to ~80% of their maximum and held this intensity for 3s before resting for 5s in each in rep. Shaded rows depict supersets, whereby participants alternated between exercises with small rest (~15-45s) between each exercise and longer rest (~90-150s) between sets. Warm-up sets have not been included in the programme detailed. Participants had followed a home-based (predominantly bodyweight) strength programme for 3 weeks prior to the start of the baseline period

Speed notes: rest between sets for drills and jumping exercises typically involved a slow walk back between each set. For throw-based exercises rest between sets was typically ~90s. For sprint-based activities 60s of rest for every 10m travelled in the effort was employed between sets (e.g., a 20 m sprint would result in a 120s rest). The exception to this was during testing where 4-5 minutes of rest were taken between sprints. On testing occasions, sprint efforts were completed before all other activities. Warm-up sets have not been included in the programme detailed. Participants had followed a home-based speed programme including sprinting over distances progressing from 5 m to 20 m over 3 weeks prior to the start of the baseline period

Figure G.2. Strength training undertaken by participants T1-T4, S1 and C1-C3 during the intervention phase.

	Phase 1					Phase 2		
	Week	1	2	3	4	5	6	7
	Exercise	Sets x reps				Sets x reps		
Session 1	Squat jump	3 x 3 (20kg)	3 x 3 (20kg)	3 x 3 (30kg)	3 x 3 (30kg)	3 x 4 (30kg)	3 x 4 (30kg)	-
Session 1	Hurdle rebound jump	3 x 6	3 x 6	-	3 x 6-8	3 x 6-8	3 x 6-8	-
Session 1	Back squat	3 x 3	4 x 3	3 x 3	-	3 x 5	4 x 3	1 x 3
Session 1	DB walking lunge	3 x 7	3 x 7	3 x 7	3 x 7	3 x 6	3 x 7	-
Session 1	Romanian deadlift	3 x 5	3 x 5	3 x 5	3 x 5	3 x 6	3 x 5	2 x 5
Session 2	Bench press	4 x 4	4 x 3	4 x 3	-	3 x 5	4 x 3	1 x 3
Session 2	Seated DB press	4 x 8	4 x 8	4 x 8	4 x 8	4 x 6	4 x 6	3 x 6
Session 2	Incline DB fly	4 x 10	4 x 10	4 x 8	4 x 8	4 x 8	3 x 8	3 x 8
Session 2	Weighted chin ups	4 x 10	4 x 10	4 x 10	4 x 10	3 x 8	3 x 8	3 x 8
Session 2	Nordic curl (band assisted)	3 x 5	3 x 5	3 x 5	3 x 5	3 x 4	3 x 4	3 x 4
	Exercise	Sets x reps				Sets x reps		
Session 1	Skipping routine[a]	2 x 15s/15s	3 x 15s/15s	3 x 15s/15s	-	4 x 15s/15s	3 x 20s/20s	4 x 20s/20s
Session 1	Hurdle rebound jump	3 x 6	3 x 6	3 x 8	3 x 8	3 x 8	3 x 8	-
Session 1	Hip thrust	3 x 8	3 x 6	3 x 5	4 x 5	3 x 3	4 x 3	2 x 3
Session 1	Seated SL ankle ISOs[c]	2 x 5 3s/5s	3 x 5 3s/5s	3 x 5 3s/5s	-	3 x 3 3s/5s	3 x 3 3s/5s	3 x 5 1s/10s
Session 1	Romanian deadlift	3 x 5	3 x 5	3 x 5	3 x 5	3 x 6	3 x 5	2 x 5
Session 2	Supine SL hip ext. ISOs[e]	2 x 5 3s/5s	3 x 5 3s/5s	3 x 5 3s/5s	-	3 x 3 3s/5s	3 x 3 3s/5s	3 x 5 1s/10s

	Phase 3			
	Week	8	9	10
	Exercise	Sets x reps		
Session 1	Power clean	3 x 4	4 x 4	-
Session 1	Hurdle rebound jump	3 x 6	3 x 6	3 x 3
Session 1	Back squat	4 x 5	4 x 4	3 x 3
Session 1	DB Bulgarian split squat	3 x 5	3 x 6	3 x 7
Session 1	Romanian deadlift	3 x 6	3 x 6	-
Session 2	Bench press	3 x 5	4 x 5	5 x 5
Session 2	Seated DB press	4 x 10	4 x 8	3 x 6
Session 2	Incline DB fly	-	4 x 10	4 x 8
Session 2	Weighted chin ups	-	3 x 5	4 x 5
Session 2	Nordic curl (band assisted)	3 x 5	-	3 x 5
	Exercise	Sets x reps		
Session 1	Skipping routine[a]	3 x 25s/25s	3 x 30s/30s	-
Session 1	SL low hurdle rebound jump	3 x 4	3 x 5	3 x 6
Session 1	SL hip thrust	3 x 6	3 x 5	4 x 5
Session 1	Seated SL ankle ISOs[c]	2 x 8 1s/10s	2 x 10 1s/10s	3 x 10 1s/10s
Session 1	Romanian deadlift	3 x 6	3 x 6	-
Session 2	Supine SL hip ext. ISOs[e]	2 x 8 1s/10s	2 x 10 1s/10s	3 x 10 1s/10s

	Phase 4					Phase 5			
	Week	11	12	13	14	15	16	17	18
	Exercise	Sets x reps				Sets x reps			
Session 1	Power clean (hang position)	4 x 4	3 x 3	-	4 x 3	4 x 4	4 x 3	-	3 x 3
Session 1	Back squat	-	3 x 4	3 x 5	4 x 3	3 x 4	5 x 3	3 x 3	-
Session 1	SL DB calf raise	2 x 10	2 x 10	-	2 x 10	2 x 10	2 x 10	2 x 10	-
Session 1	Step up w/hip flexion	3 x 5	3 x 5	3 x 6	3 x 6	3 x 7	3 x 6	-	3 x 5
Session 1	Romanian deadlift	-	3 x 6	-	3 x 6	3 x 5	-	3 x 6	3 x 7
Session 2	Bench press	-	4 x 4	5 x 3	2 x 3	-	4 x 4	3 x 3	2 x 3
Session 2	Weighted chin up	5 x 5	5 x 5	5 x 5	-	5 x 5	5 x 5	-	5 x 5
Session 2	Seated DB press	-	4 x 8	4 x 6	-	4 x 8	4 x 6	4 x 4	-
Session 2	Seated cable row	4 x 12	4 x 10	4 x 8	4 x 6	4 x 10	4 x 8	4 x 6	4 x 4
Session 2	Nordic curl (band assisted)	-	3 x 5	-	3 x 5	3 x 5	-	3 x 5	-
	Exercise	Sets x reps				Sets x reps			
Session 1	Skipping routine[b]	3 x 20s/20s	3 x 25s/25s	-	3 x 30s/30s	3 x 30s/30s	3 x 30s/30s	-	2 x 30s/30s
Session 1	SL low hurdle rebound jump	-	3 x 6	-	3 x 8	3 x 6	2 x 4	3 x 8	3 x 5
Session 1	Single leg hip thrust	3 x 4	3 x 4	-	3 x 3	4 x 3	3 x 3	3 x 3	-
Session 1	Standing SL ankle ISOs[d]	2 x 8 1s/10s	2 x 8 1s/10s	3 x 10 1s/10s	-	2 x 10 1s/10s	-	3 x 10 1s/10s	2 x 10 1s/10s
Session 1	Romanian deadlift	-	3 x 6	-	3 x 6	3 x 5	-	3 x 6	3 x 7
Session 2	Supine SL hip ext. ISOs[e]	2 x 8 1s/10s	2 x 8 1s/10s	3 x 10 1s/10s	-	2 x 10 1s/10s	-	3 x 10 1s/10s	2 x 10 1s/10s

Session 2: Participant S1 carried out the same session 2 programme as completed by participants T1-4 and C1-C3, apart from the nordic curl exercise which was replaced as follows: Supine SL hip ext. ISOs[e] (as detailed above).

Session 3: On a separate occasion in the week, participant S1 also repeated the Seated / Standing SL ankle ISOs and Hurdle rebound jump / SL low hurdle rebound jump exercises as detailed in session 1

Key: SA = single arm; SL = single leg; DB = dumbbell; ISOs = isometrics; blue shaded boxes represent the training completed by participants T1-T4 and C1-C3, whereas orange shaded boxes represent the training completed by participants S1; red shaded week numbers = weeks during which acceleration technique and performance data were obtained from participants

Notes: Generally, participants selected a load whereby 1-3 reps were left in reserve for each set. Rest between sets were typically 90s-150s, with the lower and higher ends of this rest continuum applied to exercises when intensity was lower and higher respectively. [a]Participant skipped (using a skipping rope) with consecutive bilateral foot contacts (time specified to the left and right of a forward slash depicts duration of skipping and resting respectively in each set). [b]Participant skipped (using a skipping rope) with 2 unilateral foot contacts on the left side followed by 2 unilateral contacts on the right side and alternated in this fashion for a specified duration (left of a forward slash) before resting for a specified duration (right of the forward slash) in each set. [c]Participant used a seated calf raise machine (knee angle ~90°; ankle angle ~0°) which was weighted such that it was not possible to move the load. The participant 'pushed' against the immovable load for a specified time (to the left of the forward slash) and then rested for a specified time (to the right of the forward slash) in each repetition and rested for ~2-3 minutes between each set. [d]Participant was in a standing position in a custom squat cage, positioned under an immovable bar which rested across their upper trapezius muscles (with legs straight and ankle joints at ~0°). In each rep, the participant raised one foot off the ground (hip flexed to ~90°) and then attempted to lift the bar upwards by trying to plantarflex the ankle in contact with the ground. They 'pushed' against the immovable load for a specified time (to the left of the forward slash) and then rested for a specified time (to the right of the forward slash) in each repetition and rested for ~2-3 minutes between each set. [e]Participant completed in the set up position for the hip torque test, attempting to 'push' the immovable bar upwards for a specified time (to the left of the forward slash) and then rested for a specified time (to the right of the forward slash) in each repetition and rested for ~2-3 minutes between each set. For weeks 1-5 in isometric exercises performed by participant S1, the participant gradually increased their effort (similar to Balshaw et al., 2016) to ~100% of their maximum and held this intensity when 'pushing' during each rep. For remaining weeks the participant was required to 'push' as fast and as hard as possible from the outset of 'pushing' (similar to Lum et al., 2021) and for the duration specified in each rep. Shaded rows depict supersets, whereby participants alternated between exercises with small rest (~30-45s) between each exercise and longer rest (~90-150s) between sets. Warm-up sets have not been included in the programme detailed.

Figure G.3. Speed training undertaken by participants T1-T4, S1 and C1-C3 during the intervention phase. A PDF copy of this with video demonstrations of the exercises undertaken can be accessed here: https://www.dropbox.com/s/e3ofmmt26cacpd7/Figure%20D.3.%20Speed%20intervention.pdf?dl=0

	Phase 1					Phase 2		
	Week	1	2	3	4	5	6	7
	Exercise	Sets x reps				Sets x reps		
Session 1	Switch (triple, stick OH)	3 x 10m	3 x 10m	3 x 15m	3 x 15m	2 x 10m	2 x 10m	2 x 10m
	Acceleration bound	2 x 10m	2 x 10m	-	-	-	1 x 20m	3 x 20m
	Resisted sprint	-	2 x 10m (40kg)	2 x 10m (50kg)	-	2 x 10m (50kg)	2 x 10m (50kg)	-
	Sprint (2-point start)	3 x 10m	2 x 10m	1 x 10m	2 x 10m	2 x 10m	1 x 20m	3 x 30m
	Sprint (2-point start)	3 x 20m	2 x 20m	3 x 30m	2 x 20m	4 x 30m	2 x 30m	-
	Sprint (2-point start)	-	2 x 30m	1 x 40m	2 x 30m	-	3 x 40m	-
	Exercise	Sets x reps				Sets x reps		
Session 2	A-skip	2 x 15m	2 x 20m	2 x 20m	-	2 x 10m	2 x 15m	-
	Dribble (ascending)	2 x 30m	2 x 30m	2 x 30m	-	2 x 30m	2 x 30m	-
	Sprint (2-point start)	1 x 10m	1 x 20m	1 x 10m	-	2 x 20m	2 x 10m	-
	Sprint (2-point start)	2 x 20m	2 x 20m	1 x 20m	-	2 x 20m	3 x 20m	-
	Sprint (sprint-float-sprint)	3 x 10-10-10m	2 x 20-10-10m	4 x 10-10-10m	-	2 x 20-10-10m	-	-

	Phase 3			
	Week	8	9	10
	Exercise	Sets x reps		
Session 1	Switch (triple, medball OH)	2 x 10m	2 x 10m	2 x 10m
	Bounding	-	2 x 30m	-
	Resisted sprint	1 x 10m (60kg)	2 x 10m (60kg)	1 x 10m (60kg)
	Sprint (2-point start)	2 x 20m	2 x 20m	3 x 30m
	Sprint (2-point start)	2 x 30m	2 x 30m	1 x 40m
	Sprint (2-point start)	2 x 40m	2 x 40m	-
	Exercise	Sets x reps		
Session 2	Dribble (speed, ascending)	3 x 30m	-	-
	Wicket run	2 x 40m	-	-
	Sprint (2-point start)	1 x 10m	-	-
	Sprint (upright, rolling start)	2 x 20m	-	-
	Sprint (sprint-float-sprint)	2 x 20-10-20m	-	-

	Phase 4					Phase 5			
	Week	11	12	13	14	15	16	17	18
	Exercise	Sets x reps				Sets x reps			
Session 1	Str. leg bound (medball OH)	2 x 20m	2 x 20m	2 x 20m	-	2 x 20m	2 x 20m	2 x 20m	-
	Speed bound	2 x 30m	2 x 30m	-	3 x 30m	3 x 30m	-	3 x 30m	-
	Resisted sprint	2 x 10m (60kg)	2 x 10m (60kg)	-	2 x 10m (60kg)	-	2 x 10m (60kg)	-	2 x 10m (60kg)
	Sprint (2-point start)	2 x 10m	2 x 20m	3 x 30m	1 x 10m	3 x 30m	2 x 40m	3 x 30m	3 x 30m
	Sprint (2-point start)	3 x 20m	2 x 30m	-	3 x 40m	-	-	1 x 40m	-
	Sprint (2-point start)	1 x 40m	2 x 40m	-	1 x 20m				
	Exercise	Sets x reps				Sets x reps			
Session 2	Dribble (speed, ascending)	3 x 30m	-	3 x 30m	-	-	3 x 30m	-	-
	Wicket run	2 x 40m	-	2 x 40m	-	-	2 x 40m	-	-
	Sprint (2-point start)	1 x 10m	-	1 x 10m	-	-	1 x 10m	-	-
	Sprint (upright, rolling start)	2 x 20m	-	2 x 20m	-	-	3 x 30m	-	-
	Sprint (sprint-float-sprint)	2 x 20-10-20m	-	2 x 20-10-20m	-	-	1 x 20-10-20m	-	-

Key: m = metres; red shaded contents = testing sessions during which acceleration technique and performance data were obtained from participants; exercises underlined are linked to video demonstrations which can be accessed through a PDF version of this programme

Notes: rest between sets for drills and jumping exercises typically involved a slow walk back between each set. For sprint-based activities 60s of rest for every 10m travelled in the effort was employed between sets (e.g., a 20 m sprint would result in a 120s rest). The exception to this was during testing where 4-5 minutes of rest were taken between sprints. On testing occasions, sprint efforts were completed before all other activities. Warm-up sets have not been included in the programme detailed.

APPENDIX H: RELATIONSHIPS OF WHOLE_BODY KINEMATIC STRATEGIES AND NORMALISED SPATIOTEMPORAL VARIABLES WIITH INITIAL ACCELERATION PERFORMANCE (see Figure 7.2 for participant 33 who was the other participant [n = 19] included in this analysis)

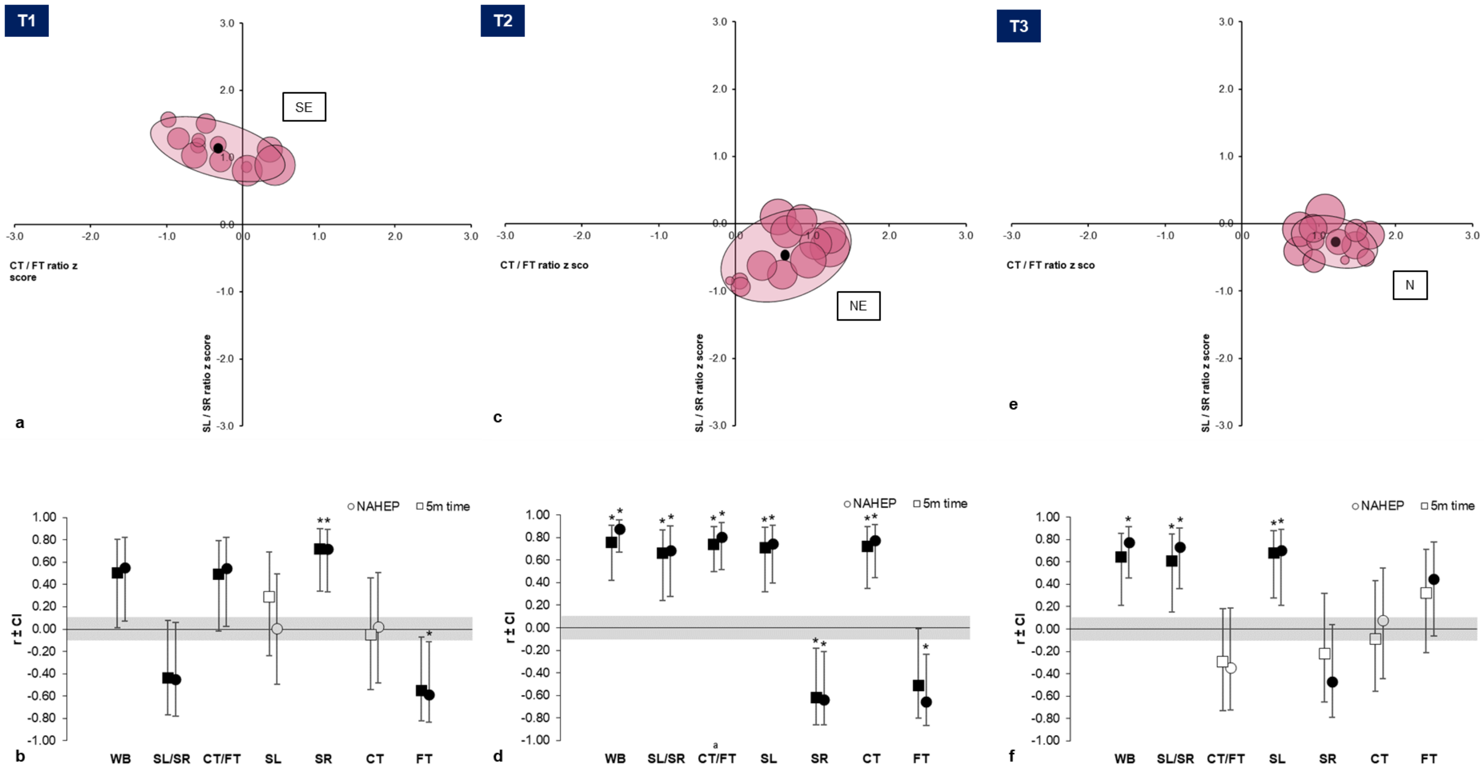

Figure H.1. Whole-body kinematic strategy (a,c and e) of participants T1-T3. Each marker depicts a single sprint with marker sizes reflecting acceleration performance (a larger marker size equates to greater NAHEP). Where whole-body kinematics are meaningfully related to NAHEP, the theoretical favourable direction change in strategy for better sprint performance is included as a compass bearing. Relationships (with 90% confidence intervals) of their whole-body kinematic strategy, normalised spatiotemporal variables and length/rate and contact/flight ratios with NAHEP and 5 m time are also shown (b, d and f). For clarity, to aid comparisons between relationships of NAHEP and 5 time with variables, the direction of relationships between 5 m time and variables has been inverted. Black filled makers depict relationships $r \geq 0.43$ and asterisks indicate that relationships are statistically significant ($p < 0.05$). Dark blue, participant number boxes denote individuals who underwent a technical intervention

WB = whole-body kinematic strategy; SL/SR = length/rate ratio; CT/FT = contact/flight ratio; SL = step length; SR = step rate; CT = contact time; FT = flight time

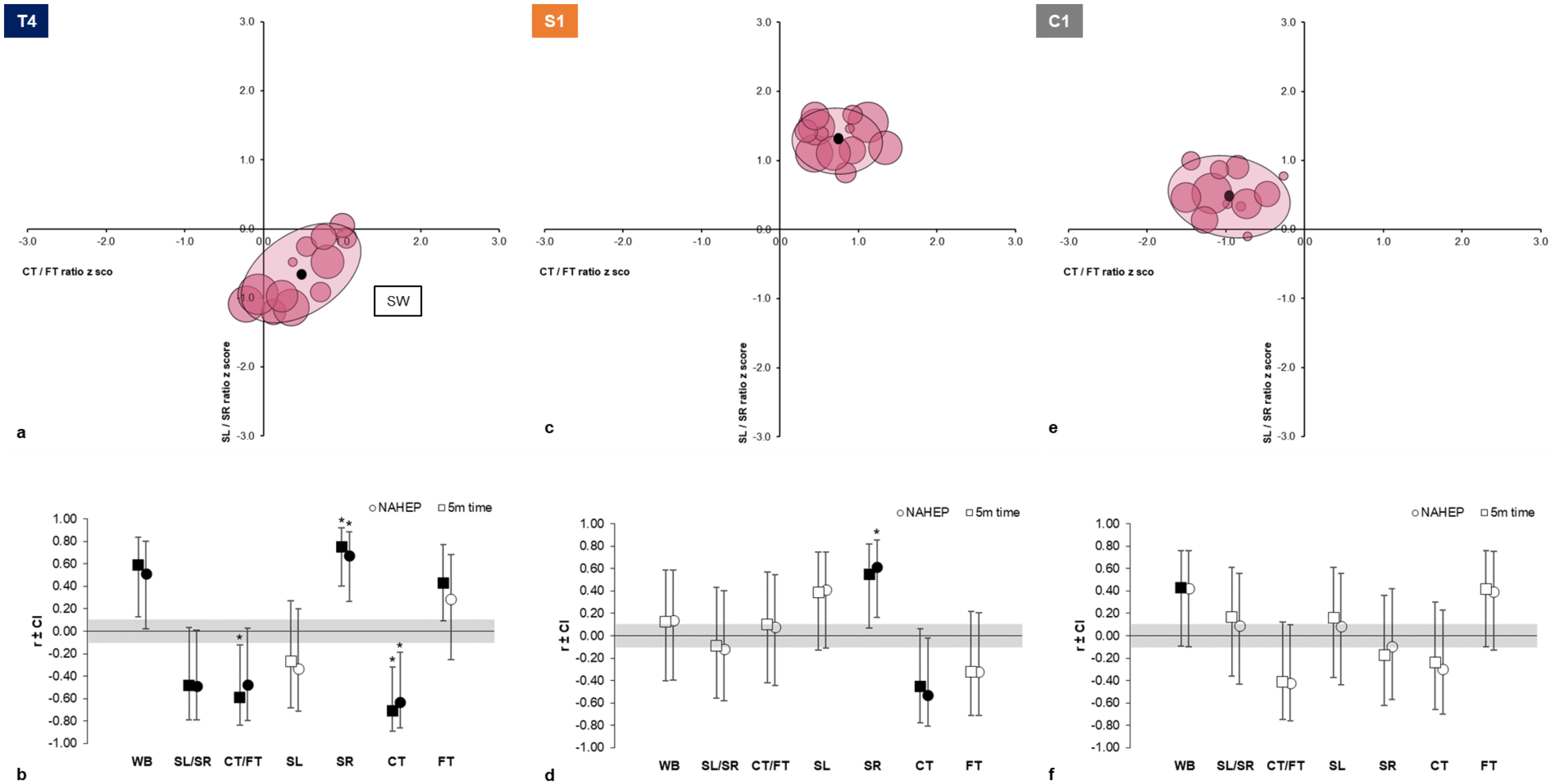

Figure H.2. Whole-body kinematic strategy (a,c and e) of participants T4, S1 and C1. Each marker depicts a single sprint with marker sizes reflecting acceleration performance (a larger marker size equates to greater NAHEP). Where whole-body kinematics are meaningfully related to NAHEP, the theoretical favourable direction change in strategy for better sprint performance is included as a compass bearing. Relationships (with 90% confidence intervals) of their whole-body kinematic strategy, normalised spatiotemporal variables and length/rate and contact/flight ratios with NAHEP and 5 m time are also shown (b, d and f). For clarity, to aid comparisons between relationships of NAHEP and 5 time with variables, the direction of relationships between 5 m time and variables has been inverted. Black filled makers depict relationships $r \geq 0.43$ and asterisks indicate that relationships are statistically significant ($p < 0.05$). Dark blue, orange or grey-filled participant number boxes denote technical intervention, strength intervention or control participants respectively.

WB = whole-body kinematic strategy; SL/SR = length/rate ratio; CT/FT = contact/flight ratio; SL = step length; SR = step rate; CT = contact time; FT = flight time

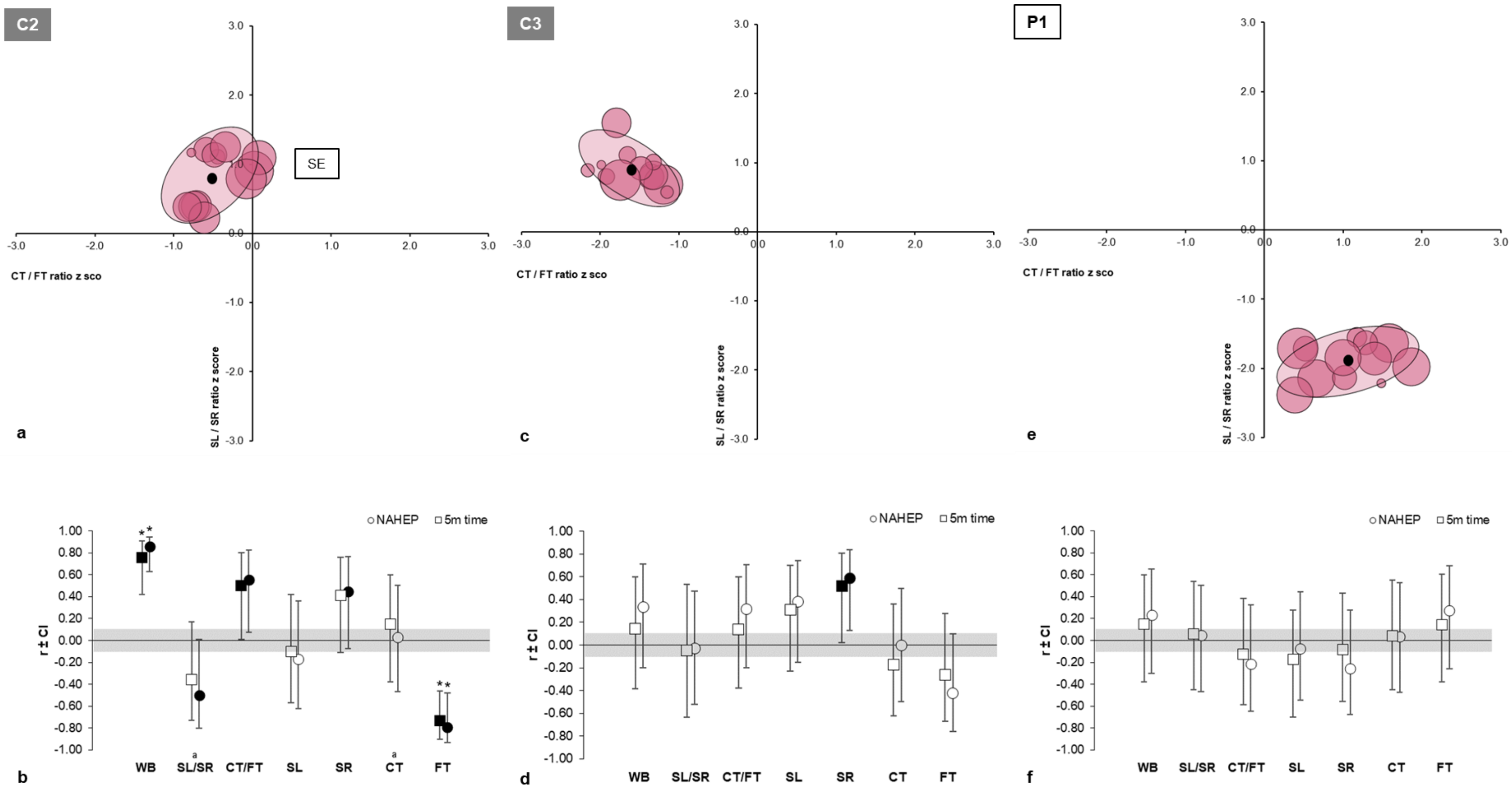

Figure H.3. Whole-body kinematic strategy (a,c and e) of participants C2, C3 and P1. Each marker depicts a single sprint with marker sizes reflecting acceleration performance (a larger marker size equates to greater NAHEP). Where whole-body kinematics are meaningfully related to NAHEP, the theoretical favourable direction change in strategy for better sprint performance is included as a compass bearing. Relationships (with 90% confidence intervals) of their whole-body kinematic strategy, normalised spatiotemporal variables and length/rate and contact/flight ratios with NAHEP and 5 m time are also shown (b, d and f). For clarity, to aid comparisons between relationships of NAHEP and 5 time with variables, the direction of relationships between 5 m time and variables has been inverted. Black filled makers depict relationships $r \geq 0.43$ and asterisks indicate that relationships are statistically significant ($p < 0.05$). Grey-filled participant number boxes denote control participants and white-filled participant number boxes denote participants involved in baseline (Stages 1 and 2) only.

WB = whole-body kinematic strategy; SL/SR = length/rate ratio; CT/FT = contact/flight ratio; SL = step length; SR = step rate; CT = contact time; FT = flight time

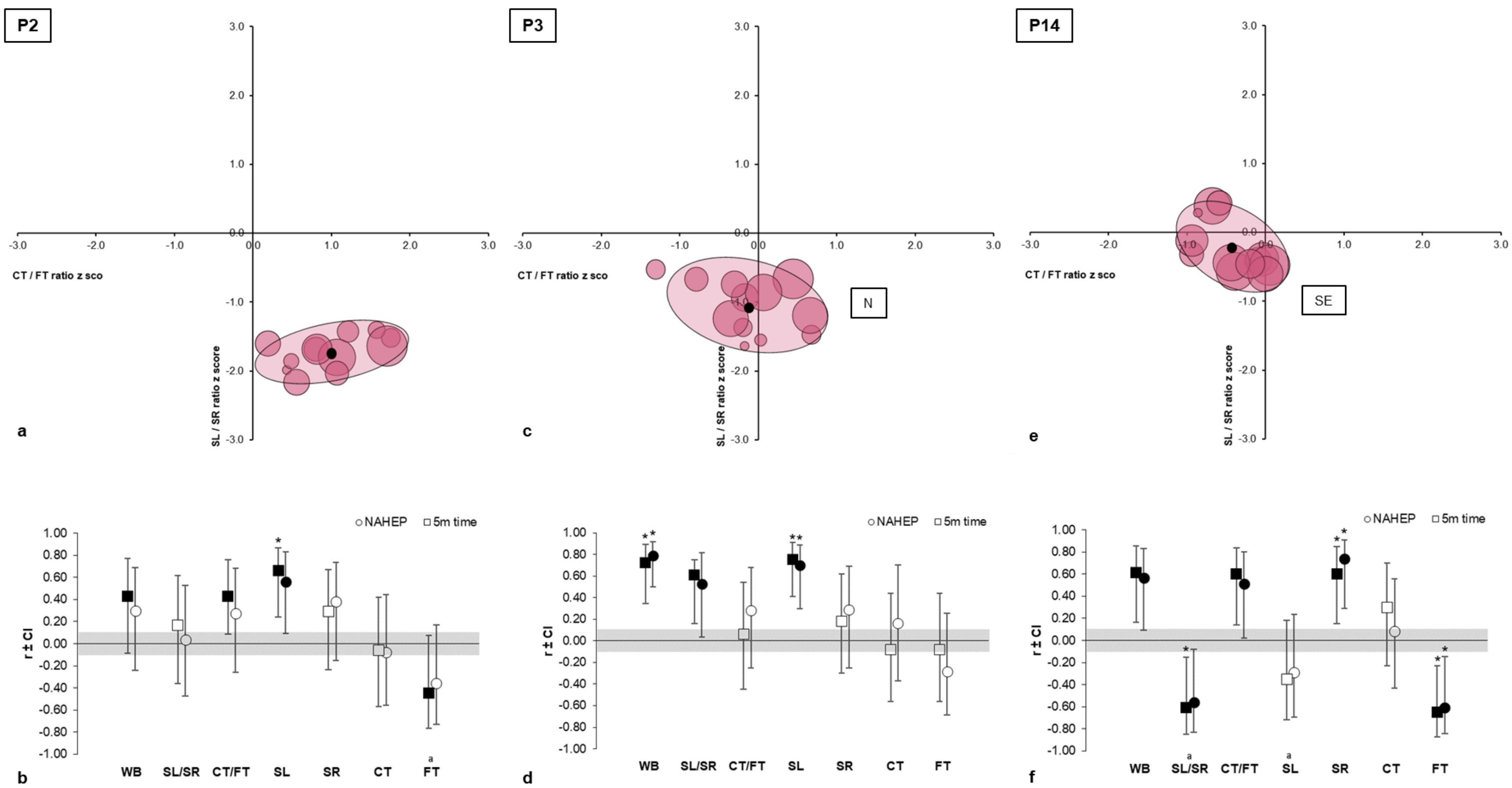

Figure H.4. Whole-body kinematic strategy (a,c and e) of participants 2,3 and 14. Each marker depicts a single sprint with marker sizes reflecting acceleration performance (a larger marker size equates to greater NAHEP). Where whole-body kinematics are meaningfully related to NAHEP, the theoretical favourable direction change in strategy for better sprint performance is included as a compass bearing. Relationships (with 90% confidence intervals) of their whole-body kinematic strategy, normalised spatiotemporal variables and length/rate and contact/flight ratios with NAHEP and 5 m time are also shown (b, d and f). For clarity, to aid comparisons between relationships of NAHEP and 5 time with variables, the direction of relationships between 5 m time and variables has been inverted. Black filled makers depict relationships larger than $r \geq 0.43$ and asterisks indicate that relationships are statistically significant ($p < 0.05$). Participants were involved in baseline (Stages 1 and 2) only

WB = whole-body kinematic strategy; SL/SR = length/rate ratio; CT/FT = contact/flight ratio; SL = step length; SR = step rate; CT = contact time; FT = flight time

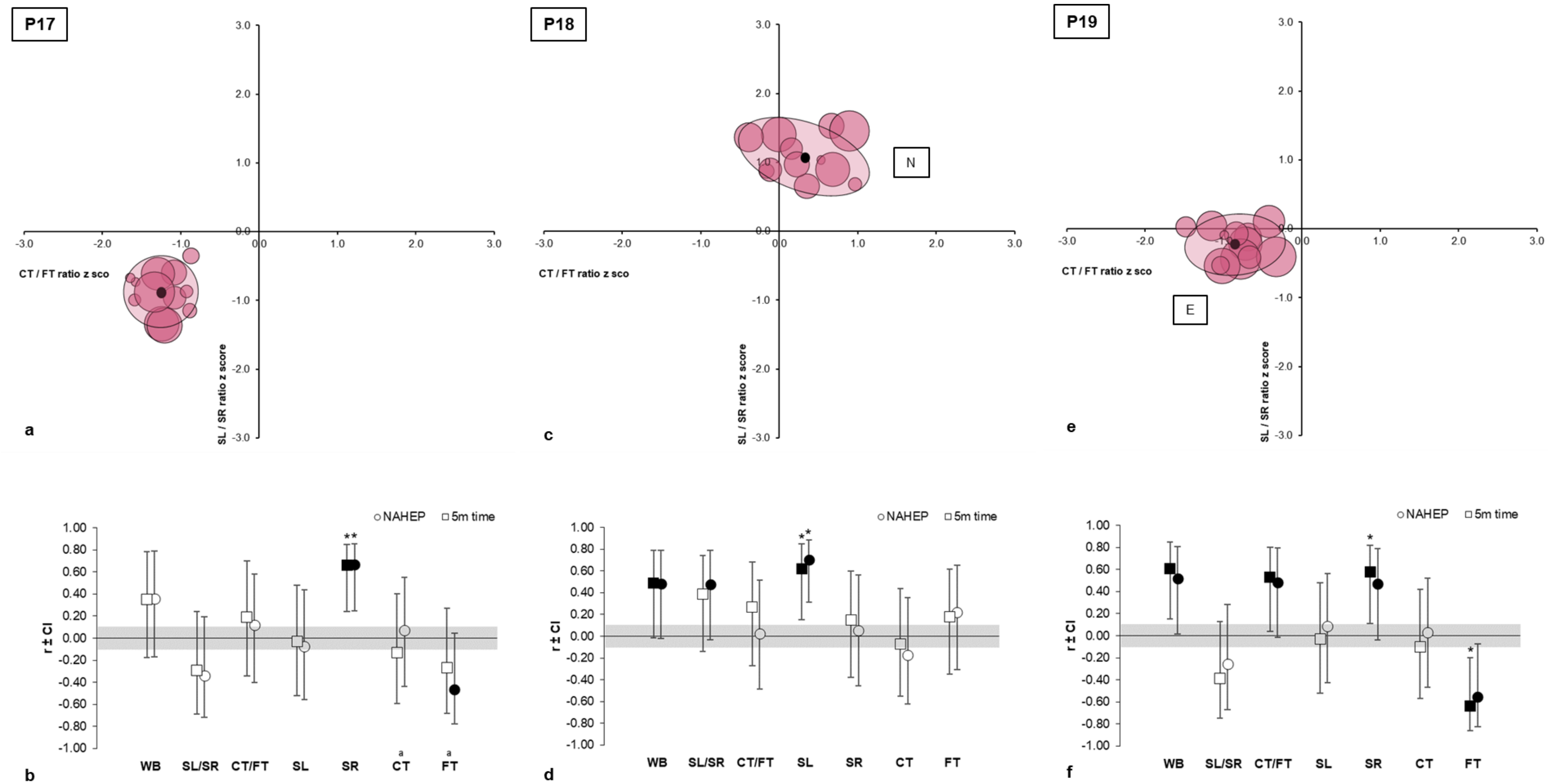

Figure H.5. Whole-body kinematic strategy (a,c and e) of participants 17-19. Each marker depicts a single sprint with marker sizes reflecting acceleration performance (a larger marker size equates to greater NAHEP). Where whole-body kinematics are meaningfully related to NAHEP, the theoretical favourable direction change in strategy for better sprint performance is included as a compass bearing. Relationships (with 90% confidence intervals) of their whole-body kinematic strategy, normalised spatiotemporal variables and length/rate and contact/flight ratios with NAHEP and 5 m time are also shown (b, d and f). For clarity, to aid comparisons between relationships of NAHEP and 5 time with variables, the direction of relationships between 5 m time and variables has been inverted. Black filled makers depict relationships larger than $r \geq 0.43$ and asterisks indicate that relationships are statistically significant ($p < 0.05$). Participants were involved in baseline (Stages 1 and 2) only.

WB = whole-body kinematic strategy; SL/SR = length/rate ratio; CT/FT = contact/flight ratio; SL = step length; SR = step rate; CT = contact time; FT = flight time

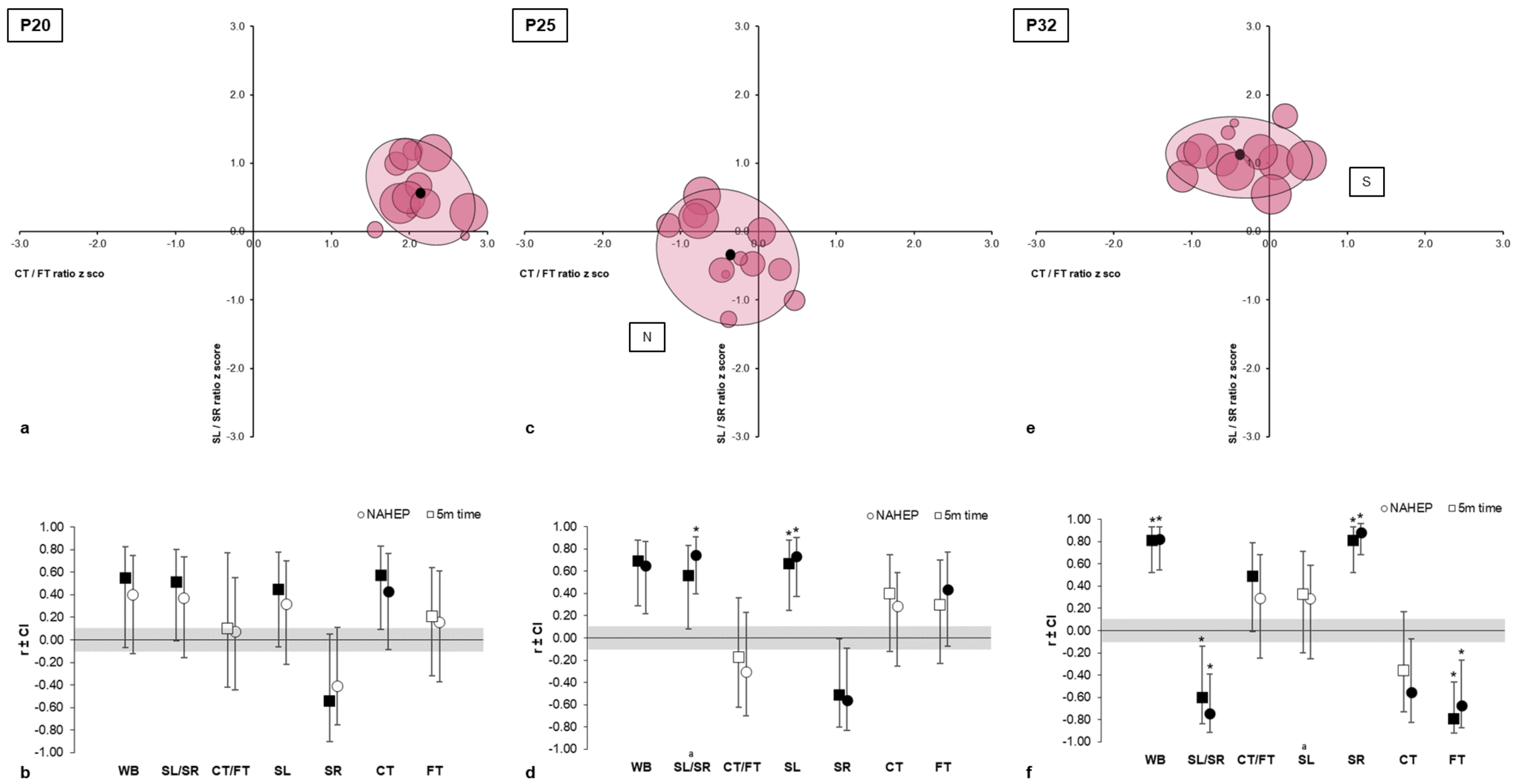

Figure H.6. Whole-body kinematic strategy (a,c and e) of participants 20,25 and 32. Each marker depicts a single sprint with marker sizes reflecting acceleration performance (a larger marker size equates to greater NAHEP). Where whole-body kinematics are meaningfully related to NAHEP, the theoretical favourable direction change in strategy for better sprint performance is included as a compass bearing. Relationships (with 90% confidence intervals) of their whole-body kinematic strategy, normalised spatiotemporal variables and length/rate and contact/flight ratios with NAHEP and 5 m time are also shown (b, d and f). For clarity, to aid comparisons between relationships of NAHEP and 5 time with variables, the direction of relationships between 5 m time and variables has been inverted. Black filled makers depict relationships larger than $r \geq 0.43$ and asterisks indicate that relationships are statistically significant ($p < 0.05$). Participants were involved in baseline (Stages 1 and 2) only.

WB = whole-body kinematic strategy; SL/SR = length/rate ratio; CT/FT = contact/flight ratio; SL = step length; SR = step rate; CT = contact time; FT = flight time