Effects of Approach Step Strategy on Kinematics of Sprint Hurdling

Lee J. Rowley

A thesis submitted in partial fulfilment of the requirements of
Sheffield Hallam University
for the degree of Doctor of Philosophy

December 2022

Candidate Declaration

I hereby declare that:

1. I have not been enrolled for another award of the University, or other academic or professional organisation, whilst undertaking my research degree.

2. None of the material contained in the thesis has been used in any other submission for an academic award.

3. I am aware of and understand the University's policy on plagiarism and certify that this thesis is my own work. The use of all published or other sources of material consulted have been properly and fully acknowledged.

4. The work undertaken towards the thesis has been conducted in accordance with the SHU Principles of Integrity in Research and the SHU Research Ethics Policy.

5. The word count of the thesis is 34,499.

Name	*Lee James Rowley*
Date	*December 2022*
Award	*PhD*
Research Institute	*Health and Wellbeing*
Director of Studies	*Dr Sarah Churchill*

Abstract

Effects of Approach Step Strategy on Kinematics of Sprint Hurdling

Lee J. Rowley, Sheffield Hallam University, 2022

The aim of this thesis was to investigate the effects of first hurdle step strategy on sprint hurdle performance in the senior men's 110 metre hurdles event.

A series of kinematic analyses were undertaken, using high-performance domestic sprint hurdlers, and with data collected from previously recorded footage of elite athletes competing in the final of the previous ten World Athletics Championships. Comparisons were made between athletes with seven-step approach and eight-step approach strategies.

The studies found that mean block spacing was 0.08 m further apart, block contact time 0.06 s longer, first step 0.25 m longer and first ground contact 0.03 s longer for seven-step athletes compared with eight-step athletes. There was also a greater vertical displacement of the centre of mass (CoM) (0.04 m) for the seven-step athletes. The front hip mean angular acceleration was $197°/s^2$ slower for the seven-step athletes than the eight-step athletes. Additionally, seven-step athletes reduced the length of the final step before hurdle take-off by 0.14 m compared with the previous step, whereas the eight-step athletes extended their final step by 0.17 m. Take-off distance was 0.20 m further from the hurdle and touchdown was 0.42 m closer to the hurdle for seven-step athletes.

There was no difference between groups for mean horizontal velocity at the moment of block exit (0.14 m/s), throughout the hurdle clearance (0.02 m/s) or the approach time to the first hurdle from the block clearance (0.01 s).

This body of research makes a considerable contribution to academic knowledge, has relevant practical implications pertaining to performance for coaches and athletes, and provides the basis for a wealth of future research within this specific aspect of the sprint hurdles race performance. There was no identified difference between the absolute race performance of seven- and eight-step athletes.

Publications

Published Journal Manuscripts

Rowley, L.J., Churchill, S., Dunn, M., and Wheat, J., (2021). Effect of hurdling step strategy on the kinematics of the block start. *Sports Biomechanics.*

Rowley, L.J., Churchill, S., Dunn, M., and Wheat, J., (2021). Effect of hurdling step strategy on the kinematics of the hurdle technique. *Sports Biomechanics.*

In Preparation

Rowley, L.J., Churchill, S., Dunn, M., and Wheat, J., (2022). Effect of step strategy on World Championship 110-metre hurdles performance. *Sports Biomechanics.*

Acknowledgements

This body of research would not have been possible without the support provided by a number of people. My supervisory team, including Professor Jon Wheat, Dr Marcus Dunn, and my Director of Studies, Dr Sarah Churchill, played a huge part in making this all happen. Thank you all for having the faith in me to complete this, both from my initial proposal and as I encountered numerous life challenges throughout the programme.

I am hugely grateful for the assistance provided by my friends and other researchers who accompanied me around the country, assisting me with numerous data collections. Thank you to all the athletes and their coaches who were a part of the research programme and I hope you benefit from both the findings of this research and the biomechanical data provided to you from the collected footage.

World Athletics, and particularly Michael Lasserre (Creative Producer/Chief Editor) were a huge help in providing historical footage and I thank them for their cooperation, enthusiasm, and willingness to support the body of research.

I must also thank those who have coached and supported me for many years within the sport of athletics and those that have fuelled the fire that is my passion for the event of sprint hurdling. Without the encouragement of people like Barry Priest, my first hurdles coach, and Mr Chris Smith, the teacher who introduced me to hurdling, none of this would have been possible.

I am particularly thankful to my wife for all of her love and support, and having the belief in me, even when I didn't. I am eternally sorry for spending the equivalent of a decent holiday every year for the past seven years, on many absent days and evenings of stress. I hope I will be more present now this is completed and look forward to spending the extra available time with Katie and my beautiful young children Elliott and Emilia.

Table of Contents

Abstract......i
Candidate Declaration......ii
Publications......v
Published Journal Manuscripts......v
In Preperation......v
Acknowledgements......vi
List of Figures......x
List of Tables......xi
1. Introduction......1
1.1 Motivation for Research......1
1.2 Aim and Objectives......2
1.2.1 Aim......2
1.2.2 Objectives......2
1.3 Thesis Structure......3
2. Literature Review......5
2.1 Introduction......5
2.1.1 Context of Sprint Hurdling......5
2.1.2 Technical Considerations......6
2.2 Biomechanics of the start and block clearance......8
2.2.1 Spatio-temporal variables.......8
2.2.2 Kinematic Variables......12
2.2.3 Kinetic variables......17
2.3 Acceleration phase......19
2.3.1 Spatio-temporal variables......19
2.3.2 Kinematic variables......22
2.3.3 Kinetic variables......25
2.4 Hurdle clearance phase......26

2.4.1 Spatio-temporal variables 26

2.4.2 Kinematic variables 30

2.4.3 Kinetic variables 32

3. Effect of hurdling step strategy on the kinematics of the block start 33

3.1 Introduction 33

3.2 Methods 36

3.2.1 Participants 36

3.2.2 Data collection 36

3.2.3 Data Processing 42

3.2.4 Statistical Analysis 43

3.3 Results 48

3.4 Discussion and Implications 51

3.5 Conclusion 56

4. Effect of hurdling step strategy on the kinematics of the hurdle technique 57

4.1 Introduction 57

4.2 Methods 62

4.2.1 Participants 62

4.2.2 Data collection 62

4.2.3 Data Processing 62

4.2.4 Statistical Analysis 63

4.3 Results 67

4.4 Discussion and Implications 67

4.5 Conclusion 78

5. Effect of step strategy on World Championship 110-metre hurdles performance. 80

5.1 Introduction 80

5.2 Methods 83

5.2.1 Participants 83

5.2.2 Data collection 83

5.2.3 Data Processing 86

5.2.4 Statistical Analysis 86

5.3 Results 87

5.4 Discussion and Implications 90

5.5 Conclusion 94

6. Discussion 95

6.1 Summary of Findings 95

6.2 Limitations 101

6.3 Future Research 103

6.4 Practical Implications 105

6.5 Contribution to Knowledge 109

6.6 Conclusion 110

7. References 112

List of Figures

Figure 2.2.1.1 Bunched, medium and elongated block spacings (Reproduced from data provided by Harland and Steele, 1997).

Figure 2.3.2.1 Identification of breakpoints from CoM (CG) location (shown with open circles). Reproduced from Nagahara et al. 2014.

Figure 3.2.2.3 Plan view of camera set-up for hurdle trials (not to scale).

Figure 3.2.2.3 Plan view of camera set-up for hurdle trials (not to scale).

Figure 3.3.1 Mean first step differences of seven-step athletes compared with eight-step athletes.

Figure 3.3.2 Seven and eight-step strategy mean (±SD) step lengths and time to fourth step (not to scale).

Figure 4.2.2.1 Plan view of camera set-up for hurdle trials (not to scale).

Figure 4.3.1 Seven and eight-step strategy mean (SD±) step lengths (to touchdown step cone), take-off distances and approach times to hurdle take-off (shown adjacent to hurdle) (not to scale).

Figure 4.4.1 Trajectory of CoM over the hurdle for seven and eight-step strategies.

Figure 5.2.2.1 Frames showing block clearance, first hurdle, and second hurdle clearances from the World Athletics Championships - Berlin 2009.

Figure 5.4.1 Take-off and touchdown distances for seven- and eight-step strategists over hurdles one and two (not to scale).

List of Tables

Table 3.2.2.1 Description of technique variables calculated from the start camera view.

Table 3.2.2.2 Description of technique variables calculated from the overview camera view.

Table 3.2.3.1 Description of anthropometric variables.

Table 3.2.4.1 Seven and eight-step group mean values (±SD), effect size and p values for kinematic variables.

Table 3.2.4.2 Seven and eight-step group mean values (±SD), effect size and p values for approach step variables.

Table 3.2.4.3 Seven and eight-step group mean anthropometric measurements (±SD), effect size and p values.

Table 4.2.3.1 Description of technique variables calculated from the hurdle camera view.

Table 4.2.3.2 Description of technique variables calculated from the overview camera view.

Table 4.2.3.3 Description of anthropometric variables.

Table 4.3.2 Seven and eight-step group mean values (±SD), effect size and significant differences for technique variables.

Table 4.3.3 Seven and eight-step group mean values (±SD), effect size and significant differences for approach step variables.

Table 4.3.4 Seven and eight-step group mean anthropometric measurements (±SD), effect size and p values.

Table 5.2.1.1 Footage provided by World Athletics for analysis.

Table 5.2.3.1 Description of technique variables.

Table 5.2.4.1 Seven and eight-step group mean values (±SD), effect size and significant differences for technique variables.

1. Introduction

1.1 Motivation for Research

The men's sprint hurdles event is one of only five track disciplines to have been part of the Olympic programme since the first modern day Olympics held in Athens in 1896 (Warden, 1995). Hurdling is a sprint event where the aim is to cover the 110 m horizontal distance, clearing each of the hurdles in the shortest time.

The first instance of the current hurdle technique in use was by a single competitor at the 1900 Olympic Games in Paris (Warden, 1995). The technique involved turning the hurdle clearance from a leap into an adapted sprint step, effectively allowing the athlete to maintain momentum throughout the race. The event was won in a time of 15.5 s in Paris whereas the fastest athletes in the world are currently capable of completing the 110 m hurdles in less than 13.00 s and the World Record stands at 12.80 s, set in 2012.

The ability to generate a high level of horizontal velocity is ultimately the key factor for success. Sprint hurdlers must possess exceptional basic sprint speed allied to effective hurdling technique to achieve a mastery of the event.

Each athlete must clear a series of ten evenly spaced (9.14 m apart) barriers which stand vertically at 1.067 m. The first hurdle is 13.72 m from the start line and the last hurdle is 14.02 m from the finish line. The spatial constraints of the intra-hurdle distance dictate that a three-step pattern between hurdles is the most suitable, taking off with a dedicated leg and landing using the opposite for each of the hurdles (Hay, 1992).

The success of the start and first hurdle approach phases can be decisive to the outcome of the race. Hurdlers typically perform either an eight-step or, what is now becoming more common amongst international athletes, a seven-step approach. The restrictions of the approach distance results in changes to natural step length and step frequency.

There is currently a lack of published research into the first hurdle clearance or the start and approach phases of sprint hurdling (Iskra & Čoh, 2006) and, no published research which differentiates participants by approach step-strategy. There is a void in the understanding of both athletes and coaches in respect of whether there is a key performance difference, whether the seven-step strategy is a suitable option for all hurdlers, or where differences occur throughout the block clearance, approach and hurdle clearance phases. By informing an individualistic approach to profiling and enabling training for seven- or eight-step strategies, improvements can be made to both performance and training practice by reducing wasted time on ineffective training practices. This programme of research addresses many of the gaps in the knowledge in order for coaches and athletes to make more informed decisions when considering transitioning athletes form an eight- to a seven-step strategy. The focus is the positioning of the starting blocks and the block clearance, the individual approach steps, and the hurdle clearances. The research is broken down into specific phases of the event and focuses upon considered spatio-temporal and kinematic parameters.

1.2 Aim and Objectives

1.2.1 *Aim*

To investigate the effects of first hurdle step strategy on sprint hurdle techniques and performance in the senior men's 110 m hurdles event.

1.2.2 *Objectives*

1. To investigate the effect of step strategy to the first hurdle on the kinematics of the block start.
2. To investigate the effect of step strategy to the first hurdle on the kinematics of first hurdle clearance.

3. To investigate the effect of step strategy to the first hurdle on the kinematics of the approach steps.

4. To investigate whether step strategy group differences in sub-elite athletes are repeated by elite athletes during world class performances.

1.3 Thesis Structure

Chapter 2: A critical appraisal of the current body of published research into the sprint hurdles, and the key phases of the event. The start, acceleration and hurdle clearance phases were reviewed spatio-temporally, kinematically, and kinetically, with supporting research from flat sprints. A thorough understanding of the event and the relevant research helped to shape the design of the proposed research.

Chapter 3: A study into the effect of first hurdle step strategy on the kinematics of the block start. Investigative research into the block position, the block clearance and the first four steps out of the blocks. The research programme was broken down into phases and this chapter focused upon the first phase of the event.

Chapter 4: A study into the effect of first hurdle step strategy on the kinematics of the hurdle clearance technique. Investigative research into the hurdle clearance and the final four steps prior to the hurdle take-off. This chapter focused upon the second phase of the event.

Chapter 5: A study into whether step strategy group differences in sub-elite athletes are repeated by elite athletes during world class performances. Investigation from recorded television footage of historical World Athletics Championships performances. This chapter considered the findings of chapters 3 and 4 and whether they are repeated amongst world class athletes.

Chapter 6: A culmination of this program of research, providing discussion and synthesis of the findings, the practical implications, and the contribution to current understanding. Conclusions presented from the research, including the limitations of the research methods and the direction of future investigation.

2. Literature Review

2.1 Introduction

2.1.1 *Context of Sprint Hurdling*

The men's sprint hurdles event is one of only five track disciplines to have been part of the Olympic programme since the first modern day Olympics held in Athens in 1896 (Warden, 1995). It is a sprint-based event where the aim is to cover the 110 metre (m) horizontal distance, clearing each of the hurdles, in the shortest time. Therefore, the ability to generate a high level of horizontal velocity is ultimately the key factor for success.

Each athlete must negotiate a series of ten evenly spaced (9.14 m) barriers which stand vertically at 1.067 m. The first is approached from a start line 13.72 m away with 14.02 m from the last hurdle to the finish line. The event has previously been broken down into the following phases: start phase and approach, clearance steps, inter-hurdle steps and run-in from the final hurdle (Tidow, 1991). The constraints of the inter-hurdle distance dictate that a three-step pattern between hurdles is the most suitable, taking off with a dedicated leg and landing using the opposite for each of the hurdles. All elite hurdlers conform to a three-step rhythm. Sprint hurdling has been the subject of several biomechanical studies which attempt to identify the key parameters of hurdle clearance (Iskra & Čoh, 2006).

The first instance of the current hurdle technique in use was by a single competitor at the 1900 Olympic Games in Paris (Warden, 1995). The technique involved turning the hurdle clearance from a leap into an adapted sprint step, effectively allowing the athlete to maintain momentum throughout the race. The event was won in a time of 15.5 seconds (s) in Paris whereas the fastest athletes in the world are currently capable of completing the 110 m hurdles in less than 13.00 s and the World Record stands at 12.80 s, set in 2012.

2.1.2 *Technical Considerations*

The sprint hurdles are technically among the most demanding of track and field events (Čoh, 2004). Sprint hurdlers must possess exceptional basic sprint speed and 100 m performances approaching ten seconds (with a single occurrence of a sprint hurdler clocking a sub 10 second performance in 2016) are often reported in the worlds' best athletes (Arnold, 1993). This level of speed must be allied to correct hurdling technique to achieve a degree of mastery of the event.

Hitting any of the hurdles negatively impacts performance. Therefore, the ability to clear each of the hurdles in the shortest time possible whilst maximising sprint speed is the key element defining the competition outcome (Čoh, Jošt & Škof, 2000) and even minor technical errors can cause catastrophic outcomes with it common for hurdlers to fall at all competitive levels (Hommel, 2003). Subsequently, biomechanical investigation has previously focused upon the characteristics of successful hurdle clearance (Čoh & Iskra, 2012; Sidhu & Singh, 2012) and generally, the clearance of hurdles throughout the middle of the race (Iskra & Čoh, 2006; McDonald & Dapena, 1991). This represents the phase where the athlete has the greatest horizontal velocity and this shows a strong correlation between the end performance of the race (Čoh, 1993; Grimshaw, 1995). Additionally, there has been some focus on hurdle three (Salo & Grimshaw, 1998; Mero & Luhtanen, 1985).

When athletes leave the starting blocks, they must develop acceleration via a suitable step strategy which also positions them correctly for clearance of the first hurdle. Elite hurdlers take-off approximately 2.10 - 2.40 m from the first hurdle (Tidow, 1991; Mann, 2011), leaving 11.32 – 11.62 m from the start line to the point of take-off for the athlete to generate as much horizontal acceleration as possible. This phase of the race presents a dilemma where athletes must consider whether to use either an eight-step approach to the first hurdle or to opt for the less conventional seven-step approach (Salo, 2002). Traditionally, seven-step approaches have been the reserve of taller athletes (those over 2.00 m tall) who, because of longer leg and step lengths have found it difficult to approach the first hurdle from eight steps. An eight-step approach led to either getting too close to the first hurdle or having to cut step lengths to an extent that it is counterproductive in developing horizontal velocity.

In recent years the seven-step approach has become more commonplace amongst senior world-class hurdlers and in 2015, was used by fifteen of the twenty fastest men in the world with a stature range from 1.82 m to 1.96 m tall (collated by the author from multiple open access resources). From anthropometric data of Olympic athletes at the 1960 Olympics, Tanner (1964) measured the stature of all male sprint hurdles and identified a mean of 1.83 m. From the data collated by the author, the mean stature of the world's top twenty athletes in 2015 was 1.86 m. It was also found to be 1.87 m for seven-step approach athletes whereas the mean average for the eight-step approach athletes was 1.82 m (range of 1.78 – 1.88 m). Whilst the average world-class sprint hurdler now appears taller than in 1960 (as well as faster) the structure of the event has remained entirely the same and the possible benefits of a seven-step approach should be investigated.

Both leg length and flexibility are possible relevant factors which could play a considerable part in defining the success of the hurdle clearance. Athletes with shorter legs typically need to elevate their centre of mass (CoM) to a relatively greater extent than athletes with longer legs to achieve the same height and clear the same sized hurdle, effectively increasing the length of the path that the CoM must take and possibly the hurdle flight time. Increases in the length of the path of the CoM can lead to a greater time taken to cover the same horizontal distance on the track and ultimately, a slower race performance.

The start, approach, and clearance of the first hurdle have received very little attention in the published biomechanics literature. Whilst there has been considerable investigation into the biomechanics of the block clearance and start phase of flat sprint races, hurdlers execute either a seven- or eight-step approach. This causes alterations to their natural sprint step length (Tidow, 1991) and frequency which may influence the position of the starting blocks and the athlete in the set position.

To allow coaches and athletes to make more informed decisions about step strategy, biomechanical investigations into the seven-step approach need to identify whether there is a race performance benefit, where differences occur throughout the event phases, and the adaptations athletes need to make to complete a seven-step strategy.

2.2 Biomechanics of the start

2.2.1 *Spatio-temporal variables.*

It has previously been identified in both flat and hurdle sprint races that the success of the start and approach phases are decisive to the outcome of the race (Charalambous, Irwin, Bezodis & Jošt, 2012; Tidow, 1991; Mero & Luhtanen, 1985). Sprint hurdlers start from block positions much the same as flat sprinters do (Bezodis, Brazil, Von Lieres und Wilkau, Wood, Paradisis, Hanley, Tucker, Pollitt, Merlino, Vazel, Walker & Bissas, 2019). In the crouch position the front foot is positioned roughly in-line with the grounded knee of the rear leg and the hands are positioned with the tip of the first finger and the thumb up to the start line. Bezodis, Brazil, von Lieres und Wilkau, Wood, Paradisis, Hanley, Tucker, Pollitt, Merlino, Vazel, Walker and Bissas (2019) found that seven-step approach hurdlers position the blocks further apart, with the front foot closer to the start line than flat sprinters. This crouch position provides four areas of contact with the ground and the blocks whilst the athlete is in the 'set' position using the tips of the fingers of both hands and the toes of both feet. If the sprinter or hurdler fails to carry out the block clearance correctly, it is particularly difficult to recover any loss of time throughout the later phases of the race (Mann, 2011). Therefore, correct positioning of the whole body in the set position is extremely important.

The placement of the starting blocks on the start is critical and research shows that the distances for the front and rear block from the start line directly influence the position of the CoM in the set position (Harland and Steele, 1997). Once movement is initiated from the blocks the trajectory and velocity of the athlete's CoM throughout the first step is dependent upon correct positioning of the CoM (Čoh, Tomažin & Štuhec, 2006; Schot & Knutzen, 1992). Harland and Steele (1997) identify three general options for the spacing between the starting blocks; elongated (spacing between the block faces > 0.5 m), medium (spacing between the block faces > 0.3 < 0.5 m) and bunched (spacing between the block faces < 0.3 m) (Figure 2.2.1.1).

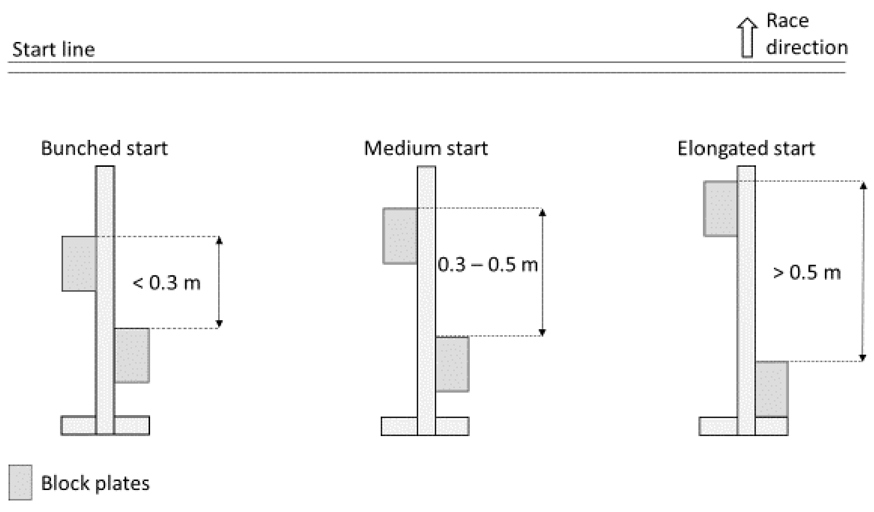

Figure 2.2.1.1 Bunched, medium and elongated block spacings (Reproduced from data provided by Harland and Steele, 1997).

The first step of an elongated start has been found to be 6% longer than the first step of a bunched start (Schot & Knutzen, 1992). At the point of first foot contact the elongated start resulted in greater horizontal displacement and velocity of the CoM, maintenance of a lower position of the CoM and larger propulsive impulses (Schot & Knutzen, 1992). It was further suggested that a limit to first step length exists and that the increased effect of braking force due to overreaching may not be beneficial to the development of acceleration throughout subsequent steps. Although for both the bunched and elongated starts, the position of the CoM was behind the first foot contact in both instances (Schot & Knutzen, (1992). These findings suggest that the potentially detrimental effects of overreaching with the first step do not occur from either an elongated or bunched start position. When using a seven-step strategy, athletes must be aware of the potential increases in braking force if they overreach on the first step, and the effect it could have on the development of acceleration as they approach the first hurdle.

Whilst it has been identified that the bunched start allows the athlete's feet to leave the surface of the blocks in the shortest time, this method of starting may be counter-productive to the development of acceleration in the flat sprints (Bezodis, Trewartha & Salo, 2015; Schot & Knutzen, 1992). Due to the short distance between the start line and first hurdle, a more upright position is required by sprint hurdlers earlier in the race to elevate the CoM to a suitable take-off position, and the requirement for more vertical ground reaction force. Whether the use of a bunched start is a limiting factor in hurdling is not fully understood and has not been observed in any of the world's highest performing athletes. Ground contact times were shorter for the bunched start which resulted in a reduced time in which to generate the necessary mass specific ground reaction forces. This reduction in ground contact times led to a subsequent reduction in propulsive horizontal ground reaction force (Schot & Knutzen, 1992).

From the authors' experience, for both flat sprint races and sprint hurdle races, a medium start is most commonly observed at all levels and often accepted in coaching practice as the most effective way of developing acceleration as sprint distance increases. Previous studies have shown the medium start to result in the quickest performance times at distances of up to 50 yards (45.72 m) (Henry, 1952; Čoh, 1998) but it has also been concluded that due to variations in physiology and anthropometrics there is no single optimum position that is appropriate for all athletes (Bezodis, Salo and Trewartha, 2010a; Atwater, 1982). A suggested distance for positioning of the front block from the start line was proposed by Mann (2011), whereby it is placed at 60% of the distance of the rear block.

It is possible that one of the potential drawbacks of a seven-step approach is the necessity to adapt the start position, moving the feet closer to the start line and creating a bunched position (Arnold, 1992) where the acuteness of the knee angles is increased. This has not been investigated and whether this occurs in practice and whether it is detrimental to sprint hurdle start performance requires further investigation. If seven-step strategists are attempting to push harder on the front block to create a longer first step then the duration of block contact may be increased, leading to an overall drop in race performance. Again, this parameter requires further investigation.

When athletes start from the blocks, they must compromise the amount of force that they apply to the block with the total duration of block contact. From high-performance coaching practice, the author is aware that the sprint-based nature of the hurdles event requires rapid initiation of movement allied to the production of mass specific forces for the greatest degree of acceleration to occur. Whereas less capable sprint starters simply recover the rear foot from the block surface at the initiation of movement to position the foot for the first step, better starters actively use the rear leg for force production against the block surface (Bezodis et al., 2015). Previous findings have shown that the duration of block contact of the rear foot on the blocks may assist with the generation of horizontal power, which in turn could assist in the generation of block exit velocity (Bezodis et al., 2010a). This increased duration of rear block contact is a critical element that defines the sprint start of elite starters in comparison to non-elite starters (Payne and Bladder, 1971). Bezodis, Salo & Trewartha, (2010b) identified that an increased duration of rear block contact led to increases in average external horizontal power and suggested power to be a more suitable measure of sprint start performance as it accounts for changes in both the parameters of time and velocity.

2.2.2 *Kinematic Variables*

The angle of each block face is adjustable to suit each individual athlete's preference. Guissard, Duchateau and Hainaut (1992) investigated the effects of altering block face obliquity. As the block face obliquity of the front block decreased from 70° to 50° and finally to 30° it had a significant effect of increasing start velocity and acceleration. Guissard et al., (1992) identified this improvement in start performance was due to increased muscle stretch along the posterior shank in the set position, inducing a greater contribution of the muscle stretch-shortening cycle. There was no significant change in block contact time for either block face angle. Although, it was beyond the scope of the study to consider obliquity of the block face at angles of less than 30°, it is reasonable to assume that as block face obliquity further decreases that the generation of horizontal power may become difficult to develop as the absolute angle of the force vector increases.

It is possible that there is a limit to the degree of front block face obliquity before it starts to hinder the generation of horizontal power required for a successful start phase, but this is unknown and requires further investigation. In a study of a single elite sprinter (100 m personal best of 10.14 s), Čoh (2006) suggested that the participant's exceptional capability to produce a high degree of horizontal velocity following block clearance (4.11 ± 0.17 $m.s^{-1}$) is in part, a consequence of an effective action of the rear lower limb and a low block face angle (40.8° ± 1.19°) although most sprint starting blocks only permit a limited number of settings with a minimum block face angle dictated by the design of the block and the foot plate. Whether seven- and eight-step hurdlers use different front block positions to adjust their block exit parameters is not yet understood and warrants investigation.

Correct angles of the front and rear knee in the set position are critical components of an effective block clearance. The set position knee angles of skilled sprinters have been quantified several times in previous studies with amalgamated mean front knee angles found to be between 89° and 111° and rear knee angles between 118° and 136° (Slawinski, Bonnefoy, Ontonon, Leveque, Miller, Riquet, Chèze & Dumas, 2010; Mero & Komi, 1990; Mero, 1988; Tellez & Doolittle, 1984). Mann (2011) suggests that the front knee angle should be 90° and the rear knee angle 135° when stationary in the set position but these figures must be used with caution. Atwater (1982) previously identified that no single descriptive set position exists which can be adopted by all sprinters due to the physiological and morphological individualities of sprinters. It is possible though, that the constraints imposed by the event specifications (particularly the approach distance to the first hurdle and the hurdle height) may influence the kinematics of the start position and similarities between step-strategists may be evident.

Milanese, Bertucco & Zancanaro (2014) investigated the rear knee angle in the set position under three conditions. Eleven participants completed a total of thirty sprints over five metres from blocks, ten with rear knee angles at 90°, ten at 115° and ten at 135°. Milanese et al., (2014) found that 90° is preferential to angles of 115° and 135°. It was concluded that a greater amount of horizontal velocity was due to an increased duration of block contact of the rear foot, greater muscular activation and a better push off from the rear leg. Despite a longer duration of block contact of the rear leg, no significant difference was identified between total block duration for each of the three conditions. This notion supports the coaching theory that the stronger the sprinter the more acute the knee joint angles can be in the set position due to the increased strength permitting a greater range of joint extension and a subsequent increase in the degree of acceleration, and a greater block clearance velocity. Bezodis et al., (2010b) claimed that a greater force application by the rear leg on the block surface is what distinguishes superior sprint starters from less able starters.

The height of the CoM in the set position is a critical element of the start phase and is directly influenced by the positioning of the front and rear blocks and the degree of extension of the knee and hip joint angles when moving into the set position. When studying a single elite sprinter, Čoh (2006) identified the position of the CoM in the set position to be 32% (0.54 m) of the athlete's standing height. The block setting was representative of a medium spacing. This figure is in keeping with previous studies by Čoh (1998) where mean relative heights of the CoM were found to be 30 ± 0.02% (0.54 ± 0.05 m) from a sample of thirteen sub-elite (mean 100 m time of 10.73 s) male sprinters.

It has been suggested that positioning the CoM as close as possible horizontally to the start line effectively reduces the distance over which the athlete must displace the CoM from the start line to the finish. Baumann (1976) investigated the position of the

CoM in the set position of three groups of sprinters, classed as either fast, medium or slow. Baumann (1976) found that as the performance level decreased, the horizontal position of the CoM was further from the start line (0.16 m for fast sprinters, 0.20 m for medium sprinters and 0.27 m for slow sprinters).

Moving the blocks closer to the start line and leaning the shoulders, trunk and hips forward in the set position is one method the author has seen of moving the CoM closer to the start line. The result is loading a greater percentage of the body weight onto the hands to create an unstable position when the hands are removed from the track surface, approximately 0.15 s after the gun is fired (Ozolin, 1988). The feet remain in contact with the blocks after the hands have been removed and as such form the only remaining base of support throughout the start phase. Harland & Steele (1997) advocate that any excessive loading of the body weight onto the hands to improve dynamic stability is of no benefit to the athlete's start and would in effect lead to lengthening of the hip extensor load arm and less acute hip, knee and ankle joint angles, resulting in a less efficient start position. Findings from research into the distribution of body weight when in the set position by Mero et al., (1983) found that consistently less than 50% of the total body weight was distributed to the hands (40.5 to 42.6%) irrespective of the performance level whereas Baumann (1976) found that as sprint start performance increased athletes positioned their CoM closer to the start line (0.16 m) and a greater percentage of body weight was loaded upon the hands (73 – 82%), although there was little change identified in the height of the CoM as performance levels increased. It must be noted that Baumann's (1976) research is approaching 50 years old, and reflects a period where athletes were encouraged to 'load' the hands in the 'set' position so that when removed from the track surface as the gun was fired, the athlete would be propelled forwards out of the blocks, almost in a 'falling' motion. This understanding has now been replaced with removing the loading of the hands and greater emphasis being placed upon the 'push' of the feet on the starting blocks and the stability of the start phase. The benefits of moving the load from the hands to the feet enables force to be generated quicker on the block surface and a more efficient block clearance to be achieved. Haarland & Steele's (1997) more recent research reflects this change and further identifies the benefits of not loading the hands in preference of more acute joint angles and a beneficial start position. In current experiential practice, athletes are not encouraged to load the hands as coaching practice appreciates the identified benefits. Research conducted solely with elite sprinters identified the position of the CoM to be 0.12 – 0.20 m from the start line (Atwater, 1982). It is not yet understood whether the step strategy of individual hurdlers influences the positioning of the CoM.

The first step following block clearance is the most difficult to execute correctly yet the most important step of the entire flat sprint race (Mann, 2011). Mann (2011) further identifies that the ground contact of the athlete's first step is critical and particularly its location in relation to the position of the whole-body CoM. For each ground contact, there is a period of braking followed by a period of propulsion and the balance between these two phases must be carefully executed. If the CoM is behind the ground contact of the first step, then a braking phase will occur which the athlete will firstly have to overcome before further acceleration can happen. As such, the position of the athlete's first step ground contact must fall behind the whole-body CoM and it is reasonable to evaluate the position of the CoM as an angle from the metatarsophalangeal (MTP) joint of ground contact of the first step (Bezodis, Salo & Trewartha, 2012). Hunter, Marshall & McNair, (2005) identified that better sprinters use an active touchdown (reduced horizontal velocity of the foot) and a small touchdown distance (horizontally from the CoM to the position of the foot) to significantly minimise horizontal braking force.

2.2.3 *Kinetic variables*

When athletes are in the starting blocks, they generate force in both the vertical and the horizontal directions which produces a resultant force vector. Only the horizontal force component is correlated to sprint start performance and the greater the average horizontal force produced the greater the resulting sprint start velocity (Rabita, Dorel, Slawinski, Saez-de-Villarreal, Couturier, Samozino & Morin, 2015). Based on previous research, Mann (2011) suggested high performance sprint starters should aim for a block contact time of 0.28 s during which a force of over 900 N is produced and a resultant horizontal velocity of 4 $m \cdot s^{-1}$. As much of the 900 N force as possible produced must be directed in the horizontal direction but due to necessity imposed in recovering the legs from behind the body and subsequently supporting body weight for the first step, it is not possible to direct all the force generated in this way. In fact, the vertical component yields more force than the horizontal component, otherwise the location of the body in the start position would cause the athlete to lose balance or possibly fall. To maximise horizontal force production during the block clearance and initial acceleration phases, the athlete gradually transitions to fully upright sprinting once at maximal velocity and the ability to produce horizontal force is traded for the benefits of increased step-length and step-frequency (Weyand, Sandell, Prime & Bundle, 2010). As hurdlers take only seven- or eight-steps before take-off, correct application of force throughout the start may be even more crucial due to having less steps to correct a poor force application. Mann (2011) further stated that almost 60% of the maximal horizontal velocity of a flat sprint is generated throughout the start phase (by the end of the second step) and the most suitable method for increasing horizontal force production is via the development of the magnitude of resultant force production at the start. The mean horizontal velocity of the CoM during the first step has previously been identified as a key element defining the success of the block clearance and the development of acceleration (Čoh, Jošt, Škof, Tomažin & Dolenec, 1998).

Statistically significant correlations have been reported between horizontal force production and sprint velocity with the degree of horizontal force being attributed to the amount of leg strength of the athlete (Mero, 1988). This finding may suggest why some hurdlers are not able to successfully execute a seven-step approach until later in their careers when high levels of leg strength have been established, and the ability to generate a greater impulse for each step has been developed. Ilbeigi, Friso & Van Gheluwe (2010) further identified that muscle mass and volume can be a good predictor of horizontal force production and sprint start performance.

Whilst the amount of force which can be applied to the starting blocks is correlated strongly with sprint start performance, due to the nature of the event it is essential that athletes do not achieve greater force production by increasing contact times. Impulse is a product of the force per unit of time and Morin, Slawinski, Dorel, Saez-de-Villarreal, Couturier, Samozino, Brughelli & Rabita, (2015) found that greater horizontal impulse led to greater changes in the velocity of the CoM throughout the block clearance. When working with two groups of sprinters (one of which was elite, 100 m time 10.27 s ± 0.14) Slawinski et al., (2010) found that as 100 m sprint performance level increased so did the degree of impulse generated on the blocks. The aim of sprinting is to cover the required distance in the fastest possible time; therefore, impulse should be increased via an increase in force production and not an increase in block contact time. For this reason, it may be more suitable to measure impulse in favour of force due to impulse considering the duration of the force application throughout the block clearance phase.

The parameters that best define block clearance success are reaction time, propulsive horizontal impulse from the front block and horizontal velocity of the CoM (Čoh et al., 1998). Further to these findings, Bezodis et al., (2010b) suggested that average horizontal external power is the decisive parameter for assessing sprint start performance. The importance of the first step in sprinting is strongly supported in previous literature with several studies identifying that the most favourable strategy for sprint performance time is effective impulse production from the first step (Salo, Keränen & Viitasalo, 2005; Rabita et al., 2015; Morin et al., 2015).

2.3 Acceleration phase

2.3.1 *Spatio-temporal variables*

Sprint velocity is the product of step frequency and step length and an increase in either (as long as it is not detrimental to the other), or both will result in a greater horizontal velocity. The opportunity for a hurdler to alter step lengths is limited beyond the first clearance due to the regular distance between each of the hurdles and the necessity to execute a three-step pattern. Therefore, for hurdling, the ability to increase step frequency is the dominant performance factor. This is achieved predominantly by a decrease in absolute ground contact time of the foot and not because of repositioning the legs faster during the flight time (Weyand, Sternlight, Bellizzi & Wright, 2000).

The four ground contacts following first hurdle clearance have been postulated to represent the step frequency of an eight-step approach more closely than a seven and it has been stated that an eight-step approach is favourable for this reason (Arnold, 1992). Conversely though, it has been identified that changes to step length occur over several steps and the limiting factor when sprinting is step length and not step frequency. Athletes have been found to achieve over 80% of step frequency within the first step and over 95% by 10 metres (Debaere, Delecluse, Aerenhouts, Hagman & Jonkers, 2012; Rabita et al., 2015). Due to this, it may be that the step frequency is of limited importance prior to the hurdle because the hurdler will be able to increase step frequency almost immediately after touchdown. That is, providing the necessary horizontal velocity of the CoM has been achieved from increased step lengths before take-off.

To investigate the interplay between step length and step frequency, a series of 100 m flat sprint performances were studied using footage from publicly available television broadcasts (Salo, Bezodis, Batterham & Kerwin, 2010). A total of 52 elite performances were reviewed (11 athletes in total) with the aim of establishing whether individual sprinters are step length or step frequency reliant. Overall, the findings identified that there was a large variation between individual performers and that some athletes are more step frequency reliant, and some are more step length reliant. Extrapolating these findings to hurdling, it is possible that those hurdlers that are predominantly step length reliant when sprinting, may be more suited to the increased step lengths of a seven-step approach. Salo et al., (2010) identified that most sprinters are neither step frequency nor step length reliant and manage a balance between the two inversely related variables, suggesting that hurdlers may be able to select the most appropriate step strategy based upon other more significant factors.

Salo et al., (2010) postulated that step length is closely related to magnitude of force production whereas step frequency is closely related to the rate of force production. Inter-hurdle distance represents a spatial constraint to an athlete's step length, and if the hypothesis is correct, subsequently the magnitude of force production too. However, as identified from the sprint research, it is the rate of force production and not the magnitude which is positively correlated at maximum velocity (Weyand et al., 2010). Therefore, limitations to magnitude of force production may be irrelevant with improvements to inter-hurdle race performance focusing upon increasing the rate of force production primarily.

Mero, Komi & McGregor, (1992) suggested that at maximal velocity, step frequency has a more decisive effect on performance than step length and as athletes reach the final phase of approaching their maximal velocity, due to the maximum step length being achieved first, the final increases are primarily a result of faster step frequency. In agreement with Weyand et al., (2000) these final increases in step frequency must be achieved from shorter ground contact times for each step and not a result of repositioning of the legs faster throughout the flight time. Essentially, the fastest sprinters at maximum velocity are temporally defined by a shorter ground contact time, resulting in a greater step frequency, and comparably suitable step-lengths to slower sprinters. Whereas increases in step frequency are predominantly achieved via conditioning of the neuromuscular system, Hunter et al., (2004) suggested that increases in step length are a result of long term increases in strength and power. This was supported by Moir, Sanders, Button & Glaister (2007) in a longitudinal study into the effects of eight weeks of resistance training on the first three steps from the blocks. It was found that increases in maximal and explosive strength led to increased step lengths and reduced step frequencies (a result of increases to both flight and ground contact times). Although, increases in initial step length were not proportional to offset the decrease in step frequency for the first 10 m and improvements were not noted until the 10-20 m phase. As a result, the mean average time for the first 10 m was slower after the eight-week intervention (pre; 1.84 ± 0.13 s, post; 1.95 ± 0.13 s), this was attributed to a possible slow adaptation of the neuromuscular system to effectively use the increases in strength. Strength, power and speed are inherently related and Delecluse (1997) identified that reductions in initial sprint acceleration because of heavy resistance training could be caused by changes in muscle fibre type from IIb into IIa, effectively increasing sprint endurance at the detriment of explosive power from the blocks. This suggests that limiting factors as to whether hurdlers can successfully use a seven-step approach are the levels of maximal and explosive strength of the legs and buttocks and the ability to utilise their strength effectively. This hypothesis warrants further investigation, and the use of strength and power tests should be considered in future studies in conjunction with the measurement of performance related variables. This is currently missing from the published literature. At present, there is no research which identifies where or how throughout the approach to the first hurdle the changes to step lengths occur between seven- and eight-step strategies.

2.3.2 *Kinematic variables*

The kinematics of the acceleration phase were measured by Nagahara, Matsubayashi, Matsuo & Zushi (2014) who investigated 12 male sprinters (mean 100 m time: 10.71 ± 0.33 s) over a 50 m distance. Following examination of the position and trajectory of the CoM the entire acceleration phase was found to comprise of three distinct sub-phases. The transition between each sub-phase was termed a breakpoint with the first occurring between the third and sixth steps (mean: 4.4 ± 0.9) and the second between the tenth and twentieth (mean: 14.1 ± 2.0) steps.

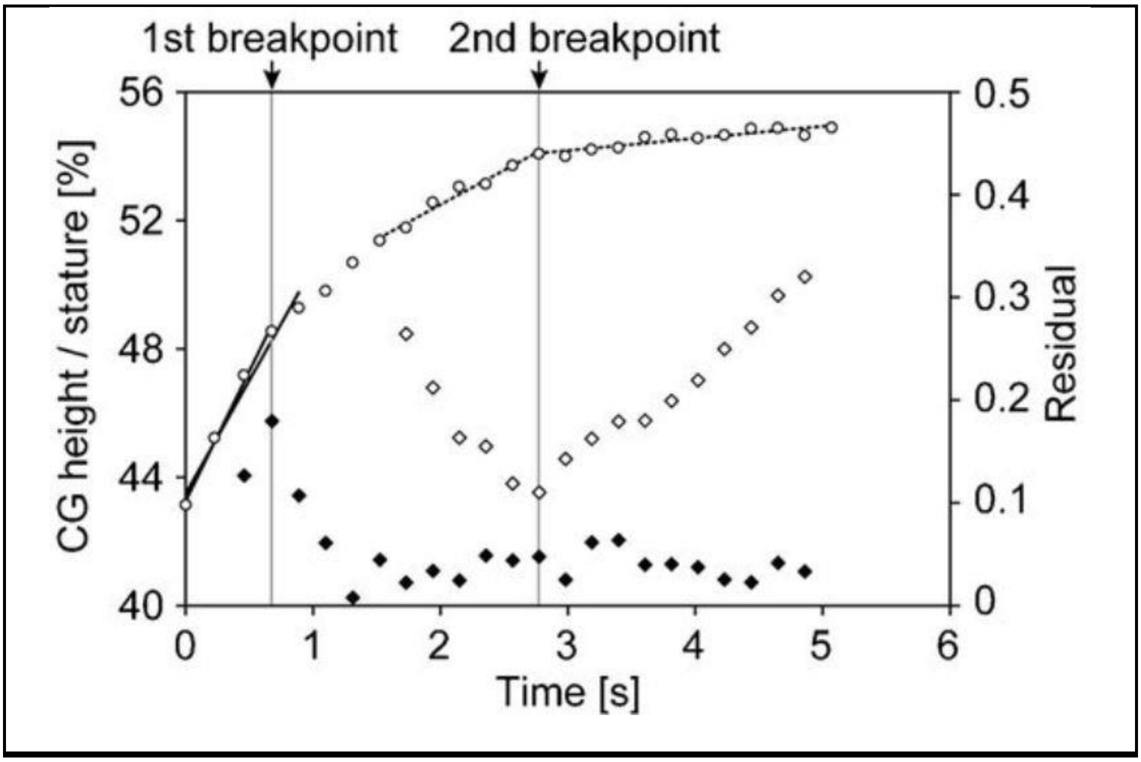

Figure 2.3.2.1 Identification of breakpoints from CoM (CG) location (shown with open circles). Reproduced from Nagahara et al., 2014.

Maximal horizontal velocity was achieved by the 23rd step (mean velocity: 10.04 ± 0.29 $m \cdot s^{-1}$). The instances of breakpoint were identifiable via movements of the CoM. These findings are partially supported by previous studies that claim the first breakpoint occurs at step three (Mero, 1992) due to the first two steps contacting the ground behind the CoM or conversely at step five where the first instance of knee flexion during ground contact was identified (Fukunaga, Matsuo & Ichikawa, 1981).

Despite reductions in the angular displacement of the hip joint as maximal horizontal velocity was approached, sprint speed continued to increase. Inter-step characteristics of the anterior-posterior trunk angle were previously presented by Plamondon & Roy (1984) whereby the cessation of any change was found to occur at the 14th step. These findings strongly support the mean figure of 14.1 ± 2.0 steps presented by Nagahara et al., (2014) although the biomechanical reasons for each of the sub-phases requires further investigation. As sprint hurdlers have only seven or eight steps before hurdle clearance the second breakpoint either does not occur in the same way that it does for flat sprinters or occurs earlier than the tenth step.

The role of the hip joint throughout the early stance phase of each step has been identified as being an important factor in both acceleration and maximum velocity sprinting (Johnson & Buckley, 2001). In a study investigating first step mechanics from the blocks, Charalambous et al., (2011) identified that the role of the hip extensors in generating power was confined to the first 70% of the entire ground contact phase. Further, it was limited throughout the final 30% due to the mechanical requirement of recovering the rear leg during the flight phase for the following step. Rapid mean extension during this initial 70% was linked to greater horizontal propulsive impulse, whereas no correlation has been found which links actively striving to increase hip extension throughout the stance phase and horizontal propulsive impulse (Hunter et al., 2004). This agrees with the findings of Charalambous et al., (2011) whereby any increase in hip motion throughout the ground contact phase would occur during the final 30% of ground contact and be ineffectual in generating power, impulse or velocity. It is possible that some of the differences in step characteristics of seven and eight-step athletes occurs at the hip joint of the propulsive leg with a more rapid extension occurring for one of the step strategies. Despite the action of the hip joint receiving some attention in the sprint acceleration literature, it has not previously been investigated when considering the first hurdle approach phase. It should be noted though, that the single participant in the study by Charalambous et al., (2011) was in fact, an elite level sprint hurdler (110 m hurdle personal best – 13.48 s) and not a flat sprinter. This may mean that this study actually investigated the block clearance of a sprint hurdler who needs to be in a position to clear the first hurdle by 13.72 m, as opposed to a flat sprinter who does not have this requirement. Analysis including the first hurdle was beyond the scope of the study.

2.3.3 *Kinetic variables*

Whilst the acceleration phase of a flat 100 m sprint can extend beyond 30 m and will vary for each athlete, for a sprint hurdle race there is a set distance of 13.72 m before the first hurdle, leaving around 11.50 m from the start line to the point of take-off. Throughout this phase the correct application of force is crucial to generate as much horizontal velocity as possible by the point of take-off for the hurdle. Any error made will be particularly difficult to recover in the following 9.14 m inter-hurdle phases due to the specific requirements for consistent step-lengths and the limited distance to further develop horizontal velocity.

The ability to generate a high degree of propulsive horizontal impulse has been identified as a principal determinant factor in the development of acceleration (Hunter et al., 2005) and is strongly correlated with acceleration ability (Rabita et al., 2015; Morin et al., 2015). Throughout the first hurdle approach, athletes who use a seven-step approach must generate a net propulsive horizontal impulse which is at least equal to that of an eight-step approach to achieve any kinetic benefit. Although it has not previously been measured, from observation of footage of elite level competition, athletes hit the take-off mark at roughly the same time from seven- and eight-step approaches. It is not currently understood where differences in force production occur throughout the approach phase between seven and eight-step athletes.

Morin et al., (2011) proposed a concept previously used to investigate pedalling mechanics termed the 'ratio of force' (RF). It was identified as a parameter to determine effective application of force throughout the acceleration phase and measures a sprinter's ability to orientate their total GRF in the horizontal direction. An RF value of 100%

identifies that the total force is being directed horizontally and an RF of 0% identifies that the total force is being directed vertically, however in sprinting, both values are unachievable. Twelve male athletes (of which two were sprinters) each performed a single eight second sprint on an instrumented treadmill and a 100 m sprint on a standard athletics track (Morin et al., 2011). RF was calculated from the treadmill data (1000 Hz) as a mean ratio of the horizontal force to total force for each contact period. RF was found to start high with the first step and to incrementally decrease up to maximal velocity leading the researchers to measure the rate of reduction in RF. The decrement in RF (D_{RF}) measures to what degree the sprinter can maintain a more horizontal force vector despite increasing velocity. D_{RF} was found to be positively related to maximum velocity, 100 m mean velocity and the distance covered in four seconds. RF and D_{RF} were found to be highly correlated to overall acceleration performance at sprints up to 40 m (Rabita et al., 2015) and whilst this parameter has seen some use to date to assess sprint performance, it is yet to be used in hurdling research. When comparing the seven and eight-step approaches, RF and D_{RF} could be useful parameters to determine the extent to which a hurdler is able to orientate their ground reaction force vector in the horizontal direction for each of the approach steps. From the research it may be possible to identify where throughout the approach phase the steps differ between seven- and eight-steppers.

2.4 Hurdle clearance phase

2.4.1 *Spatio-temporal variables*

There has been limited biomechanical investigation into the clearance of the first hurdle and none into the seven-step approach. The first four hurdles were studied by Salo (2002) with particular focus upon the changing characteristics of the hurdle clearance throughout the initial phases of the event. Whilst the performance level of the participants was relatively high (each having previously run a sub-13.85 s 110 m hurdles race), the study only considered the performances of two athletes. Mean first hurdle clearance velocity was 7.55 ± 0.05 $m \cdot s^{-1}$, this was the slowest clearance for each of the four hurdles and corresponded with the shortest hurdle step lengths (mean: 3.51 ± 0.25 m), the shortest take-off distances (mean: 2.05 ± 0.07 m) and the shortest touchdown distances (mean: 1.46 ± 0.31 m). Despite these findings, the four hurdle flight times showed no significant difference for each hurdler and one participant executed each hurdle clearance in the same time (0.42 s). This suggests that hurdlers do not wait to re-establish ground contact with the lead leg foot and actively strive to clear each barrier in the fastest time they are capable of, and alter take-off, touchdown and subsequently hurdle step lengths accordingly to achieve the quickest possible clearance.

Due to a lower horizontal velocity at the point of take-off for the first hurdle compared to the following hurdles, athletes appear to reduce their take-off distance (Salo, 2002) and as previously identified by Mann (2011), there is only an allowable horizontal variation of 0.08 m for which to place the take-off foot for hurdle clearance to be effective. This distance is velocity dependent (identifiable by increases in take-off distance as hurdlers continue to accelerate to maximal velocity) and it is possible that seven-step hurdlers reach the first hurdle with a greater horizontal velocity of the CoM. They may in turn, effectively increase the hurdle take-off distance and help to offset some of the distance lost by not taking an eighth step. This could lead to an increase in mean horizontal velocity of the hurdle clearance. However, this is currently speculative and investigation into first hurdle step lengths and clearance times of seven-step athletes requires investigation.

The optimal ratio of take-off to touchdown distance is a key element which defines the success of the hurdle clearance. This in turn, directly affects the biomechanics of the take-off and touchdown phases (Sidhu & Singh, 2012). Correct execution of the first hurdle is critical and if the athlete takes off too far from the hurdle the path of the CoM is increased via both increases in the horizontal and vertical distance over which it must travel. Consequently, the athlete will not only waste time in the air but may also hit the hurdle if the CoM begins to fall too early throughout the clearance phase. Likewise, as further acceleration can only be achieved via ground contact, the athlete must actively strive to re-establish this once their CoM has crossed the plane of the hurdle. This is achieved by driving the lead leg foot down under the CoM and reducing braking forces caused by excessive touchdown distance. In a study (Sidhu and Singh, 2015) of two male junior national hurdlers, runs from starting blocks were completed with the clearance of the first five hurdles. It was found that efficient hurdle clearance technique is generated by, amongst other findings, the ratio of the point of take-off to landing. Sidhu and Singh (2015) propose a suitable ratio of 65:35 for take-off and touchdown distance step lengths (distance of take-off and touchdown foot from the hurdle base). This figure is somewhat in agreement with the measurements recorded from a previous world record holder whose ratio was 56.9:43.1 (Čoh, 2003) for the clearance of hurdle four. The slight deviations in this ratio may well be due to the athlete's relatively short stature (1.82 m) compared with other hurdlers, requiring him to take off and land further away from the hurdle to control the path of the CoM (Mann, 2011). Despite much of the research identifying 60:40 to 65:35 (La Fortune, 1991; Salo & Grimshaw, 1998) as optimal, this parameter is evidently athlete specific, and athletes should consider the correct execution of other key performance parameters primarily. Sidhu and Singh's (2015) study must be interpreted with caution though as the athletes represented only a small sample group, and despite being national level competitors, were both junior (under 20 years of age) athletes. Any future study into the spatio-temporal measurements of hurdle clearance should be supported with anthropometric data pertaining to leg length and stature in order for normalisations to be applied to the data.

Minimising round contact time for both the take-off and touchdown steps is crucial. In a study by Čoh & Iskra (2012) investigating the kinematic parameters of the hurdle clearances of four sprint hurdlers (14.63 ± 0.59 s) over the fifth hurdle, the fastest athlete (13.90 s, 7.87 $m \cdot s^{-1}$) had the shortest ground contact times at both take-off (0.132 s) and touchdown (0.098 s). McLean (1994) found that a faster athlete had both the shortest ground contact times at take-off and touchdown when compared to a slower athlete but found no difference between the athlete's hurdle flight times or hurdle step lengths. As with flat sprinting, it appears that faster hurdlers increase their horizontal velocity via a reduction in ground contact times and not by repositioning the limbs faster during the flight time.

The greater the change in height of the CoM from take-off to clearing the hurdle and back to touchdown, the greater the distance the CoM must travel. Consequently, if the path of the CoM is increased because of a more vertical take-off angle (due to excess vertical velocity) this leads to an increased hurdle flight time and a subsequent loss of horizontal velocity of the CoM due to undesirable braking forces. The ability of a hurdler to limit vertical oscillations of the CoM is identified as a key component for a fast hurdle clearance and subsequent maintenance of horizontal velocity (Čoh, 2000). It has been found that the maximum mean height of the CoM across the hurdle for elite hurdlers was 0.27 ± 0.03 m (Salo & Grimshaw, 1998). Amara, Mkaouer, Chaabene, Negra & Bensalah (2019), conducted research with 10 national level hurdlers and found that of the 20 variables considered, limiting the vertical oscillations of the CoM was a clear differentiator between performance levels. Amara et al. (2019), also identify that for hurdlers to improve, this must be one of the key technical parameters considered.

In previous research, the total horizontal length of a hurdle clearance step has been identified to be more than 3.50 m (Mann, 2011; Salo, 2002) and from research into world-class athletes, cleared at a velocity of over 9.0 $m \cdot s^{-1}$ (Čoh, Bončina, Štuhec & Krzysztof, 2020; Čoh, 2003). The forces generated must be controlled by the foot of the lead leg as it re-establishes ground contact. Firstly, the lead leg must not collapse, dropping the CoM and unnecessarily increasing the length of the path over which it must travel. Secondly, the control of these forces must occur in as short a time as possible, limiting the braking forces from the initial contact and generating propulsive forces into the recovery step. When considering the biomechanical implications of the seven- and eight-step approach strategies it is particularly important to consider the kinematics of the touchdown phase and the ground contact time. Excessive braking will negatively affect performance, and this is crucial for successful execution of the inter-hurdle steps, and directly affected by the success of the take-off position (Čoh & Iskra, 2012).

2.4.2 *Kinematic variables*

There are several parameters which have been used to quantify the technical success of the take-off phase. The most important of these measurements consider the position and trajectory of the CoM at the point of take-off. Once the athlete loses contact with the ground, it is not possible to make any further adjustments to the horizontal motion and velocity of the CoM and correct technical execution directly affects the success of the hurdle clearance, the touchdown phase and the inter-hurdle steps. The deviation angle is a measure of the absolute position of the CoM in relation to the MTP joint of the take-off foot and a line horizontal with the ground from the MTP towards the hurdle. Previous research suggests that this angle is a key parameter which defines the success of the take-off phase and better hurdlers have a deviation angle which is less than 70° (Wen, 2003; Li, Zhou, Li & Wang, 2011). The negative effect of a deviation angle which is too great is that the resultant force vector is excessively vertical leading to consequential loss of horizontal velocity as the hurdler jumps rather than steps over the barrier. If the deviation angle is too shallow, the athlete will hit the hurdle. This parameter is directly influenced by the take-off distance from the hurdle with a greater distance (providing sufficient horizontal velocity has been achieved) enabling the hurdler to have a greater anterior trunk lean when "attacking" the hurdle.

Whereas the deviation angle is a measurement of the position of the CoM at the point of take-off irrespective of the motion of the CoM, the take-off angle is a measure of the resultant force vector of the CoM identified from the vectors of the vertical and horizontal velocities and represents the initial motion of the CoM for the hurdle clearance. Deviations in the motion of the CoM must be limited to prevent unnecessary elongation to the path of motion of the CoM, therefore, take-off angle should be as small as possible and results of less than 14° have been found when comparing better hurdlers to less capable hurdlers (Salo, Grimshaw & Marar, 1995).

A fast hurdle clearance is made possible by rapid flexion and extension phases of the lead leg hip. Despite this understanding in coaching, there is little evidence of the lead leg hip action being measured in the hurdle research. It has though, been documented in sprint literature (Charalambous, Irwin, Bezodis & Kerwin, 2011; Mann & Sprague, 1980) where hip power generation was found to be extremely important throughout both acceleration and maximal velocity phases. Based upon these findings, kinematic parameters of the lead leg hip joint should be included in future studies of the hurdle clearance technique. As athletes increase their horizontal velocity, the necessity to rapidly flex and extend the lead leg hip becomes more important to avoid hitting the hurdle with the leading foot.

2.4.3 *Kinetic variables*

Whilst there is increasing interest in the kinetic parameters of the sprint phases as well as jumping, this has failed to transfer into sprint hurdling and research is still relatively scarce. Force plates have previously been used by McLean (1994) to evaluate the hurdling technique of seven high-performance hurdlers from the force data produced (vertical and anteroposterior ground reaction forces at 1000 Hz). By placing a force plate at the point of take-off for the second hurdle and a further force plate at the point of touchdown, Mclean (1994) could identify the horizontal braking and propulsion phases of both ground contacts and evaluate the hurdle clearance action of each athlete at each phase of the clearance. The athlete with the shortest braking phases at take-off (0.65 s) and touchdown (0.07 s) was identified as the most technically correct, placing the foot more closely underneath the CoM as opposed to in front. Consequently, his braking phase at take-off caused a reduction in horizontal velocity of -0.47 $m \cdot s^{-1}$ and was reported as 0.0 $m \cdot s^{-1}$ at touchdown (only one decimal place was provided). Collection of force plate data may be a suitable method to evaluate the kinetic parameters of the approach steps for seven- and eight-step athletes and an amalgamation of data from a series of trials (Morin et al., 2015) could provide information with reference to the impulse and orientation of ground reaction force vectors for each step. From force plate data it may be possible to identify where throughout the approach phase seven- and eight-steppers differ.

THE WORK IN THIS CHAPTER FORMED THE BASIS OF THE FOLLOWING PEER-REVIEWED JOURNAL ARTICLE:

Rowley, L.J., Churchill, S., Dunn, M., and Wheat, J., (2021). Effect of hurdling step strategy on the kinematics of the block start. *Sports Biomechanics.*

3. Effect of hurdling step strategy on the kinematics of the block start

3.1 Introduction

The 110 m hurdles event is essentially a sprint, with a series of ten barriers. While there was no documented use of a seven-step strategy to reach the first hurdle until the 1960 Olympic Games, a seven-step approach has now become the preferred strategy of many elite hurdlers. A seven-step strategy was used by six of the eight finalists at the 2012 Olympic Games, including all three medallists (Pinho, Lima, Claudino, Andrade, Soncin, Mezêncio, Bourgeois, Amadio & Serrão, 2017). At the 2016 Olympic Games, six of the eight finalists used a seven-step approach, including the silver and bronze medallists. The decision to use either a seven or eight-step approach strategy directly influences the relationship between step length and step frequency. Sprint speed is the product of step length and step frequency and an increase in either (as long as it is not detrimental to the other) or both will result in a greater horizontal velocity (Hunter, Marshall & McNair, 2004). There is no absolute consensus on the preferred way to increase sprint speed in individual athletes (Salo, Bezodis, Batterham & Kerwin, 2010), but it is considered to be essential that an optimal relationship between the two is a primary focus when selecting a step strategy. Sprint hurdlers are required to maximise step frequency to the first hurdle without compromising the step lengths necessary for successful execution of their selected approach step strategy. Irrespective of step strategy, athletes are required to alter their step lengths and step frequency from those which they would use for a flat sprint.

These alterations might influence the positioning of the athlete in the set position and the technique of the block clearance (Tidow, 1991).

The placement of the starting blocks is critical to a successful approach phase and clearance of the first hurdle, and research shows that the distances for the front and rear block from the start line directly influence the position of the centre of mass (CoM) in the set position (Čoh et al., 2006). Once movement is initiated from the blocks the trajectory and velocity of the athlete's CoM throughout the first step is in part, dependent upon correct positioning of the CoM in the set position (Schot & Knutzen, 1992). For both flat and hurdle sprint races, a medium start (spacing between the block faces between 0.3 and 0.5 m) is most commonly used and often accepted as the most effective way of developing acceleration as sprint distance increases. Several studies have shown the medium start to result in the quickest performance times at distances of up to 50 yards (45.72 m) (Henry, 1952; Čoh, Jošt, Škof, Tomažin & Dolenec, 1998), although, Čoh et al (1998) identified positive correlations between the 20-30 m phase of acceleration from the blocks and not the initial acceleration phase. Sprint hurdlers have 13.72 m to accelerate before the first hurdle clearance and it is possible that, based upon a chosen step strategy, athletes are adopting start positions that are not optimal to developing horizontal acceleration.

It has previously been identified in both flat (Charalambous, Irwin, Bezodis & Jošt, 2012; Mero & Luhtanen, 1985) and hurdle (Tidow, 1991) sprint races that the success of the start and acceleration phases are decisive to the outcome of the race. When hurdlers leave the starting blocks, they must develop horizontal acceleration via a suitable step strategy, which also positions them correctly for clearance of the first hurdle. Elite hurdlers take-off approximately 2.10 - 2.40 m from the first hurdle (Tidow, 1991; Mann, 2011). This leaves 11.32 – 11.62 m from the start line to the point of take-off for the athlete to generate as much horizontal acceleration as possible. Whilst there has been considerable investigation into the biomechanics of the block clearance and start phase of flat sprint races (Bezodis, Willwacher & Salo, 2019; Čoh & Žvan, 2015; Morin, Slawinski, Dorel, Saez-de-Villarreal, Couturier, Samozino, Brughelli & Rabita, 2015; Debaere, Delecluse, Aerenhouts, Hagman & Jonkers, 2012; Čoh, Tomažin & Štuhec, 2006), there has been little investigation into the seven or eight-step first hurdle approach used by sprint hurdlers.

The first step following the block clearance is the most difficult to execute correctly, yet the most important step of the entire race (Mann, 2011). The first ground contact is critical and particularly the foot's location in relation to the position of the whole-body CoM. If the CoM is behind the ground contact of the first step, then unnecessary braking occurs. Therefore, if seven-step athletes are taking longer steps out of the blocks to cover the same approach distance as eight-step athletes, it essential to ensure the first step ground contact continues to occur posterior of the CoM.

As the athlete approaches the first hurdle, adjustments are made to the technique of each step in preparation for hurdle clearance. It is therefore not possible to compare like-for-like steps throughout the entire acceleration phase. Essentially, there is a functional difference between the strategy used to balance the need for continued acceleration alongside preparation for the hurdle clearance. Previous research (McDonald & Dapena, 1991) has identified a reduction in both step length and flight time prior to take off, rendering like-for-like step parameters throughout the final approach steps, incomparable. Previous research has also identified initial acceleration to last only four to six steps following block clearance (Nagahara, Matsubayashi, Matsuo & Zushi, 2014).

The aim of this study was to investigate the effect of first hurdle step strategy on the start position and block clearance phase kinematics, and the spatio-temporal characteristics of seven and eight step approaches throughout the first four steps. It was hypothesised that seven-step athletes position themselves differently in the blocks compared to eight-step athletes to achieve different block exit kinematics. Block contact times and first step lengths are parameters which are likely to differ; however, this is not yet known.

3.2 Methods

3.1.1 *Participants*

Twelve male sprint hurdlers (mean age, 22 ± 2.11 years; body mass, 79.4 ± 11.8 kg; stature, 1.83 ± 0.07 m) volunteered to take part in the study. All were experienced athletes, had a personal best performance time of under 15.00 s in the senior men's 110 m hurdles event (mean: 14.13 ± 0.39 s; range from 13.48 to 14.68 s) and were ranked in the top 35 in Great Britain at the time of data collection. Participants comprised of two groups of six, based on the number of steps taken to the first hurdle during a competitive performance (mean personal best: seven-step; 14.04 ± 0.42 s, eight-step; 14.21 ± 0.42 s). Research study procedures were approved by Sheffield Hallam University Research Ethics Committee. Participants were provided with an information sheet and gave written informed consent before taking part.

3.1.2 *Data collection*

Data were collected at seven locations, in order to minimise disruption to the athletes' normal training. Standard outdoor athletics tracks were used at the Loughborough University Athletics Centre, Leeds Beckett University Athletics Centre and Brunel University Sports Park. Standard indoor athletics facilities were used at Birmingham Alexander Stadium, University of Bath Sports Training Village, Gateshead International Stadium and Lea Valley Athletics Centre. Each individual athlete's data were collected during a single session. All participants wore their usual running spikes and skin-tight clothing.

Participant mass (BC543, Tanita, Amsterdam, The Netherlands), stature (Marsden Leicester height measure, Rotherham, UK) and leg-length (measured in the anatomical standing position using a tape measure from location of surface markers at ankle joint centre to hip joint centre) was collected.

Each participant completed a self-managed warm-up before carrying out three starts from blocks in response to an audible stimulus. Once leaving the blocks participants were required to clear the first two hurdles at their normal race intensity, with hurdle spacings and specifications in-line with 2017-2018 International Association of Athletics Federations (IAAF, 2016) competition rule 168 (hurdle height, 1.067 m; start line to first hurdle distance, 13.72 m; first hurdle to second hurdle distance: 9.14 m). A full recovery was permitted between trials (at least 5 minutes). If participants knocked down the first hurdle, then the trial was not included for analysis. Consequently, not all participants were able to complete three successful trials. In total, 16 trials were captured for seven-step athletes and 16 trials for eight-step athletes. The successful trial was selected for analysis for those who completed only one trial and the second trial was selected from those who completed either two or three successful trials.

High-speed video footage (200 Hz) of the sprint start and first step from standard starting blocks (set-up to the participants individual race settings) was collected using a single camera aligned with the start line (Table 3.2.2.1). A further high-speed camera was aligned mid-way between the start line and the first hurdle to capture the spatio-temporal parameters of the approach steps (Table 3.2.2.2). All footage was collected with Phantom Miro M110 high-speed cameras (Vision Research, Wayne, New Jersey, USA) which were positioned 20 m perpendicular to the centre of the running lane and provided images of the sagittal plane. Cameras were set up as illustrated in Figure 3.2.2.3 and identified as either the 'start' or 'overview' camera.

Table 3.2.2.1 Description of technique variables calculated from the start camera view.

Parameter	Description
Front block distance (m)	Horizontal distance from the metatarsophalangeal joint (MTP) of the front foot on the starting block to the near edge of the starting line.
Rear block distance (m)	Horizontal distance from the MTP of the rear foot on the starting block to the near edge of the starting line.
Block spacing (m)	Horizontal distance from the MTP of the rear foot on the starting block to the MTP of the front foot on the starting block.
First step length (m)	Horizontal distance from the MTP of the rear foot on the starting block to the MTP of the first step at the first point of ground contact.
Normalised First step length	Non-dimensional normalisation. First step length divided by leg-length.
First ground contact time (s)	Time that the foot can positively be identified as in contact with the ground from the video footage to the first frame of loss of ground contact. This is the first ground contact following block clearance.
Block contact time (s)	Time from frame of first identifiable initiation of movement of the athlete to the frame that the front foot loses contact completely with the front block.
CoM set angle (°)	Angle formed between the vector from the nearest edge of the start line to the position of the centre of mass (CoM) and the horizontal whilst static in the set position.
CoM relative height (%)	Vertical distance of the CoM from the track surface whilst in the set position expressed as a percentage of the athletes standing stature.
CoM vertical displacement (m)	Difference between the vertical height of the CoM at the point of first step ground contact and the height in the set position.
Normalised CoM vertical displacement	Non-dimensional normalisation. CoM vertical displacement divided by leg-length.
CoM touchdown angle (°)	Angle measured from the MTP of the first step at the first frame of ground contact and the position of the CoM.
Front block obliquity (°)	Inside angle of the front foot block face measured from the track surface.
Front knee set angle (°)	Posterior angle of the knee of the front leg whilst static in the set position.
Rear knee set angle (°)	Posterior angle of the knee of the rear leg whilst static in the set position.
Front hip angle change (°)	Change in the anterior angle of the front leg hip from the set position to the end of contact of the front foot on the blocks.
Rear hip angle change (°)	Change in the anterior angle of the rear leg hip from the set position to the end of contact of the front foot on the blocks.
Front hip peak extension (°)	Maximum anterior angle of the front hip throughout the block clearance phase.
Rear hip peak extension (°)	Maximum anterior angle of the rear hip throughout the block clearance phase.
Front hip exit angle (°)	Anterior angle of the front hip at the end of contact of the front foot with the blocks.
Rear hip exit angle (°)	Anterior angle of the rear hip at the end of block contact of the rear foot with the blocks.
Front hip mean angular acceleration ($°/s^2$)	Mean angular acceleration of the front hip from the first frame of movement in the set position to the end of block contact.
Rear hip mean angular acceleration ($°/s^2$)	Mean angular acceleration of the rear hip from the first frame of movement in the set position to the end of block contact.
Rear foot block contact time (%)	Time that the rear foot is in block contact expressed as a percentage of the total block contact time.
Block exit horizontal velocity (m/s)	Horizontal velocity of the CoM at the end of front foot block contact.

Table 3.2.2.2 Description of technique variables calculated from the overview camera view.

Parameter	Description
Step length (m)	Horizontal distance between the metatarsophalangeal joint (MTP) of the touchdown step and the MTP of the following contralateral touchdown step.
Step frequency to Step 4 (Hz)	Mean number of steps taken per second from the initiation of motion in the blocks to the end of ground contact of the fourth step. Calculated by dividing the time to end of fourth ground contact by the number of approach steps.
Ground contact time (s)	Time that each step foot can positively be identified as in contact with the ground from the video footage to the first frame of loss of ground contact.
Flight time (s)	Time between steps that neither foot is in contact with the ground.
Approach to Step 4 Take-off (TO) (s)	Time from the initiation of motion to the end of ground contact of the fourth step.
Approach to (s)	Time from the initiation of motion to the end of ground contact of the first hurdle take-off step.

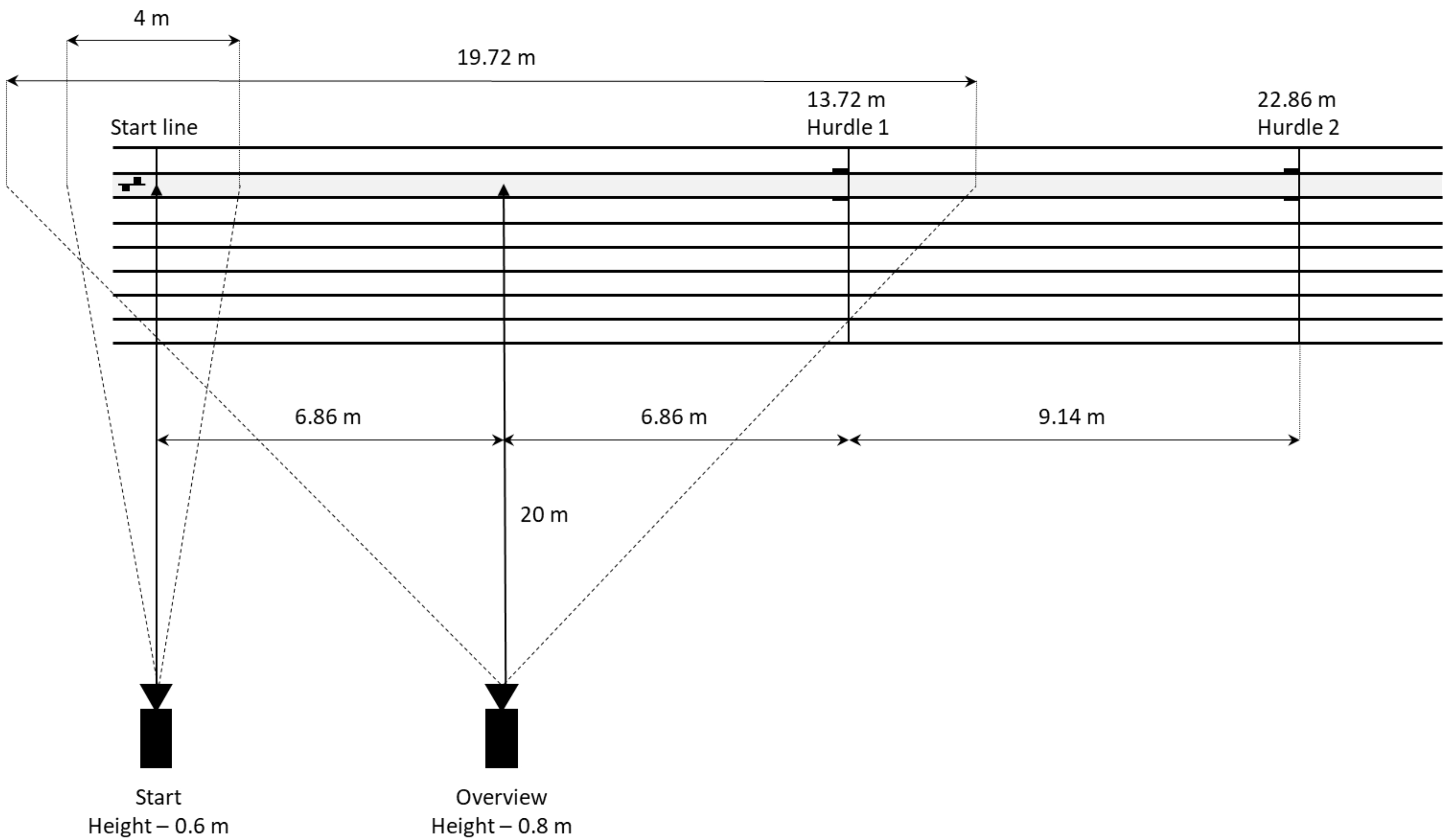

Figure 3.2.2.3 Plan view of camera set-up for hurdle trials (not to scale).

Cameras were manually focused, and the field of view was set to 4.00 m wide for the start camera and 19.72 m wide for the overview camera. Shutter-speed was $^{1}/_{500}$ s (exposure of 2000 μs) and aperture was fully open for each camera .

3.1.3 *Data Processing*

Calibration data were collected using a checkerboard method for the start camera and using track markings and hurdle height for linear scaling of the overview camera. To calibrate the start camera a checkerboard (7 x 7 squares each measuring 0.08 m) was held in different positions and orientations across the camera image and a series of frames captured. These were used to calibrate the intrinsic and extrinsic camera parameters using Check2D software (V1.5; Centre for Sports Engineering Research, Sheffield Hallam University, UK). Track markings were used to determine the parameters of the overview camera, completed using SimiMotion 9.2.1. (Simi Reality Motion Systems GmbH, Max-Planck-Strasse 11, 85716 Unterschleissheim, Germany). Footage was manually digitised using SimiMotion 9.2.1 software with an additional ten frames at the start and end of the required start camera footage to allow for end-point errors due to filtering (Smith, 1989).

A total of 18 anatomical landmarks were identified and digitised to create a 16-segment kinematic model based upon de Leva (1996). Segments were; head, trunk, left and right upper arms, forearms, hands, thighs, shanks, and feet. Trunk data was created from virtual coordinates of mid-hip (mid-point between left and right hip joint centres) and mid-shoulder (mid-point between left and right shoulder joint centres). Gait events were determined by visual inspection of the footage.

Raw image coordinate data were filtered using a second order low pass Butterworth filter with a cut-off frequency of 7 Hz. The cut-off frequency was identified via residual analysis. For the start camera, raw image coordinate data and camera calibration data were subsequently exported, and planar position data reconstructed

(Dunn, Wheat, Miller, Haake & Goodwill, 2012) using Matlab R2017a (The MathWorks, Natick, MA, USA). Along with the anthropometric data, a total of 32 parameters were determined, 25 from the start camera (Table 3.2.2.1), six from the overview camera (Table 3.2.2.2) and one from the anthropometric data (Table 3.2.3.1). To quantify intra-rater reliability, re-digitisation of markers and gait events was completed by one operator on two of the athletes' trials (one seven-step and one eight-step athlete). A total of eight re-digitisations were completed for each trial. The re-digitised results of the start camera demonstrated low variability with a mean coefficient of variation (CV) of 1.63 ± 1.88 and a maximum of 6.85% (Rear hip angle change) for the seven-step athlete, along with a mean CV of 1.41 ± 1.94 and a maximum of 6.29% (Rear hip angle change) for the eight-step athlete. Similarly, re-digitising of the overview camera yielded a mean CV of 1.19 ± 1.70 and a maximum of 6.58% (Step 1 flight time) for the seven-step athlete, along with a mean CV of 1.42 ± 1.46 and a maximum of 5.35% (Step 1 flight time) for the eight-step athlete. These results were accepted as good intra-rater reliability.

3.1.4 *Statistical Analysis*

Independent-sample *t*-tests (SPSS for Windows, version 24.0; SPSS, Inc., Chicago, IL, USA) were performed to determine differences between the groups for all variables (Tables 3.2.4.1 and 3.2.4.2). Athlete stature, mass, leg-length and leg-length as a percentage of stature were also compared to assess whether there was a difference between groups in anthropometric variables (Table 3.2.4.3).

The criterion alpha level was set at $p < 0.05$ for statistical significance, and to reduce the possibility of type II errors occurring from low participant numbers $p < 0.1$ was accepted as a tendency. This approach has been taken by Alt, Heinrich, Funken &

Table 3.2.3.1 Description of anthropometric variables.

Parameter	Description
Stature (m)	Stature of seven and eight-step athlete groups.
Mass (kg)	Mass of seven and eight-step athlete groups.
Leg-length (m)	Leg-length of seven and eight-step athlete groups measured from the ankle-joint centre to the hip-joint centre.
Leg-length % of stature	Leg-length as a percentage of stature.

Table 3.2.4.1 Seven and eight-step group mean values (±SD), effect size and *p* values for kinematic variables.

	Seven-step			Eight-step						
							Cohen's *d*		*p*	
Front block distance (m)	0.43	±	0.11	0.53	±	0.11	0.93	§	0.137	
Rear block distance (m)	0.80	±	0.09	0.83	±	0.12	0.27		0.652	
Block spacing (m)	0.38	±	0.08	0.30	±	0.02	1.34	§	0.043	*
First step length (m)	1.65	±	0.17	1.40	±	0.08	1.91	§	0.008	*
Normalised First step length	1.83	±	0.20	1.59	±	0.05	1.65	§	0.017	*
First step ground contact time (s)	0.23	±	0.03	0.20	±	0.02	1.18	§	0.073	#
Block contact time (s)	0.42	±	0.05	0.36	±	0.02	1.51	§	0.022	*
CoM set angle (°)	72.7	±	1.9	72.8	±	4.8	0.05		0.938	
CoM relative height (%)	34.5	±	1.4	35.6	±	1.3	0.81	§	0.193	
CoM block contact angle (°)	39.0	±	2.1	38.7	±	1.8	0.17		0.771	
CoM vertical displacement (m)	0.24	±	0.04	0.20	±	0.03	1.12	§	0.081	#
Normalised CoM vertical displacement	0.27	±	0.48	0.22	±	0.31	0.12		0.092	#
CoM touchdown angle (°)	84.3	±	5.8	81.8	±	2.6	0.56		0.356	
Front block obliquity (°)	46.7	±	6.5	48.3	±	7.0	0.25		0.678	
Front knee set angle (°)	93.0	±	7.5	94.0	±	8.2	0.13		0.830	
Rear knee set angle (°)	111.2	±	17.0	121.2	±	8.9	0.73		0.232	
Front hip angle change (°)	129.2	±	13.5	122.7	±	10.2	0.54		0.368	
Rear hip angle change (°)	49.0	±	19.6	38.0	±	12.6	0.67		0.274	
Front hip peak extension (°)	165.2	±	7.5	169.8	±	7.7	0.61		0.313	
Rear hip peak extension (°)	116.3	±	13.6	116.5	±	11.2	0.01		0.982	
Front hip exit angle (°)	161.8	±	7.9	166.2	±	8.9	0.52		0.393	
Rear hip exit angle (°)	115.2	±	13.9	111.3	±	11.3	0.30		0.611	
Front hip mean angular acceleration (°/s^2)	741	±	220	938	±	102	1.15	§	0.075	#
Rear hip mean angular acceleration (°/s^2)	1028	±	375	1061	±	306	0.10		0.869	
Rear foot block contact time (%)	53.1	±	4.5	50.7	±	4.4	0.54		0.370	
Block exit horizontal velocity (m/s)	3.66	±	0.53	3.52	±	0.23	0.34		0.568	

Note: * significant at $p < 0.05$; # tendency at $p < 0.10$; § effect size > ± 0.8.

Table 3.2.4.2 Seven and eight-step group mean values (±SD), effect size and *p* values for approach step variables.

		Seven-step			Eight-step						
								Cohen's *d*		*p*	
Step length (m)											
	Step 1	1.65	±	0.17	1.40	±	0.08	1.91	§	0.008	*
	Step 2	1.43	±	0.26	1.13	±	0.12	1.48	§	0.028	*
	Step 3	1.47	±	0.17	1.38	±	0.14	0.65		0.281	
	Step 4	1.75	±	0.07	1.45	±	0.07	4.20	§	0.000	*
Step GCT (s)											
	Step 1	0.23	±	0.03	0.20	±	0.02	1.18	§	0.073	#
	Step 2	0.19	±	0.02	0.17	±	0.02	0.90	§	0.148	
	Step 3	0.17	±	0.02	0.15	±	0.01	1.64	§	0.018	*
	Step 4	0.16	±	0.02	0.14	±	0.01	1.25	§	0.055	#
Step flight time (s)											
	Step 1	0.07	±	0.03	0.07	±	0.02	0.24		0.680	
	Step 2	0.08	±	0.02	0.06	±	0.02	1.00	§	0.115	
	Step 3	0.09	±	0.02	0.09	±	0.03	0.07		0.905	
	Step 4	0.11	±	0.02	0.09	±	0.01	1.27	§	0.052	#
Approach to Step 4 Take-off (TO) (s)		1.51	±	0.08	1.34	±	0.56	2.52	§	0.001	*
Step Freq to Step 4 (Hz)		2.66	±	0.14	3.00	±	0.13	2.59	§	0.001	*
Approach to (s)		2.29	±	0.09	2.28	±	0.10	0.09		0.791	

Note: *significant at $p < 0.05$; # tendency at $p < 0.10$; § effect size > ± 0.8.

Table 3.2.4.3 Seven and eight-step group mean anthropometric measurements (±SD), effect size and *p* values.

	Seven-step			Eight-step			Cohen's *d*		*p*	
Stature (m)	1.87	±	0.05	1.79	±	0.07	1.31	§	0.047	*
Mass (kg)	85.3	±	8.6	73.6	±	13.3	1.05	§	0.100	
Leg-length (m)	0.91	±	0.02	0.88	±	0.04	0.65		0.290	
Leg-length % of stature	48.3	±	0.94	49.3	±	2.13	0.61		0.366	

Note: # significant at $p < 0.10$; * significant at $p < 0.05$; § effect size > ± 0.8.

Potthast (2015) when investigating lower extremity kinematics of athlete curve sprinting with low participant numbers (n = 6). Effect size was calculated for each variable using Cohen's *d* (Cohen, 1988). Only large effect size differences ($d \geq 0.80$) were deemed relevant and examined.

3.2 Results

Seven-step athletes were 0.08 m taller ($p = 0.047$, $d = 1.31$) than eight-step athletes, and tended to be heavier (11.7 kg, $p = 0.100$, $d = 1.05$). There was no real difference in leg-length ($p = 0.290$, $d = 0.65$) between the seven and eight-step athletes (seven-step; 0.91 ± 0.02 m, eight-step; 0.88 ± 0.04 m). There was also no identifiable difference between the groups when considering leg-length as a percentage of stature ($p = 0.360$, $d = 0.61$).

In the set position, the seven-step athletes positioned the front foot and rear foot plates of the starting blocks 0.08 m further apart ($p = 0.043$, $d = 1.34$) compared with the eight-step athletes. Block contact time of the front foot was 0.06 s longer ($p = 0.022$, $d = 1.51$) for the seven-step athletes than the eight-step athletes. The first step length was also 0.25 m longer ($p = 0.008$, $d = 1.91$) for the seven-step athletes than the eight-step athletes. There was a tendency for a longer first ground contact time for the seven-step athletes, contacting the ground for 0.03 s longer ($p = 0.073$, $d = 1.18$) than the eight-step athletes. From the set position to the point of first ground contact, there was also a tendency for seven-step athletes to increase the vertical displacement of the CoM by 0.04 m ($p = 0.081$, $d = 1.12$) compared with eight-step athletes. Additionally, the seven-step athletes showed a tendency of 197°/s^2 slower hip extension acceleration ($p = 0.075$, $d = 1.15$) than the eight-step athletes throughout the block contact phase (Figure 3.3.1; Table 3.2.4.1).

Both the second and the fourth steps were 0.30 m ($p = 0.028$ and 0.000, $d = 1.48$ and 4.20 respectively) longer for the seven-step athletes than the eight-step athletes

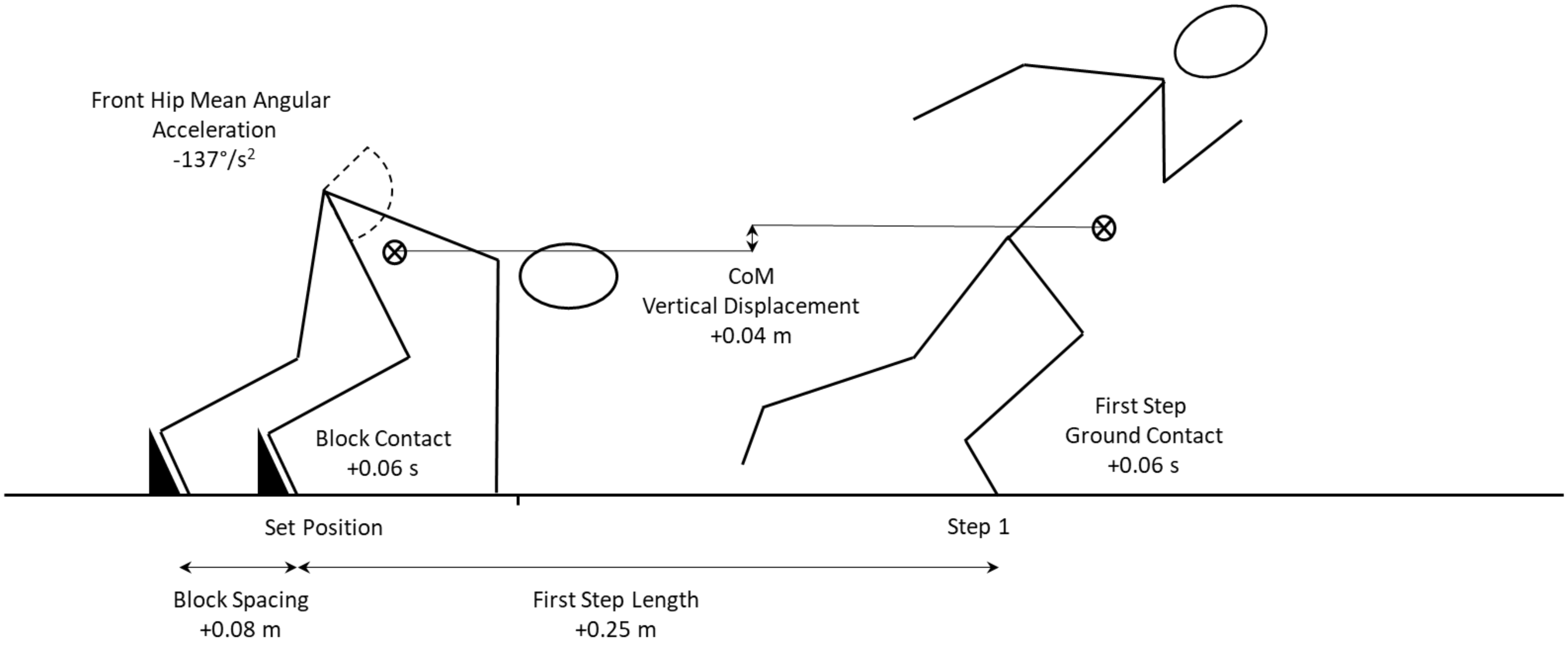

Figure 3.3.1 Mean first step differences of seven-step athletes compared with eight-step athletes.

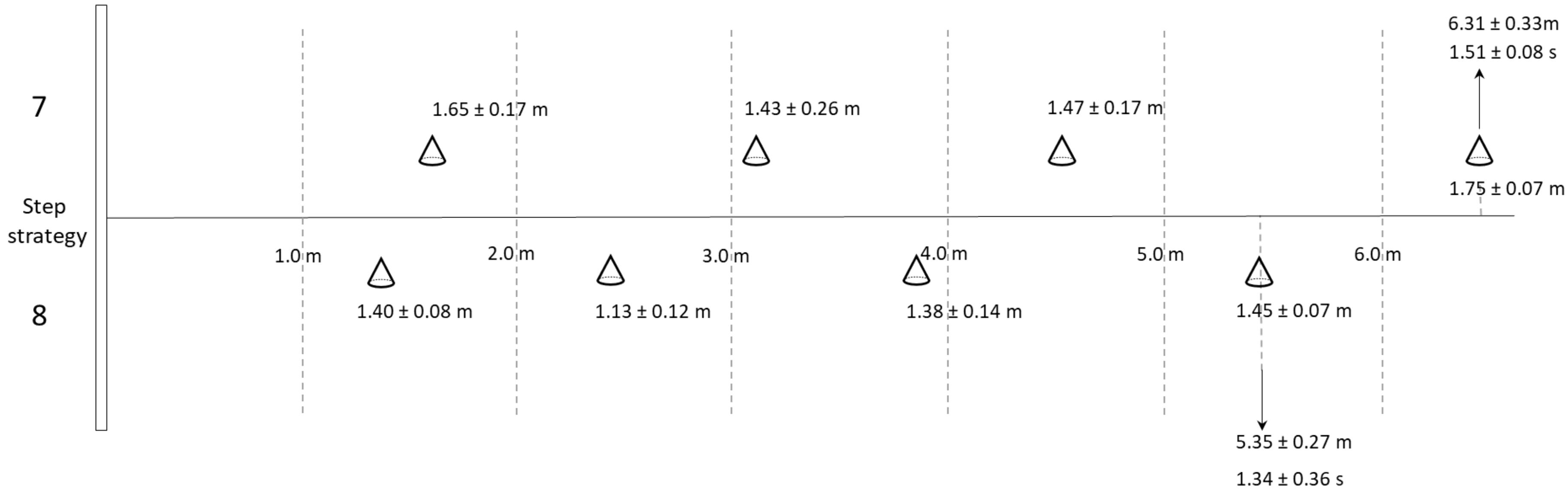

Figure 3.3.2 Seven and eight-step strategy mean (±SD) step lengths (m) and time to fourth step (s) (not to scale).

(Figure 3.3.2). The first ground contact time showed a tendency to be 0.03 s longer (p = 0.073, d = 1.18). The fourth ground contact time also showed a tendency, being 0.02 s longer (p = 0.055, d = 1.25) for the seven-step athletes compared with the eight-step athletes. The third step ground contact time was also 0.02 s longer (p = 0.018, d = 1.64). Additionally, the flight time of the fourth step showed a tendency to be 0.02 s longer (p = 0.052, d = 1.52) for the seven-step athletes. The seven-step athletes also had a 0.34 Hz lower step frequency (p = 0.001, d = 2.59) and were 0.17 s slower (p = 0.001, d = 2.52) over the first four steps (Table 3.2.4.2).

There was no reportable difference between the seven and eight-step performance times from the blocks to the take-off for the first hurdle (p = 0.791, d = 0.09) (Table 3.2.4.3).

3.3 Discussion and Implications

The aim of this study was to investigate the effect of first hurdle step strategy on the start position and block clearance phase kinematics, and the spatio-temporal characteristics of the first four steps. The results are in agreement with the hypothesis; that seven-step athletes position themselves differently in the blocks compared to eight-step athletes to achieve different block exit kinematics.

In the set position, the seven-step athletes set up the blocks with the block plates further apart, which appeared primarily due to positioning of the front block plate closer to the start line rather than the rear block further from the start line. Although no tendency was identified for either of these parameters, this finding is in keeping with previous research into initial acceleration between both flat sprinters and hurdlers (Bezodis et al., 2019). Subsequently, the front foot of the seven-step athletes remained in contact with the block plate for longer than the eight-step athletes. The front hip mean angular acceleration of the seven-step athletes was almost 27% slower than that of the eight-step athletes. It is likely that the lower mean hip extension acceleration identified in the seven-step athletes was linked to an increased block contact time, itself due to the increased distance between the starting blocks in the set position.

The greater spacing between the blocks led to a longer first step for the seven-step athletes. Schot and Knutzen (1992) identified that athletes who set up their blocks with an elongated position (> 0.5 m) took a first step which was 6% longer than athletes using a medium position (0.3 – 0.5 m). Although seven-step athletes used a medium position, based upon Schot and Knutzen's (1992) definitions, it is reasonable to conclude that as block spacing increases within the medium start thresholds, first step length also increases. Schot & Knutzen (1992) further suggested that an athlete's physical characteristics can be used to determine the medium block spacing by measuring the athlete's leg-length from the greater trochanter to the lateral malleolus. The front block position suggested was at 60% of the leg-length from the start line, and the inter-block spacing, 45% of the leg-length. Consequently, the longer the athlete's leg-length, the further the feet from the start line and the longer the block spacing. Further to Schot and Knutzen's (1992) suggestions, Cavedon, Sandri, Pirlo, Petrone, Zancanaro & Milanese (2019) found that using the Cormic Index (ratio of height whilst sitting to stature) to identify block placement led to an improvement in the kinematic and kinetic block start performance, when compared to usual block placement. Despite differences in block positions between the seven and eight-step athletes, calculating the leg-length as a percentage of the stature confirmed that this was not due to any difference in leg-length between the two groups. Further, the normalised first step length identified that the longer step taken by the seven-step athletes was not due to leg-length (Table 3.2.4.3).

To limit the horizontal velocity lost at each touchdown, it is important that the braking phase during foot contact is as short as possible (Harland & Steele, 1997).

Hunter, Marshall & McNair, (2005) identified that better sprinters use an 'active touchdown' (reduced horizontal velocity of the foot and minimised touchdown distance) to minimise horizontal braking force. Due to the longer first step, for a seven-step approach to be successful it is crucial that the first step touchdown remains posterior of the CoM and that an active touchdown can be used to prevent unnecessary braking forces. CoM touchdown angle in the present study was not different to the eight-step athletes despite a longer step length. Thus, it is likely seven-step athletes were able to minimise braking by ensuring the CoM touchdown angle was less than 90°.

Seven-step athletes elevated their CoM higher than the eight-step athletes at the point of first ground contact, despite there being no difference in the relative height of the CoM in the set position between groups. Čoh et al. (1998) previously reported slightly lower figures for mean relative height of the CoM in the blocks (30% of stature) from a sample of thirteen sub-elite (mean 100 m time of 10.73 s) male sprinters. It might be that hurdlers use the blocks differently to flat sprinters due to needing to be more upright in fewer steps to clear the first hurdle. Seven-step athletes took a first step that was almost 18% longer than the eight-step athletes and might have required more space below the CoM to position the foot for the first ground contact. The normalised data for leg-length and the change in height of the CoM identified only a tendency for the difference to be due to leg-length and therefore casts doubt upon leg-length being a decisive factor. It must be considered though, that the seven-step athletes were taller than the eight-step athletes and the longer step length might be a result of increased stature despite there being no identifiable difference in leg-length (Hunter et al., 2004).

Despite the first four like-for-like step lengths being longer for the seven-step athletes than the eight-step athletes, step three does not satisfy the criteria as defined by the statistical analysis. It does though appear that the third step behaved as a recovery step for the seven-step athletes following the longer first two steps. In agreement with findings from previous sprint-based literature (Salo, Keränen & Viitasalo, 2005), there was a regular progression of increasing step lengths following the first step from the eight-step athletes, but the third step of the seven-step athletes was only slightly longer than the second step. The step frequency of the seven-step athletes was, as expected, lower than the eight-step athletes. Likewise, the seven-step athletes took 0.17 s longer to reach the end of the fourth ground contact. For seven-step athletes this event occurred almost one metre further from the front block plate, or one metre closer to the first hurdle.

All like-for-like ground contact times were longer for the seven-step athletes although, only the first, third and fourth ground contact times satisfied the criteria as defined by the statistical analysis. As the seven-step athletes completed longer steps, it is possible that this was achieved from generating greater horizontal impulse. Previous findings have shown that as sprinters move through the acceleration phase to maximum velocity, the time of each flight phase increases and the time of each ground contact decreases (Salo et al., 2005). This occurred, step-by-step for both seven and eight-step athletes in this study. Only the flight time of the fourth step was longer for the seven-step athletes. Compared with the eight-step athletes, the fourth step length of the seven-step athletes was longer, which accounts for the increase in flight time. Despite the seven-step athletes taking longer steps out of the blocks, there was no real increase in equivalent flight times compared with the eight-step athletes. This is consistent with current maximal velocity sprint literature whereby the ability to exert mass specific forces during ground contact, in the shortest possible time and not the ability to reposition the limbs, is a limiting performance factor (Weyand, Sternlight, Bellizzi & Wright, 2000).

The findings of this study identify that seven-step athletes are positioning the block plates further apart in the set position, front block contact was maintained for longer and the CoM was raised. This led to a longer first step and a longer first ground contact time. Despite reducing angular acceleration of the front hip, the increased block contact time of the seven-step athletes may have led to an increase in impulse. Although horizontal velocity of the CoM at the point of block exit was not different, it is not yet known whether there is a difference at the point of first hurdle take-off or where any difference might occur throughout the approach phase. There was no discernible difference between the time taken from the blocks to the take-off for the first hurdle but, this parameter must be interpreted with caution as the position of the take-off event in relation to the hurdle position is not considered. It is not possible to favour either step strategy from the findings of this study alone. The research does though, provide an important insight into the sprint hurdle start performances of seven and eight-step athletes. Compared with the eight-step approach, seven-step athletes position the block plates further apart, maintain contact with the front block for longer, elevate the CoM to a greater extent and take a longer first step.

There are limitations associated with this study. The use of two-dimensional analysis of footage with manual digitisation as a research method has accuracy limitations when compared to more favourable methods such as three-dimensional analysis or motion capture. Two-dimensional footage was deemed suitable for this study due to the predominantly planar motion and the non-invasive nature of this research method. As well as the first hurdle clearance, future research should look closely at the steps prior to the hurdle clearance and identify whether the step differences seen in this study continue throughout the entire acceleration phase. Additionally, future studies should consider the kinetics of each of the approach steps to achieve a more comprehensive understanding of the seven-step strategy. There is a lack of research into the influence of anthropometric characteristics on the sprint start, therefore, research is needed into the physical characteristics of the athlete and the optimum block settings.

3.4 Conclusion

The effect of step strategy to the first hurdle on the block start was investigated in this study. Seven-step athletes position their blocks with a greater distance between the front and rear block plates. This allowed seven-step athletes to maintain contact with the front foot for longer and results in displacing of the CoM to a greater extent during a longer first step. Presented technical alterations to the block positioning and the execution of the first steps are useful considerations for coaches and athletes who may be experimenting with the transition between seven or eight-step strategies. By ensuring the athlete trains with a block spacing which is increased from their normal eight-step block spacing, and takes a longer first step, the capacity to perform a seven-step approach is increased. However, care should be taken to ensure increases in block spacing and first step length do not lead to subsequent increases in approach step time parameters. To gain a clearer understanding of the seven and eight step strategies, further studies must investigate the kinematics of the steps prior to the first hurdle and the hurdle clearance, as well as the individual step kinetics of the entire phase.

THE WORK IN THIS CHAPTER FORMED THE BASIS OF THE FOLLOWING PEER-REVIEWED JOURNAL ARTICLE:

Rowley, L.J., Churchill, S., Dunn, M., and Wheat, J., (2021). Effect of hurdling step strategy on the kinematics of the hurdle technique. *Sports Biomechanics.*

4. Effect of hurdling step strategy on the kinematics of the hurdle technique

4.1 Introduction

The aim of the 110 m sprint hurdles event is to cover the horizontal distance, clearing each of the ten hurdles in the fastest time. Therefore, as with flat sprinting, the ability to generate a high level of horizontal velocity is ultimately the key factor for success. The spatial constraints of the inter-hurdle distance (9.14 m) dictate that a three-step pattern between hurdles is the most suitable for all athletes, but step strategy prior to the first hurdle differs between athletes. Some hurdlers use an eight-step approach whereas others use a seven-step approach. An eight-step approach has previously dominated coaching practice. Every Olympic athlete prior to the 1960 Olympic Games favoured the eight-step strategy (Pinho, Lima, Claudino, Andrade, Soncin, Mezêncio, Bourgeois, Amadio & Serrão, 2017). Despite historical resistance, the seven-step approach has now become commonplace amongst senior world-class hurdlers (Bezodis et al., 2019).

When athletes leave the starting blocks, they accelerate via a suitable step strategy which positions them correctly for clearance of the first hurdle. Elite hurdlers take-off 2.01 - 2.40 m from the first hurdle (Tidow, 1991; Mann, 2011; González-Frutos, Veiga, Mallo & Navarro, 2020), leaving 11.32 – 11.71 m from the start line to the point of take-off for the athlete to generate horizontal acceleration.

There are several parameters which have previously been used to quantify the technical success of the hurdle take-off phase (Iskra, 2006). The most important of these measurements identify the position and trajectory of the whole body centre of mass (CoM). The smaller the decrease of the horizontal velocity of the CoM across the hurdle, the more technically effective the hurdle clearance.

Take-off directly affects the success of the hurdle clearance, the touchdown phase, and the inter-hurdle steps (Mann, 2011). The deviation angle is a measure of the absolute position of the CoM in relation to the metatarsal phalangeal (MTP) joint of the take-off foot and a line horizontal with the ground from the MTP towards the hurdle. Previous research suggests that this angle is a key parameter which defines the success of the take-off phase, defining the trajectory of the CoM and the hurdle flight time (Čoh, Jost & Skof, 2000). Better hurdlers have a deviation angle which is less than 70˚ (Wen, 2003; Li, Zhou, Li & Wang, 2011). There has been no documented research into the first hurdle clearance where athletes have been grouped according to step strategy. Therefore, whether both seven and eight-step athletes take-off with an angle of less than 70˚ is currently unknown.

Effective clearance of the first hurdle is critical and if the athlete takes off too far from the hurdle, the path of the CoM is lengthened via both increases in the horizontal and vertical distances over which it must travel. Upon crossing the hurdle, the athlete must actively extend the lead leg hip joint and re-establish ground contact as opposed to passively waiting for the ground contact to occur.

The optimal ratio of take-off to touchdown distance is a key element which defines the success of the hurdle clearance (Mann, 2011; Amara et al., 2019). Sidhu and Singh (2015) proposed a ratio of 65:35 for take-off and touchdown distance step lengths. This ratio allows enough space to rapidly extend the lead leg anteriorly prior to crossing the hurdle and considering the need to re-establish ground contact as immediately practical. When considering the biomechanical implications of the seven and eight-step approach strategies it is likely that the take-off ratio will be increased for the seven-step athletes because they have one step fewer to position the foot for take-off. It is particularly important to consider the kinematics of the touchdown phase and the ground contact time. This phase is crucial for successful execution of the inter-hurdle steps and directly affected by the success of the take-off position (Čoh & Iskra, 2012).

Unnecessary increases in ground contact time of the touchdown foot indicate a ground contact ahead of the CoM position, leading to negative horizontal braking forces and limiting the velocity which can be maintained between the hurdles. The cumulative result of which, is a detrimental effect upon overall race performance. Elite athletes have been found to complete both shorter ground contact and flight times throughout the hurdle clearance phase than high-level athletes (González-Frutos, Veiga, Mallo and Navarro, 2019). Should seven-step athletes compensate for having one fewer step by taking off further from the first hurdle, the position of the touchdown may as a consequence, be closer to the hurdle, making it difficult for the seven-step athletes to position the CoM correctly.

A fast hurdle clearance is made possible by rapid flexion and extension phases of the lead leg hip (Arnold, 1992). Despite this understanding, there is only one study where the velocity of the lead leg hip action has been recorded (Salo, 2002). However, in flat sprint literature the hip action was found to be extremely important throughout both acceleration (Charalambous, Irwin, Bezodis & Kerwin, 2011) and maximal velocity phases (Mann & Sprague, 1980). In hurdling, as athletes increase their horizontal velocity, the necessity to rapidly flex and extend the lead leg hip becomes more important to avoid hitting the hurdle with the leading foot, and to re-establish ground contact in the correct position. Failure to rapidly extend the lead leg hip upon crossing the hurdle will cause the athlete to apply unwanted horizontal braking forces upon ground contact, as ground contact will be established ahead of the whole body CoM. If seven-step athletes are taking off further from the hurdle, with more available space to raise the lead leg, a slower lead leg hip flexion will lead to a technically poorer hurdle clearance as the hurdle flight time increases.

A three-step pattern between hurdles is accepted as the most effective method for negotiating the spatial constraints of the inter-hurdle distance (9.14 m). Athletes make alterations to normal sprint step characteristics (ground contact time, flight time and step length) to successfully position themselves for clearance of the next hurdle, and to satisfy the four ground contacts required of a three-step pattern. These alterations must allow for the generation of further acceleration throughout the first phase of the event (positive acceleration; 0-30 m), and maintenance of optimum horizontal velocity throughout the middle (maintenance; 30-70 m) and final phases (negative acceleration; 70-110 m). To effectively satisfy each phase, athletes reduce step lengths between the hurdles, with only the second comparable in step length to a normal sprint step length (McDonald & Dapena, 1991). Irrespective of approach step strategy, there should be no detrimental effect to the intra-hurdle step kinematics. Although it is not known how approach strategy affects the inter-hurdle steps, any differences in the dynamics of the touchdown (both in absolute position and in relation to the CoM) are likely to affect primarily the first inter-hurdle step, and the ability of the athlete to maintain horizontal velocity into the following hurdle.

As the athletes approach the first hurdle, the dynamics of each step change in preparation for hurdle clearance. This is particularly evident when comparing seven and eight-step strategists, whereby there is a need to balance the development of horizontal velocity with suitable step lengths to position for optimum hurdle clearance. Essentially, there is a functional difference between the strategy used for acceleration and the preparation for the hurdle clearance.

To date only one published study has differentiated participant groups by first hurdle step strategy (Chapter 3). The omission of step strategy consideration from the methods of previous studies, may affect the findings amongst other comparative research of first hurdle clearance technique, and a more favourable method would be to group step strategists independently (and provide independent group statistics), as opposed to identifying single group statistics). Especially so, whereby spatio-temporal measurements have been made pertaining to the approach steps and hurdle clearance parameters.

Sprint hurdlers reduce both step length and flight time prior to take-off (Mann, 2011). It is therefore not possible to compare like-for-like steps from the block clearance as the seventh step serves a different purpose for the different strategies. A more suitable method is to contextualise steps with reference to the hurdle, comparing the ‘take-off step’, the ‘take-off step minus one', the ‘take-off step minus two' and the ‘take-off step minus three'.

The aim of this study was to investigate the effect of first hurdle step strategy on the kinematics of the hurdle technique, and the spatio-temporal characteristics of seven and eight-step approaches throughout the final four approach steps. It was hypothesised that seven-step athletes would clear the first hurdle differently to eight-step athletes to accommodate having one fewer approach step. Take off distance from the first hurdle, hurdle step length and oscillations pertaining to the centre of mass are parameters which are likely to differ based upon anecdotal observations; however, this is not yet known.

4.2 Methods

4.2.1 *Participants*

Participants were in accordance with Chapter 3, subsection 3.2.1. The same participants partook in both studies and data was collected as part of a single data collection.

Research study procedures were approved by Sheffield Hallam University Research Ethics Committee. Participants were provided with an information sheet and gave written informed consent before taking part.

4.2.2 *Data collection*

Data were collected as per Chapter 3, subsection 3.2.2.

High-speed video footage (200 Hz) of the hurdle clearance was collected using a single camera aligned with the first hurdle. A second high-speed camera was aligned mid-way between the start line and the first hurdle to capture the spatio-temporal parameters of the approach steps. All footage was collected with Phantom Miro M110 high-speed cameras (Vision Research, Wayne, New Jersey, USA) which were positioned 20 m perpendicular to the centre of the running lane and provided images of the sagittal plane. Cameras were set up in accordance with Figure 4.2.2.1 and identified as either the 'hurdle' or 'overview' camera. Cameras were manually focused, and the field of view was set to 6.00 m wide for the hurdle camera and 19.72 m wide for the overview camera. Shutter-speed was $^{1}/_{500}$ s (exposure of 2000 μs) and aperture was fully open for each camera.

4.2.3 *Data Processing*

Data processing was completed as per Chapter 3, subsection 3.2.3 for the hurdle and overview cameras.

Raw image coordinate data were filtered using a second order low pass Butterworth filter with a cut-off frequency of 8 Hz. The cut-off frequency was identified via residual analysis (Winter, 2009). For the hurdle camera, raw image coordinate data and camera calibration data were subsequently exported, and planar position data reconstructed (Dunn, Wheat, Miller, Haake & Goodwill, 2012) using Matlab R2017a (The MathWorks, Natick, MA, USA). A comprehensive review of available literature yielded a total of 34 parameters which were investigated, 25 from the hurdle camera (Table 4.2.3.1), five from the overview camera (Table 4.2.3.2) and four from the anthropometric data (Table 4.2.3.3).

4.2.4 *Statistical Analysis*

Independent-sample *t*-tests (SPSS for Windows, version 24.0; SPSS, Inc., Chicago, IL, USA) were performed to determine differences between the step strategy groups for all variables Athlete stature, mass, leg-length, and leg-length as a percentage of stature were also compared to assess whether there was a difference between groups in anthropometric variables The study included the final four ground contacts prior to the hurdle clearance. The hurdle take-off step was defined as the TO step. Therefore, steps back from the hurdle take-off were defined as TO-1 (take-off step minus one) to TO-3.

To reduce the possibility of type II errors occurring from low participant numbers, the criterion alpha level was set at $p < 0.05$ for statistical significance with $p < 0.1$ accepted as a tendency. This approach has been taken by Alt, Heinrich, Funken & Potthast (2015) when investigating lower extremity kinematics of athlete curve sprinting with low participant numbers (n = 6). Effect size was calculated for each variable using Cohen's *d* (Cohen, 1988; Coe, 2002). Only large effect size differences ($d \geq 0.80$) were deemed relevant and examined, in-line with Cohen's effect size suggestions, although a contextual approach was taken when considering moderate effect sizes ($d \geq 0.50$ and $d < 0.80$).

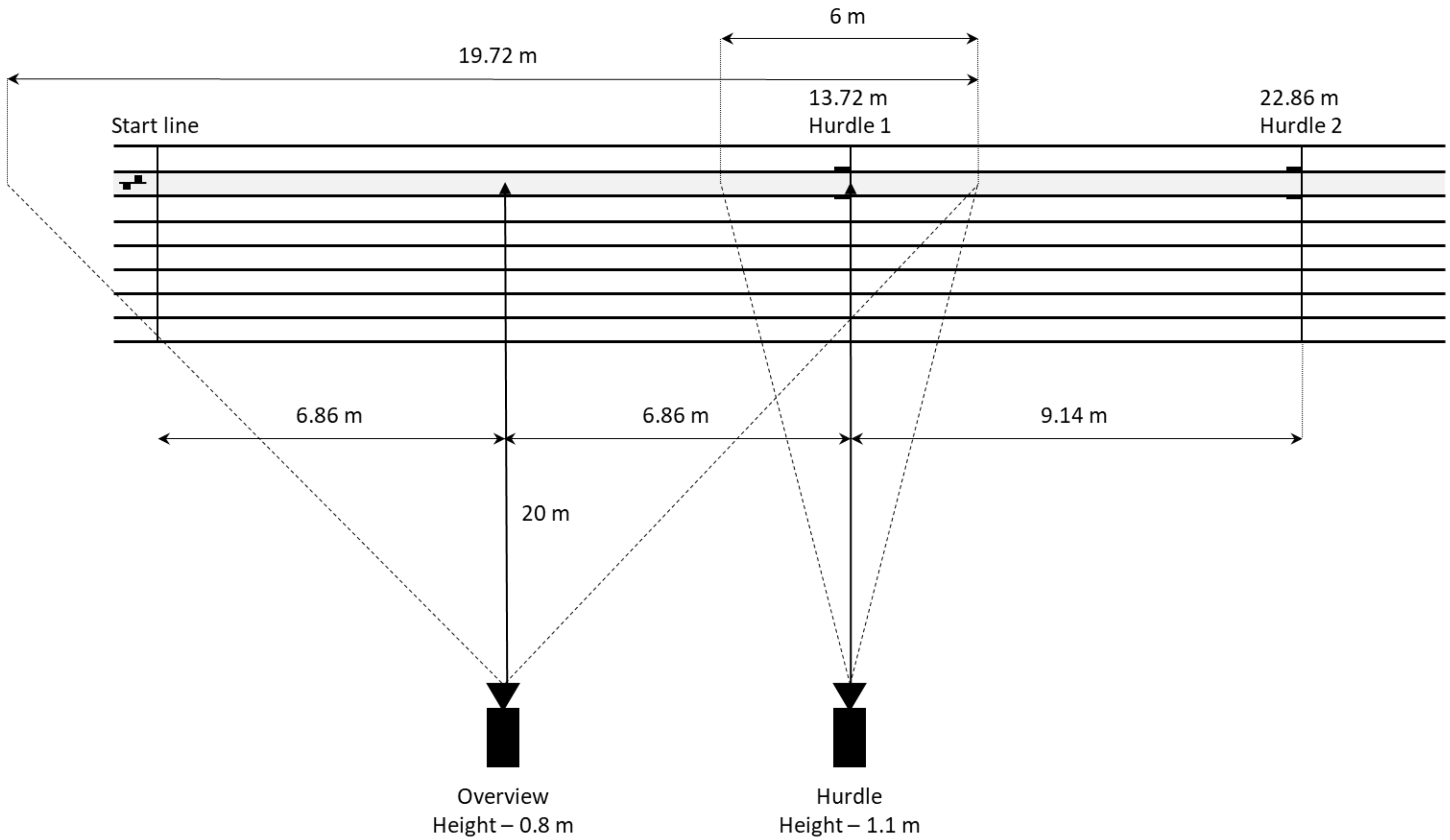

Figure 4.2.2.1 Plan view of camera set-up for hurdle trials (not to scale).

Table 4.2.3.1 Description of technique variables calculated from the hurdle camera view.

Parameter	Description
Hurdle step length (m)	Horizontal distance from the metatarsophalangeal joint (MTP) of the take-off foot to the MTP of the touchdown foot.
Take-off distance (m)	Horizontal distance from the MTP of the take-off foot to the base of the hurdle.
Normalised take-off distance	Non-dimensional normalisation. Take-off distance divided by leg-length.
Touchdown distance (m)	Horizontal distance from the MTP of the touchdown foot to the base of the hurdle.
Take-off distance (%)	Percentage of the hurdle step length occurring prior to the hurdle from the MTP of the take-off foot to the base of the hurdle.
Take-off step ground contact time (s)	Time that the take-off foot can positively be identified as in contact with the ground to the first frame of loss of ground contact.
Touchdown step ground contact time (s)	Time that the touchdown foot can positively be identified as in contact with the ground to the first frame of loss of ground contact.
Hurdle flight time (s)	Time that the take-off foot loses ground contact to the first frame of ground contact of the touchdown foot.
CoM mean horizontal velocity (m/s)	Mean horizontal velocity of the CoM throughout the hurdle clearance phase.
CoM take-off vertical velocity (m/s)	Vertical velocity of the CoM at hurdle take-off
CoM touchdown vertical velocity (m/s)	Vertical velocity of the CoM at hurdle touchdown
CoM height at take-off (m)	Height of the CoM from the ground at the point of take-off.
CoM height at touchdown (m)	Height of the CoM from the ground at the point of touchdown.
CoM change (m)	Change in the vertical position of the CoM from take-off to touchdown.
CoM maximum height (m)	Maximum relative height of the CoM above the height of the hurdle throughout the hurdle clearance phase.
CoM height above hurdle (m)	Height of the CoM as it crosses the hurdle plane.
CoM difference at take-off to above hurdle (m)	Change in the height of the CoM from take-off to height above hurdle.
CoM difference above hurdle to touchdown (m)	Change in the height of the CoM from height above hurdle to touchdown.
CoM take-off angle (˚)	Absolute angle of the CoM from the first frame of loss of ground contact of the take-off foot and the following frame.
MTP to CoM take-off angle (˚)	Absolute angle between the CoM and the MTP of the take-off foot at take-off.
MTP to CoM touchdown angle (˚)	Absolute angle between the CoM and the MTP of the touchdown foot at touchdown.
Lead hip mean angular velocity throughout take-off. (˚/s)	Mean angular velocity of the lead leg hip throughout the ground contact phase of the take-off foot.
Lead hip mean angular acceleration throughout take-off (˚/s^2)	Mean angular acceleration of the lead leg hip throughout the ground contact phase of the take-off foot.
Lead hip mean angular velocity throughout touchdown (˚/s)	Mean angular velocity of the lead leg hip from the first frame of lead leg hip extension throughout the hurdle clearance phase, to the point of ground contact of the lead leg foot.
Lead hip mean angular acceleration throughout touchdown (˚/s^2)	Mean angular acceleration of the lead leg hip from the first frame of lead leg hip extension throughout the hurdle clearance phase, to the point of ground contact of the lead leg foot.

Table 4.2.3.2 Description of technique variables calculated from the overview camera view.

Parameter	Description
Step length (m)	Horizontal distance between the MTP of the touchdown step and the MTP of the following contralateral touchdown step.
Step frequency TO-3 to take-off (Hz)	Mean number of steps taken per second from the TO-4 step loss of ground contact to the loss of ground contact of the hurdle take-off step. Calculated by dividing the time to end of fourth ground contact by the number of approach steps.
Ground contact time (s)	Time that each step foot can positively be identified as in contact with the ground to the first frame of loss of ground contact.
Flight time (s)	Time between steps that neither foot is in contact with the ground.
Approach TO-3 to take-off (s)	Time from TO-4 step loss of ground contact to the loss of ground contact of the hurdle take-off step.

Table 4.2.3.3 Description of anthropometric variables.

Parameter	Description
Stature (m)	Stature of seven and eight-step athlete groups.
Mass (kg)	Mass of seven and eight-step athlete groups.
Leg-length (m)	Leg-length of seven and eight-step athlete groups measured from the ankle-joint centre to the hip-joint centre.
Leg-length % of stature	Leg-length as a percentage of stature.

4.3 Results

As per Chapter 3, seven-step athletes were 0.08 m taller (p = 0.047, d = 1.31) than eight-step athletes (Table 4.3.4) and had a tendency to be heavier (11.7 kg, p = 0.100, d = 1.05). There was no difference in leg-length between the seven and eight-step athletes (seven-step; 0.91 ± 0.02 m, eight-step; 0.88 ± 0.04 m; p = 0.290, d = 0.65). There was also no difference between the groups when considering leg-length as a percentage of stature (p = 0.360, d = 0.61).

Seven-step athletes took off 0.20 m further from the hurdle (p = 0.019, d = 1.62) and touched down 0.42 m closer to the hurdle (p = 0.036, d = 1.40); (Figure 4.3.1). TO-1 was 0.33 m longer for the seven-step athletes (p = 0.048, d = 2.65) and TO-2 was 0.24 m longer (p = 0.003, d = 3.96) compared to the eight-step athletes. Ground contact times of steps TO-3, TO-2 and TO-1 were longer for seven-step athletes and yielded a large effect size (d = 1.74, 1.35 and 0.91 respectively), but did not meet the criteria to be expressed as a tendency for a difference between groups. The flight time of the TO step yielded a large effect size (d = 1.16), and the flight times of TO-2 and TO-3 were different between the two groups (p = 0.041 and 0.013 respectively). Additionally, the seven-step athletes had a 0.40 Hz lower step frequency than the eight-step athletes (p = 0.003, d = 2.26; Table 4.3.2).

There was no difference between the mean seven and eight-step performance times from the blocks to the take-off for the first hurdle (0.01 s; p = 0.791, d = 0.09; Table 4.3.3).

4.4 Discussion and Implications

The aim of this study was to investigate the effect of first hurdle step strategy on the kinematics of the hurdle technique and the spatio-temporal characteristics of seven and eight-step approaches throughout the final four approach steps. The results are in

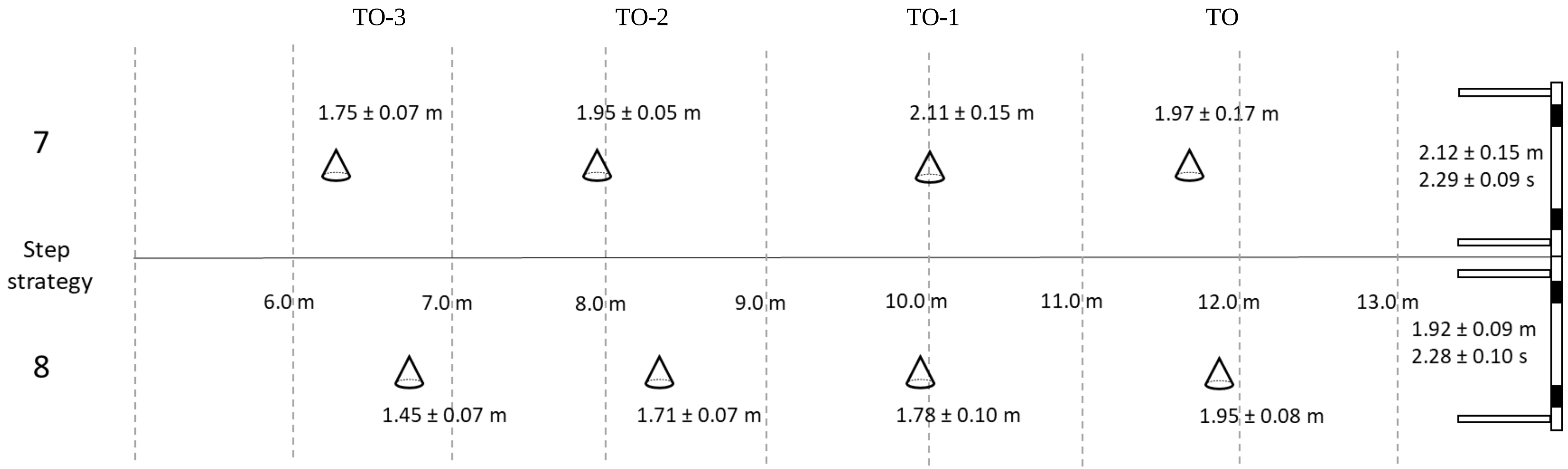

Figure 4.3.1 Seven and eight-step strategy mean (SD±) step lengths (to touchdown step cone), take-off distances and approach times to hurdle take-off (shown adjacent to hurdle) (not to scale).

Table 4.3.2 Seven and eight-step group mean values (±*SD*), effect size and significant differences for technique variables.

	Seven-Step			Eight-Step			Cohen's *d*		*p*	
Hurdle step length (m)	3.36	±	0.13	3.58	±	0.37	0.78		0.206	
Take-off distance (m)	2.12	±	0.15	1.92	±	0.09	1.62	§	0.019	*
Normalised take-off distance	2.35	±	0.19	2.18	±	0.14	1.02	§	0.110	
Touchdown distance (m)	1.24	±	0.16	1.66	±	0.39	1.40	§	0.036	*
Take-off distance (%)	63.3	±	4.46	54.2	±	5.85	1.75	§	0.120	
Take-off ground contact time (s)	0.14	±	0.02	0.13	±	0.01	0.47		0.437	
Touchdown ground contact time (s)	0.10	±	0.01	0.10	±	0.01	0.07		0.900	
Hurdle flight time (s)	0.36	±	0.02	0.38	±	0.05	0.32		0.589	
CoM mean horizontal velocity (m/s)	7.45	±	0.29	7.47	±	0.37	0.05		0.932	
CoM take-off vertical velocity (m/s)	1.72	±	0.30	1.86	±	0.24	0.53		0.379	
CoM touchdown vertical velocity (m/s)	-1.10	±	0.30	-1.21	±	0.32	0.37		0.537	
CoM height at take-off (m)	1.15	±	0.04	1.13	±	0.01	0.54		0.369	
CoM height at touchdown (m)	1.21	±	0.05	1.16	±	0.07	0.85		0.171	
CoM change (m)	0.06	±	0.07	0.03	±	0.07	0.47		0.437	
CoM maximum height (m)	1.33	±	0.02	1.31	±	0.03	0.62		0.305	
CoM height above hurdle (m)	1.32	±	0.02	1.31	±	0.03	0.52		0.389	
CoM difference at take-off to above hurdle (m)	0.17	±	0.04	0.18	±	0.02	0.10		0.872	
CoM difference above hurdle to touchdown (m)	0.11	±	0.05	0.15	±	0.07	0.63		0.303	
CoM take-off angle (°)	14	±	2	15	±	2	0.31		0.607	

MTP to CoM take-off angle (°)	65	±	4	65	±	2	0.00	1.000
MTP to CoM touchdown angle (°)	82	±	4	81	±	7	0.20	0.671
Lead hip mean angular velocity throughout take-off (°/s)	780	±	138	813	±	71	0.31	0.606
Lead hip mean angular acceleration throughout take-off (°/s)	5876	±	1830	6245	±	820	0.26	0.662
Lead hip mean angular velocity throughout touchdown (°/s)	547	±	81	514	±	79	0.41	0.489
Lead hip mean angular acceleration throughout touchdown (°/s)	3099	±	674	2724	±	866	0.48	0.422

Note: * significant at $p < 0.05$; § effect size > ± 0.8.

Table 4.3.3 Seven and eight-step group mean values (±*SD*), effect size and significant differences for approach step variables.

	Seven-Step			Eight-Step			Cohen's *d*		*p*	
Step length (m)										
TO-3	1.75	±	0.07	1.45	±	0.07	4.20	§	0.340	
TO-2	1.95	±	0.05	1.71	±	0.07	3.96	§	0.003	*
TO-1	2.11	±	0.15	1.78	±	0.10	2.65	§	0.048	*
TO	1.97	±	0.17	1.95	±	0.08	0.16		0.054	#
Step GCT (s)										
TO-3	0.16	±	0.02	0.13	±	0.01	1.74	§	0.797	
TO-2	0.15	±	0.01	0.13	±	0.01	1.35	§	0.712	
TO-1	0.14	±	0.02	0.13	±	0.01	0.91	§	0.234	
TO	0.14	±	0.01	0.13	±	0.01	0.54		0.073	#
Step flight time (s)										
TO-3	0.105	±	0.016	0.108	±	0.016	0.15		0.013	*
TO-2	0.114	±	0.012	0.118	±	0.024	0.22		0.041	*
TO-1	0.130	±	0.013	0.115	±	0.026	0.73		0.148	
TO	0.113	±	0.028	0.086	±	0.019	1.16	§	0.369	
Approach to TO (s)	2.29	±	0.09	2.28	±	0.10	0.09		0.791	
Step Freq (Hz)	3.06	±	0.12	3.52	±	0.15	3.37	§	0.000	*
Approach TO-3 to TO (s)	0.26	±	0.03	0.24	±	0.03	0.67		0.003	*
TO-3 to TO Step Freq (Hz)	3.84	±	0.12	4.24	±	0.22	2.26	§	0.003	*

Note: * significant at $p < 0.05$; # tendency at $p < 0.10$; § effect size > ± 0.8.

Table 4.3.4 Seven and eight-step group mean anthropometric measurements (±SD), effect size and *p* values.

	Seven-step			Eight-step			Cohen's *d*		*p*	
Stature (m)	1.87	±	0.05	1.79	±	0.07	1.31	§	0.047	*
Mass (kg)	85.3	±	8.6	73.6	±	13.3	1.05	§	0.100	
Leg-length (m)	0.91	±	0.02	0.88	±	0.04	0.65		0.290	
Leg-length % of stature	48.3	±	0.94	49.3	±	2.13	0.61		0.366	

Note: * significant at $p < 0.05$; § effect size > ± 0.8

agreement with the hypothesis that seven-step athletes cleared the first hurdle differently to eight-step athletes. Seven-step athletes had a longer take off distance. However, a longer hurdle step length and a flatter trajectory of the centre of mass did not meet the statistical criteria, although respectively, a large effect size was identified for the hurdle step length.

Seven-step athletes took off further away from the hurdle and touched down closer to the hurdle (Figure 4.4.1). Despite differences in these parameters, there was only a moderate effect size difference in hurdle step lengths and a trivial difference in the mean horizontal velocities of the CoM throughout the hurdle step between groups. This suggests both step strategists completed a hurdle step of similar length and horizontal velocity, but that the seven-step strategists completed a greater percentage of the hurdle step phase prior to the CoM crossing the hurdle plane. A large effect size was identified but not a significant difference when normalising the take-off distance for leg length, indicating that a difference might exist. Take-off distance, normalised to leg length, should be considered as a possible technical difference between the step strategies, and warrants future investigation. The hurdle step length should also be considered in future research and studies with larger numbers of participants may well find that the suggested differences indicated in this study, become statistically significant.

Seven-step hurdlers in this study had a take-off to touchdown ratio more closely aligned than the eight-step strategists to the recommendations of Sidhu and Singh (2015), with 63% of their hurdle clearance phase taking place prior to the hurdle and 37% after the hurdle. Sidhu and Singh (2015) suggest a take-off distance of 65% to allow for the kinematic requirements of a successful hurdle clearance technique, limiting unnecessary motion of the CoM and optimum take-off and touchdown position.

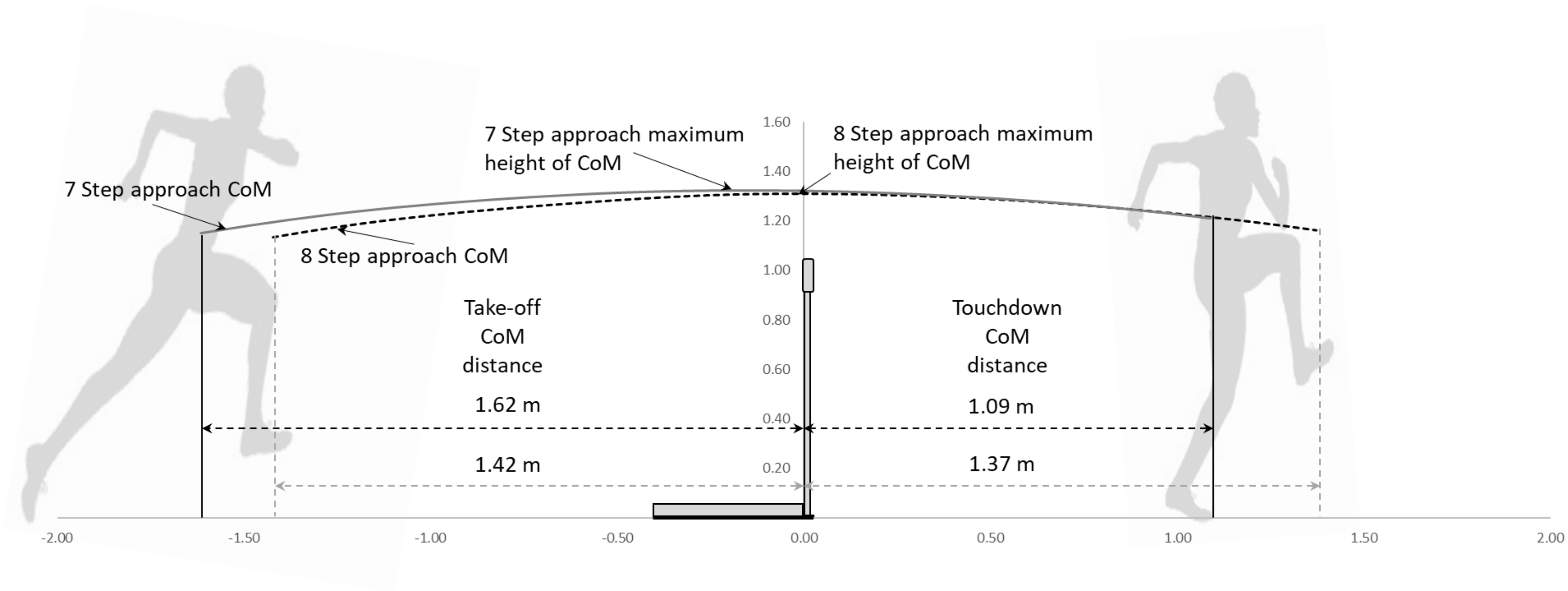

Figure 4.4.1 Trajectory of CoM over the hurdle for seven and eight-step strategies.

Only a minor difference between the CoM height at take-off and the CoM maximum height was identified between both seven- (0.17 m) and eight-step (0.18 m) athletes. However, the CoM height at touchdown was 0.05 m higher for the seven-step athletes and yielded a large effect size. Amara et al. (2019) identified limiting vertical displacement of the CoM as a key parameter defining the success of the hurdle clearance. The results of the present study suggest that the seven-step athletes, in touching down closer to the hurdle, were able to limit undesirable negative vertical motion of the CoM to a greater extent than the eight-step athletes (Salo, Grimshaw & Marer, 1997). In support of this finding, the seven-step athletes also accelerated the extension of the lead hip 375˚/s^2 more throughout the touchdown phase, suggesting a more active driving of the lead leg foot towards the ground. This prevents 'floating' (a performance term whereby the body segments are not involved in independent motion and simply track the motion of the whole body CoM), and allows for an effective touchdown ground contact, and continued race acceleration (Arnold, 1992). These parameters must be interpreted with caution though as they do not satisfy either of the criteria for significance or tendency but did show moderate or large effect sizes.

Seven-step athletes completed a similar hurdle clearance trajectory to the eight-step athletes, but the clearance phase was moved closer to the start line, with the CoM passing the hurdle plane later in the hurdle clearance. Previous research has identified the CoM to cross the hurdle plane close to its maximum height, although there was no consideration of the step strategy used (McDonald & Dapena, 1992). Further findings from the same study found female hurdlers CoM was at its maximum height 0.30 m prior to crossing the hurdle plane, a similar location to the seven-step athletes in this study. This is attributed to the lower hurdle height in the female event. As with much of the previous research, had McDonald & Dapena (1992) differentiated by step strategy the findings may well have been different, therefore step strategy should be a key consideration for inclusion in future research, especially where first hurdle clearance is investigated.

Steps TO-1 and TO-2 were significantly longer for the seven-step athletes than the eight-step athletes, but the step prior to the take-off (TO) had only a minor difference (0.02 m longer for seven-step strategists). The seven-step athletes appeared to reduce the length of the final step (TO) compared with their previous step (TO-1). However, this did not occur for the eight-step athletes who extended their final step by 0.17 m compared with the previous step. Reduction in the final step prior to take-off is a technique used by long jumpers (Hay & Nohara, 1990) to position the CoM over the take-off foot, thereby reducing horizontal braking force and accelerating the CoM into the jump phase. It is possible that the seven-step athletes were utilising a similar technique to accelerate the CoM into the hurdle clearance, allowing them to take-off from further away and consequently, complete more of the hurdle motion prior to the CoM crossing the hurdle. This may mean they are better positioned to re-establish ground contact of the lead leg closer to the hurdle, allowing an increased distance between the first and second hurdles for seven-step athletes to continue race acceleration. In-turn, this limits the degree to which seven-step athletes need to shorten their normal sprint strides to accommodate the spatial constraints of the inter-hurdle distance. Although logical, this theory has not been tested and further investigation should focus upon the spatio-temporal parameters of the intra-hurdle steps between the first and second hurdle, along with the intra-hurdle time differentiation between seven and eight-step strategists. It is possible that a performance difference due to the alternative touchdown position may become evident.

There was no difference in the approach times to the first hurdle between the two groups. Consequently, step frequency over the entire approach phase was significantly lower for the seven-step athletes compared with the eight-step athletes. Whilst repositioning of the limbs is not a factor determining sprint speed (Weyand, Sternlight, Bellizzi & Wright, 2000), the eight-step athletes must have repositioned their limbs faster than the seven-step athletes. Therefore, it is logical to conclude that the seven-step athletes generated a total horizontal impulse of at least equivalent quantity to the eight-step athletes throughout the acceleration phase to the first hurdle. Further investigation into the kinetic parameters may prove insightful to identify the characteristics of individual approach steps.

The effect of first hurdle step strategy on the kinematics of the hurdle technique, and the spatio-temporal characteristics of seven and eight-step approaches throughout the final four approach steps was investigated in this study. Seven-step athletes took off further from the hurdle and touched down closer to the hurdle but completed a hurdle step of like distance. This meant the position of the maximum height of the CoM occurred further from the hurdle and the trajectory of the CoM was dropping as it crossed the hurdle plane. The position of the touchdown being closer to the hurdle permitted a greater distance between the first hurdle touchdown and the second hurdle take-off. Subsequently, a greater distance to continue race acceleration may have been available, limiting the need to shorten step lengths between the hurdles.

There were limitations associated with this study. The use of two-dimensional analysis of footage with manual digitisation as a research method has accuracy limitations when compared with more favourable methods such as three-dimensional analysis or motion capture. However, two-dimensional analysis was deemed suitable for the design of this study due to the predominantly planar motion of the selected parameters, the field based capability, and the non-intrusive nature of the data collection. The scope of the study was also limited to the first hurdle and consideration of the later stages of the race may provide a more detailed insight into step strategy performance. Additionally, the relatively low number of participants and the training based nature of the footage collection may have limitations when applied to competitive performances, especially considering arousal state and competitive instinct.

Future research should consider both the kinematic and kinetic characteristics of the inter-hurdle steps as well as the first hurdle clearance. Additionally, future studies should consider the kinetics of each of the approach steps to achieve a more comprehensive understanding of the seven-step strategy. There is an absence of research into the influence of anthropometric characteristics on the step strategy. Seven-step athletes were significantly taller and there was indication from a large effect size that the seven-step athletes had a greater mass. If the greater mass was the result of increased muscle mass, there is the potential for the seven-step athletes to possess greater strength. Therefore, research is needed into the effect of physical characteristics on the hurdle clearance and initial acceleration, as well as investigation into the efficacy of isolated strength tests as predictors of step strategy affinity. A longitudinal study would be a useful insight into athletes transitioning from one step strategy to the other.

4.5 Conclusion

The effect of first hurdle step strategy on the kinematics of the hurdle technique, and the spatio-temporal characteristics of seven and eight-step approaches throughout the final four approach steps was investigated in this study. Seven-step athletes took off further from the hurdle and touched down closer to the hurdle but completed a hurdle step of like distance. This meant the position of the maximum height of the CoM occurred further from the hurdle and the trajectory of the CoM was dropping as it crossed the hurdle plane. The position of the touchdown being closer to the hurdle permitted a greater distance between the first hurdle touchdown and the second hurdle take-off. Subsequently, a greater distance to continue race acceleration may have been available, limiting the need to shorten step lengths between the hurdles.

Coaches and athletes should be aware of the further take-off distance required to complete a hurdle clearance of comparable length when performing a seven-step approach strategy, as well as the fact that their CoM will be dropping as it crosses the hurdle plane. The potential increase of available space between the first and second hurdles must also be accounted for. Performance timings between the first and second hurdle may indeed be a better measure for coaches and athletes when comparing seven and eight-step approach strategies, especially as athletes' transition from one strategy to the other. Additionally, the findings from this research may be useful to athletes competing in sports such as the long and triple jump, where foot targeting, and the positioning of the CoM are essential elements for success.

To gain a clearer understanding, further studies should investigate the dynamics of the steps following the first hurdle clearance and the kinematics of the second hurdle clearance, particularly the second hurdle take-off positions of seven and eight-step athletes, along with the characteristics of the inter-hurdle steps. Future research into first hurdle clearance technique should consider the impact of step strategy upon the research design.

5. Effect of step strategy on World Championship 110-metre hurdles performance.

5.1 Introduction

The 110 m sprint hurdles event is an integral part of the Summer Olympic Games and has appeared in every iteration since the inaugural 1896 Games in Athens. The race is contested by male athletes only, the 100 m sprint hurdles being the equivalent for females.

The event is a sprint with a series of ten equidistant 1.067 m high barriers. Consequently, the ability to generate a high level of horizontal velocity is ultimately the key factor for success. The spatial constraints of the inter-hurdle distance (9.14 m) dictate that a three-step pattern between hurdles is the most suitable for all athletes, but step strategy prior to the first hurdle differs between athletes. An eight-step approach has previously dominated coaching and performance practice with every Olympic athlete prior to the 1960 Olympic Games favouring the eight-step strategy (Pinho, Lima, Claudino, Andrade, Soncin, Mezêncio, Bourgeois, Amadio & Serrão, 2017). A seven-step approach has now become commonplace amongst senior world-class hurdlers and is now used by most elite athletes at the Olympic Games and the World Athletics Championships (Bezodis et al., 2019).

A number of biomechanical studies have reported upon the 110 m sprint hurdle performances at the World and Olympic Championships however, they have omitted comparison between step strategy (Brüggemann, Koszewski, & Müller, 1999; Grauberg & Eberhard, 2011; Pollitt, Walker & Bissas, 2018). To date only two studies (Chapter 3 and Chapter 4) have differentiated participant groups by first hurdle step strategy (Rowley, Churchill, Dunn & Wheat, 2021a; Rowley, Churchill, Dunn & Wheat., 2021b). The research focused on the block clearance, approach steps and the clearance of the first hurdle. However, these studies were completed with data from sub-elite athletes, none of the participants having competed in either an Olympic or World Championship final. As the findings of Bezodis et al. (2019) identify, the majority of the World's elite hurdlers are now favouring the seven-step strategy with no published research to support the preference. Much of the current understanding related to step strategy is anecdotal or extrapolated from an established understanding of the event. It is therefore essential to investigate whether the findings of the previous research are repeated amongst elite performers, particularly as this strategy decision could be affecting the performances at the highest level of the event. Initial research beyond the clearance of the first hurdle is also required to identify whether previously identified differences extend beyond the first hurdle clearance.

Athletes accelerate from the blocks towards the first hurdle with a step strategy which positions them correctly for an effective clearance. If the athlete takes off from the wrong position, the hurdle clearance, the touchdown position and intra-hurdle steps are negatively affected. The effect of these alterations leads to a reduction in horizontal velocity, a sub-optimal hurdle clearance, or hitting one or more of the hurdles (Mann, 2011).

Sidhu and Singh (2015) proposed an optimal take-off to touchdown ratio of 65:35. This ratio is a key element which defines the success of the hurdle clearance (Mann, 2011; Amara et al., 2019). When investigating the biomechanical implications of the seven- and eight-step approach strategies, the research in Chapter 4 found that seven-step strategists take-off ratio was greater than eight-step strategists (d = 1.75), because they have one step fewer to position the foot for take-off. Seven-step strategists were found to take off 0.20 m further from the first hurdle and touchdown 0.42 m closer to the first hurdle, as well as taking an overall longer hurdle step.

As the athletes approach the first hurdle, the dynamics of each step change in preparation for hurdle clearance whereby there is a need to balance the development of horizontal velocity with suitable step lengths to position the take-off foot and centre of mass for optimum hurdle clearance. A three step strategy between the first and second hurdle means that elite athletes make alterations to normal sprint step characteristics (ground contact time, flight time and step length) to successfully position themselves for clearance of the next hurdle, and to satisfy the four ground contacts required of a three-step pattern. These alterations must allow for the generation of further acceleration throughout the first phase of the event (positive acceleration; 0-30 m), and maintenance of optimum horizontal velocity throughout the middle (maintenance; 30-70 m) and final phases (negative acceleration; 70-110 m). To effectively satisfy each phase, athletes reduce step lengths between the hurdles, with only the second comparable in step length to a normal sprint step length (McDonald & Dapena, 1991).

Previous research by in Chapter 4 identified that seven-step hurdlers touchdown the lead leg foot 0.42 m closer to the first hurdle than eight-step strategists. Thus, seven-step strategists have a further available 0.42 m before the take-off for the second hurdle, providing both seven- and eight-step strategists take off from like distances from the second hurdle. Seven-step strategists potentially use the extra 0.42 m to limit the extent to which they are required to shorten each of the inter-hurdle steps when compared to flat sprint step characteristics. Due to the relatively short distance between the start line and the first hurdle, and the inter-hurdle steps, acceleration continues beyond the first and second hurdle clearances. Shortening of the inter-hurdle step lengths negatively affects the athletes' ability to continue to accelerate throughout the first part of the race. Whether seven-step strategists clear the second hurdle similar to the first hurdle, or whether it is more alike to the spatial characteristics of the eight-step strategists is not yet known.

The aim of this study was to investigate the effect of step strategy on 110-metre hurdles World Championship performance from the block clearance to the first two hurdle clearances. It was hypothesised that seven-step athletes would take off further from, and touch down closer to the first hurdle than eight-step athletes. It was also hypothesised that seven-step athletes would clear the second hurdle in a spatially similar manner to the first hurdle, although to a lesser extent as the extra available space between hurdles is used for acceleration. Take-off and touchdown distances from each hurdle, and hurdle step lengths are likely to differ in agreement with previous research from Chapter 4.

5.2 Methods

5.2.1 *Participants*

Footage was provided of forty-seven male sprint hurdlers, all of whom competed in the men's 110 m hurdles final at the World Athletics Championships between 2001 and 2019 (Table 5.2.1.1). These athletes represented the best hurdlers in the world at the time (mean performance: 13.29 ± 0.23 s; range: 12.95 to 13.87 s) and three of them have at some point held, the World Record.

Two groups comprised of participants based upon the number of steps taken to the first hurdle during a competitive performance. Twenty-two were seven-step strategists and 25 were eight-step strategists (mean race performance: seven-step athletes: 13.29 ± 0.20 s; eight-step athletes: 13.30 ± 0.23 s). Research study procedures were approved by Sheffield Hallam University Research Ethics Committee (ER40925938).

5.2.2 *Data collection*

Two-dimensional video footage were provided by the international governing body, World Athletics, of the Men's 110 m hurdles finals from 2001 to 2019 (Table 5.2.1.1).

Ten video files were provided, each from a single panning television camera positioned roughly half-way along the home straight. Positioning allowed for a suitable view of the participants for the block clearance, first, and second hurdles (Figure 5.2.2.1). The footage was analysed from the frame of each qualifying athletes' initiation of motion in the set position to the first frame of ground contact of the lead leg foot after the second hurdle clearance.

Table 5.2.1.1 Television Footage provided by World Athletics for analysis.

Year	Location	Athletes		Eligible Athletes*	Resolution			Frame Rate (fps)
		Starters	Finishers					
2019	Doha	9	8	5	1920	x	1080	25
2017	London	8	8	4	1920	x	1080	25
2015	Beijing	8	8	5	1920	x	1080	25
2013	Moscow	8	8	5	1920	x	1080	25
2011	Daegu	8	6	2	1920	x	1080	25
2009	Berlin	8	8	4	1920	x	1080	25
2007	Osaka	8	8	8	720	x	576	25
2005	Helsinki	8	8	4	720	x	527	25
2003	Paris	8	7	2	1920	x	1080	25
2001	Edmonton	8	8	8	720	x	486	30
	Total			47				

*Eligible athletes were those who were not disqualified, completed the whole race, and the fastest performance for those who completed in multiple finals.

Hurdle spacings and specifications were in-line with 2020 World Athletics competition rule 168 (hurdle height, 1.067 m; start line to first hurdle distance, 13.72 m; first hurdle to second hurdle distance: 9.14 m). If participants failed to complete the event (DNF – Did Not Finish) or were disqualified (DQ) then the performance was discounted as it might not have been possible to identify the point throughout the race which led to the DNF/DQ.

A) Block Clearance B) Hurdle 1 Clearance C) Hurdle 2 Clearance

Figure 5.2.2.1 Frames showing block clearance, first hurdle, and second hurdle clearances from the World Athletics Championships - Berlin 2009.

Where athletes competed in multiple Championships, the fastest performance was analysed.

5.2.3 *Data Processing*

Calibration data were collected using Kinovea v0.8.27 software (https://www.kinovea.org). Track markings and hurdle locations (start line, lane widths, distance of first hurdle from start line, distance of second hurdle from start line) were used to determine the spatial parameters via 2D-direct linear transformation, and footage was manually digitised using Kinovea v0.8.27 software.

The perceived location for identification of spatial parameters was the second metatarsal phalangeal joint (MTP) of the ground contact foot. Temporal gait events and phases were determined by visual inspection of the footage and frame counting. Nineteen parameters were analysed, three from each hurdle clearance, three from the inter-hurdle steps, seven temporal and three calculations (Table 5.2.3.1).

5.2.4 *Statistical Analysis*

Independent-sample *t*-tests (SPSS for Windows, version 24.0; SPSS, Inc., Chicago, IL, USA) were performed to determine differences between the groups for all variables.

To quantify intra-rater reliability, re-digitisation of joint locations and gait events was completed by one operator on one of the athletes' trials. A total of eight re-digitisations were completed. The re-digitised results demonstrated low variability with a maximum coefficient of variation (CV) of 1.92% (mean CV: 1.01 ± 0.02) for the spatial parameters, and absolute agreement for the temporal parameters. These results were accepted as good intra-rater reliability.

The criterion alpha level was set at $p < 0.05$ for statistical significance with $p < 0.1$ accepted as a tendency (Alt, Heinrich, Funken & Potthast, 2015; Rowley et al., 2021a;

2021b). Effect size was calculated for each variable using Cohen's *d* (Cohen, 1988; Coe, 2002). As per Cohen's (1988) effect size suggestions, only effect size differences found to be large ($d \geq 0.80$) were deemed relevant and examined, although a contextual approach was taken when discussing moderate effect sizes ($d \geq 0.50$ and $d < 0.80$) based upon a holistic interpretation of the results.

5.3 Results

Seven-step athletes took off 0.25 m further from the first hurdle ($p = 0.001$ $d = 0.86$) and there was a tendency for touchdown to occur 0.12 m closer to the hurdle ($p = 0.056$, $d = 0.41$) than eight-step athletes. There was also a tendency for seven-step athletes to take a longer first hurdle step (0.13 m; $p = 0.061$, $d = 0.40$) than eight-step strategists. Seven-step athletes took off 0.20 m further from the second hurdle ($p = 0.000$, $d = 0.69$) than eight-step athletes, although this was 0.04 m closer to the hurdle than the seven-step strategist's take-off for the first hurdle. For the seven-step strategists, 3 percentage points more of the first hurdle step occurred before the hurdle ($p = 0.004$, $d = 0.51$) than the eight-step strategists. This was repeated for the second hurdle where a 4 percentage point difference was identified ($p = 0.017$, $d = 0.51$).

There was no difference between the seven- and eight-step performance times from the blocks to the touchdown for the second hurdle (0.00 s; $p = 0.95$, $d = 0.01$; Table 5.2.4.1).

Table 5.2.3.1 Description of technique variables.

Parameter	Description
Take-off (TO) distance to Hurdle 1 (H1) (m)	Horizontal distance from the second metatarsophalangeal joint (MTP) of the take-off foot to the base of the first hurdle.
Touchdown (TD) distance from H1 (m)	Horizontal distance from the MTP of the touchdown foot to the base of the first hurdle.
Hurdle step length for H1 (m)	Horizontal distance from the MTP of the take-off foot to the MTP of the touchdown foot for the first hurdle.
TO distance for H1 (%)	Percentage of the hurdle step length occurring prior to the hurdle from the MTP of the take-off foot to the base of the first hurdle.
Hurdle step flight time for H1(s)	Time that the take-off foot loses ground contact to the first frame of ground contact of the touchdown foot for the first hurdle.
Inter-hurdle step lengths (m)	Anteroposterior distance between the MTP of contralateral ground contacts for each step.
TO distance to Hurdle 2 (H2) (m)	Horizontal distance from the MTP of the take-off foot to the base of the second hurdle.
TD distance from H2 (m)	Horizontal distance from the MTP of the touchdown foot to the base of the second hurdle.
Hurdle step length for H2 (m)	Horizontal distance from the MTP of the take-off foot to the MTP of the touchdown foot for the second hurdle.
TO distance for H2 (%)	Percentage of the hurdle step length occurring prior to the hurdle from the MTP of the take-off foot to the base of the second hurdle.
Hurdle step flight time for H2 (s)	Time that the take-off foot loses ground contact to the first frame of ground contact of the touchdown foot for the second hurdle.
Horizontal velocity H1 TD to H2 TO	Frame counting. Mean horizontal velocity from the first frame of ground contact of the first hurdle touchdown foot to the last frame of ground contact of the second hurdle take-off foot.
Time to H1 TO from blocks (s)	Time from the first frame of motion in the 'set' position to the last frame of ground contact of the first hurdle take-off foot.
Time to H1 TD from blocks (s)	Time from the first frame of motion from the 'set' position to the first frame of ground contact of the first hurdle touchdown foot.
Time to H2 TO from blocks (s)	Time from the first frame of motion from the 'set' position to the last frame of ground contact of the second hurdle take-off foot.
Time to H2 TD from blocks (s)	Time from the first frame of motion from the 'set' position to the first frame of ground contact of the second hurdle take-off foot.
Time to H2 TD from H1 TD (s)	Time from the last frame of ground contact of the first hurdle touchdown foot to the first frame of ground contact of the second hurdle take-off foot.

Table 5.2.4.1 Seven and eight-step group mean values (±*SD*), effect size and significance for technique variables.

		Seven Step			Eight Step			Cohen's *d*		*p*	
Take-off (TO) distance to H1 (m)		2.39	±	0.22	2.14	±	0.19	0.86	§	0.001	*
Touchdown (TD) distance from H1 (m)		1.22	±	0.19	1.34	±	0.24	0.41		0.056	#
Hurdle step length for H1 (m)		3.61	±	0.22	3.48	±	0.23	0.40		0.061	#
TO distance for H1 (%)		66	±	4.8	63	±	5.5	0.51		0.004	*
Hurdle step flight time for H1(s)		0.35	±	0.03	0.35	±	0.04	0.00		0.782	
Inter-hurdle step lengths (m)	Step 1	1.36	±	0.22	1.40	±	0.18	0.14		0.554	
	Step 2	2.14	±	0.16	2.10	±	0.31	0.10		0.631	
	Step 3	1.97	±	0.30	1.92	±	0.33	0.11		0.587	
TO distance to H2 (m)		2.48	±	0.20	2.28	±	0.19	0.69		0.002	*
TD distance from H2 (m)		1.25	±	0.20	1.36	±	0.23	0.35		0.100	
Hurdle step length for H2 (m)		3.73	±	0.21	3.64	±	0.23	0.29		0.167	
TO distance for H2 (%)		66.0	±	4.90	62.0	±	5.40	0.51		0.017	*
Hurdle step flight time for H2 (s)		0.34	±	0.02	0.34	±	0.04	0.04		0.831	
Horizontal velocity H1 TD to H2 TO		7.02	±	0.15	7.02	±	0.16	0.01		0.951	
Time to H1 TO from blocks (s)		2.04	±	0.05	2.06	±	0.07	0.19		0.374	
Time to H1 TD from blocks (s)		2.39	±	0.05	2.41	±	0.07	0.21		0.316	
Time to H2 TO from blocks (s)		3.10	±	0.04	3.12	±	0.07	0.21		0.317	
Time to H2 TD from blocks (s)		3.43	±	0.06	3.45	±	0.07	0.17		0.419	
Time to H2 TD from H1 TD (s)		1.04	±	0.02	1.04	±	0.03	0.09		0.678	

Note: * significant at $p < 0.05$; # tendency at $p < 0.10$; § effect size > ± 0.8.

5.4 Discussion and Implications

The aim of this study was to investigate the effect of step strategy on 110-metre hurdles World Championship performance from the block clearance to the second hurdle clearance. The results agree with the hypothesis that seven-step athletes would take off further from, and touch down closer to the first hurdle than eight-step athletes. It was also hypothesised that seven-step athletes would clear the second hurdle in a similar manner to eight-step athletes, although to a lesser extent if the extra available space between hurdles was used for to increase horizontal velocity.

Seven-step athletes took off further away from both the first and second hurdles than the eight-step athletes. Despite differences in these parameters, there was a tendency for seven-step athletes to touchdown closer to the first hurdle than the eight-step athletes, with there being no statistical difference between the touchdown distance from the second hurdle (Figure 5.4.1). When taking a contextual approach, the data suggests there may be a difference in the touchdown positions of seven- and eight-step athletes for both the first and second hurdle, which may become evident in future studies. This should be considered when conducting further research. The increased take-off distance for seven-step athletes is further reinforced by a greater percentage of the hurdle clearance occurring prior to the hurdle location.

Mean horizontal velocities of the athletes from hurdle one touchdown to hurdle two take-off were identical, although, this parameter should be interpreted with caution due to the parameter failing to consider the differences in touchdown and take-off positions of the individual step-strategies. Despite this omission, it is likely that due to the relatively homologous nature of the participants, that there would be little differentiation between horizontal velocity. Further, the timings from the block clearance

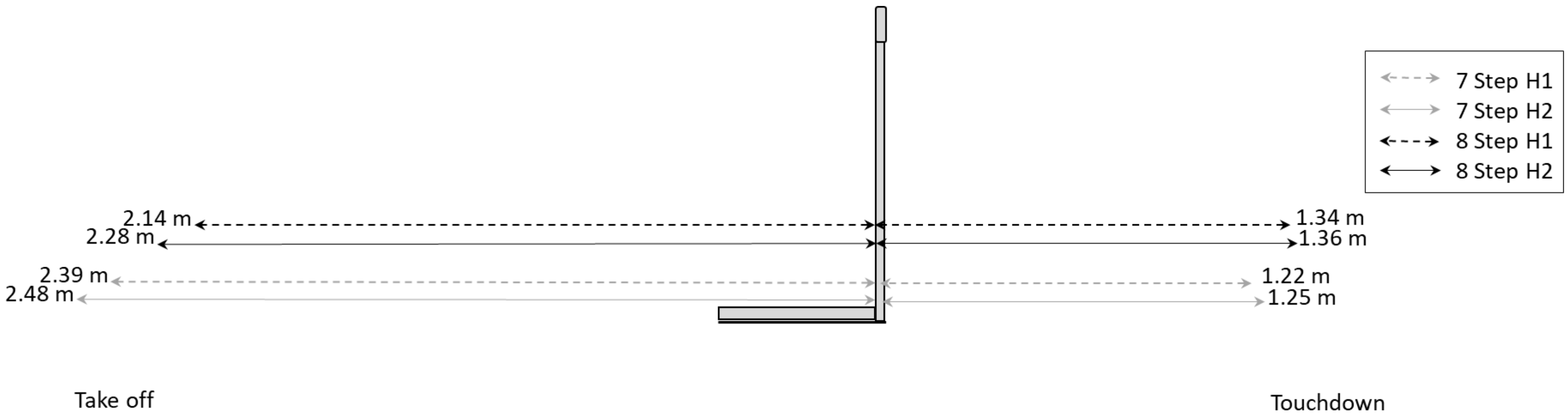

Figure 5.4.1 Take-off and touchdown distances for seven- and eight-step strategists over hurdles one and two.

to first and second hurdle events (take-off/touchdown) were not different between step-strategies. This suggests both groups completed similar temporal performances to the point of the second hurdle touchdown, which is likely to be expected at such a high performance level. Further research should consider the velocity of the centre of mass as a more suitable performance measure.

Seven-step hurdlers had a significantly different take-off distance to hurdle 1 compared to eight-step hurdlers. Seven-step take-off to touchdown ratio was more closely aligned to the recommendations of Sidhu and Singh (2015) than eight-step hurdlers, with 66% of their hurdle clearance phase taking place prior to the hurdle and 34% after the hurdle for both first and second hurdle clearances. This correlation between the suggested and identified performance ratio may imply that seven-step hurdlers are completing a more technically sound hurdle clearance than eight-step strategists. Sidhu and Singh (2015) suggest a take-off distance of 65% to allow for the kinematic requirements of a successful hurdle clearance technique, limiting unnecessary motion of the CoM, and optimum take-off and touchdown positioning for suitable inter-hurdle steps.

There was no difference in like-for-like step length for any of the three inter-hurdle steps between step strategies. This is contrary to the hypothesis that seven-step hurdlers would use the increased available space between the first and second hurdle (due to touching down closer to the first hurdle) to assimilate step lengths more closely with their natural sprint step lengths. The results of this study, along with previous research from Chapter 4, suggest that seven- and eight-step strategists complete hurdle clearances which are similar, but that seven-step strategists take-off further from the hurdle, touchdown closer to the hurdle, and consequently complete a greater percentage of the hurdle motion prior to crossing the hurdle plane. This adaptation to clearing the first hurdle from further away appears to affect the overall hurdle clearance technique and to influence the second hurdle clearance. The spatial differentiation may continue to occur throughout hurdles three to ten or it may be that there is no difference in spatial parameters by the tenth hurdle. Whether hurdle clearance spatial parameters more closely aligned between seven- and eight-step strategists beyond the first two hurdles is currently unknown and further research into step dynamics beyond the first two hurdles is required.

There were limitations associated with this study. The use of two-dimensional analysis of footage with manual digitisation as a research method has accuracy limitations when compared with more favourable methods such as three-dimensional analysis or motion capture. The footage was also a low frame rate (25-30 fps) compared with high-speed footage, and the resolution was not always optimal (from 720 x 527 up to 1920 x 1080). These limitations led to careful considerations being made about which parameters could be meaningfully investigated, with a preference for spatial parameters over temporal parameters due to some events occurring in a very short time span. For example, touchdown ground contact time would have yielded the exact number of frames counted for each participant, despite with a higher frame rate this would have been unlikely. Two-dimensional analysis was deemed suitable for the design of this study due to the volume of footage available, the performance level of the participants, and the non-intrusive nature of the data collection. This study is the first to investigate the effects of step-strategy with a large number of world-class elite performers

Future research should build upon current understanding by considering the characteristics of the approach and inter-hurdle steps as well as the first and second hurdle clearances. To gain a clearer understanding of first hurdle step-strategy, further studies should investigate the spatio-temporal dynamics of the event beyond the second hurdle clearance. Whether the differences identified in take-off and hurdle step distances remain as the event progresses is unclear. Despite there being significant differences between the two strategies for both hurdle clearances, the data shows that the take-off difference is decreased by 0.05 m for the second hurdle compared to the first hurdle. This minor change may continue incrementally for each hurdle throughout the race until the spatio-temporal hurdle clearance parameters more closely assimilate between the two strategies. Essentially, despite this research being unable to satisfy the hypothesis that seven-step strategists use the increased distance available between hurdles one and two to assimilate step-lengths more closely to flat sprinting, it may be that this does occur but progressively over the entirety of the remaining nine hurdle clearances, and not only by the point of second hurdle take-off.

There is also a need for research into the kinetic parameters of the approach and inter-hurdle steps of seven- and eight-step strategists, particularly when focusing on the block clearance and first hurdle take-off step. A longer first step out of the blocks is likely correlated to an increased impulse of the front foot on the blocks. Similarly, a longer hurdle step is also likely to be due to an increased impulse and differences in the orientation of the take-off force vector. The kinetics of each of the seven approach steps may differ to an eight-step approach however, whether this occurs uniformly throughout the approach phase, or whether it is more significant for particular steps would be a useful contribution to knowledge.

Coaches and athletes should be aware of the further take-off distance required to complete the first hurdle clearance when performing a seven-step approach strategy and the implications this increased distance may have on performance during the initial transition period. Taking off from further from the hurdle means the athlete's CoM reaches its maximum vertical height prior to crossing the hurdle plane. The athlete needs to be aware of the fact that the CoM will consequently be dropping as it crosses the hurdle plane, and that this technical adaptation is normal. When taking off further than normal from the hurdle (for example, from hitting a previous hurdle or stumbling), athletes can often 'float' (a coaching term defined by an increased hurdle flight time) over the hurdle by attempting to stay in the air longer so as not to hit the hurdle, and disproportionately directing take-off forces vertically. In turn, this leads to a poor hurdle clearance, often hitting of the hurdle, and 'collapsing' upon landing due to incorrect placement of the touchdown foot at the point of ground contact, especially when compared to the horizontal position of the whole body CoM which tends to be behind the touchdown foot at the point of ground contact. The identified spatial changes to the first hurdle clearance can also be evident in the second hurdle clearance and a progressive approach to hurdle spacings should be considered to allow for a phased transition to a longer take-off distance. Of note to coaches is the consideration that there was no performance difference found at the point of touchdown of the second hurdle. Whether there is a benefit to a seven-step approach has yet to be identified in the research and therefore coaches should continue to use a holistic and contextual approach when considering whether athletes should opt for a seven-step approach strategy. As yet uninvestigated parameters such as those pertaining to strength, flexibility or anthropometry for example, may identify whether a particular step-strategy is more suitable for a particular athlete. The development of 'test batteries' to identify the significant parameters which must be achieved for a seven-step strategy to be employed is a potential outcome of further research.

5.5 Conclusion

The effect of step strategy on 110-metre hurdles World Championship performance was investigated in this study. The study considered the first two hurdles from the block clearance and focused upon the key spatio-temporal parameters of the approach, first and second hurdle clearances, and the inter-hurdle steps. Seven-step athletes took off further from the first hurdle, touched down closer to the first hurdle, and completed a larger percentage of the hurdle clearance prior to crossing the hurdle plane. Seven-step strategists had a longer available distance between the first and second hurdles. However, the seven-step strategists did not use this extra distance to assimilate step lengths with flat sprint step lengths, alternatively clearing the second hurdle much the same as the first. Seven-step strategists took off from a further distance than the eight-step strategists and with a greater percentage of the hurdle clearance occurring prior to the hurdle plane for both hurdle clearances.

Future research into first hurdle clearance technique should continue to consider the impact of step-strategy within the research design, interpretation of the results, and the validity of the findings. Grouping by step-strategy should be included to eliminate misinterpretation of the results, especially pertaining to the spatial parameters of the hurdle clearance.

6. Discussion

The aim of this research programme was to investigate the effects of first hurdle step strategy on sprint hurdle performance in the senior men's 110 metre hurdles event. Four key objectives were identified, and research designed to satisfy each objective. The studies presented in Chapters 3 to 5 set out to address the objectives and the following is a summary of the findings for each objective, the limitations of the research programme, suggested direction for future research, the practical implications which relate to senior male sprint hurdle performance, and the contribution to knowledge and understanding.

6.1 Summary of Findings

There is in general a lack of research into the first sprint hurdle approach phase, and particularly those which differentiate by step strategy. The following findings were identified from the programme of research and contributed to the objectives of this research.

1. To investigate the effect of step strategy to the first hurdle on the kinematics of the technique of the block start.

Chapter 3 investigated the effect of step strategy on the start position, the block exit and the first four approach steps. Two-dimensional video data were collected in the sagittal plane from 12 male sprint hurdlers, grouped as seven-step (n = 6) or eight-step (n = 6) strategists. Mean block spacing was 0.08 m greater, block contact time 0.06 s longer, first step 0.25 m longer and first ground contact 0.03 s longer for seven-step athletes compared with eight-step athletes. There was also a greater vertical displacement of the centre of mass (0.04 m) for the seven-step athletes compared with the eight-step athletes. Additionally, the front hip mean angular acceleration was 197°/s^2 lower for the seven-step athletes than the eight-step athletes. There was no difference between groups for mean horizontal velocity at the moment of block exit. The findings identify the position in the starting blocks, and the key parameters which pertain to the initial phases for a seven-step approach strategy to be employed. As several significant differences were identified between the strategists, it was evident that the approach phase may affect the clearance of the first hurdle. Therefore, research objective 2. had a clear need for investigation.

2. To investigate the effect of step strategy to the first hurdle on the kinematics of the hurdle clearance technique.

Chapter 4 investigated the effect of step strategy on the hurdle clearance technique and spatio-temporal parameters of the four steps prior to hurdle clearance. Two-dimensional video data were collected in the sagittal plane from 12 male sprint hurdlers, grouped as seven-step (n = 6) or eight-step (n = 6) strategists. Take-off distance was 0.20 m further from the hurdle and touchdown was 0.42 m closer to the hurdle for seven-step athletes. There was no significant difference between the mean horizontal velocities of the two groups throughout the hurdle clearance (0.02 m/s) or the approach time to the first hurdle from the block clearance (0.01 s). The findings identify the take-off and touchdown distance parameters of the hurdle clearance technique for a successful seven-step approach strategy to be employed by athletes transitioning from an eight- to a seven-step technique. From the findings of the research objectives 1. and 2. it is reasonable to deduce that the approach steps would be different between the two strategists, thus a clear indicator of further investigation being required. Where these suggested spatio-temporal and kinematic differences would occur was not evident from the findings of the first two research objectives and so individual step characteristics required investigation.

3. To investigate the effect of step strategy to the first hurdle on the kinematics of the approach steps.

Chapters 3 and 4 investigated the approach steps to the first hurdle. Seven-step athletes took longer steps to the first hurdle and had longer ground contact times for the initial steps, however there was no difference between step flight times. This finding was to be expected due to the seven-step strategists having one step less than the eight-step strategists to cover the approach distance, despite evident lengthening of the first step out of the blocks and taking off further from the first hurdle. Seven-step athletes reduced the length of the final step before hurdle take-off by 0.14 m compared with the previous step, whereas the eight-step athletes extended their final step by 0.17 m compared with the previous step length. Step frequency was lower for seven-step athletes although there was no difference between approach times to the first hurdle. The findings identify the individual approach step characteristics for a successful seven-step approach strategy to be employed.

4. To investigate whether step strategy group differences in sub-elite athletes are repeated by elite athletes during world class performances.

Chapter 5 investigated the effect of step strategy on kinematic and spatio-temporal parameters of finalists of the 110-m hurdles in ten World Championships between 2001 and 2019. Ten video files were analysed investigating 19 spatio-temporal parameters from the start to the second hurdle. Forty-seven athletes qualified for analysis, grouped as seven-step (n = 22) or eight-step (n = 25) strategists. Seven-step athletes took off 0.24 m further from the first hurdle and there was a tendency for touchdown to occur 0.12 m closer to the hurdle. There was also a tendency for seven-step athletes to take a 0.13 m longer first hurdle step. Seven-step athletes took off 0.20 m further from the second hurdle although this was 0.04 m closer to the hurdle than the take-off for the first hurdle. A greater percentage of the first and second hurdle steps of seven-step athletes occurred before the hurdle.

Whilst the findings of Bezodis et al., (2019) identify that both sprint hurdlers and sprinters adopt a similar block position, it is evident that differences occurred between sprint hurdlers when grouped according to step strategy. This research identified that seven-step strategists positioned the blocks further apart and with the front block closer to the start line. Although there appears to be no performance difference when considering the key performance parameters measured (mean horizontal velocity, hurdle flight time etc.,), this does not preclude the potential benefit of a seven-step strategy if we consider research beyond the scope of this study. For example, athletes with greater levels of maximum or dynamic leg strength, with faster sprint performance times, or certain anthropometric characteristics, may be better suited to the seven-step strategy. This may suggest why at an elite level, where physical performance characteristics are optimised, that the seven-step strategy is now the favoured option.

Mann (2011) emphasises the criticality of positioning the starting blocks correctly in the 'set' position due to the resultant position of the CoM (Čoh, 2006; Čoh, Tomažin & Štuhec, 2006; Schot & Knutzen, 1992, Čoh, 1998). Despite seven-step strategists adopting a block position more closely aligned to the suggestions of Schot & Knutzen (1992) and displacing the CoM to a greater extent than eight-step strategists, there is no overall negative impact upon the performance of the block clearance or the acceleration phase. The elongated first step is also in agreement with Schot & Knutzen's (1992) findings however, as their research suggests, a limit would exist whereby positioning of the first ground contact ahead of the position of the CoM would yield unwanted braking forces. None of the athletes in this body of research reached that limit (i.e., contact foot was behind CoM) and there was no evident impact upon the following approach steps. This research found no evidence to support the suggestion by Arnold, 1992, that seven-step athletes would need to 'bunch' their feet (and consequently their CoM) closer to the start line in order to satisfy the step length required for the seven-step strategy. Baumann (1976) further identified that as performance level increases, sprint starters are able to position the CoM closer to the start line and despite not being 'elite', the participants of this study were a high level competitors. It must also be considered that when switching from an eight- to a seven-step strategy, the athlete is required to adopt a start position with the opposite foot closer to the line, and essentially carrying out most of the 'push' phase from the blocks. This transition requires a period of relearning whereby the athlete will have to move from using a technique which may have been learnt over a number of years to an unfamiliar technique. As identified previously, this start phase and first step are absolutely crucial and consequently this change in technique will require some time to be executed competently. Despite the difficulty in refining the new start technique, it is evidently favourable to switching the hurdle clearance legs, which is a more complex skill.

The reduction in step length of the step prior to take-off (comparable to the previous approach steps) for the seven-step athletes was an unexpected finding from this research. Reduction in step-length prior to take-off is a method used by long and triple jumpers to 'project' the CoM forward of the body, positioning the take-off foot to reduce braking forces. Therefore, when the jumper leaves the take-off board the CoM is further in front of the body than would be achieved with a normal step length approach. As the body 'attempts' to regain the position if the CoM, a resultant further jump can be completed (Hay & Nohara, 1990). The seven-step strategists might be employing a similar technique to cover the further 0.40 m distance from the first hurdle, in a way similar to the clearance of hurdles throughout the middle of the race. It is reasonable to deduce that the reduction in step length and increased take-off distance for the seven-step technique would allow for a flatter trajectory of the CoM and as a consequence, smaller vertical deviations throughout the hurdle clearance phase. This would be in agreement with the findings of Amara et al. (2019) whereby limiting vertical oscillations of the CoM throughout the hurdle clearance phase is identified as a key performance parameter for faster hurdlers.

The optimal ratio of take-off to touchdown distance is a key element which defines the success of the hurdle clearance. Sidhu and Singh (2015) propose a ratio of 65:35 for take-off and touchdown distance step lengths (distance of take-off and touchdown foot from the hurdle base). This distance was more closely aligned to the seven-step strategists in this study and despite taking off from further from the hurdle, and touching down closer to the hurdle, there was no detrimental effect upon the hurdle clearance performance, or any significant difference between the hurdle techniques.

In general, this research programme does not identify either step-strategy as beneficial to the other in terms of absolute performance (i.e., race time or horizontal velocity), but it identifies significant differences in the technical execution between both options. The current body of research into first hurdle step strategy is particularly limited therefore, these findings provide essential insight knowledge for both athletes and coaches, will contribute to shaping future performance, and provide fundamental direction for future research investigation.

6.2 Limitations

Individual study limitations have been addressed at the end of each chapter however, further and more general limitations within the research are identified here.

Two-dimensional video capture was deemed the most suitable, most practical, and least invasive method of collecting footage. It is also accepted that other methods of data collection would have yielded more precise results, but although considered, the practical applications prevented their feasibility. Motion capture and three-dimensional analysis capture multi-planar movement, and therefore the medio-lateral aspects of the research can be investigated. As sprint hurdling is a predominantly a sagittal plane event, and the novel nature of the research meant that there was no published indication of where significant differences have previously occurred, two-dimensional analysis was deemed suitable. Two-dimensional analysis also allowed for the participants to complete their normal training session, at their normal place of training, with no alterations to their schedules, their clothing or equipment, the track conditions, or the parameters of the event. The high-performance calibre of the athletes in these studies must also be recognised as the decision was made to capture footage of the highest performers in Great Britain, performing within their usual training environment, in favour of a larger sample of potentially 'technically poorer' hurdlers.

For the research in Chapter 5, pre-recorded television footage was obtained by the international governing body, World Athletics. This footage was a relatively low frame rate of 25 fps when compared with the high-speed footage used in Chapters 3 and 4 (200 fps). This unfortunately meant some short duration temporal measurements would not be sensitive to short duration events, such as contact time. An example would be the hurdle take-off and touchdown ground contact times of each athlete (from Chapter 4) which are shorter than the frame rate of 0.04 s. Whilst the frame rate limited the selection of certain temporal parameters for investigation, important parameters identified in both Chapters 3 and 4 were able to be included (Hurdle step flight time, timings from the block clearance). Despite the lower frame rate of the television footage, many of the findings were in agreement with the findings from Chapters 3 and 4. This is the first study to investigate step-strategy at an elite level, and the first in a World Class competitive environment.

Research beyond the first and second hurdles would help to identify whether the hurdle technique of seven-step athletes more closely assimilates with the technique of eight-step athletes towards the end of the race. Seven-step athletes take-off from further from the hurdle and touchdown closer to the hurdle for both the first and second clearances. Whether these spatial differences remain or to what degree the seven-step hurdlers clear the hurdles differently as the race progresses are beyond the scope of this research programme.

Chapter 5 investigated the parameters of 47 international hurdlers. Due to strict inclusion criteria for Chapters 3 and 4, only 12 athletes were part of the studies, six for each step strategy. This is a relatively low group number and consequently, a *p* value of 0.1 was accepted as a tendency for a difference to be present. A greater sample size may well have strengthened the statistical findings. The ‘tendencies’ highlighted parameters which might have become significant differences should the group sizes be increased and alleviated the binary nature of assigning a significant/not significant interpretation.

Further to the inclusion of a tendency, Effect size (*d*) was calculated for each parameter and the agreement between the *p* and *d* values considered in the interpretation of the findings.

6.3 Future Research

Whilst this research contributes significantly to the current understanding around first hurdle step strategy, it has highlighted several areas for future research which will need to be investigated to further enhance the practical applications.

This programme of research focuses heavily upon the kinematic and spatio-temporal parameters of the block clearance, first and second hurdle clearances, and the approach phase. To develop a more complete understanding, kinetic investigation into each of these phases will be required. The research in Chapter 3 identified that seven-step athletes position themselves differently in the 'set' position in the blocks and 'push' for longer on the block plate with the front foot, ultimately leading to a longer first step length. Investigation into the kinetic elements of the block contact will help to answer questions raised about how the seven-step athletes apply force, such as whether it is applied consistently, or whether there are similarities between the eight- and seven-step block contact phases. Further to this, Chapter 3, Chapter 4, and Chapter 5 identified no difference in absolute performance time form the start to the first hurdle take off. An understanding of the previously identified kinetic parameters of each of the seven or eight ground contacts will identify whether differences exist between each strategy, and whether these differences are consistent for like-for-like steps out of the blocks, or back from the first hurdle.

If seven-step athletes generate differences in ground reaction force for each of the approach steps or the first hurdle step, then an understanding of this is useful to coaches and athletes looking to transition from an eight- to a seven-step strategy. If the athlete is not able to generate the necessary forces during the acceleration phase, then it is unlikely that they will be able to successfully transition strategies. This could lead to a test battery whereby athletes measure their ground reaction forces throughout acceleration before trying to implement certain other changes to their technique such as adjusting block positioning or hurdle take off distance.

Whilst kinetic parameters were considered for investigation in this programme of research it was concluded that due to the absence of existing research, there were more basic answers which need clarifying firstly. Particularly pertaining to the hurdlers' technical execution of the phases. Once an understanding of the spatio-temporal and kinematic performance variables was established then the indications from the findings would be suitably positioned to shape investigations considering impulse or other kinetic parameters. The research was designed to categorise the differences which exist between step strategies which can immediately be applied to a coaching and performance environment for improvement and understanding at all levels. Access to kinetic variables is often not fully understood or not accessible to many hurdles' coaches and therefore of limited application to their practice. The adjustment of block spacings, first step length, or hurdle take-off distance for example are more readily incorporated and identifiable within a coaching and performance environment. Whilst an understanding of the kinetic parameters would provide interesting answers, coaches at novice levels are not able to directly influence performance as a consequence of the increased awareness. They can though, adjust a block setting, and observe the resultant technical outcome, quite simply.

In absolute race performance terms, Chapters 3, 4, and 5 identified no difference in the key race parameters (approach to take-off time, horizontal velocity etc.,) between the seven- and eight-step strategists. Despite this finding, a more complete understanding would be gained from a longitudinal study into athletes attempting to transition from an eight-step strategy and the differences between these athletes' own performances. It may be that a number of elements must be achieved before a seven-step strategy can suitably be performed. These could include elements of flexibility, strength or core stability for example. Alternatively, it may be that certain athletes are more naturally suited to either a seven- or eight-step strategy, much the same as flat sprinters step lengths differ between individual athletes.

Future understanding would be particularly benefited from a longitudinal intervention study, whereby a group of eight-step athletes make the switch to a seven-step strategy. The study would need to consider the effects of switching the feet around in the block positions (and the necessary relearning of the block positioning and block clearance technique), the differences that occur over the transition period, and the eventual success of the strategy change. The work in this thesis would now provide significant indication of the changes the athletes would need to make, both positionally and technically, for a successful transition.

The research for Chapters 3, 4, and 5 all involved two-dimensional video footage from either a single fixed or panning camera. Whilst two-dimensional video footage was deemed suitable for each of the studies, a more complete understanding could be attained from three-dimensional footage or from motion capture. Medio-lateral elements of the athletes' techniques could then be included in the research parameters to provide a greater understanding. This could include a measure of to what extent athletes laterally move the lead-leg when clearing the hurdle, or whether the trail leg fully completes its action when athlete's touchdown from the hurdle. Either of these technical differences could affect the spatio-temporal parameters of the hurdle take-off, touchdown, and inter-hurdle steps.

Whilst this thesis improves the biomechanical understanding of first hurdle step strategy, a more holistic approach would be beneficial from an ecological dynamics approach in future study. Not only would the research consider the biomechanical performance characteristics but, the wider understanding of physical performance analysis and motor behaviour. A study grounded in movement coordination theory and considering the individual and environmental constraints of athletic task would allow coaches and athletes to have a greater understanding of not only the biomechanical adaptations required, but also the processes required to ensure the strategy change is as effective as possible.

6.4 Practical Implications

This body of research makes a significant contribution to the understanding of step-strategy, and to the application of current coaching practice. Prior to this program of research, there was very limited research into the biomechanical performance factors of the seven-step strategy.

From the findings, coaches and athletes are now able to implement the identified technical changes required when considering transitioning to a seven-step strategy. The following key findings from the research will allow a smoother transition and a greater chance of success;

- For a seven-step strategy, alterations are required to the positioning of the starting blocks, including a longer space between the front and rear blocks, predominantly due to positioning of the front block closer to the start line. In accordance with an increased spacing between the front and rear blocks, the athlete will also be required to switch the front and rear feet on the block plates to allow for a hurdle clearance using their ‘usual’ lead and trail legs. This relearning of the block positioning will take some time to master to achieve the level of effectiveness of an eight-step block position but will ultimately be a quicker acquisition than switching the hurdling legs. Coaches will need to consider the implications of when to attempt a transition to a seven-step strategy so as not to negatively impact the athletes’ immediate performances. Early in a cycle would be the most practical (Olympic four-year cycle, or summer to winter cycle for example) to allow the embedding and honing of a new technique at such a critical phase of the race.

- Athletes will be required to push on the front block for a longer duration and develop a further first step length from the blocks. Whilst a further first step has now been identified as a key parameter, coaches must ensure that athletes do not over-compensate by increasing block contact time excessively, or by positioning the foot of the first ground contact ahead of the vertical position of the CoM. Both of these minor, yet critical adaptations could lead to a poor block clearance and negative braking forces being applied.
- Athletes will need to take-off further from the first hurdle and touchdown closer to the first hurdle, with a greater percentage of the hurdle clearance occurring prior to the CoM crossing the hurdle. This may seem awkward to sprint hurdlers adapting to this new technique and it may be that ‘mastering’ the block clearance first would be a preferential approach to attempting to retrain these critical elements concurrently. When athletes take off further from the hurdle than they are accustomed to, there is a propensity to feel like the hurdle is too far away,

leading to negative effects on the hurdle clearance technique and the steps following the hurdle clearance. Amara et al., (2019) identified that vertical fluctuations of the CoM should be minimised for a successful hurdle clearance (including the touchdown off the hurdle) and coaches must bear this in mind as the athlete transitions. The learning of a poor technique throughout this period for the sake of satisfying the spatial recommendations of this research would inevitably lead to further delays as the athlete will be required to relearn again once the spatial parameters have been satisfied. A feasible option may be to use an approach already used within hurdling coaching practice, and to bring the hurdle closer to the start line and progressively 'nudge' the hurdle further away as the hurdler becomes adept at each increased distance.

- Hurdle clearance technique may need to be altered for consecutive hurdles after the first hurdle, to align spatio-temporal measurements more closely to those of the first hurdle clearance. Once the hurdler has mastered the seven-step block clearance and the first hurdle clearance, their ability to take off further from the first hurdle will have been ingrained, therefore the capability for them to clear the second hurdle (and the rest of the hurdles throughout the race) from a greater take-off distance should become more attuned to their new first hurdle take-off distance. Hurdling technique, coaches must appreciate from this research, does not change dependent upon step-strategy. The fundamental execution is the same, with the only alterations required being made to the take-off and touchdown positions.

Whilst these practical findings appear to be key to the seven-step strategy, the method to achieve each of these will rely heavily upon the holistic knowledge of the coach and the athletes' support team. Further research may be able to identify the key adaptation for example, for athletes to be able to complete a longer first step from the blocks (potentially strength developments, increased flexibility etc.,).

6.5 Contribution to Knowledge

Prior to this programme of study (Chapters 3, and 4), there was no peer reviewed published research into the seven-step approach strategy. Additionally, Chapter 5 further extends current understanding and the application of step-strategy at the highest level of the sport. This research goes some way to addressing this void, both in terms of credible scientific research and the practical considerations for coaches and athletes to transition from an eight- to a seven-step strategy. The key contributions to knowledge include;

- An understanding of the way seven-step athletes adapt their block settings to have a longer distance between the block plates, predominantly due to positioning the front block closer to the start line.
- Have a different position whilst in the 'set' and leave the blocks differently to eight-step athletes by pushing on the front block for longer and taking a longer first step.
- Seven-step athletes take longer steps for each of the approach steps along with longer ground contact times.
- Seven-step athletes take-off further from the first hurdle and touchdown closer to the first hurdle, with the CoM reaching its highest point further from the first hurdle than eight-step athletes.
- There is no identifiable race performance difference between either step-strategy, however there may be athlete specific differences due to physiological/anthropometric differences.

Whilst these are the key findings of the research, how coaches implement them into their practice will be down to interpretation and depend upon the level of expertise of the coach, and the performance capability of the athlete. It is evident that coaches will need further understanding of the seven-step strategy, whether a seven-step strategy is suitable for their athlete, or whether to attempt a transition. Coaches must ensure not to be biased towards the seven-step strategy because of its current trend in elite levels of performance but should continue to coach in an athlete centred way, accepting that both step strategies showed no identifiable race performance difference within this body if research. However, whether there are actual performance benefits will warrant investigation of a greater scope than currently exists within this body of research.

6.6 Conclusion

The aim of this thesis was to investigate the effects of first hurdle step strategy on sprint hurdle performance in the senior men's 110 metre hurdles event. Four specific research objectives were developed to satisfy the aim. The first objective was achieved predominantly within Chapter 3, whereby it was found that seven-step athletes have a different set-up in the blocks and leave the blocks differently to eight-step athletes. Predominantly, positioning the front foot closer to the start line. The second objective was answered predominantly within the fourth chapter where seven-step strategists were found to take-off from further from, and touchdown closer to, the first hurdle. This was supported from findings in Chapter 5 where elite performers were found to be in agreement with these parameters, and also to take-off further from the second hurdle. The third objective was answered in part across Chapters 3, 4 and 5. Seven-step athletes take a longer first step from the blocks, generally longer approach steps, and generally a longer ground contact time for each approach step. The fourth objective was addressed with direction from Chapters 3 and 4. Chapter 5 investigated some of the key findings within a World Class race performance and found that many of the significant results from Chapters 3 and 4 were repeated.

This body of research makes a considerable contribution to academic knowledge, has relevant practical implications pertaining to performance for coaches and athletes, and provides the basis for a wealth of future research within this specific aspect of the sprint hurdles race performance.

7. References

Alt, t., Heinrich, K., Funken, J. and Potthast, W., (2015). Lower extremity kinematics of curve sprinting. *Journal of Sports Sciences,* 33(6): 552-560.

Amara, S., Mkaouer, B., Chaabene, H., Negra, Y. and Bensalah, F., (2019). Key kinetic and kinematic factors of 110-m hurdles performance. *Journal of Physical Education and Sport*, 19(1): 658-668.

Arnold, M., (1992). Hurdling. *British Athletics Federation.* Birmingham, UK. ISBN: 0851341071

Atwater, A.E., (1982). Kinematic analysis of sprinting. *Track and Field Quarterly Review*, 82(2): 12-16.

Baumann, W., (1976). Kinematic and dynamic characteristics of the sprint start. *Biomechanics V-B.* Baltimore: University Park Press, 194-199.

Bezodis, I., Brazil, A., Von Lieres und Wilkau, H., Wood, M., Paradisis, G., Hanley, B., Tucker, C., Pollitt, L., Merlino, S., Vazel, P-J., Walker, J. and Bissas, A., (2019). World-class male sprinters and high hurdlers have similar start and initial acceleration techniques. *Frontiers in Sport and Active Living*, 1: 23.

Bezodis, N.E., Willwacher, S. and Salo, A.I., (2019). The Biomechanics of the Track and Field Sprint Start: A Narrative Review. *Sports Medicine,* 49: 1345-1364.

Bezodis, N., Trewartha, G. and Salo, A., (2015a). Understanding the effect of touchdown distance and ankle joint kinematics on sprint acceleration performance through computer simulation. *Sports Biomechanics*, 14(2): 232-245.

Bezodis, N., Salo, A. and Trewartha., (2015b). Relationships between lower-limb kinematics and block phase performance in a cross section of sprinters. *European Journal of Sport Science*, 15(2): 118-125.

Bezodis, N., Salo, A. and Trewartha., (2012). Modelling the stance leg in two-dimensional analyses of sprinting: inclusion of the MTP joint affects joint kinetics. *Journal of Applied Biomechanics,* 28(2): 222-228.

Bezodis, N., Salo, A. and Trewartha., (2010a). Kinematic aspects of block phase technique in sprinting. *International Symposium on Biomechanics in Sport*, 28(1):

Bezodis, N., Salo, A. and Trewartha., (2010b). Choice of sprint start performance measure affects the performance-based rankings within a group of sprinters: which is the most appropriate measure. *Sport Biomechanics*, 9(4): 258-269.

Brüggemann, G. P., Koszewski, D. and Müller, H., (1999). Biomechanical research project Athens 1997 final report. *Oxford Meyer & Meyer Sport (UK) Ltd.* ISBN: 1-84126-009-6.

Cavedon, V., Sandri, M., Pirlo, M., Petrone, N., Zancanaro, C., & Milanese, C. (2019). Anthropometry-driven block setting improves starting block performance in sprinters. *PloS one*, 14(3).

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

Coe, R., (2002). It's the effect size, stupid. What effect size is and why it is important. Paper presented at the Annual Conference of the British Educational Research Association, University of Exeter, England, 12-14 September.

Čoh, M. and Iskra, J., (2012). Biomechanical studies of the 110 m hurdle clearance technique. *Sport Science,* 5(1): 10-14.

Čoh, M., Tomažin, K. and Štuhec, S., (2006). The biomechanical model of the sprint start and block acceleration. *Physical Education and Sport,* 4(2): 103-114.

Čoh, M., (2006). The biomechanical model of the sprint start and block acceleration. *Physical Education and Sport*, 4(2): 103-114.

Čoh, M., (2004). Biomechanical analysis of 110 m hurdle clearance technique. Modern Athlete and Coach, 42(4): 4-8.

Čoh, M., Zvan, M. and Jošt, B., (2004). Kinematic model of the hurdle clearance technique. *XXII International Symposium on Biomechanics in Sport*. Ottawa, Canada.

Čoh, M., (2003). Biomechanical analysis of Colin Jackson´s hurdle clearance technique. *New Studies in Athletics,* 18: 37-45.

Čoh, M., Jošt, B. and Škof, B., (2000). Kinematic and dynamic analysis of hurdle clearance technique. *XVIII International Symposium on Biomechanics in Sport*. Hong Kong, China.

Čoh, M., Jošt, B., Škof, B., Tomažin, K. and Dolenec, A., (1998). Kinematic and kinetic parameters of the sprint start and start acceleration model of top sprinters. *Gymnica,* 28: 33-42.

Cohen, J., (1988). Statistical Power Analysis for the Behavioral Sciences, 2nd ed. *Hillsdale, New Jersey: Erlbaum.* ISBN: 9780203771587.

Debaere, S., Delecluse, C., Aerenhouts, D., Hagman, F. and Jonkers, I., (2012). From block clearance to sprint running: characteristics underlying an effective transition. *Journal of Sports Sciences*, 31(2): 137-149.

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

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

Dunn, M., Wheat, J., Miller, S., Haake. S. and Goodwill, S., (2012). Reconstructing 2D planar coordinates using linear and non-linear techniques. In *Proceedings of the 30th International Conference on Biomechanics in Sports*, 381 – 383.

Fukunaga, T., Matsuo, A. and Ichikawa, M., (1981). Mechanical energy output and joint movements in sprint running. *Ergonomics*, 24: 765-772.

González-Frutos, P., Veiga, S., Mallo, J. and Navarro, E., (2020). Evolution of the Hurdle-Unit Kinematic Parameters in the 60 m Indoor Hurdle Race. *Applied Science*, 10: 7807.

González-Frutos P., Veiga S., Mallo J. and Navarro, E., (2019). Spatiotemporal Comparisons Between Elite and High-Level 60 m Hurdlers. *Frontiers in Psychology*, 10: 2525.

Grauberg, R. and Eberhard, N., (2011). Biomechanical Analysis of the Sprint and Hurdles Events at the 2009 IAAF World Championships in Athletics. *New Studies in Athletics* 26(1/2), 19-53.

Grimshaw, P., Marer, L. and Salo, A., (1995). Biomechanical analysis of sprint hurdles. *Athletics Coach Summer*, 29(2): 5-7.

Guissard, N., Duchateau, J. and Hainaut, K., (1992). EMG and mechanical changes during sprint starts at different block face obliquities. *Medicine and Science in Sports and Exercise*, 24: 1257-1263.

Harland, M.J. and Steele, J.R., (1997). Biomechanics of the sprint start. *Sports Medicine*, 23(1): 11-20.

Hay, J G. and Nohara, H., (1990). Techniques used by elite long jumpers in preparation for take-off. *Journal of Biomechanics*, 23 (3): 229-239.

Henry, F.M., (1952). Force-time characteristics of the sprint start. *The Research Quarterly*, 23: 301-318.

Hommel, H., (1993). NSA photo sequence 26 -110m hurdles: Roger Kingdom. *New Studies in Athletics*, 8(2): 65-71.

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

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

Ilbeigi, S., Hagman, F. and Van Gheluwe., (2010). Velocity and starting block variables during a 30 m sprint run. *British Journal of Sports Medicine*, 44(1): 25.

International Association of Athletics Federations., (2016). *Competition Rules 2017-2018,* 6-8 Quai Antoine 1er – BP 359 MC 98007 MONACO Cedex.

Iskra, J. and Čoh, M., (2006). A review of biomechanical studies in hurdle races. *Kinesiologia Slovenica*, 12(1): 84-102.

Iwasaki, R., Shinkai, H. and Ito, N., (2020) How hitting the hurdle affects performance in the 110 m hurdles. *ISBS Proceedings Archive*, 38(1): Article 69

Johnson, M.D. and Buckley, J.G., (2001). Muscle power patterns in the mid acceleration phase of sprinting. *Journal of Sports Sciences,* 19: 263-272.

LaFortune, M.A., (1987). Biomechanical analysis of the 110 m hurdles. Excel, 3: 2-4.

Li, X., Zhou, J., Li, N., and Wang, J., (2011). Comparative biomechanics analysis of hurdle clearance techniques. *Portuguese Journal of Sport Science.* 11: 307–309.

Li, J. and Fu, D., (2000). The kinematic analysis of the transition technique between run and hurdle clearance of 110 m hurdles. *XVIII International Symposium on Biomechanics in Sport.* Hong Kong, China.

Mann, R.V., (2011). The mechanics of sprinting and hurdling. *CreateSpace Independent Publishing Platform*, California, USA. ISBN: 9781461136316.

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

McDonald, C. and Dapena, J., (1991). Linear kinematics in the men's 110 m and women's 100 m hurdles races. *Medicine and Science in Sports and Exercise*, 23: 1382-1391.

McLean, B., (1994). The biomechanics of hurdling: force plate analysis to assess hurdling technique. *New Studies in Athletics*, 4: 55-58.

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

Mero, A. and Komi, P.V., (1990). Reaction time and elecromyographic activity during a sprint start. *European Journal of Applied Physiology*, 61: 73-80.

Mero, A., (1988). Force-time characteristics and running velocity of male sprinters during the acceleration phase of sprinting. *Research Quarterly for Exercise and sport*, 59(2): 94-98.

Mero, A. and Luhtanen, P., (1985). A biomechanical analysis of top hurdling. *Modern Athlete and Coach,* 3: 3-6.

Mero, A., Luhtanen, P. and Komi, P.V., (1983). A biomechanical study of the sprint start. *Scandinavian Journal of Sports Sciences*, 5(1): 20-28.

Milanese, C., Bertucco, M. and Zancanaro, C., (2014). The effects of three different rear knee angles on kinematics of the sprint start. *Biology of Sport*, 31: 209-215.

Moir, G., Sanders, R., Button, C. and Glaister, M., (2007). The effect of periodized resistance training on accelerative sprint performance. *Sports Biomechanics*, 6(3): 285-300.

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

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

Nagahara, R., Wakamiyab, M., Shinoharac, Y. and Naganoe, A., (2021). Ground reaction forces during sprint hurdles. *Sports Medicine and Biomechanics*, 39(23): 2706–2715.

Nagahara, R., Matsubayashi, T., Matsuo, A. and Zushi, K., (2014). Kinematics of transition during human accelerated sprinting. *Biology Open*, 3: 689-699.

Ozolin, E., (1988). The technique of the sprint start. *Modern Athlete & Coach*, 26(3): 38-39.

Payne, A.H. and Bladder, F.B., (1971). The mechanics of the sprint start. J. Vredenbregt & J. Wartenweiler (Eds.), *Biomechanics II*, 225-231.

Pinho, J.P., Lima, M., Claudino, J.G., Andrade, R.M., Soncin, R., Mezêncio, B., Bourgeois, F.A., Amadio, A.C., and Serrão, J.C., (2017). Eight-steps' paradigm shift in men's 110 metres hurdles: an 89 years retrospective study. *Revista Brasileira De Educação Física E Esporte*, 31(3), 543-551.

Plamondon, A. and Roy, B., (1984). Kinematics and kinetics of sprint acceleration. *Canadian Journal of Applied Sports Science*, 9: 42-52.

Pollitt, L., Walker, J. and Bissas, A., (2018). Biomechanical Report for the IAAF World Championships 2017: 110 m Hurdles Men's. *2017 IAAF World Championships Biomechanics Research Project.*

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

Rowley, L.J., Churchill, S., Dunn, M., and Wheat, J., (2021a). Effect of hurdling step strategy on the kinematics of the block start. *Sports Biomechanics.* DOI: 10.1080/14763141.2021.1896028

Rowley, L.J., Churchill, S., Dunn, M., and Wheat, J., (2021b). Effect of hurdling step strategy on the kinematics of the hurdle clearance technique. *Sports Biomechanics.* DOI: 10.1080/14763141.2021.1970214

Salo, A.I.T., Bezodis, I.N., Batterham, A.M. and Kerwin, D.G., (2010). Elite sprinting: are athletes individually step-frequency or step-length reliant? *Medicine and Science in Sports and Exercise*, 43(6): 1055-1062.

Salo, A.I.T., Keränen, T. and Viitasalo, J.T., (2005). Force production in the first four steps of sprint running. In: Wang, Q., ed. *Proceedings of XXIII International Symposium on Biomechanics in Sports - Vol. 1. Beijing: The China Institute of Sport Science.* 313-317.

Salo, A., (2002). Technical changes in hurdle clearances at the beginning of 110 m hurdle event - a pilot study. ISBS 2002, Caceres - Extremadura – Spain.

Salo, A., and Grimshaw, N., (1998). An examination of kinematic variability of motion analysis in sprint hurdles. *Journal of Applied Biomechanics*, 14: 211-222.

Salo, A., Grimshaw, P. and Viitasalo, J., (1997). Reliability of variables in the kinematic analysis of sprint hurdles. *Medicine and Science in Sports and Exercise*, 3: 383-389.

Salo, A,. Grimshaw, P. and Marer, L., (1997). 3D biomechanical analysis of sprint hurdles at different competitive levels. *Medicine and Science in Sport and Exercise,* 29: 2, 231-237.

Schlüter, W., (1981). Kinematisch merkmale der 110-m-hürdentechnik (Kinematic characteristics of 110-m hurdles technique). *Leistungssport,* 2, 118-127.

Schot, P.K. and Knutzen, K.M., (1992). A biomechanical analysis of four sprint start positions. *Research Quarterly for Exercise and Sport*, 63(2): 137-147.

Sidhu, A.S. and Singh, M., (2015). Kinematical analysis of hurdle clearance technique in 110 m hurdle race. *International Journal of Behavioural, Social and Movement Sciences*, 4(2): 28-35.

Slawinski, J., Bonnefoy, A., Ontanon, G., Leveque, J-M., Miller, C., Riquet, A., Cheze, L. and Dumas, R., (2010). Segment-interaction in sprint start analysis of 3D angular velocity and kinetic energy in elite sprinters. *Journal of Biomechanics*, 43: 1494-1502.

Smith, G., (1989). Padding point extrapolation techniques for the Butterworth digital filter. *Journal of Biomechanics*, 22: 967-971.

Tanner, J.M., (1964). The physique of the Olympic athlete. George, Allen and Unwin Ltd, London. ISBN: 004611002X.

Tellez, T. and Doolittle, D., (1984). Sprinting from start to finish, *Track Technique*, 88: 2802-2805.

Tidow, G., (1991). Model technique analysis sheets for the hurdles, Part VII: high hurdles. *New Studies in Athletics,* 6(2): 51-66.

Wen, C., (2003). The High-Grade Tutorial of Track and Field. *People's Sports Press*: Beijing, China.

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

Weyand, P.G., Sternlight, D.B., Bellizzi, M.J. and Wright, S., (2000). Faster top running speeds are achieved with greater ground reaction forces not more rapid leg movements. *Journal of Applied Physiology,* 81: 1991-1999.

Winter, D.G., (1999). Biomechanics and motor control of human movement, fourth edition. *John Wiley and Sons,* Hoboken, New Jersey. ISBN: 9780470398180.

World Athletics., (2020). *Competition Rules 2017-2018,* 6-8 Quai Antoine 1er – BP 359 MC 98007 MONACO Cedex.