Cardiff School of Sport

DISSERTATION ASSESSMENT PROFORMA:

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Comments	Section
	Title and Abstract (5%) Title to include: A concise indication of the research question/problem. Abstract to include: A concise summary of the empirical study undertaken.
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	To include: description and justification of data treatment/ data analysis procedures; appropriate presentation of analysed data within text and in tables or figures; description of critical findings.
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Biomechanics

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The biomechanics of the sprint start in a cerebral palsied athlete

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This study would not have been possible without the help and support of many people, and I would like to thank them.

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ABSTRACT

Since athletes with disabilities have progressively entered the world of competitive sport, growing pressure and expectation has been placed on their standard of performance. The aim of this study was, therefore, to perform an in-depth kinematic and kinetic analysis of the sprint start, from block start to the third step out of the blocks, in an elite T36 cerebral palsy sprinter. One sprinter, fitted with 69 spherical retro-reflective markers, performed six maximal sprint starts. An automatic opto-electronic motion analysis system comprising of fifteen cameras (250 Hz), with synchronised force plates (Kistler, 1000 Hz), collected three-dimensional (3-D) marker trajectories of the four-segment model and corresponding ground reaction forces (Nexus, Vicon). This provided the necessary data for further inverse dynamics analyses (Visual3D). The results showed that predominant contributors to performance were step lengths over the first three steps, knee extensor moments, vertical centre of mass velocity at block exit, and extension of the trunk in the first three steps. Most notably, a more flexed trunk at block exit (28°), continued flexion until step three (38°), and a lower vertical velocity at block exit (0.31 $m \cdot s^{-1}$), while exhibiting a large knee peak extensor moment (212 N and 141 N for consecutive touchdowns), is suggested to produce a superior performance (values taken from the best performed trial). Additionally body mass, average horizontal external power, resultant centre of mass velocity and step length were significantly reduced in the T36 sprinter when compared to existing literature on able-bodied sprinters. The limited power production during the sprint start in this specific T36 athlete was likely due to the reduced body mass and velocity exhibited, which may be manifestations of cerebral palsy itself that cannot be overcome.

CHAPTER 1: INTRODUCTION

1.1 Cerebral palsy background

A growing population of Paralympic athletes are taking centre stage, as equal sporting opportunities have started being offered to both able-bodied (AB) and disabled groups, especially in Britain during the 2012 London Paralympic Games (Anon., 2012; Butler, 2011). Growing acknowledgment of the achievements of disabled individuals, encourage these athletes to improve upon their own performance and to emulate performances seen in AB athletes. There has been a significant body of biomechanical research done on AB athletes, especially joint kinematics and kinetics during all phases of the sprint, to determine areas that may accentuate or hinder performance. There have also been a number of similar studies on various disabled groups, however, very little is known about the true biomechanical data for elite, adult athletes with cerebral palsy (CP) during sprinting. There have been some studies, few and far between, highlighting differences in the kinematic data for running in participants with cerebral palsy, and often these studies exclusively used children as their participants.

Cerebral palsy is a general term for a series of neurological conditions that affect movement and coordination. Cerebral refers to cerebrum; the affected area of the brain along with connections between the cortex and the cerebellum. Palsy refers to paralysis and, in this case, describes the weakness due to nerve damage, uncontrolled muscle movement or loss of sensation-not complete paralysis (Berker & Yalçin, 2010). Cerebral palsy is usually associated with physical disability, but can also cause cognitive and communicative difficulties. This condition is acquired during pregnancy or at birth and is a non-degenerative permanent condition, which is normally picked up at a young age (NHS choices). The physical burden is usually characterised by; muscle stiffness or floppiness, muscle weakness, random and uncontrolled body movements and/or balance and coordination problems, which justifiably have detrimental effects on sporting performance.

Cerebral palsy, with regards to sports competitions, is classified differently to the categories outlined by Bagnara et al., (2000), who divided CP into movement categories; spastic, dyskinetic and ataxic. In sport there are eight separate classes of CP, which are described in Appendix 1 (IPC, 2011). Athletes of the first four classes use wheelchairs in their respective sports, whereas the latter four do not. Athletes who compete in track sports have the prefix ‘T’ followed by the number three to indicate cerebral palsy, with the numbers 1-8 subsequently.

1.2 Sprinting biomechanics

Sprinting is a demanding physical task requiring the coordination and synchronisation of central movement regulation processing and a sprinters' biomotor aptitude to achieve a controlled rapid movement, which for elite athletes becomes an automatic, almost unconscious skill. It is especially imperative to find the optimal relationship between the significant block start phase and subsequent acceleration, where the athlete must integrate an acyclic movement into a cyclic movement, for a most advantageous sprint start, which can account for up to 64% of the final performance (time) of a 100 m sprint (Tellez & Doolittle, 1984; van Ingen Schenau et al., 1994). There are a number of biomechanical parameters, which are favourable for efficient sprinting, such as high power production (van Ingen Schenau et al., 1994; Cunha et al., 2007; Smimiotou et al., 2008), large range of motion of joints (Bezodis, 2009), higher joint torques in the legs (Alexander, 1989; Bezodis et al., 2008; Bezodis et al., 2013), as well as greater step length and frequency (Mann & Herman 1985; Hay, 1994; Donati, 1995; Gajer et al., 1999; Čoh et al., 2006; Babić et al., 2011) . For the acceleration phase of the sprint start, the key independent kinematic parameters are the length of the first step; the path of the vertical rise of centre of mass (COM) in the first 3 m, and its (COM) velocity at each touchdown (Mero et al., 1992; Locatelli & Arsac, 1995; Bezodis et al., 2008); the contact: flight phase index over 10 m; the step length: frequency ratio (Čoh et al., 2006) as well as the block phase power production and knee flexor moment during the first step (Bezodis, 2009; Bezodis et al., 2013). These studies provide ranges of many different parameters, which can be used as 'AB norms'. Studies that have focused on CP athletes have used ranges from these AB studies to compare their results against (Pope & Wilkerson, 1986; Andrews et al., 2011), which was the same form of comparison that the current study applied.

1.2.1 Propulsion and braking phases

The sprint step can be divided into a contact and flight phase, as it is in Čoh et al.'s study (2006). Contact is classified as when the foot is touching the ground, exerting force, and flight is when both feet are off the ground. The contact phase can be further divided into braking and propulsion phases (Luthanen & Komi, 1980), which have a significant influence over the sprint start performance. For acceleration to occur the increase in velocity of the propulsion phase needs to outweigh the decrease in velocity of the breaking phase as sizeably as possible (Holm & Stålbom, 2006), which is indisputably correlated to the length of the first step and the positioning of the foot with respect to the COM in the braking phase. This was confirmed by Salo et al, (2005), who divided the braking phase into two components; braking time and braking impulse. It was demonstrated that, for the first four steps, braking time remained relatively stable (12 – 14 ms), though the peak braking force magnitude was shown to increase over these steps (from 215 – 672 N). This resulted in an increased braking impulse, which consequently reduced net propulsive impulse over the first four steps from 87 N during the first step, to 54 N in the fourth step. Čoh et al. (2006) interpreted their own data differently and related braking and propulsion phases to COM velocity. An increase in COM velocity from 4.41 ± 0.13 $m \cdot s^{-1}$ at the end of the first step to 6.00 ± 0.17 $m \cdot s^{-1}$ at the end of the second step was recorded, due to the decrease in the reduction of velocity (1.2%) in the braking phase of the second step compared to the reduction in velocity in the braking phase of the first step (45.3%). Whereas the velocity of the propulsion phases for each step were relatively similar.

1.2.2 Contact: Flight index

The contact: flight index is a ratio of time spent in contact to the time spent in flight. During the acceleration phase, values for the average contact: flight index have been shown to be 2: 1 with 67% ground contact, changing to 1: 1.3 - 1: 1.5 with 40-45% ground contact at maximal velocity (Housden, 1964; Atwater, 1982). These values were replicated in Čoh et al.'s (2006) study, where the ratio was 2.45: 1 for the first five steps out of the blocks. Subsequently, flight phase lengthening and contact phase shortening occurred until the eighth step (on average), where time in contact roughly equalised flight phase time. The fastest trial for the participant in the Čoh et al. (2006) study was that where maximum velocity was reached fastest (between the seventh and eighth steps), while maximum velocity in the slowest trial was only achieved between the tenth and eleventh steps.

1.2.3 Step length and frequency

Throughout the sprint, step length (principally dependent on the height and leg length of the sprinter), step frequency (dependent on central nervous system functioning, which is strongly genetically determined), and the relationship between the two, are fundamentally important (Donati, 1995). Many studies have proposed that the step length is the most significant parameter for superior sprint performance (Mero & Komi, 1985; Gajer et al., 1999; Mackala, 2007; Krzysztof & Mero, 2013), where others have indicated step frequency to be the more significant contributor (Mann & Herman, 1985; Bezodis et al., 2008), however Salo et al., (2011) described there to be an individual preference of reliance on step length or step frequency. These mutually dependent parameters have complex transitional relationships throughout the sprint and it is important that both are maximised for optimal performance (Kunz & Kaufman, 1981; Hunter et al., 2004), but with emphasis on increasing whichever parameter the individual athlete is more reliant on (Salo et al., 2011). A study by Babić et al (2011) carried out trials on 133 male non-athlete students aged 19-24, and recorded average step lengths of 1.41 m and average step frequencies of 4.14 steps·s^{-1} in the acceleration phase. These values were significantly lower in comparison to the results of a study by Bruggemann et al (1999) of elite athletes at the World Championships, who presented average step lengths of 1.93 m and average step frequencies of 4.34 steps·s^{-1}

1.2.4 Centre of Mass Velocity

Many previous studies, analysing the sprint start in AB athletes, have used block velocity as the determinant of performance during the sprint start (Baumann, 1976; Mero, 1988; Mero & Komi, 1990; Mendoza & Schöllhorn, 1993). Values between 3.32 – 3.48 m·s^{-1} have been recorded at block exit. The use of block velocity as a determination of performance at the sprint start has, however, been disputed more recently; Bezodis et al. (2010) explained that block velocity is directly determined by horizontal impulse, which is the product of force and time. Therefore an increased velocity can be due to increased force production in the blocks, or due to an increased time spent in the blocks, the latter of which conflicts with the accepted suggestion that faster reaction times were beneficial for performance (Baumann, 1976).

COM velocity during the first touchdown in aforementioned AB studies ranged from 4.42 – 4.93 m·s^{-1}, which continue to increase until maximal velocity is reached. At maximal velocity values between 8.77 and 10.16 m·s^{-1} were recorded (Mero & Komi, 1987; Delecluse et al., 2012), and even at just 16 m AB sprinters demonstrated an average COM velocity of 8.29 ± 0.34 m·s^{-1}. Thus far, COM velocity has only been analysed in CP athletes at near-maximal velocity in the mid-acceleration phase of a sprint (Pope & Wilkerson, 1986). The results demonstrated a significantly inferior range in COM velocity, of 5.79 – 7.14 m·s^{-1}, in comparison to equivalent AB athletes.

COM velocity can be broken down into horizontal and vertical components, as it has been in lots of research. The horizontal component has been shown to be most influential over sprint start performance (Mero & Komi, 1990; Skripko, 2003; Bezodis et al., 2010), with additional contribution from vertical COM velocity for the flight phase (Čoh et al., 2006).

However, it is emphasised that achieving too much vertical COM velocity can detrimentally affect horizontal COM velocity and acceleration (Novacheck, 1997).

It was suggested by Mero (1988) that muscle strength strongly affects running velocity at the sprint start, and due to the reduced strength nature of CP, it may be that lower velocities are observed during the starting phase; an area worthy of exploration.

1.2.5 Joint Moment and Power

Recent studies have drawn attention to joint moments and powers during the sprint start in elite AB athletes (Bezodis 2009; Bezodis et al., 2008; Charalambous et al., 2012; Debaere et al., 2012; Bezodis et al., 2013). A theory, recurrently proposed, was that a greater knee extensor moment contributed to a superior performance (measured as average horizontal external power). Debaere et al., (2012) supported this concept but emphasised that the contribution, from the knee extensors to performance, was only present for the first touchdown when the athlete was more leaned forward. After this point, greater hip and ankle activation was required for continued superior performance. A powerful hip extension, in particular, combined with greater body mass was suggested to increase the ground reaction force produced, and therefore the resultant COM velocity (Kunz & Kaufman, 1981; Bezodis et al., 2008). Usain Bolt, for example, has a body morphology that is vastly superior for sprinting than other elite sprinters, and his leg/hip extension is biomechanically most favourable (Krzysztof & Mero, 2013). Although kinetic data was not available, presumably his superior morphology allowed greater creation of extension moments and therefore force against the ground. An advantage that may well be a limiting factor for other elite sprinters relying on higher step frequencies (Salo et al., 2011; Krzysztof & Mero, 2013).

The range of extensor moments at the hip, knee and ankle were 160-315, 116-234 and 169-284 N, respectively, for AB athletes during first touchdown (Bezodis, 2009). The peak power values were not given in numerical form, however the range at the hip, knee and ankle can be deduced from a power-time graph to be between 1500-2500 W, 500-1600 W and 1200-3000 W for respective joints. Percentage power contributions have been shown to be diverse for different stages of the sprint; but during the first touchdown, Debaere et al., (2012) and Charambalous et al., (2012) agreed on power contributions of 54% from the hip, 31% from the knee and 15% from the ankle for the starting phase.

Overall it is recognised that transferring the force created at joints during the sprint start, to power against the ground, is an imperative manifestation for a winning performance in elite AB athletes, (Krzysztof & Mero, 2013) which is also likely the case for elite CP athletes. To the author's knowledge there have been no in-depth analyses of joint moments or powers for CP sprinters, so this assumption cannot yet be made. This leads us to the studies for CP running and sprinting that have, thus far, been carried out.

1.3 Sprinting biomechanics and cerebral palsy

The difficulty of movement experienced by CP individuals impacts greatly on favourable conditions for the sprint start, and a significant body of research has noted what they believe to be the main mechanical or physiological constraints experienced by CP individuals during sprinting. Earlier studies concentrate on step length and frequency and power generation during upright running in children with CP (Davids et al., 1998; Mann, 1983; Samilson & Dillin, 1978), whereas later studies convey more focus on kinematic parameters of sprinting in CP athletes (Pope & Wilkerson, 1986) most relevantly at the sprint start and initial acceleration phase (Andrews et al., 2011; Andrews, 2014). These studies all have the same objective of exploring the fundamental reasons for the reduced performance associated with CP individuals, in comparison to AB individuals.

1.3.1 Running biomechanics in cerebral palsied children

A study by Davids et al. (1998) included CP and AB children running in an *upright position*, so kinematics cannot be directly compared to the kinematic norms above in Čoh et al.'s 2006 study. It was shown that AB children increased velocity during running by increasing their step length (76% increase) *and* cadence (74% increase), whereas CP children were mainly reliant on increasing cadence. The CP children exhibited a comparatively higher percentage increase in cadence (65%) than step length (48%) to increase speed. An equal reliance on both parameters for AB children to increase speed, served to highlight the heightened dependence on amplified cadence for speed in CP children (Davids et al., 1998). The inability to increase step length is thought to be multifactorial; caused by diminished selective control, spasticity, dynamic/myostatic deformities and weakness seen with CP (Gage, 1991; Pope et al., 1993). Davids' (1998) study also highlights that the deficits seen in sprint velocity and step length in CP children were more pronounced in running than walking, as was the deficit in power generation. During running, power generation at the ankle, knee, and hip were significantly less in CP children. The hip joint of CP children showed the largest difference during running, compared to AB children. Peak power generation was 3.96 ± 0.81 N·m·kg^{-1}, compared to 7.65 ± 6.93 N·m·kg^{-1} in

AB children. The significant limitation displayed at the hip likely had a direct effect on increasing speed by power generation, as the three main sources of power are known to be from; *(a)* the hip extensors during the second half of swing and the first half of stance; (b) the hip flexors after toe-off; and (c) the hip adductors during stance phase generation. (Novacheck, 1997).

Power production is important for optimal sprint performance and has been examined in various literature. It has been established that the performance of a 100 m sprint is strongly associated with strength-power parameters, and optimal predictors proved to be a squat jump (Smimiotou et al., 2008) and '5 horizontal jumps' (Cunha et al., 2007). Power = Force·velocity, therefore a sprinter must achieve high joint and COM velocities along with forceful extension of the legs, for a maximally powerful start (Debaere et al., 2012). CP individuals are known to display reduced power, but a better understanding of how individual segments, and even individual muscles contribute to the force and velocity components separately, would be valuable. It may be that CP individuals exhibit an apparent disadvantage in just one of these components that affects their power production.

1.3.2 Elite cerebral palsied athletes and sprinting

After the Committee on Sports for the Disabled encouraged research development in training, coaching and performance analysis of specific disabilities, Roper (1984) noticed the lack of research done on CP in sport and aimed to find commonalities of CP athletes with AB athletes. As discussed above, former studies focussed on walking and running patterns (Mann, 1983; Samilson & Dillin, 1978), devoid of athletic sprinting patterns, until Pope & Wilkerson (1986) centred their attention on CP athletes in three different classes; class 6, 7 and 8. 17 athletes were involved and multiple kinematic measures, recorded over one stride cycle 35 m into a sprint, using two video cameras from left and right due to the asymmetry exhibited in running gaits in CP individuals, which have more recently been shown to be emphasised at higher running velocities (Böhm & Döderlein, 2012; Pyanzin et al., 2012). During upright sprinting the extent of forward trunk lean (the angle of the trunk, measured counter-clockwise from the horizontal) was significantly smaller for CP athletes (75°; Pope & Wilkerson, 1986) than the literature suggests for AB athletes (80°-85°; Bates, 1973; Haven, 1977), and the range of motion of the hip was significantly limited for CP athletes (89°) in comparison with AB athletes (94°; Dillman, 1970). Both of these limitations are thought to hinder the ability of the thigh being brought forwards, and therefore have a direct impact on step length (Mann, 1983; Skrotzky, 1983; Pope & Wilkerson; 1986). Another important finding was the increased percentage time spent in contact than in flight for the CP athletes, who displayed a contact flight ratio of 53 : 47, contrary to AB athletes' 43 : 57 ratio (Atwater, 1982). These significant differences contribute to the noticeably shorter mean stride length during maximal velocity sprinting recorded for the CP athletes (3.11 ± 0.15 m), in contrast to the range of 3.72 – 4.60 m indicated by AB sprint research (Deston & Nelson, 1964; Dillman, 1970; Bruggemann et al., 1999; Babić et al., 2011). The CP athletes (Pope & Wilkerson, 1986) demonstrated a step frequency of 4.63 steps·s^{-1}, which falls between the values recorded for the non-elite (4.26 steps·s^{-1}) and elite (4.78 steps·s^{-1}) AB athletes, demonstrating that CP athletes may increase their step frequency to compensate for their diminished stride length as proposed by Davids et al., (1998) and van Der Hecke et al., (2007).

1.3.3 Elite cerebral palsied athletes and the sprint start

Kinematic parameters of, more specifically, the sprint start, which will be comparable to the current study, have been brought to light in a recent thesis (Andrews, 2014). The study included four disabled participants of different classes; two of whom had cerebral palsy, class T37 and T38 respectively. The thesis concentrates on stride length and stride frequency in the initial acceleration phase, as well as incorporating the idea that Paralympic athletes have a larger variability in these parameters and their overall performance due to their disability (Ferrara et al., 1992). For both the T37 and T38 athletes (Andrews, 2014) stride frequency was the key performance indicator over the first 10 m, and from the third stride to 10 m, increased stride length was associated with faster times for the T37 athlete. The length of the *first* stride proved to be more crucial in producing faster times over 10 m for the T38 athlete than the T37 athlete. Instead of having cameras in one plane as this thesis did, the current study will use a motion capture system that creates a 3-D representation of movement, as well as force plates, so as to yield a full, in-depth analysis of the sprint start.

Another recent study (Andrews et al., 2011), centering on stride length and frequency over the first three strides, as well as trunk and lower limb joint angles, underlines the possibility of using AB biomechanical models to compare CP athletes to, when analysing performance. The kinematic norms for AB athletes, in this particular study taken from research by Mero (1988), can identify areas of concern, or areas that can be improved upon, for the benefit of a disabled athlete. The three athletes used in this study were CP class T35, T37 and T38. (The T37 and T38 class of CP display asymmetrical CP symptoms; see Appendix 1). It was discovered that the T37 and T38 athletes exhibited the same pattern of movement in their first few strides; their first stride being significantly shorter than recommended (T37, 1.12 m; T38, 1.00 m compared to the recommended 1.14 m) but then their second stride being longer (T37, 1.31 m; T38, 1.22 m compared to the recommended 1.14 m), indicating possible overcompensation on the side not affected by CP, and the third stride was, again, much shorter (T37, 1.24 m; T38, 1.27 m) than the AB norm of 1.45 m. The T35 athlete, on the other hand, demonstrated shorter stride length for all steps in the acceleratory phase, as the nature of CP in the T35 classification is symmetrical. For all CP athletes a common area of concern that was highlighted was the degree of trunk lean in the 'set' position (measured as the trunk angle anticlockwise from the horizontal), which, if improved, may force a stronger and faster block exit and a longer first stride (Hommel et al., 2009). The trunk angle during block exit and the following strides of the sprint start have not yet (to the authors knowledge) been analysed for CP athletes, but studies including AB athletes have shown there to be a correlation between a more flexed trunk and an increased horizontal COM velocity during the sprint start (Kyröläinen et al., 1999; Hunter et al., 2008). Ranges of 32-42° for trunk angle were recorded over the first four steps after block exit (Mero et al., 1983; Mero, 1988). The current study analysed both trunk lean and horizontal COM velocity at block exit and the first two touchdowns to gather whether this same correlation between trunk angle and horizontal COM velocity was observed in a T36 CP athlete.

1.4 Summary

The more recent research has demonstrated the need for further investigation into the biomechanics of the sprint start in CP athletes, as specific areas of concern have been isolated, but now require more in-depth analysis. As the sprint start and acceleration phase out of the blocks can account for 64% of the total result in a 100 m race (Tellez & Doolittle, 1984), and require the most coordination and efficiency of rapid movement, they are crucial areas to analyse for CP athletes. The results shown by some T37 and T38 athletes are useful; however there has been limited research done in this field, especially on other CP classes. For example, T36 class athletes, whose kinematics, to the author's knowledge, have not been recorded during any phase of sprinting. It is imperative to analyse the kinematics and kinetics of all the different CP classes to enable more universal comparisons to be made between AB and CP athletes, but also *within* the CP athlete population. Commonalities or variance may show patterns experienced by all CP athletes or highlight noteworthy differences between CP classes. It is important to remember the principal reality that no two people with CP are affected in exactly the same way (Sports Coach UK, 2012), which is why it is essential for each CP athlete to gain information about their main contributors to performance. The aim of the current study was, therefore, to focus on the sprint start of a class T36 CP athlete with the objective of producing an in-depth analysis and description of a number of kinematic and kinetic parameters in their sprint start. The performance measure that was used to determine the quality of performance in each trial was the average horizontal external power produced. A within-participant analysis was performed to associate variations in kinematic and kinetic parameters to performance. Additionally, average values for these parameters were associated to the previous sprint literature in this chapter, to propose similarities or differences between this athlete and other CP athletes of different classes, as well as in comparison to AB athletes.

CHAPTER 2: METHODS

2.1 Participant and procedures

Ethical approval was given from the Cardiff Metropolitan University Research Ethics Committee for a chosen, formally trained, 25-year-old male, T36 class, paralympic athlete (height= 1.73 m, mass= 55.4 kg) to partake in the study. The participant is of the highest standard in his disability class, having won a silver and a bronze medal at the 2012 London Paralympics. The participant's personal best for the 100 m is 12.47 s, and for the 400 m is 54.2 s. Shortly after data was collected, the participant won a gold medal and a bronze at the IPC Athletics Grand Prix in Dubai in the 400 m and 100 m respectively. The athlete gave informed consent for data to be collected away from his usual indoor sprint-training arena, in Bath, and without his coach.

The participant was requested to perform six maximal effort sprints over 10 m from starting blocks, which were adjusted to his liking before the trials began. The participant was instructed to complete a full warm-up as he would have done before a normal sprint training session, to reduce the risk of potential injury. During the trials the participant was asked to set up in the starting blocks in the 'ready' position and subsequently the technician, gave a vocal signal of 'set' and then clapped to emulate a starting signal. As the technician clapped, a button on the laptop was synchronously pressed to instigate the data collection. A practice trial was done before the six trials were completed, and between each trial the participant was allocated a rest period of between one and two minutes.

2.2 Data collection

A VICON motion capture system was used for this data collection (Vicon Motion Systems, Oxford Metrics, Oxford, UK), which consisted of 15 high speed infra-red cameras (3 MX-F20 and 12 MX-F13 cameras, recording data at 250 Hz) of differing heights, viewing a calibrated capture volume of 8 m x 8 m. These cameras captured the three-dimensional spatial coordinates of the spherical retro-reflective markers, placed on the participant's skin. The cameras' signals were collected by Vicon Datastation (on a laptop), and were synchronised with data from two force plates (9287BA models with internal amplification; Kistler Instrumente AG, Winterthur, Switzerland). The two Kistler force plates were positioned immediately beyond the start line to record the first two steps of the sprint start, with data being recorded at 1000 Hz. The cameras were set up so that as little unwanted reflection as possible was present in the capture volume, and then these were calibrated statically and dynamically with a standard reference object (the Vicon “T” calibration object). The starting blocks were placed behind the start line and two retro-reflective markers were placed either side of the start line so that the start was visible on the computerised image.

Prior to the trials, a static calibration was done with the participant standing still in the classic anatomical position, but with his hands pronated, to define the position and orientation in space of the body segments (Cappozzo et al., 1995). During the static calibration 83 markers were placed on important anatomical landmarks to generate segment reference frames, which approximated the sagittal, frontal and transverse planes of the bone. 14 markers were removed as to not hinder sprinting motion, but the remaining tracking markers calculated the technical reference frames (which vary between trials since the tracking markers do not always stay in the same location relative to the bone), and which determine the motion of the underlying bone. The static calibration calculated the position and orientation of the technical frame relative to the segment frame, which, if a rigid bone is assumed, remains constant during motion (Schmitz, 2009).

During the dynamic trials, the participant had a total of 69 retro-reflective markers placed onto his body in a model that captured full six degrees of freedom (DoF) body movement (McLester & St.Pierre, 2008). A hybrid marker set was used with 37 of the retro-reflective markers arranged in a shared marker set while 32 markers independently assessed all 6 segmental DoF, which is suggested to provide a more accurate representation of joint angles and translations (Schmitz et al., 2008), and also has the advantage of being able to account for abnormal joint kinematics, for example in a CP sprinter (Spoor & Veldpaus, 1980; Andriacchi et al., 1998). The independent markers were placed directly onto bony landmarks on the skin, except markers for the foot (metatarsals, toes and heels), which were affixed to the participants running shoes (depicted in Figure 1, see Appendix 2 for exact locations of markers). Shared markers consisted of; (a) a headband, with markers placed anteriorly, posteriorly, medially and laterally, used to track the movement of the head; and (b) rigid ‘clusters’ made of three or four markers, affixed on a plastic plate, used to enhance tracking of each segment (upper arm (UA), lower arm (LA), thigh and shank), and to reduce soft tissue artefact (Cappozzo et al., 1997).

Figure 1: The retro-reflective marker set on the participant, for the movement trials; anteriorly (left) and posteriorly (right)

2.3 Data processing

2.3.1 Data handling

The Vicon Datastation collected the raw 2-D data from each MX-F20 or MX-F13 camera, combining it with calibration data to reform the corresponding digital motion in 3-D, and trajectories for each marker, by joining their respective positions from frame to frame; a process known as reconstruction (Vicon Manual). This data was passed to the Vicon Nexus 1.8.5 software (Vicon, Oxford, UK) where a digitised marker model was created, tracked and labelled. The tracked and labelled data was then processed into the Visual3D software (C-Motion, Inc. Germantown, Maryland, USA), where the rest of the analysis took place (the joint kinematics and kinetics). Visual3D bases all its calculations on the relative angular velocity of one segment to the other, where the biomechanical model defines each joint to have six DoF, so that joints (centres) are automatically created when two segments end near each other. All joints in the current study were modelled like this, except the hip joint. The pelvis was created manually using markers on the posterior superior iliac spine(s), anterior superior iliac spine(s), greater trochanter(s), and iliac crest(s), along with body mass and height, to define its width and depth, and to create a virtual hip joint centre. A static standing configuration would have the x axis pointing right, the y axis pointing straight ahead and the z axis pointing up, where extension/flexion occurred about the x axis, adduction/abduction occurred about the y axis and external/internal rotation about the z axis. The actions of most relevance in the current study were extension and flexion, where flexion was positive and extension was negative. To remove unwanted components and to reduce noise, all the data was filtered. First of all, a cut-off frequency to filter at was determined by performing a residual analysis of all the marker coordinates, for each trial, based on the methods of Winter (2005). A second-order Butterworth low pass filter (Butterworth, 1930) was used and the chosen cut-off frequency was 30 Hz.

2.3.3 Defining events and variables

Defining events

To enable the determination of variables that were examined in the current study, certain events such as block start, block exit, touch-down 1, 2, and 3 (TD1, TD2 and TD3 respectively), and toe-off 1, 2 and 3 (TO1, TO2 and TO3) had to be defined in Visual3D (Table 1 and Figure 2).

Table 1: Definition of events in Visual3D

Event	Definition
Block Start	The time when the vertical angular velocity of the distal end of the head becomes negative (head extension)
Block Exit	The time when there is a peak in the horizontal acceleration of the right toe
TD1	The time when the vertical GRF exceeds 10 N (Force Plate 1 data)
TD2	The time when the vertical GRF exceeds 10 N (Force Plate 2 data)
TO1	The time when the vertical GRF falls below 10 N (Force Plate 1 data)
TO2	The time when the vertical GRF falls below 10 N (Force Plate 2 data)
TD3	The time when there is a peak in the vertical velocity of the right toe

Defining and calculating variables

The position of COM was determined using the segmentation method (Bartlett, 1997) in the Nexus software, which estimates mass and position of COM of each segment based on cadaveric data. These along with effects of each segment on the body are summed to give a COM location. COM velocity was calculated using the first derivative of the COM position at each touchdown and toe-off, which can further be broken down into vertical velocity (z direction) and horizontal velocity (y direction), which were used in the determination of subsequent variables. Step length (SL) was defined using the y position of the MTP joint at each touchdown in relation to the global coordinates. Therefore the first SL was the difference between the y positions of the MTP joint at block exit and TD1, the second SL was the difference between TD1 and TD2 and the third SL was between TD2 and TD3. Step frequency (SF) was calculated by obtaining firstly the step velocity. This was the average horizontal velocity of COM between block exit and TD1 for the first step, between TD1 and TD2 for the second and between TD2 and TD3 for the third. By dividing the step velocity by SL, SF was obtained. Contact time (CT) was defined as the time between TD and TO for each step; i.e. CT1 was between TD1 and TO1 and CT2 was between TD2 and TO2. The flight time (FT) can also be worked out like this but instead between TO and TD, so FT1 was between T01 and TD2, and FT2 was between TO2 and TD3. The contact phases were further broken down into braking and propulsion phases. The transition between the braking phase and the propulsion phase was defined as the moment the horizontal GRF went above 0 N (TD-Trans). Therefore the time spent in the braking phase is the time between TD and TD-Trans, and the time in the propulsion phase is between TD-Trans and TO, for each step. From these two values, propulsive: braking ratios were calculated. The velocity, and therefore impulse, during these two phases were calculated by means of the mathematical equation for impulse; [Impulse = Force·Time]. The impulse for the braking phase, and propulsion phase, was calculated by the product of the average GRF and time spent in braking, and propulsion, respectively.

Joint angles are defined on Visual3D as the orientation of one segment relative to another; to determine the transformation of a segment to another, usually the local coordinate system of the more proximal segment is used as the reference segment, which is how they were calculated in this study (C-Motion, 2004). Joint moments were determined in Visual3D via traditional inverse dynamics methods, which utilise the

Newton-Euler equations of (a) Force = Mass·acceleration and (b) Moment= I·α (where I= mass moment of inertia, and α= angular acceleration).

From these equations, inverse dynamics derived moments (torques) at individual joints, based on movement of the limbs attached to that joint. Joint (internal) power was calculated by the product of the angular velocity of the segment and the joint moment, which was a further derivation of the traditional inverse dynamics methods adopted by Visual3D. As well as internal power, external power was calculated and most importantly the average horizontal external power, which was used as the performance measure for the current study. This was based on the conclusion drawn by Bezodis et al. (2010) that it was the most appropriate and accurate performance measure for the sprint start. The external power was calculated by the COM velocity multiplied by the GRF vector, therefore the average horizontal external power will be the value found in the y direction.

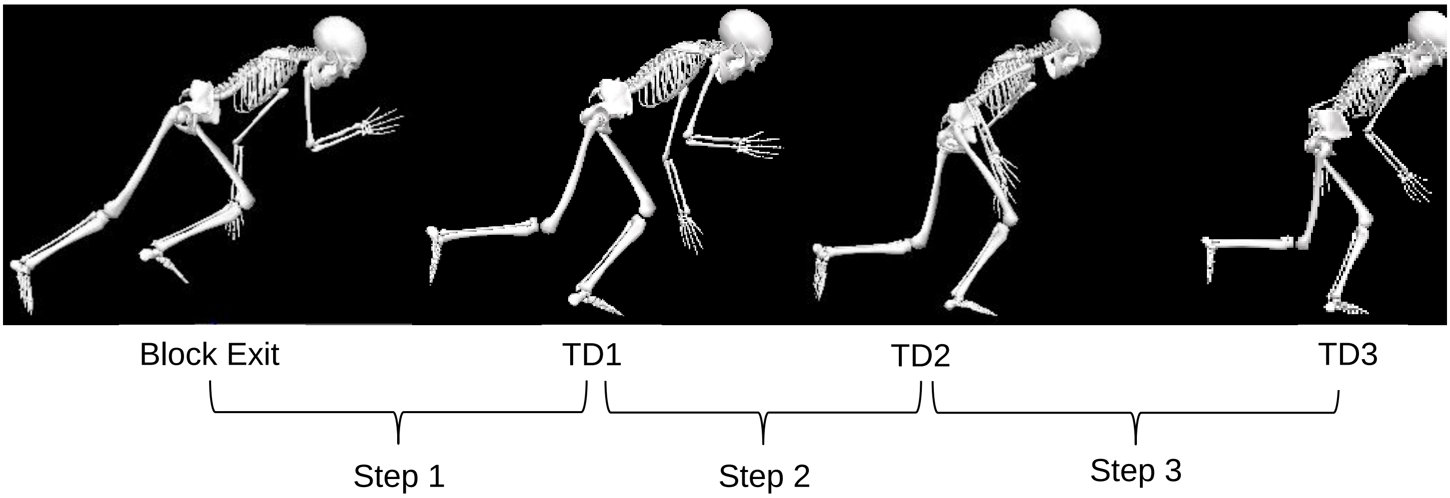

Figure 2: 3-D skeletal images of the participant at the main events analysed, taken from Visual3D. Values recorded for step 1 were averages or peaks between block exit and TD1, for step 2 were between TD1 and TD2, and for step3 were between TD2 and TD3.

CHAPTER 3: RESULTS

3.1 Average horizontal external power

Figure 3 demonstrates the average horizontal external power (AHEP); the parameter used as the performance indicator in the current study. The graph shows the variability in AHEP for all six trials during TD1, TD2 and a combined average. From the graph it can be seen that AHEP was greatest in TR6, for TD1 (914 W), and smallest in TR2 (731 W). However, for TD2, TR2 exhibited the greatest AHEP of 1114 W, as well as the largest increment in AHEP between the two touchdowns (an increase of 383 W). TR6 on the other hand showed the smallest change between TD1 and TD2. Combined AHEP for TD1 and TD2 was greatest in TR1 (1990 W) and smallest in TR5 (1809 W), which was used as the overall performance indicator.

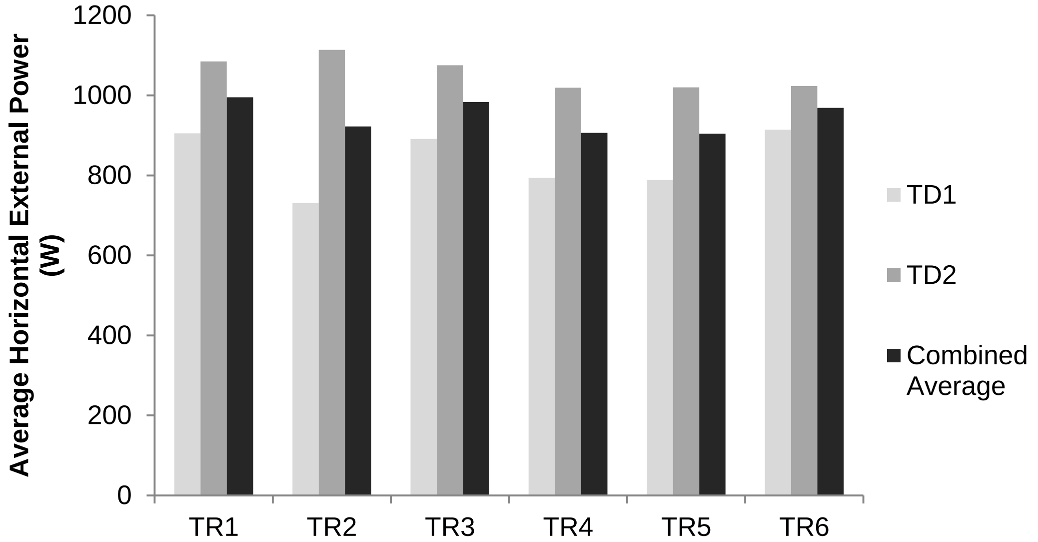

Figure 3: Average horizontal external power for each trial at TD1 and TD2, including a combined average for both touchdowns

3.2 Step characteristics

The values for all step characteristic parameters, of the six trials, are depicted in Table 2, with average values for each step highlighted in bold. For all trials, the SL and SF increased from step one to step two, by average increases of 0.10 ± 0.04 m and 0.29 ± 0.14 steps·s^{-1} respectively, and then again from step two to three by a larger degree 0.14 ± 0.02 m and 0.39 ± 0.07 steps·s^{-1}. The greatest total length achieved over the three steps occurred in TR3, and the smallest in TR4, whereas the greatest overall step frequency occurred in TR5.

Braking impulse showed a substantial decrease from step two to step three (1.9 ± 0.6 N·s), whereas the time spent in the braking phase remained roughly similar. The propulsive impulse, on the other hand, demonstrated a lesser decrease between these two steps of 7.8 ± 4.9 N·s. The impulse itself, however, was much larger and overcame the braking impulse in every trial to give an average positive net impulse of 48.3 ± 4.7 N·s in step two and 42.4 ± 0.9 N·s in step three. In both steps more time was spent in propulsion than braking, though the time in propulsion decreased from 0.18 s in step two to 0.16 s in step three. Therefore overall, due to the decrease in propulsion impulse and time from step two to step three, the net impulse displayed an average decrease of 5.9 ± 4.8 N·s between the steps. The propulsion: braking index always gave a positive value as time spent in propulsion was always greater than time spent in braking, however this index also decreased from step two to step three due to the percentage decrease in propulsion time outweighing the percentage decrease in braking time. TR1 demonstrated the largest total braking impulse as well as largest total propulsion impulse.

The contact: flight index had an average value of 5.60 ± 1.76 for step two, which was almost halved to 2.65 ± 0.33 in step three, clearly demonstrating the increased time spent in flight than in contact as the participants COM velocity rose. TR6 displayed the largest contact: flight index for both steps as well as the largest decrease between the steps two and three.

Table 2: Step characteristics for all six trials over the first three steps out of the blocks, including averages and standard deviation

				Braking		Propulsion			Indices	
		Step Length (m)	Step Frequency ($m \cdot s^{-1}$)	Impulse (N·s)	Time (s)	Impulse (N·s)	Time (s)	Net Impulse (N·s)	Propulsion: Braking Index	Contact:Flight Index
Step 1	TR 1	0.81	3.52	-	-	-	-	-	-	-
	TR 2	0.84	3.26	-	-	-	-	-	-	-
	TR 3	0.89	3.31	-	-	-	-	-	-	-
	TR 4	0.78	3.36	-	-	-	-	-	-	-
	TR 5	0.83	3.44	-	-	-	-	-	-	-
	TR 6	0.82	3.47	-	-	-	-	-	-	-
	Average	**0.83**	**3.39**	-	-	-	-	-	-	-
	SD	0.04	0.10	-	-	-	-	-	-	-
Step 2	TR 1	0.94	3.65	-4.1	0.01	56.6	0.19	52.5	13.5	4.95
	TR 2	0.89	3.73	-2.4	0.01	44.6	0.18	42.2	14.7	3.24
	TR 3	0.94	3.72	-3.7	0.01	57.6	0.20	53.9	14.3	5.94
	TR 4	0.92	3.53	-2.2	0.01	50.8	0.19	48.7	13.2	4.74
	TR 5	0.92	3.76	-3.2	0.01	46.9	0.18	43.7	12.9	6.29
	TR 6	0.94	3.68	-2.7	0.01	51.6	0.17	48.9	12.3	8.45
	Average	**0.93**	**3.68**	**-3.0**	**0.01**	**51.4**	**0.18**	**48.3**	**13.5**	**5.60**

	SD	0.02	0.08	0.8	0.00	5.2	0.01	4.7	0.9	1.76
	Average Change	**0.10**	**0.29**	-	-	-	-	-	-	-
	SD	0.04	0.14	-	-	-	-	-	-	-
Step 3	TR1	1.07	4.08	-2.2	0.01	44.3	0.157	42.1	12.1	2.70
	TR 2	1.06	4.00	0.2	0.01	42.2	0.154	42.4	12.8	2.52
	TR 3	1.09	4.07	-1.3	0.01	42.8	0.156	41.5	13.0	2.21
	TR 4	1.06	3.95	-0.4	0.01	43.2	0.162	42.8	13.5	2.56
	TR 5	1.03	4.24	-1.4	0.01	43.0	0.164	41.6	12.6	2.72
	TR 6	1.08	4.09	-1.9	0.01	45.9	0.175	44.0	12.5	3.20
	Average	**1.07**	**4.07**	**-1.2**	**0.013**	**43.6**	**0.16**	**42.4**	**12.8**	**2.65**
	SD	0.02	0.10	0.9	0.00	1.3	0.01	0.9	0.5	0.33
	Average Change	**0.14**	**0.39**	**1.9**	**0.00**	**-7.8**	**-0.02**	**-5.9**	**-0.7**	**1.57**
	SD	0.02	0.07	0.6	0	4.9	0.016	4.8	0.9	-2.95
Total	TR1	2.83	3.75	-6.3	0.03	101.0	0.35	94.6	25.6	7.65
	TR 2	2.79	3.66	-2.2	0.02	86.8	0.33	84.6	27.5	5.76
	TR 3	2.92	3.70	-5.0	0.03	100.4	0.36	95.4	27.3	8.15
	TR 4	2.76	3.62	-2.6	0.03	94.0	0.35	91.4	26.7	7.30
	TR 5	2.79	3.81	-4.5	0.03	89.8	0.35	85.3	25.5	9.01
	TR 6	2.83	3.75	-4.6	0.03	97.5	0.35	92.9	24.8	11.66
	Average	**2.82**	**3.71**	**-4.2**	**0.03**	**94.9**	**0.35**	**90.7**	**26.2**	**8.25**
	SD	0.06	0.07	1.5	0	5.8	0.01	4.7	1.1	2.09

3.3 Centre of Mass velocity

The average COM horizontal and vertical velocities can be seen in Table 3. At block exit the horizontal COM velocity was low in magnitude (2.82 ± 0.11 m·s^{-1}), compared to TD1 and TD2 (as the participant started from a horizontal velocity of 0 m·s^{-1}). From block exit to TD1, COM horizontal velocity increased by 0.04 ± 0.04 m·s^{-1} and COM vertical velocity changed from a positive value to a negative (downward) value. From TD1 to TD2, COM horizontal velocity rose from 2.86 ± 0.12 m·s^{-1} to 3.85 ± 0.12 m·s^{-1}, while the negative vertical velocities (due to the lowering of COM at every touchdown) decreased in magnitude from -0.30 ± 0.11 m·s^{-1} to -0.05 ± 0.09 m·s^{-1}. At block exit, TR5 exhibited a significantly greater COM vertical velocity (0.46 m·s^{-1}) than all other trials, while TR1 exhibited a significantly smaller vertical velocity (0.31 m·s^{-1}). Throughout the first step an average horizontal COM velocity of 2.81 ± 0.11 m·s^{-1}, and an average vertical COM velocity of 0.06 ± 0.03 m·s^{-1} were recorded as the participant accelerated forwards and upwards from the crouched starting position. A resultant COM velocity was calculated as 2.81 ± 0.11 m·s^{-1} for step one, 3.40 ± 0.10 m·s^{-1} for step two, and 4.35 ± 0.10 m·s^{-1} for step three. The horizontal, and resultant, COM velocity was greatest at every event, and during every step in TR3, and lowest in TR4.

Table 3: Centre of Mass Velocity and trunk angle at events, and centre of mass velocity for the first three steps for every trial, including averages and standard deviation (SD)

		TR1	TR2	TR3	TR4	TR5	TR6	**Average**	SD
Horizontal COM Velocity (ms-1)	Block Exit	2.86	2.74	2.96	2.63	2.86	2.84	**2.82**	0.11
	TD1	2.84	2.82	2.96	2.65	2.94	2.93	**2.86**	0.12
	TD2	3.90	3.70	3.98	3.70	3.93	3.89	**3.85**	0.12
	Step 1	2.86	2.73	2.93	2.62	2.87	2.84	**2.81**	0.11
	Step2	3.45	3.33	3.50	3.23	3.47	3.45	**3.40**	0.10
	Step3	4.38	4.23	4.45	4.20	4.38	4.41	**4.34**	0.10
Vertical COM Velocity	Block Exit	0.31	0.45	0.36	0.39	0.46	0.40	**0.39**	0.06
	TD1	-0.20	-0.38	-0.16	-0.36	-0.28	-0.45	**-0.30**	0.11
	TD2	0.01	-0.22	0.03	-0.11	0.00	-0.03	**-0.05**	0.09
	Step 1	0.05	0.05	0.10	0.05	0.09	0.01	**0.06**	0.03
	Step2	0.18	0.11	0.16	0.08	0.10	0.00	**0.10**	0.07
	Step3	0.21	0.06	0.24	0.18	0.19	0.20	**0.18**	0.06
Resultant COM Velocity	Block Exit	2.88	2.78	2.98	2.66	2.90	2.87	**2.84**	0.11
	TD1	2.85	2.84	2.96	2.67	2.95	2.96	**2.87**	0.11
	TD2	3.90	3.70	3.98	3.70	3.93	3.89	**3.85**	0.12
	Step 1	2.86	2.73	2.94	2.62	2.88	2.84	**2.81**	0.11
	Step2	3.45	3.33	3.50	3.23	3.47	3.45	**3.40**	0.10
	Step3	4.38	4.24	4.46	4.20	4.39	4.41	**4.35**	0.10
Trunk Angle (°)	Block Exit	28	27	30	26	30	30	**29**	1
	TD1	30	33	30	30	32	33	**31**	1
	TD2	38	41	40	39	41	42	**40**	2

3.4 Joint angles

For all events analysed (Table 4) the hip demonstrated an extended angle. At block exit the extended angle was greater at the rear hip (37 ± 2°) than the front (13 ± 3°). The knee demonstrated the same patterns of a greater angle in the rear leg than the front, but unlike the hip was at a flexed angle for each event. The ankle displayed individualist patterns; at block exit the front ankle was flexed (-21 ± 2°) and the rear ankle was also flexed but to a lesser extent (-4 ± 2°). TD1 joint angles for the ankle, knee and hip were all of greater magnitude than the angles seen at TD2. During TD 1 and TD2, TR2 joint angles were smallest in magnitude at all joints, while TR1 and TR6 demonstrated greatest extension (ankle and hip) and flexion (knee) angles. At block exit angles in TR4 for all joints were generally greatest in magnitude. The ROM (Table 4) for the ankle and hip both decreased from step two to step three, contrary to the knee ROM, which rose. Hip ROM was recorded as nearly double the ROM seen at both the ankle and the knee. The greatest ROM over all joints for both steps was seen in TR1, 3 and 6 whereas the most limited range was seen consistently in TR2. Trunk angle (Table 3) was 29 ± 1° at block exit, which gradually extended to 31 ± 1° at TD1, and 40 ± 2° at TD2. Even at TD2, the angle of 40° revealed that the participant's trunk position was still relatively acute to the horizontal. The trunk was most extended at block exit in TR5, and most flexed in TR1, in which trial the trunk angle remained the most flexed by TD2.

Table 4: Joint angles of the ankle, knee and hip at events, and their range of motion during steps two and three for every trial, including averages and standard deviation

			TR1	TR2	TR3	TR4	TR5	TR6	**Average**	SD
Joint angle (°)	Front Block Exit	Ankle	-18	-22	-23	-19	-20	-22	**-21**	2
		Knee	-22	-17	-19	-26	-20	-19	**-21**	3
		Hip	11	14	10	17	12	14	**13**	3
	Rear Block Exit	Ankle	-1	-4	-2	-7	-6	-4	**-4**	2
		Knee	-57	-51	-57	-59	-52	-49	**-54**	4
		Hip	36	38	38	40	35	34	**37**	2
	TD1	Ankle	14	13	18	13	14	15	**15**	2
		Knee	-67	-58	-65	-63	-61	-68	**-64**	4
		Hip	67	53	66	55	58	56	**59**	6
	TD2	Ankle	14	8	11	11	12	13	**11**	2
		Knee	-63	-56	-61	-61	-62	-67	**-62**	3
		Hip	58	50	58	54	57	61	**56**	4
ROM (°)	Step 2	Ankle	25	21	28	24	23	23	**24**	2
		Knee	30	18	24	25	25	28	**25**	4
		Hip	64	45	63	54	58	57	**57**	7
	Step3	Ankle	22	20	20	21	23	24	**22**	2
		Knee	28	25	26	29	26	32	**28**	3
		Hip	54	44	52	48	52	57	**51**	5
	Total	Ankle	48	41	48	45	46	48	**46**	3
		Knee	58	43	50	55	52	60	**53**	6
		Hip	118	89	115	102	110	114	**108**	11
		All joints	224	174	213	201	207	222	**207**	18

3.5 Peak joint extensor moment

On the left of Figure 4 the peak extensor moments (PEM) of the ankle, knee and hip for all trials during TD1 (top) and TD2 (bottom) are depicted. The largest hip PEM was seen in TR3 (280 N), which corresponded with the lowest ankle PEM for TD1 (154 N). The highest ankle PEM was found in TR2, where conflictingly to TR3, hip PEM was lowest (197 N). Knee PEM was greatest for TR1 (212 N), and the three trials with largest values for knee PEM coincided with those where knee PEM exceeded ankle PEM. There was an overall trend for an increased PEM at TD2 (versus TD1) for the hip and ankle, however the average knee PEM dropped significantly from 166 ± 35 N at TD1 to 102 ± 25 N at TD2; the lowest value was found in TR2 (72 N). Comparably to TD1 the largest hip PEM was, again, found in TR3 (323 N), but the lowest value was seen in TR4 (229 N), this, similarly to TD1, was where the largest ankle PEM was found (207 N). For all trials during TD2, ankle PEM always exceeded knee PEM, but itself was always exceeded by hip PEM. The greatest differences seen between ankle and hip PEM were found in TR2 and TR4.

3.6 Peak joint power

On the right of Figure 4, the peak power (PP) at each lower limb joint is displayed for all trials during TD1 (top) and TD2 (bottom). During both touchdowns the greatest PP is always exhibited at the hip, followed by ankle PP and lastly by knee PP. At TD1 the largest hip PP was found in TR5 (2724 W), and the smallest in TR2 (1571 W). The ankle PP is similar for all trials but was highest in TR2 (1493 W) and lowest in TR3 (1171 W), while knee PP was greatest in TR6 (754 W) but smallest in TR1 (418 W). The knee PP was greatest again in TR6 for TD2, but lowest in TR3, which corresponded to when hip PP was highest. During TD2, ankle PP values were even more similar for the six trials than during TD1, but the highest value was recorded during TR5. On average, ankle and hip PP increased from TD1 to TD2 (from 1341 ± 96 W to 1455 ± 71 W), and from 2277 ± 366 W to 2527 ± 359 W, respectively) but PP decreased overall at the knee (from 619 ± 112 W to 558 ± 69 W).

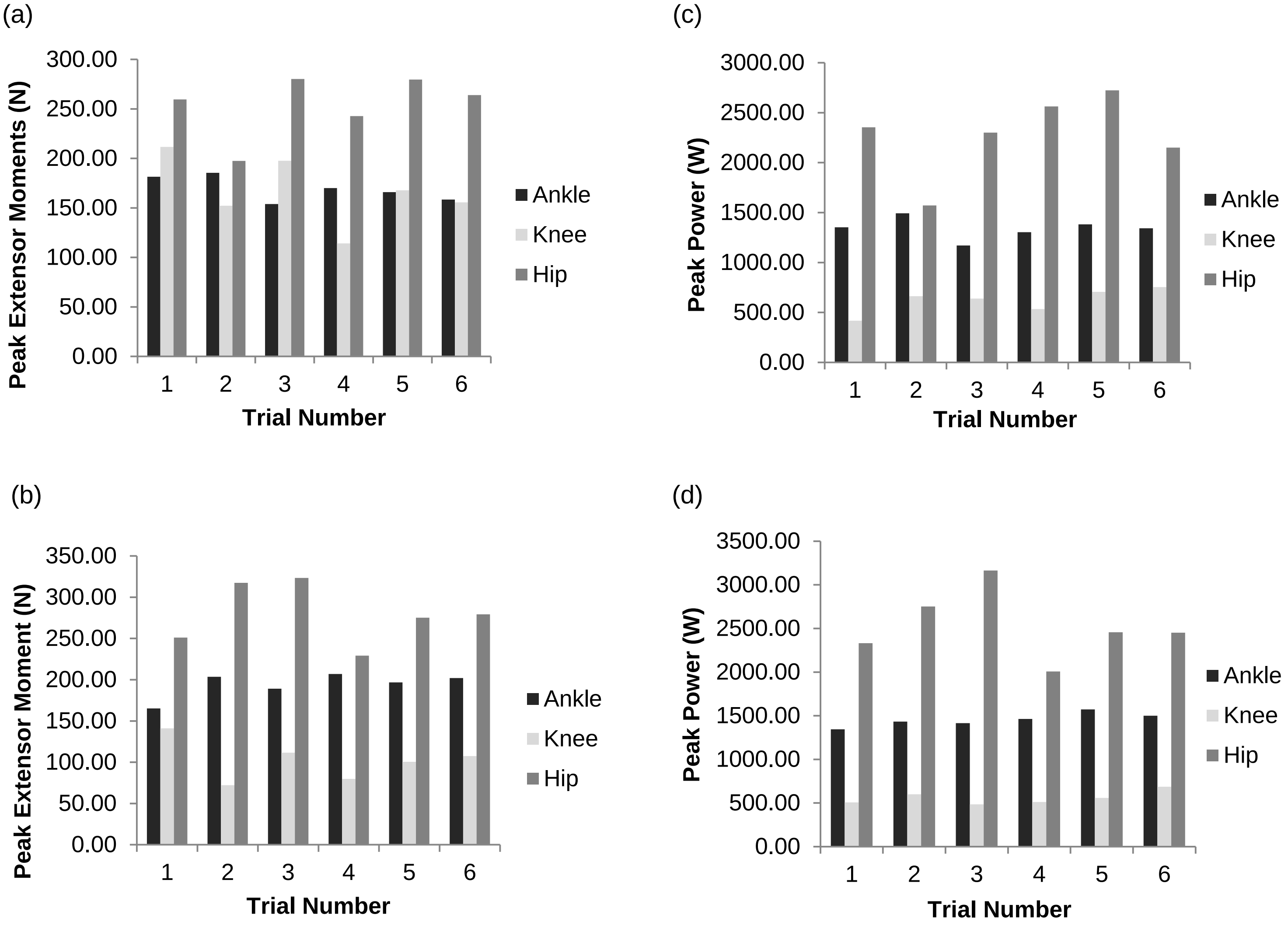

Figure 4: Peak extensor moment at the hip, knee and ankle for every trial at (a) TD1 and (b) TD2, as well as peak powers of these joints at (c) TD1 and (d) TD2

CHAPTER 4: DISCUSSION

The aim of the current study was to gather an in-depth analysis of a variety of parameters during the sprint start of a CP class T36 athlete, and to gauge which parameters may have had an influence on performance, measured as AHEP. The results revealed agreements with fundamental patterns found in sprinting for AB athletes as well as for CP athletes, although there were some interesting and significant differences exposed. These included the reduced AHEP values, step lengths and resultant COM velocities observed in the CP participant, as well as a proposed inefficiency in transferring force to power. The following discussion will aim to interpret the significance of each parameter in relation to performance, but also in relation to previous research.

4.1 Average horizontal external power

The AHEPs recorded in the current study, as the performance measure, were on average less than those recorded by Bezodis (2009) (2126 W, 2107 W and 1457 W for the three participants), ranging from 731 – 1114 W. Here, substantial disparity demonstrates the difference in external power generation between AB athletes and CP athletes, even at elite levels. The weaker values are, however, in agreement with earlier studies by Davids et al. (1998), who demonstrated children with CP to produce much less power than AB children during running, especially at the hip where power generation was almost half (3.96 ± 0.81 W compared to 7.65 ± 6.93 W). Observed lower capability of power generation at the hip may be caused by lack of musculature surrounding the hip. Recruitment of musculature around the hip strengthens the hip extensors, which has been suggested to increase performance (Guissard & Duchantou, 1990; Mero & Komi, 1990). This is due to the fact that the hip extensors generate the majority of power against the blocks in a block start. (Novacheck, 1997). When attention was brought to the height and mass of the participant (1.73 m, 55.4 kg) in the current study, a significant difference in height and corresponding total body mass was observed. AB participants ranged in height between 1.76 m and 1.88 m and had much larger total body masses of 68 – 80 kg (Bezodis et al., 2008; Debaere et al., 2012; Bezodis et al., 2013). Warren Wier is an example of an AB elite athlete of equivalent level (Olympic sprinter), age and height as the participant in the current study, but has a much greater body mass of 72.6 kg. The reduced body mass in the participant is likely to manifest itself in reduced total muscle mass, which would affect performance (particularly at the hip as mentioned above), however this cannot be accurately measured.

The greatest combined AHEP over the two touchdowns was seen in TR1 (1990 W), and the lowest seen in TR5 (1809 W), therefore for this discussion the best performed trial will be referred to as TR1, and the worst performed as TR5.

4.2 Step length and frequency

The step lengths expressed by the participant in the current study increased throughout the first three strides, much like AB athletes have shown (Atwater, 1982: Mero, 1988; Čoh et al.'s, 2006), although the lengths achieved were noticeably shorter, especially for the third step, which may be a limit caused by CP itself (Pope et al., 1993). The AB model proposed by Mero (1988) indicated an average step length of 1.14 m to be the norm for steps one and two, and an increased length of 1.45 m for the third step, which, for the participant in the current study, were 0.83 m, 0.93 m and 1.07 m in the respective steps. These values are not only shorter in comparison to AB athletes, but are shorter than results seen in CP class T37 and T38 athletes (Andrews et al., 2011). However, the trend shown by the T37 athlete was abnormal when compared to AB athletes, as their step length decreased from step two to step three (1.31 – 1.24 m), which was not the case for the T36 athlete in the current study. The disparity was most likely due to the fact that the classification of a T37 athlete is that CP is only present on one side, whereas a T36 athlete's CP is symmetrical (appendix). Taking this into account, step length for the T36 athlete was expected to be shorter due to both legs being affected, akin to a T35 athlete (also classified as having symmetrical CP), who exhibited analogous step lengths during the first three steps of 0.87, 0.93 and 1.10 m respectively (Andrews et al., 2011).

TR1, TR3 and TR6, the three best performances, as determined by AHEP, displayed the upper range of SL during step two, step three and the total distance covered by the three steps. A positive correlation of step length to performance was suggested, and when combined with SF results, an optimal SL to SF ratio for this athlete was apparent. In TR5, the highest SF for steps two (3.76 steps·s^{-1}), three (4.24 steps·s^{-1}) and average (3.82 steps·s^{-1}), were exhibited, followed by TR1, 3 and 6. Potentially, by increasing SF to compensate for lower SLs, the participant has detrimentally affected their performance, and there may be an optimal value for SF that, if exceeded, will be unfavourable. A high SL in the first three steps, combined with a high SF contributes to a greater performance, which is in agreement with Salo et al. (2011) who suggested individual athletes to have a reliance on either SL or SF. Like a number of participants in their study, the participant in the current study appeared to be equally reliant on SL and SF to better performance. Step ratios replicated in Salo et al.'s (2011) study are, however, during the maximal velocity phase of sprinting so cannot be directly compared.

4.3 Braking and propulsion

The braking phase in the current study, exhibited analogous trends to those described by Salo et al. (2005) in that the absolute time spent in the braking phase does not change from step two to step three. Meanwhile the braking impulse increased over these two steps (1.2 – 4.2 N·s) , due to an increase in braking force that contributes to the reduction in net impulse described in the results section. The propulsive impulse was much larger than the braking impulse for both steps, therefore resulted in acceleration, which was larger in step two than step three, as shown by the decrease in the propulsion: braking index from 13.5 to 12.8. This indicated that the fastest acceleration is seen immediately at the start and decreases with time. Interestingly TR1 exhibited the largest magnitude in braking impulse for steps two (2.2 N·s) and three (4.1 N·s), which contrasts to the notion that minimising braking impulse increases velocity, and therefore, performance in AB athletes (Mero et al., 1983). It must be reinforced that Mero et al. (1983) did not use AHEP as their performance measure and the participants were AB athletes, which may have resulted in the hypothesis proposed.

The net (propulsive) impulse values attained in the current study, similar to the AHEP and step length, are considerably lower than described for AB athletes. A range of 87 - 91 N·s has been recorded in the first step of a sprint (Mero, 1988; Salo et al., 2005), and the corresponding average value for the first step in the current study was 48.3 N·s. As Impulse = Force·Δtime = mass·Δvelocity, the decreased impulse was expected as the participants body mass was reduced in comparison to equivalent AB athletes. However, the greatest total net impulse over steps two and three occurred in the three best performed trials (95.4, 94.6 and 92.9 N·s), whereas the worst performed trial demonstrated a much lower net impulse (85.3 N·s). The comparably poor propulsion impulse for the T36 participant along with greater propulsions corresponding with the best performed trials, emphasised the fact that propulsion impulse directly contributed to power production in the participant.

4.4 Contact: flight index

At the start of a race, it has been commonly accepted that to retain greater acceleration, athletes shorten the time spent in the contact phase while lengthening the time spent in the flight phase (Housden, 1964; Atwater, 1982; Čoh et al., 2006). The results discovered this same pattern, which has (to the authors knowledge) not been studied in detail during the sprint start in CP athletes until now. The contact: flight ratio of 5.6: 1 in step two decreased to 2.65: 1 in the third step, and whether this continued to decrease, and eventually plateaued, as it did in Čoh et al.'s (2006) study cannot be deduced. This would be an interesting area to look at in the future as Pope & Wilkerson (1986) discovered differing contact: flight indices in CP athletes during the middle phase of the sprint (1.13: 1), compared to AB athletes (1: 1.33), which contrasts to the analogous results of CP and AB athletes found during the first three steps in the current study.

4.5 Centre of Mass velocity and trunk angle

In the current study, if performance had been described using horizontal or resultant COM velocity, as many previous studies have done, it would have been deduced that TR3 was the best performed trial followed closely by TR5. However, this is not the case, which highlights the importance to take into account vertical, as well as horizontal COM velocity, especially at the block exit. The positive value of vertical COM velocity at block exit is explained by the fact that the participant must raise their COM so as to remain balanced while accelerating (Novacheck, 1997), however not to such an extent as to impact detrimentally on horizontal COM velocity (Čoh et al., 2006). The horizontal COM velocity at block exit, for the participant in the current study, is significantly smaller in value (2.82 ± 0.11 $m \cdot s^{-1}$) than seen in top class AB athletes; ranging from 3.34 - 4.18 $m \cdot s^{-1}$ (Mero, 1988; van Coppenolle et al., 1989), which is linked back to impulse. The reduced impulse observed in the current study may not have only been due to a reduced body mass, but also to the reduced velocity achieved. External power production would have been detrimentally affected as a result because of its dependence on force and COM velocity.

For all trials the magnitude of average horizontal and vertical COM velocity increased from step one to step three (from 2.81 to 4.34 $m \cdot s^{-1}$ and from 0.06 to 0.18 $m \cdot s^{-1}$ respectively), which indicated positive acceleration, as occurs in AB sprinting. For the two best performed trials (TR1 and TR3), vertical COM velocity at TD1 and TD2, was lowest (-0.2, 0.01 $m \cdot s^{-1}$ and -0.16, 0.03 $m \cdot s^{-1}$ respectively), and positive vertical COM velocity at block exit was also lowest (0.31 and 0.36 $m{\cdot}s^{-1}$), in comparison with TR5, which exhibited a considerably greater positive vertical COM velocity at block exit of 0.46 $m{\cdot}s^{-1}$. Average positive vertical COM velocities over the three steps were largest for the best two performed trials, which is in agreement with the theory that high horizontal COM velocity with additional vertical COM velocity is required for optimal acceleration and therefore performance (Mero & Komi, 1987; Skripko, 2003; Bezodis et al., 2010).

The current study highlighted the importance of the positive vertical COM velocity being as small in magnitude as possible at block exit for optimal starting performance; values of 0.31 $m{\cdot}s^{-1}$ for TR1 compared to 0.46 $m{\cdot}s^{-1}$ for TR5 demonstrated this. From this, an association between vertical COM velocity and trunk angle (and performance) was observed, which hitherto had been more correlated to horizontal COM velocity in AB athletes (Kyröläinen et al., 1999; Hunter et al., 2008). Trunk angle in the 'set' position for different classes of CP athletes has been studied in detail (Andrews et al., 2011; Andrews 2014) and it was proposed that the T37 and T38 athletes should aim to increase their degree of trunk lean in 'set' for an improved block exit velocity, and first stride length (Delecluse et al., 1998; Hommel et al., 2009; Andrews et al., 2011). The current study focused on trunk lean at block exit and the subsequent two touchdowns, which to the authors knowledge, is an untouched area of focus for CP athletes. Trunk angles from block exit to TD2 ranged from 29 - 40°, which is in accordance with angles measured over the first four steps out of the blocks in AB athletes, which ranged from 32 - 42° (Mero et al., 1983; Mero, 1988). Pope & Wilkerson (1986) found differing trunk angles in CP athletes compared to AB athletes during the middle phase of the sprint, similar to the difference seen in contact: flight index in the middle phase. A comparable difference in trunk angle between AB athletes and CP athletes was not replicated in the current study for the starting phase of the sprint.

An important observation, which is associated with vertical COM velocity, was that the best performance was seen when the trunk remained most flexed by TD2 (38°), as well as being relatively flexed at block exit (although inferior trials demonstrated a more flexed position at block exit). TR5 exhibited one of the most extended trunk angles at block exit (30°), which may have resulted in the significantly high vertical COM velocity (0.46 $m{\cdot}s^{-1}$) gained at block exit in this trial. It can be theorised that *maintaining* a flexed trunk while accelerating may aid performance by bringing the COM ahead of the stance foot and closer to the GRF vector, which favours acceleration. (Debaere et al., 2012; Deshon et al., 2013). Developing (for both AB athletes and CP athletes) the suggestion that trunk angle should be as low (flexed) as possible during block exit (Payne & Blader, 1971). For future development, it may be interesting to draw comparisons of trunk angle, in the ‘set’ position as well as during block exit and subsequent touchdowns, between different CP classes.

4.6 Joint Angles

A number of studies have concentrated on joint angles and ROM in the block phase for AB athletes (Borzov, 1978; Atwater, 1982; Mero et al., 1983; Mero, 1988; Mero & Komi, 1990; Čoh et al., 1998), but further analysis of joint angles and ROM for the rest of the starting phase was indicated in AB athletes (Bezodis, 2009), which is what the current study also focused on. The results showed that joint angles at block exit were correlated with values found at the hip and ankle for AB athletes (Bezodis, 2009), however knee flexion angles were seen, which differed from AB studies. However this may be because overall joint angles were calculated for the current study, whereas Bezodis (2009) calculated flexion angles separately from extension angles. Overall a slightly flexed angle would be expected as, during touchdown, the leg should not be fully extended, to allow power absorption before toe-off (Novacheck, 1997). At TD1 and TD2 joint angles at the hip, for the best performed trial, were most extended in comparison to other trials (67° and 58° respectively), which again is in accordance with the correlation found between greater extension at the hip and performance by Bezodis (2009) (although the worst performed trial did not exhibit the least extension). Contrary to all previous sprint-start studies, knee flexion angles were observed at TD1 and TD2. Knee flexion has previously been noted immediately after touchdown in the middle phase (Hunter et al., 2005) and maximum velocity (Bezodis et al., 2008) phases of sprinting, and is thought to occur in attempt to slow down the foots vertical velocity, which when greater, is thought to be related to increased braking force (Putnam & Kozey, 1989; Jacobs & van Ingen Schenau, 1992). The results shown lead to another question; Is knee flexion at touchdown, in the starting phase, a pathological adaptation in sprinters with CP, and does it have a discernible effect on performance? Further understanding of joint angles and ROM during the sprint start, especially at the knee, will be necessary to determine whether the values observed are due to the disease itself.

4.7 Range of Motion

The ROM values, measured over steps one and two, demonstrated a close association to performance. The combined ROM at the hip, knee and ankle were greatest for TR1 (224°), followed by TR6 (222°) and TR3 (213°). The heightened hip and knee ROMs observed in better performance correlated with results from Bezodis (2009), although were decreased in magnitude, while the observed increased ankle ROM with performance, was not seen. Decreased ankle dorsiflexion ROM was thought to provide a stable (stiff) base for translation of extension and power from the hip and knee (Bezodis, 2009). As the current study only focused on plantarflexion ROM at the ankle, it cannot be accurately deduced whether the ankle in the CP participant was more or less stable. Determining dorsiflexion ROM as well as plantarflexion ROM may give valuable insight into differences in ankle stiffness between CP athletes and AB athletes, as this is suggested to have an influence on performance (Charambalous et al., 2012).

4.8 Peak joint extensor moment

The peak joint extensor moments and peak joint powers in the current study occurred in TD1 and TD2, and may give a valuable insight into why performances in certain trials were superior. Joint moments and powers have been studied in some detail in AB athletes during the sprint start (Mann, 1981; Jacobs & van Ingen Schenau, 1992; Johnson & Buckley, 2001; Charalambous et al., 2012; Bezodis, 2009), yet, to the authors knowledge, this method as an analysis of performance has not thus far been focussed on for CP athletes in any phase of the sprint. Nonetheless, this would be useful as joint moments and powers show the net muscular forces and powers acting about an individual joint, which gives an insight into the net effect of muscle activity during movement (Winter, 2009).

The results demonstrated that PEM at the hip and ankle joints increased from TD1 to TD2, whereas the PEM at the knee decreased; a pattern found by Debaere et al. (2012) and Bezodis (2009) in AB athletes that also corresponded to power. The pattern of decrease is hypothesised to be due to the fact that knee extensors are known (Mann, 1981) to be used at maximum velocity to terminate negative vertical COM velocity at touchdown. Seeing as these velocities are lower at touchdown, the knee extensors are able to produce a greater moment and therefore power (Mann, 1981; Debaere et al., 2012). The PEM values found at the hip (254 and 279 N), knee (166 and 102 N) and ankle (169 and 194 N) for the participant interestingly fell in the normal range for elite AB athletes (Bezodis, 2009). From the results in the current study the two best performed trials demonstrated the greatest knee PEMs in TD1 (212 and 198 N respectively), as well as TD2 (141 and 112 N respectively), reinforcing that increased knee extensor moment may be inextricably linked to improved performance in this CP athlete, as has been previously noted for AB athletes (Bezodis, 2009; Bezodis et al., 2013).

4.9 Peak joint power

The peak joint powers exhibited in the current study (unlike AHEP) fell within the accepted AB athlete range. Seeing as joint power depends on joint angular velocity, whereas external power depends on COM velocity, it was demonstrated that the depleted power production in the participant was due to lesser values of the latter velocity, which explains why peak joint power was not depleted in the same way AHEP was. Additionally, greatest peak joint powers were not always exhibited concurrently with largest peak extensor moments, which reinforces the possibility that individuals with CP are inefficient at transferring force to power (Davids et al., 1998; van den Hecke et al., 2007), likely due to variation in joint angular velocity. The power contribution to total (internal) power, at the ankle remained the same from TD1 to TD2 (32%), decreased at the knee (from 15 to 12%) and increased at the hip (from 54 to 56%). These values for TD1 are in accordance with values observed by Charalambous et al. (2012), and the higher PP found in the hip at TD2, combined with the lower PP at the knee, agrees with Debaere et al., (2012) in that there is a lesser requirement of knee power with increased COM velocity. In the better performed trials, which exhibited greater PEM at the knee, a corresponding increased PP was not found. As Power = Force·velocity, the velocity must have been the limiting factor for these trials, though this cannot be categorically confirmed because joint angular velocities were not calculated. Nevertheless for TD1, AHEP was greatest in TR6, which displayed the greatest knee PP (754 W), as was seen in TD2 where TR2 showed the greatest AHEP combined with a significant knee PP (600 W). This leads to the question of whether, if knee PEM and knee PP were both maximised, would an even greater AHEP and thus performance be seen? The variable that will effectuate the above-mentioned occurrence is greater joint angular velocity at the knee, which will be achieved by covering a larger displacement, preferably horizontally, in a shorter time. It may therefore be crucial for a T36 class CP athlete to maximise their knee joint velocity in order to increase PEM and PP at the knee, simultaneously, for maximal performance. Determining joint angular velocities in the future was indicated as these could confirm the aforementioned theory based on accurate data, as well as fundamental mathematics.

4.10 Future development

Although theories were made using the data and mathematical equations, there was an indication for quantifying changes in extensor moments and powers over time; i.e. changes throughout touchdown to toe-off in each step. Obtaining electromyographic (EMG) data may also further understanding of the underlying muscle activation patterns, which could be crucial for determining differences in CP athletes’ sprinting kinetics. Also, calculating flexor moments and power absorption may lend extra guidance to build upon current hypotheses.

A larger study sample, although difficult to obtain, would be beneficial to further knowledge of kinematic and kinetic parameters of T36 CP athletes during the sprint start. Using EMG as part of the analysis, as well as more continuous data, will offer more information about the parameters considered in the current study.

CHAPTER 5: CONCLUSION

The current study identified a number of kinematic and kinetic parameters that appeared to influence performance in the T36 CP athlete. Noteworthy agreements with previous CP research were decreased power production seen with CP individuals, in comparison to AB individuals, and the decreased step length exhibited. Observable similarities to aforementioned sprint start research in AB athletes were also presented. Findings such as the superior knee extensor moment's, and the increased hip and knee ROM's contribution to performance, as well as analogous patterns in step characteristics during the first few touchdowns found in AB athletes, were replicated in the T36 participant.

The within-participant analysis revealed that superior performance was principally determined by longer step lengths over the first three steps; greater knee extensor moments; lower vertical COM velocity at block exit, accompanied by limited trunk extension throughout the subsequent three steps; and a greater combined net impulse after three steps. A heightened step frequency over the first three steps was shown to be detrimental to performance. Body mass, resultant COM velocity and most importantly performance itself was significantly reduced in the T36 participant in comparison to AB athletes. These decreased values for body mass and COM velocity may ultimately be manifestations that occur due to the nature of CP, both of which would have contributed to diminished external power production, and may be unadaptable.

The T36 participant in the current study demonstrated the importance of maximising their horizontal propulsion for greater external power production, and thus performance. The participant achieved this by having lower vertical velocity at block exit, a more flexed body position in the first three steps, greater knee extensor moments and, most beneficially, a combination of all three components.

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APPENDIX A

Table 5: Classification of cerebral palsy with regards to sports competition (IPC, 2011)

Class	Description
CP1	Athletes with poor functional range of movement and poor functional strength in arms, legs, and trunk. The athletes use electric wheelchairs or assistance for mobility. They are unable to propel a wheelchair. These athletes compete in a wheelchair.
CP2	Athletes with poor functional strength in arms, legs, and trunk. The athletes are able to propel a wheelchair. These athletes compete in wheelchairs.
CP3	The athletes show fair amount of trunk movement when pushing a wheelchair, but forward trunk movement is often limited during forceful pushing. Although showing some trunk movement while throwing, motions are mostly from the arm. These athletes compete in wheelchairs.
CP4	The athletes show good functional strength with minimal limitations or control problems in arms and trunk. The athletes show poor balance. These athletes compete in wheelchairs.
CP5	The athletes have normal static balance, but show problems in dynamic balance. A slight shift of centre of gravity may lead to loss of balance. The athletes may need an assistance device for walking, but not necessarily when standing or throwing in athletics field events. The athletes may have sufficient function to run on the track.
CP6	The athletes do not have the capability to remain still: They show involuntary cyclic movements and usually all four limbs are affected. The athletes are able to walk without any assistance. They usually have more control problems with the arms and they have better leg functions than CP5, especially when running.
CP7	The athletes have uncontrollable muscular spasms in one half of the body. They have good functional abilities in the dominant side of the body. They walk without assistance but often with a limp due to uncontrollable muscular spasms in the leg. While running, the limp may disappear almost totally. Their dominant side has better development and good follow-through movement in walking and running. Arm and hand control is affected only on the non-dominant side; good functional control is shown on the dominant side.
CP8	The athletes show a minimum of uncontrollable spasm in one arm, one leg, or one half of the body. To be eligible, these athletes need to have a diagnosis of cerebral palsy or other non-progressive brain damage.

APPENDIX B

Table: Exact anatomical locations of retro-reflective markers during static calibration and dynamic trials

Individual markers (static calibration)	Individual markers (movement trials)	Clusters (no. of markers)
2nd Toe head	2nd Toe head	Thigh (4)
MTH-1	MTH-1	Shank (4)
MTH-5	MTH-5	Upper Arm (3)
Lateral Malleoli	Lateral Malleoli	Lower Arm (3)
Medial Malleoli	Heel	Headband (4)
Heel	Lateral Knee	
Lateral Knee	ASIS	
Medial Knee	PSIS	
Greater Trochanter	Iliac Crest	
ASIS	T8	
PSIS	T12	
Iliac Crest	Lateral Rib	
T8	Medial Rib	
T12	C7	
Lateral Rib	Xyphoid	
Medial Rib	Sternum	
C7	Acromium Process	
Xyphoid	Medial Shoulder	
Sternum	Lateral Elbow	
Acromium Process	Medial Elbow	
Lateral Shoulder	Lateral Wrist	
Medial Shoulder	Medial Wrist	
Anterior Shoulder	Middle Knuckle	
Posterior Shoulder		
Lateral Elbow		
Medial Elbow		
Lateral Wrist		
Medial Wrist		
Middle Knuckle		