BIOMECHANICAL EVALUATION OF DISTANCE RUNNING DURING TRAINING AND COMPETITION

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LIST OF ABBREVIATIONS AND DEFINITIONS

Ankle angle: determined from the lower leg to the foot. The greater the angle the more plantarflexion (unit of measurement; ^{o}).

Centre of mass (CM): a point representing the midpoint of mass (of the body).

Change in leg length (ΔL): difference between the maximum and minimum length of the leg during ground contact (units of measurement; m).

Contact time (t_c): time interval from first video frame to the last video frame where the foot is in contact with the ground (units of measurement; s).

Displacement of the centre of mass (Δy): difference between the maximum and minimum centre of mass to foot displacement during ground contact (units of measurement; m).

Flight time (t_f): time interval from the last video frame of foot contact (with the ground) to the first video frame of the next foot contact (units of measurement; s).

Hip angle: determined from the thigh to the trunk. A flexed hip represented by a value less than 180^o (unit of measurement; ^{o}).

Initial leg length (L_0): length determined at point of ground contact by measuring the vertical distance from the centre of mass to the ankle joint (unit of measurement; m).

Initial touchdown (TD): key position identified by the first video frame where the foot is in contact with the ground.

Knee angle: quantified from the thigh to the lower leg. The smaller the angle the more flexion (unit of measurement; ^{o}).

Leg stiffness (K_{leg}): A measure of resistance to change in leg length after application of internal or external forces during ground contact (units of measurement; $kN \cdot m^{-1}$).

Leg stiffness relative to body weight (K_{leg}/BW): A measure of resistance to change in leg length after application of internal or external forces during ground contact. This measure is expressed relative to body weight (units of measurement; $N \cdot m^{-1} \cdot BW^{-1}$).

Maximum knee flexion (MKF): key position identified by the lowest knee angle during contact with the ground.

Maximum vertical ground reaction force (F_{max}): A measure of the maximal vertical force (amplitude of active peak) exerted when in contact with the ground (units of measurement; kN).

Maximum vertical ground reaction force relative to body weight (F_{max}/BW): A measure of the maximal vertical force (amplitude of active peak) exerted when in contact with the ground. This measure is expressed relative to body weight (units of measurement; $N \cdot BW^{-1}$).

Middle-distance athletes: term used to refer to individuals who have achieved 800 m and/or 1500 m performance times in national competitions and perform endurance running training between five and nine times a week for more than 5 years.

Performance time: time interval quantified by the duration taken to accomplish a particular task, in this case time to complete a race or run (units of measurement; s [run] or min:sec.millisec [race]).

Step frequency (S_f): number of foot contacts per second (units of measurement; Hz).

Step length (S_l): distance between toe to toe in subsequent foot contacts (units of measurement; m).

Take-off (TO): key position identified by the last video frame where the foot is in contact with the ground.

Technique: descriptive term applied to a specific movement strategy used to accomplish a particular task, including both kinematics (e.g. joint angles) and kinetics (e.g. ground reaction forces).

Trunk angle: quantified relative to a vertical line going upwards through the mid-point of the hip joints. A negative value illustrates an incline backwards and a positive value indicates an incline forwards (unit of measurement; °).

Vertical stiffness (K_{vert}): A measure of resistance of the body to the vertical displacement of the centre of mass after the application of maximal vertical ground reaction force (units of measurement; $kN \cdot m^{-1}$).

Vertical stiffness relative to body weight (K_{vert}/BW): A measure of resistance of the body to the vertical displacement of the centre of mass after the application of maximal vertical ground reaction force weight. This measure is expressed relative to body weight (units of measurement; $N \cdot m^{-1} \cdot BW^{-1}$).

Velocity (υ): resultant measurement of the rate and direction of the centre of mass during contact with the ground (units of measurement; $m \cdot s^{-1}$).

ABSTRACT

Biomechanical evaluation of distance running during training and competition

C. F. Bridgman, University of Salford, 2015

Middle-distance athletes are faced with a unique challenge to generate high running velocities (between 6.00 and 8.00 $m{\cdot}s^{-1}$) while making movements as economical as possible (Williams & Cavanagh, 1987). Research suggests that 54% of the variation in running economy can be attributed to gait and spring-mass characteristics. The aims of this thesis were to establish a valid means of measuring gait and spring-mass characteristics away from the laboratory environment and then to provide a biomechanical evaluation of middle-distance running during competition and training in order to identify gait and spring-mass characteristics that influence performance time.

Accordingly this thesis has demonstrated that high-speed, Optojump and laser distance measurement (LDM) device all provided a valid measurement of gait and spring-mass characteristics. Spring-mass characteristics obtained through mathematical modelling (estimations based on high-speed video data only) during running were comparable to the gold standard direct measurement (using a force platform). These mathematical models allow for estimations of K_{vert} and K_{leg} to be reported away from the laboratory environment on an outdoor 400 m synthetic athletics track.

During outdoor track competition international-level athletes achieved a lower performance time as a consequence of a longer step length and lower K_{vert} and K_{leg}. For the first time this suggests that a longer step length, greater knee flexion, lower K_{vert} and

K_{leg} are differentiating factors associated with a reduced middle-distance performance time. Whereas, over a single training session and training block regional-level athletes maintained running velocity by significantly increased step frequency and a reduction in K_{vert}/BW. Overall, this thesis implies that middle-distance training should monitor how athletes sustain a high running velocity with more emphasis placed on step length to develop competitive performance by increasing flight distance. To increase the travel during flight it is suggested that athletes increase vertical ground reaction forces through plyometric exercises (e.g. stretch-shortening cycle) and continual development of middle-distance training history.

Keywords: step length, step frequency, vertical stiffness, leg stiffness

CHAPTER 1: INTRODUCTION

1.1 Research overview

Distance running represents synthetic athletic track events between 800 m and 10,000 m, with middle-distance running referring only to 800 m and 1500 m events (Billat, 2001). The goal of competitive distance running is to run a given distance in the least amount of time, with successful performance outcome often determined by maintaining a high running velocity (Anderson, 1996; Leskinen, Hakkinen, Virmavirta, Isolehto, & Kyrolainen, 2009). Running involves the conversion of muscular forces translated through complex movement patterns that utilise all the major joints in the body (Saunders, Pyne, Telford, & Hawley, 2004). High performance running is reliant on skill and precise timing in which all movement has purpose and function (Anderson, 1996). Proposed explanations for the success of middle-distance athletes has been associated with environmental factors, tactics, athlete physical characteristics, equipment and surface, as presented in Figure 1.1 (Anderson, 1996; Cavanagh, 1990; Daniels & Daniels, 1992; Hunter, Marshall, & McNair, 2004; Williams & Cavanaugh, 1986).

The majority of previous research has focused on the physiological demands of maintaining a high running velocity by quantifying heart rate, lactate threshold and maximal oxygen uptake (Daniels & Daniels, 1992; Jung, 2003). In scientific literature, an increase in maximal oxygen uptake is the most common method of demonstrating a training effect and used in the development of athletes training programmes (Bassett & Howley, 2000). Given these applications of maximal oxygen uptake, there has been great interest in identifying the physiological factors that limit maximal oxygen uptake and determining the role of this parameter in maintaining a high running velocity (Bassett & Howley, 2000). Research has suggested that a high maximal oxygen uptake is an important predictor of performance in a heterogeneous population (Sjodin & Svedenhag, 1985), it does not however appear to be so in a homogenous population such as a group of middle-distance athletes with comparatively similar maximal oxygen uptake (Conley & Krahenbuhl, 1980). When comparing Scandinavian and Kenyan distance athletes Saltin et al. (1995a) concurred with Conley and Krahenbuhl (1980) by reporting no significant differences in high maximal oxygen uptake at altitude and at sea level. Lower blood lactate concentration was noted in the Kenyan distance athletes compared to their Scandinavian counterparts. This study concluded that Kenyan distance athletes had superior running economy (compared to Scandinavian athletes) and the difference became more pronounced when measures were expressed relative to body weight (Saltin et al., 1995b).

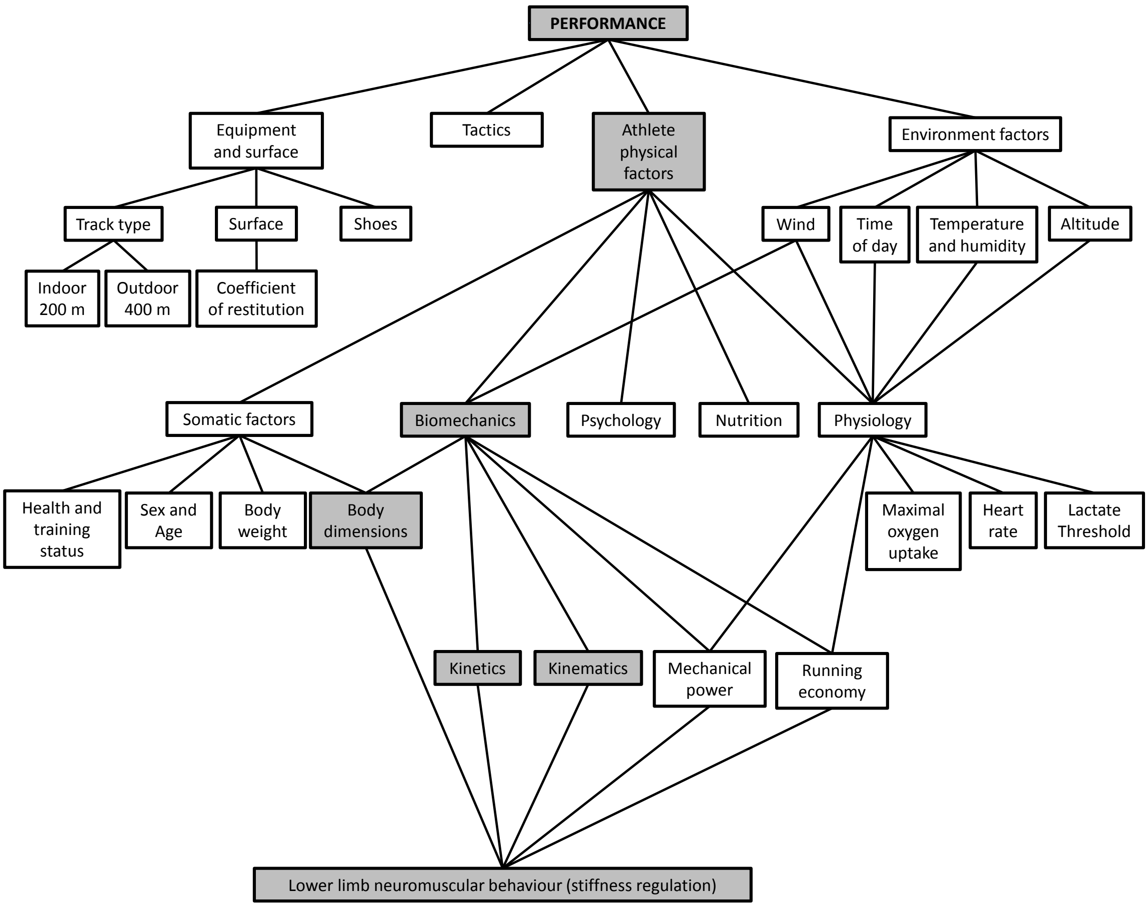


Figure 1.1 Model showing parameters that influence an athlete's running performance, adapted from Hunter et al. (2004); Anderson (1996); Brughelli and Cronin (2008a); Cavanagh (1990); Williams and Cavanaugh (1986). Focus of thesis is highlighted in grey.

Running economy is used to describe the relationship between maximal oxygen uptake and running velocity, and is defined by the oxygen cost per kilogram body mass per kilometre run (Anderson, 1996; Daniels & Daniels, 1992). Athletes with a good running economy use less oxygen than athletes with poor running economy at the same steady state velocity (Saunders et al., 2004), and this can vary by as much as 30% in athletes with similar maximal oxygen uptake values (Daniels, 1985). To illustrate the potential performance implications of good or poor running economy, Figure 1.2 depicts two international-level 10 km athletes that have similar maximal oxygen uptake values but significantly different running economies (Saunders et al., 2004). Subject 1 is 1 minute quicker over 10 km which is likely a result of better running economy (Saunders et al., 2004). Jones (2006) reported the longitudinal laboratory physiological data of Paula Radcliffe from 1992 to 2003, the current women's marathon world record holder. Over the 11 year period maximal oxygen uptake remained relatively stable at approximately 70 ml·kg^{-1}min^{-1} but running economy improved by 15% (205 ml O_2·kg^{-1}·min^{-1} versus 175 ml O_2·kg^{-1}·min^{-1}, respectively). These improvements in running economy coincided with improvement in Paula Radcliffe's performances.

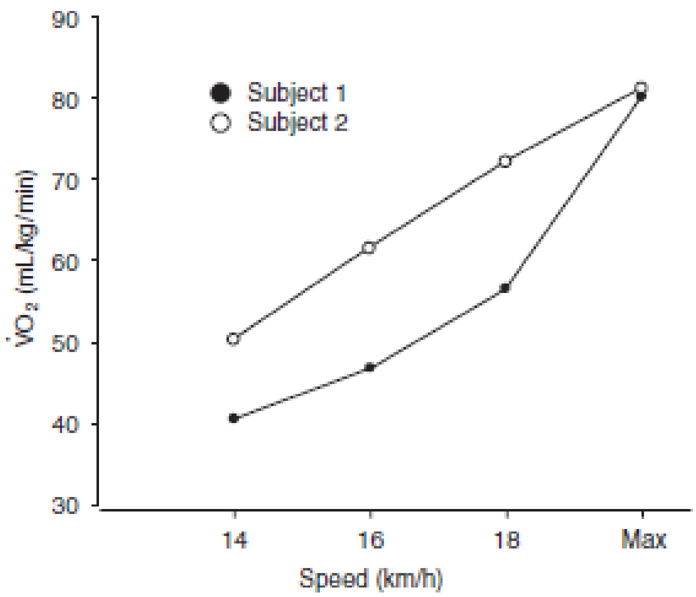


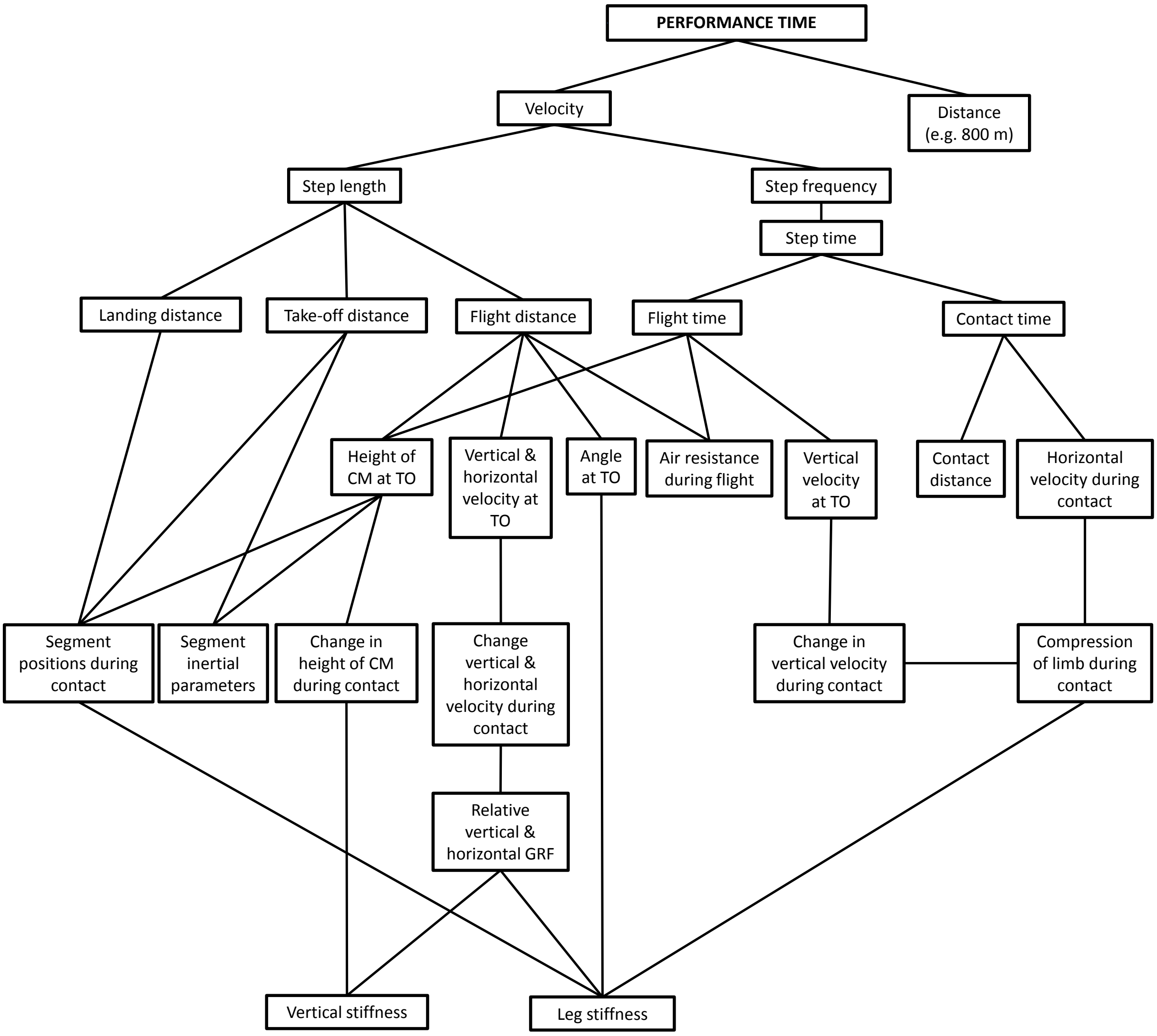
Figure 1.2 Comparison of maximal oxygen uptake (VO2max) in two international 10 km athletes. Subject 1 demonstrates good running economy with subject 2 depicting poor running economy (Saunders et al. 2004)

There is an intuitive link between physiological and biomechanical aspects of middle-distance running, with 54% of the variation in running economy attributed to gait and lower limb neuromuscular behaviour (Anderson, 1996; Paavolainen, Häkkinen, Nummela, & Rusko, 1999; Saunders et al., 2004). The movement of the body during ground contact has been considered important with respect to mechanical power, suggesting that less economic runners adopt different mechanical strategies (Heise, Smith, & Martin, 2011). Studies have also demonstrated that a low percentage body fat, mechanical power, leg mass distribution closer to the hip joint, freely chosen step length, contact time, vertical oscillation, lower extremity angles, kinetics and lower limb neuromuscular behaviour all influence the achievement of a high running velocity and running economy, Figure 1.1 (Anderson, 1996; Dalleau, Belli, Bourdin, & Lacour, 1998). At the development level, this information might be useful in identifying middle-distance athletes with favourable characteristics for maintaining a high running velocity. At higher levels of competition, it is likely that 'natural selection' tends to eliminate athletes who failed to either inherit or develop characteristics which favour maintaining a high running velocity (Anderson, 1996).

Information in the literature suggests that both physiological and biomechanical parameters are likely to impact on the achievement of a high running velocity (Figure 1.1). A variety of somatic factors influence the physiological and biomechanical abilities of an athlete to maintain a high running velocity, these include: sex, age, body weight, body dimensions, health and training status (Leskinen et al., 2009; Skof & Stuhee, 2004). Fudge (2009) reported that during intense training periods prior to competition, Kenyan athletes are in negative energy balance leading to body mass reductions that may potentially contribute to short term success by reducing energy cost of running. Other factors which influence the maintenance of a high running velocity are; track type, surface, shoes, wind (or air resistance), time of day, altitude, temperature and humidity. Some of these factors cannot be controlled for but must be overcome.

Coaches devote substantial time and resource implementing training sessions in order to develop biomechanical and physiological characteristics which favour maintaining a higher running velocity (Anderson, 1996; Paton & Hopkins, 2005). Training is therefore a prerequisite for all athletes to facilitate the process of continuous biomechanical and physiological adaptations required for competition. Research has already identified physiological factors (e.g. running economy) that are associated with performance success in middle-distance running (Foster & Lucia, 2007; Lucia et al., 2006). There is paucity in the biomechanical literature depicting how the most successful athletes maintain a high running velocity. Therefore, it is important to determine and quantify the biomechanical parameters that influence performance time (Iaia, Hellsten, Nielson, Fernstrom, & Sahlin, 2009; Le Meur et al., 2013; Morin, Samozino, & Millet, 2011b; Quinn, 2009; Thiel, Foster, Banzer, & De Koning, 2012). Performance time can be quantified by running velocity and distance which are influenced by multiple biomechanical factors (Figure 1.3).

It has been well-documented that running velocity is defined as the product of step length and step frequency (Salo, Bezodis, Batterham, & Kerwin, 2011). The maintenance of a high running velocity is therefore the result of an optimal combination of step length and step frequency (Salo et al., 2011). Middle-distance athletes are faced with a unique challenge to generate high running velocities while making movements as economical as possible (Williams & Cavanagh, 1987). Higher running velocities are associated with the generation of high vertical ground reaction forces whilst minimising ground contact time (Weyand, Sternlight, Bellizzi, & Wright, 2000b). However, a shorter contact time has been repeatedly shown to correlate with a higher metabolic cost of running (Kram & Taylor, 1990). Middle-distance athletes must therefore find a balance between generating enough vertical force on the ground to achieve a high running velocity whilst minimising the metabolic cost of running.



TD, touchdown; TO, take-off; CM, centre of mass; GRF, ground reaction force

Figure 1.3 Model showing biomechanical parameters that influence performance time, adapted from Morin et al. (2011c); Le Meur et al. (2013); Quinn (2009); Quinn et al. (2011); Thiel et al. (2012); Hay (1993)

Middle- and long-distance research has estimated that athletes typically strike the ground 750 to 2,000 times per mile (or 1609 m) (Buschbacher, Prahlow, & Dave, 2008; Leskinen et al., 2009). As greater forces are imparted to the body, greater resistance to movement is needed in order to produce controlled movements (Butler, Harrison, Crowell, & Davis, 2003). Accordingly, the lower limbs can be considered as springs loaded by the weight and inertia of the body mass. This biomechanical paradigm refers to the spring-mass model and has been applied increasingly in recent years to describe the lower limb neuromuscular behaviour (Figure 1.3) during running (Brughelli & Cronin, 2008a; Hunter & Smith, 2007). Research is yet to document the lower limb neuromuscular behaviour whilst maintaining a high middle-distance running velocity.

Small changes in gait characteristics can result in large gains in running velocity and ultimately influence performance time (Chapman et al., 2011). The performance time achieved is a consequence of how an athlete modifies their gait and lower limb neuromuscular behaviour to maintain a high running velocity (Chapman et al., 2011). At present the changes in gait characteristics and the lower limb neuromuscular behaviour associated with a successful middle-distance performance are unknown. Research has investigated international-level 400 m athletes (Hanon & Gajer, 2009). This study reported that 400 m athletes maintain a higher running velocity by means of a longer step length, rather than an increase in step frequency (Hanon & Gajer, 2009; Hunter et al., 2004; Taylor & Beneke, 2012). From a physiological and biomechanical perspective the 400 m is more representative of sprinting than middle-distance running, therefore the gait characteristics and metabolic cost of middle-distance running may also be different (Anderson, 1996; Hanon & Gajer, 2009).

The difficulty in clearly identifying the factors that affect performance time may lie in the complex nature of running and the restrictive nature of the competition environment (Leskinen et al., 2009). Only three studies have documented the gait characteristics of middle-distance athletes during official races (Hayes & Caplan, 2012; Leskinen et al., 2009; Skof & Stuhee, 2004). Identifying differences in the gait characteristics (step length, step frequency, flight and contact time) among athletes of different calibre is important, but athletes are rarely available in the same place and at the same time. Potentially only data collected during competition would provide this level of information (Leskinen et al., 2009). Since athletes prepare to perform their best at competition, this should also result in the most ‘true’ comparative data. Such competition data could provide insight into how middle-distance athletes maintain a high running velocity (Leskinen et al., 2009). For these reasons, understanding the biomechanical parameters in competition middle-distance running is critical to athlete development.

Therefore, the aim of this thesis was to initially establish a valid means of measuring gait and spring-mass characteristics away from the laboratory environment (e.g. on an outdoor 400 m synthetic athletics track), and then provide a biomechanical evaluation of middle-distance running during competition and training in order to identify gait and spring-mass characteristics that influence performance time.

Accordingly this thesis investigated the following objectives assess:

(i) the validity of gait and spring-mass characteristics captured from a range of biomechanical technologies that could be used away from the laboratory environment on an synthetic athletics track (chapter 3)

(ii) evaluate the stiffness values obtained through mathematical modelling (estimations based on high-speed video data only) compared to direct measurement (using a force platform, chapter 4)

(iii) identify the effects of athlete ability-level (e.g. international-, national- and regional-level athletes) on gait and spring-mass characteristics during competition (chapter 5)

(iv) identify the effects of speed endurance training on gait and spring-mass characteristics in regional-level athletes (chapter 6)

CHAPTER 2: REVIEW OF LITERATURE

2.1. Introduction

There has been considerable interest in the biomechanics of running, this chapter will therefore aim to discuss and critique the relevant existing literature. When it comes to documenting the biomechanics of running associated with homogenous populations (e.g. middle-distance athletes) the published research is less clear. Literature has identified specific differences in gait characteristics between sprint and endurance athletes (Bushnell & Hunter, 2007), but the differences in gait characteristics between ability levels within the same event (e.g. international- compared to national-level middle-distance athletes) is less apparent. A potential reason for this is that published literature lacks transparency in defining participant ability level. For example the documentation of personal best performances (PB), training history and training distance of participants are often omitted from the research.

Research often states that 'experienced', 'novice', 'well-trained', 'highly-trained', 'competitive', 'highest standard' and 'elite' participants have been included. This can lead to misinterpretation of study findings as the exact levels of performances are rarely defined. Studies which have explicitly stated an intention to investigate 'elite' middle-distance running have typically focused on levels of performance higher than those of a recreational runner. In these cases the term 'elite' could include athletes from a regional- to international-level (Charalambous, Irwin, Bezodis, & Kerwin, 2012; Trappe, Costill, Vukovich, Jones, & Melham, 1996).

This literature review will discuss and critique the relevant middle-distance literature and explicitly report the athletes' ability level when possible. For the purpose of this thesis, these ambiguous terminologies such as 'elite' will not be used. Instead higher-levels of performance will be defined in terms of performance times and the levels to which the athletes have competed. Middle-distance athletes included in this thesis pertain to one of three groups (no overlap in performance time); international- national- or regional-level athletes (Table 2.1). In addition to research focusing on middle-distance running, this chapter will also discuss literature relating to aspects of biomechanical methodology relevant to the investigations undertaken in this thesis.

Table 2.1 Athlete-level definitions employed in this thesis

Athlete-level	Athlete-level definition
International-level	Athletes that have competed for another country (not Great Britain and Northern Ireland) at a senior track and field competition. The international-level athletes documented within this thesis have achieved the following accolades in middle-distance running; World Junior Champion, European under 23 Champion, European Indoor Champion, World Championship finalist and Olympic finalist and medallist
National-level	Athletes that have represented Great Britain and Northern Ireland during senior track and field competition
Regional-level	Athletes that were eligible to compete at the British Athletics Trials but have not achieved the standard required to enable them to compete for Great Britain and Northern Ireland

2.2. The Running Gait Cycle

Biomechanics of running has been investigated by examining the kinematics (e.g. position, displacement, velocity and acceleration) of the joints and the body segments during the gait cycle (Saraslanidis, Panoutsakopoulos, Tsalis, & Kyprianou, 2011). The gait cycle begins when one foot comes in contact with the ground (beginning of the stance phase) and ends when the same foot contacts the ground again (Figure 2.1). These moments are referred to as initial touchdown (Buschbacher et al., 2008). Stance phase ends when the foot is no longer in contact with the ground, which is referred to as take-off. Take-off marks the beginning of the swing phase of the gait cycle (Novacheck, 1998). In this thesis the term step will be used and is defined by half a gait cycle, that is, from foot contact to the next foot contact of the opposite foot (Hunter et al., 2004). The term stride therefore defines one complete gait cycle (Cavagna & Kram, 1989).

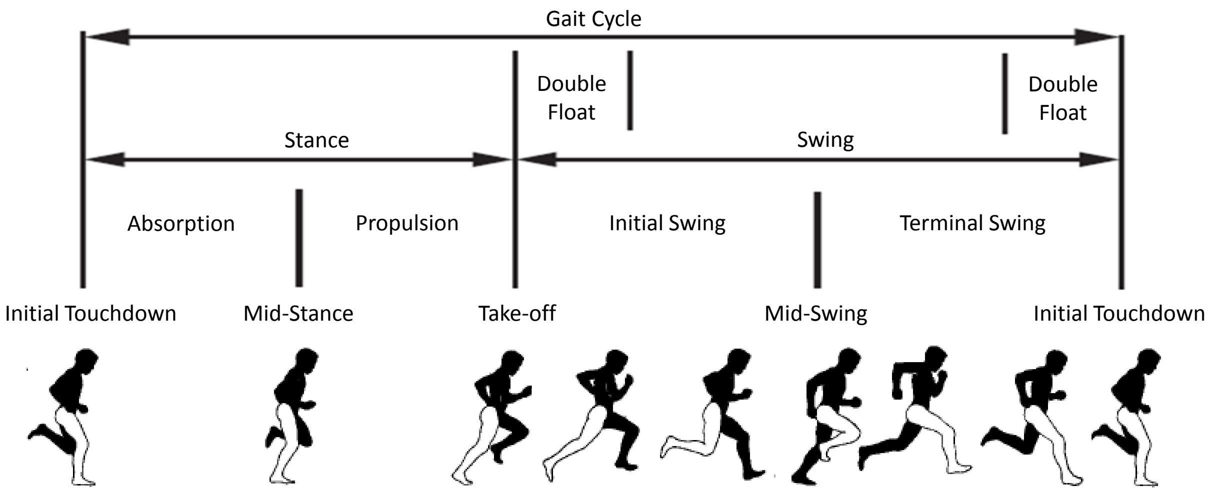


Figure 2.1 One complete gait cycle during running (Adelaar 1986; Dugan and Bhat 2005)

To explore the biomechanical events during running, the stance phase can be divided into two major components; initial touchdown to mid-stance and mid-stance to take-off (Dugan & Bhat, 2005). Typically during running take-off occurs before 50% of the gait cycle is complete and there are no periods when both feet are in contact with the ground (Buschbacher et al., 2008). Instead, there are two periods of double float when neither foot is in contact with the ground (Dugan & Bhat, 2005). This results in decreased time in stance phase and increased time in swing phase (Novacheck, 1998).

The forward momentum that is required during running is produced by the swinging leg and the arms rather than the stance leg (Dugan & Bhat, 2005).

At initial touchdown during running, the foot contacts with the ground with foot in a supinated position in front of the centre of mass (CM) (Dugan & Bhat, 2005). This occurs as the lower limb swings towards the line of progression in midline. During running, there is limited plantarflexion after initial touchdown as the foot progresses into dorsiflexion (Novacheck, 1998). Stability of the lower limb at initial touchdown is provided by the hip adductors, with the adductors remaining active throughout the running cycle (Dugan & Bhat, 2005). At initial touchdown of the running gait energy absorption (weight acceptance) is a key function of the lower limb with vertical ground reaction forces reaching a magnitude of two times body weight (Cavanagh & Lafortune, 1980). The position and acceleration of the CM determines the magnitude and direction of the ground reaction force.

After initial touchdown eccentric contraction of the rectus femoris controls the height of the CM and resists excessive knee flexion as the line of ground reaction forces passes posterior to the knee joint (Dugan & Bhat, 2005). Knee flexion at initial touchdown facilitates shock absorption and stiffness regulation at initial touchdown (Buschbacher et al., 2008). During initial touchdown the pelvis tilts and the lumbar spine flexes in order to lower the CM and to produce a horizontal force that maximises forward acceleration and propulsion (Novacheck, 1998). To conserve energy and maximise efficiency pelvic motion is often minimised (Buschbacher et al., 2008). Previous research has determined that joint motion and eccentric muscle contraction, along with the flexion of the hip, knee and ankle joint help to dissipate the forces of impact at initial touchdown (Cavanagh, 1990; Dugan & Bhat, 2005; Novacheck, 1998).

As the lower extremity progresses through the gait cycle, the CM shifts from behind the knee (initial touchdown) to in front of the knee, and thereby develops an extension moment. The hamstrings, which act as hip extensors, are active through the stance phase as the body progresses forward on the fixed lower limb. As forward progression continues (through the middle of stance phase) dorsiflexion increases (Dugan & Bhat, 2005). Dorsiflexion occurs as a result of the forward progression of the tibia which is controlled by the gastrocnemius-soleus (Novacheck, 1998). Maximum dorsiflexion and pronation occur when the CM already has passed in front of the base of support. Control of pronation is provided by eccentric contraction of the tibialis posterior and gastrocnemius-soleus complex (Novacheck, 1998). The point of maximum pronation marks the end of the absorption component of the stance phase with the subsequent propulsion component occurring through the remainder of stance (Dugan & Bhat, 2005). As the ground reaction force travel anteriorly through the knee joint, co-contraction of the quadriceps and hamstrings stabilises the knee joint (stiffness regulation) (Dugan & Bhat, 2005; McMahon, Valiant, & Frederick, 1987).

As the opposite limb swings forward, pelvic rotation occurs and results in an external rotation torque of the stance lower limb. The external rotation of the tibia causes an inversion at the calcaneus with subsequent supination of the foot. Continued forward progression of the opposite limb allows the body to prepare the stance lower limb to initiate propulsion. Acceleration of the stance lower limb as it prepares for propulsion is initiated by plantarflexion. As plantarflexion occurs while the foot is fixed to the ground, the stance limb is lengthened minimising the decrease in the CM as the opposite lower limb swings forward and prepares to contact the ground.

2.3. Gait Characteristics

This section will discuss in more detail the gait characteristics that influence an athlete's running performance outlined in the model adapted from Anderson (1996); Cavanagh (1990); Hay (1993); Hunter et al. (2004); Williams and Cavanaugh (1986), see Figure 1.3. Running velocity is a product of step length and step frequency. Step frequency is defined by step time, which is the sum of the duration of the contact and flight time for the step. Step length is composed of the contact distance and flight distance (Figure 2.2). Horizontal velocity, segment positions at initial touchdown and take-off influence contact time and contact distance. While initial touchdown and take-off height of CM as well as air resistance during flight influences flight time and flight distance. Flight time is defined by vertical velocity, air resistance, height of the CM at initial touchdown and take-off. Lower limb neuromuscular behaviour is represented by the compression of limb during contact. Compression of the limb during contact has been previously reported in terms of vertical and leg stiffness at a variety of running velocities (Brughelli & Cronin, 2008a).

2.3.1 Velocity

Running velocity is the product of step length and step frequency (Figure 1.3); however research indicates that these parameters are mutually dependent with their optimal ratio enabling the development of running velocity (Hunter et al., 2004; Krzysztof & Mero, 2013). An increase in velocity can be achieved by increasing step length or step frequency. The increase of both parameters simultaneously is quite difficult due to mutual dependency (Kratky & Muller, 2013; Weyand et al., 2000b). Therefore an increase in one gait characteristic (e.g. step length) will result in an improvement in running velocity as long as the other factor does not undergo a proportionately similar or larger decrease (Hunter et al., 2004). Increased step frequency results in a shorter step length and vice versa. This relationship is individually conditioned with the process of lower limb neuromuscular behaviour and the athletes physical characteristics (Novacheck, 1998).

2.3.2 Contact time

Ground contact may be considered a crucial part of the gait cycle because it is the only phase during which the middle-distance athlete can apply force to the ground (Kratky & Muller, 2013). The magnitude of the produced force, during ground contact, is shown to primarily affect step length, whereas step frequency is mainly dependent on the rate of force development (Mann, 2010; Salo et al., 2011). Nevertheless, it has been suggested that a more rapid turnover of the limbs during swing time (e.g. flight time) may be the preferred strategy to increase step frequency (Kratky & Muller, 2013). It is well known that increasing running velocity decreases ground contact time (Brughelli, Cronin, & Chaouachi, 2011; Bushnell & Hunter, 2007).

The benefits of a reduced contact time during middle-distance running are likely to include an improved stretch-shortening cycle function, allowing a greater contribution from the eccentric contraction phase (which provides a lower energy cost per unit force produced compared with the concentric phase) and a greater re-utilisation of elastic energy (Paavolainen et al., 1999). Paradoxically, however, the metabolic energy cost of locomotion has been shown to be inversely proportional to contact time, with increasing running velocity associated with the need to generate force over a shorter period of time at an increased metabolic cost (Kram & Taylor, 1990). Consequently, athletes who fatigue towards the end of the race are likely to increase their contact time to help minimise the metabolic cost of locomotion but are likely to reduce their running velocity as a result (Nummela, Keranen, & Mikkelsson, 2007).

Although the influence of reduced ground contact time on middle-distance performance may not be clear, the relationship between oxygen uptake relative to body weight and the inverse of contact time varies little across individuals (Oliver & Stembridge, 2011; Weyand et al., 2001). This could suggest that better middle-distance athletes are able to reduce their contact times to utilise the properties of the stretch-shortening cycle without simultaneously increasing (or even decreasing) their metabolic cost (Oliver & Stembridge, 2011). This would be reflected in superior middle-distance athletes having a lower contact time and lower heart rate at a given sub-maximal speed which would be reflected in a lower ratio between heart rate and the inverse of contact time. This ratio has been shown to accurately predict the maximal oxygen uptake in a healthy population, with heart rate and the inverse of contact time increasing in parallel with increased running velocity while the ratio between the two variables remained constant (Weyand et al., 2001)

When running at velocities greater than 4.00 $m \cdot s^{-1}$ it is proposed that contact time significantly relates to competitive performance, this may be due to the greater neuromuscular demands of running at higher velocities (Oliver & Stembridge, 2011). Hasegawa, Yamauchi, and Kraemer (2007) investigated the relationship between contact time and the finishing position of athletes during a half marathon race. This study reported a significant relationship between contact time and finishing position, with shorter contact times associated with a higher finishing position. This supports Dalleau et al. (1998) who implied that the energy cost of running was significantly related to the stiffness of the propulsive leg, which was also demonstrated by the decrease in contact times.

The few studies that have examined contact time in middle-distance running, with the majority of research focusing on the longer distance events such as 5,000 m and marathon races (Hayes & Caplan, 2012). Longer distance studies have investigated race performances over 5 km and 10 km (Paavolainen et al., 1999; Williams, Cavagna, & Ziff, 1987). To date, there is a lack of evidence regarding 'true' middle-distance running. Hayes and Caplan (2012) documented the contact times of 800 m and 1500 m athletes who participated in the 2008 British Milers Club Grand Prix. These findings reported shorter contact time to those previously reported for longer distance events (such as 5 km and 10 km), and longer than those recorded for shorter distances (e.g. 400 m). They also identified a large negative relationship between average contact time and average performance time in both 800 m and 1500 m (Hayes & Caplan, 2012). Leskinen et al. (2009) did not support this claim that contact time influenced performance time. Comparative data taken from the men's 1500 m final at the 2005 World Championships found that international- and national-level athletes demonstrated similar contact times (0.154 s ± 0.004 s and 0.150 s ± 0.006 s, respectively). The difference between middle-distance athlete-levels may not be contact time, rather the ability of the athlete to modify their lower limb neuromuscular behaviour during ground contact without simultaneously increasing metabolic cost or contact time.

2.3.3 Flight time

Research has stated that the vertical ground reaction forces and impulses required to attain any velocity are largely dependent on how rapidly the limbs can be repositioned (Weyand, Sandell, Prime, & Bundle, 2010). Relatively longer flight times lengthen the swing times necessary for limb repositioning, thereby increasing the ground contact forces and impulses required to elevate the body. Conversely, relatively shorter flight times have the opposite effect. Weyand et al. (2000b) reported that by shortening flight times by 20% caused a reduction in vertical forces and impulses required to attain the same running velocities. Since running velocity has been reported to relate to step length, step frequency and contact time, and not flight time (Weyand et al., 2000b).

Only three studies have previously examined gait characteristics of middle-distance athletes during competition. They have only reported contact time, step length, step frequency and/or the position of the lower limb during contact and did not include flight time (Hayes & Caplan, 2012; Leskinen et al., 2009; Skof & Stuhee, 2004). Presently no study has quantified the flight time of middle-distance athletes during competition or even during training. Potential influences of flight time on performance time have been inferred from studies based away from the synthetic athletics track environment. Treadmill-based run to exhaustion studies have reported modifications in gait characteristics resulting from a decrease in flight time (Dutto & Smith, 2002; Gollhofer, Komi, Miyashita, & Aura, 1987; Rabita, Slawinski, Girard, Bignet, & Hausswirth, 2011; Slawinski, Heubert, Quievre, Billat, & Hannon, 2008). Hunter et al. (2004) adapted Hay (1993) hierarchical model of sprinting to demonstrate the variables associated with successful sprint performance. They reported the most influential variables for flight time were height of CM at initial touchdown and vertical velocity of CM at take-off.

2.3.3 Step length and step frequency

Step length and step frequency are mutually dependent with their optimal ratio enabling the development of running velocity (Hunter et al., 2004; Krzysztof & Mero, 2013). When reporting step length, the length of each step can be considered as the sum of three separate distances; take-off horizontal distance that the CM is in front of the toe at the point of take-off (Figure 1.3 and Figure 2.2). Take-off distance is the horizontal distance that the CM is in front of the toe at the point of take-off. Flight distance is the horizontal distance the CM travels while in the flight phase, whereas landing distance is the horizontal distance of foot strike in front of the CM at the initial ground contact. Landing distance is often reported in the literature as CM to ankle distance or horizontal distance from the foot to CM at initial touchdown (Mann, 2010).

The contribution of take-off distance, flight distance and landing distance to step length has been reported in sprinting whilst at or near to maximal running velocity (Hay, 1993). Currently the contribution of these parameters to step length has not been determined in middle-distance athletes.

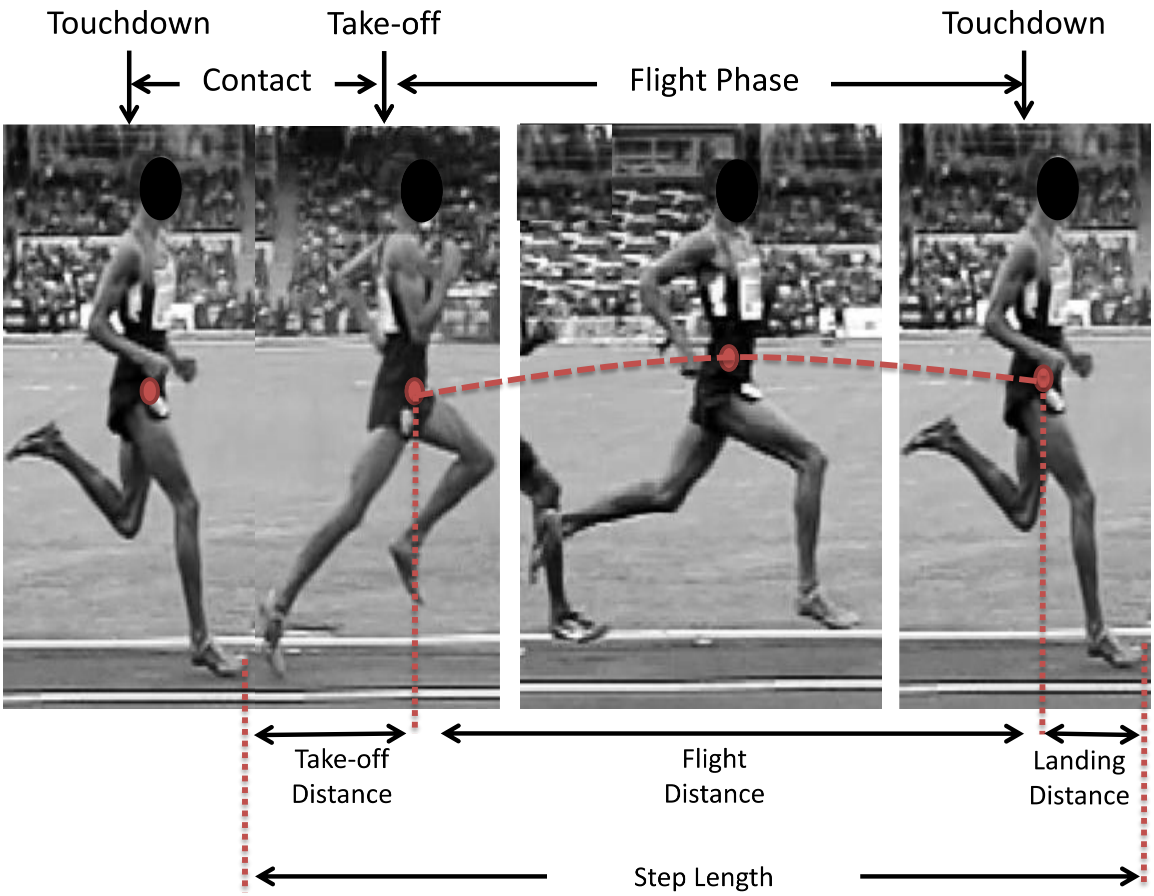


Figure 2.2 Contributions of take-off distance, flight distance and landing distance to step length (Hay 1993)

The take-off distance is determined by the segment positioning, which can be expressed as the angles formed between body segments at the instance of take-off (Hay, 1993). The extent to which the athlete extends the support leg (whilst in contact with the ground), and the shank angle (to the horizontal) have been reported as important parameters when examining take-off distance. During the flight phase in which the athlete is not in contact with the ground, the horizontal distance travelled (flight distance) is determined by the factors that govern the flight of all projectiles encountered by flight; vertical take-off velocity, angle and height of release and air resistance (Hay, 1993). The most critical parameter during the flight distance is vertical take-off velocity which is determined by the vertical ground reaction forces and lower limb neuromuscular behaviour during ground contact (Arampatzis, Bruggemann, & Metzler, 1999; Brughelli et al., 2011; Weyand et al., 2000b). While the influence of air resistance on running velocity is not confined to the flight phase of the step, it has the greatest impact on step length during the flight distance component (Hay, 1993).

The landing distance is invariably the smallest of the three contributions to the total length of the step (Hay, 1993), nevertheless sprinting literature has identified landing distance is directly related to performance (Mann, 2010; Mann & Herman, 1985; Mann, Kotmel, Herman, Johnson, & Schultz, 1984). Mann (2010) stated that landing distance was a critical determinant of sprint performance since it increases step length, provides sufficient leg range of motion to produce the necessary vertical velocity and enables forward motion to be maintained while on the ground. Conversely the greater the landing distance the larger the horizontal braking force, which will reduce the athletes running velocity. Greater landing distances increase the range of motion of the lower limb which in turn increases contact time. Therefore, a balance must be achieved whereby sufficient leg range of motion is attained to produce the necessary ground reaction forces and produce an acceptable step length; while the contact time must be reduced to a minimum to maximise step frequency and minimise the metabolic cost of running (Kram & Taylor, 1990; Mann, 2010).

2.3.4 *Relationship between step length, step frequency and performance*

Initial research examining the relationship of step length and step frequency was conducted by Luhtanen and Komi (1978) in track athletes at velocities between 3.90 $m \cdot s^{-1}$ to 9.30 $m \cdot s^{-1}$. However, this study is not directly relevant to international- national- and regional-level middle-distance athletes as the participants in this investigation were of a recreational-level. Literature has implied that careful consideration should be given when applying research findings to particular populations (Williams et al., 1987). Bailey and Messier (1991) inferred that the development of step length may be a result of several months if not years of running training, therefore the training history and status of individuals included in studies examining step length should be reported. Only a limited set of information is available concerning the gait characteristics of international-level athletes, and very little has been reported on step length and step frequency of middle-distance athletes (Cavanagh et al., 1985; Huxley, O'Connor, & Healey, 2013; Leskinen et al., 2009; Mann et al., 1984; Salo et al., 2011).

Middle-distance research has reported step length and step frequency (in isolation); and described its impact on ratings of perceived exertion and maximal aerobic capacity (Anderson, 1996; Daniels & Daniels, 1992). These studies have determined that experienced runners possessed a freely chosen step length that minimised submaximal oxygen consumption, these step lengths were larger than less experienced or novice runners (Bailey & Messier, 1991; Daniels & Daniels, 1992). Biomechanical research has concluded that during ground contact the development of; longer step length is reliant on an increase in force production, and higher step frequency is associated with faster force production (Brughelli et al., 2011; Weyand et al., 2000b). The process by which an experienced runner determines their step length and step frequency is currently unknown. It has been suggested that through conditioning and repetition in training athletes may randomly select a step length and step frequency combination that is the most optimal for the individual athlete (Cavanagh & Williams, 1982). In order to investigate the impact of step length and step frequency on middle-distance performance more thorough biomechanical analysis is required.

A number of research studies have analysed the impact of step length and step frequency on running velocity but few have evaluated these gait characteristics of the world's best athletes (Leskinen et al., 2009; Skof & Stuhee, 2004). Hanon and Gajer (2009) found that international-level athlete's peak step lengths were 0.13 m longer than their national counterparts, whilst maintaining a similar step frequency. Past research has tended to evaluate the impact of step length and step frequency on recreational participants running at velocities between 3.00 and 5.00 $m \cdot s^{-1}$ (Derrick, Dereu, & McLean, 2002; Federations, 2012-2013; Queen, Gross, & Liu, 2006). The 2012 London Samsung Diamond League 800 m final was won in a time of 1:44.49, during this race the athletes achieved average running velocities of between 6.00 and 8.00 $m \cdot s^{-1}$. New research on international-level middle-distance athletes is therefore critical to document how higher running velocities are achieved in terms of step length and step frequency. The best means by which the gait characteristics of international-level middle-distance athletes could be determined is in competition.

Using data from competition has several advantages compared to laboratory-based studies, because in these real competitions the athletes have every interest in making the maximal effort and their performances were representative of 'true' competitive performance (Ferro & Floria, 2013). Moreover, the physical characteristics of the athletes included in competition studies are considered as ideal for each competition, as coaches and athletes train conscientiously for every season to reach their optimal level at each important competition (Ferro & Floria, 2013). During sprinting, Bezodis, Kerwin, and Salo (2008), Mann and Herman (1985) and Ae, Ito, and Suzuki (1992) suggested that step frequency was a more important contributor to the increase in velocity. Mann et al. (1984) examined international-level sprinters at the 1984 Olympic men's 200 m final and reported the main differences between first, second and eighth place finishers were step frequency. These findings were in part supported by Ae et al. (1992), who analysed the 1991 World Championship final of the men's 100 m. Results from this study reported that the gold medallist exhibited that shorter step length and higher step frequency than the silver medallist. Mero and Komi (1985) and Gajar, Thepaut-Mathieu, and Lehenaff (1999) stated that step length was a more significant variable. Gajar et al. (1999) investigated the French national-level sprinters during the 1996 French Championship semi-finals and final of the men's 100 m and completed a comparison of the slowest and fastest athletes. Step length was consistently higher in the fastest group with the slowest athlete group reporting the highest step frequency. It is still not clear how step length and step frequency interact with each other during sprinting, and there is an even greater lack of understanding during middle-distance running. Only Skof and Stuhee (2004) has documented step length and step frequency during competition, this was presented as a single athlete case study on the female indoor 800 m world record holder. More research is required to determine the step length and step frequency exhibited by international-level athletes in order to achieve a higher running velocity during competition.

It is clear from the results presented on international-level athletes during competition that there is no consensus of opinion over which gait characteristic, step length or step frequency, is more important at this level of competition. These are important findings, nonetheless, since they provide insight into the performances of the highest calibre of athletes in a competitive situation something a laboratory or training-based study is not capable of doing (Salo et al., 2011). Further investigation into competitive middle-distance performance is proposed to build on previous literature. It has also been suggested by Salo et al. (2011) that training studies should be undertaken to account for how athletes prepare for competition. It should be noted that the effect of different types of training on middle-distance performance is difficult to prove due to two factors;

firstly, there is an inherent problem in getting athletes of a high calibre to participate in training studies, and secondly, it is practically impossible to isolate the training influence of one specific type of exercise or mode of exercise. However, some indirect conclusions can be drawn from the literature and observational studies based within the training environment (Salo et al., 2011).

2.4. Stiffness

The concept of lower limb neuromuscular behaviour is based on Hooke's Law which states that the force required to deform an object (F) is related to a proportionality constant (K) and the distance (x) that an object is deformed (Austin, Garrett, & Tiberio, 2002; Butler et al., 2003). That is, a spring will produce force proportional to its displacement from equilibrium length (Brughelli & Cronin, 2008a). When this occurs, the spring is called a linear spring and can be quantified by Equation 1. The negative sign indicates that the force exerted by the spring is opposite to the direction of displacement.

$$\mathrm{F} = -Kx \qquad \text{[Equation 1]}$$

The proportionality constant (K) is referred to as the spring constant, and it describes the stiffness of an ideal spring-mass system, see Figure 2.3 (Butler et al., 2003). According to Butler et al. (2003) an ideal spring is massless with the mass of the system concentrated at a point at one end of the spring. The ideal spring only moves in one direction and has a stiffness that is independent of time, length and velocity.

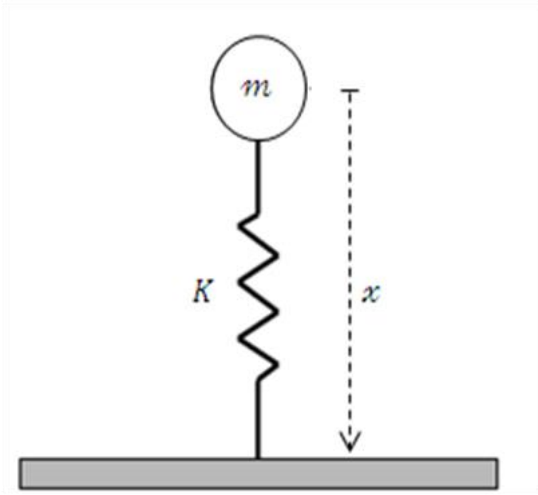


Figure 2.3 Ideal spring-mass system in accordance with Butler et al. (2003)

The ideal spring-mass system can be used to describe the stiffness of the human body, or body segments, to resist displacement once ground reaction force or moments are applied (Butler et al., 2003). Stiffness can be measured from the level of a single muscle fibre to the modelling of the entire body (Brughelli & Cronin, 2008a). During running, stiffness is determined by the interaction of anatomical structures such as tendons, ligaments, muscles, cartilage and bone are integrated so the overall musculoskeletal system acts like a simple spring (Brughelli & Cronin, 2008b; Butler et al., 2003). There are two types of stiffness that can be quantified during running; vertical stiffness (K_{vert}) and leg stiffness (K_{leg}). The relationship between these two types of stiffness (K_{vert} and K_{leg}) and running performance are complex and often misunderstood. Many studies use the terms synonymously or use the term stiffness in a global sense with little thought to the specific applications of the stiffness measure. Therefore, for the purpose of this current research the following terms apply, see Table 2.2.

Table 2.2 Stiffness definitions

Type of stiffness	Definition of stiffness
Vertical stiffness (K_{vert})	A measure of resistance of the body to the vertical displacement of the centre of mass after the application of maximal vertical ground reaction force (Brughelli & Cronin, 2008b)
Leg stiffness (K_{leg})	A measure of resistance to change in leg length after application of ground reaction forces during ground contact (Butler et al., 2003)

The advantage of the spring-mass system is its simplicity in studying the lower limb neuromuscular behaviour during ground contact by using just one spring. The spring-mass system does provide insight into the position of lower limb at initial touchdown but does not detail the individual joint angles of the hip, knee and ankle at initial touchdown and during ground contact. Past research has suggested that joint angles may facilitate in the understanding of how lower limb neuromuscular behaviour is altered to achieve a high running velocity (Kuitunen, Komi, & Kyrolainen, 2002). Farley and Morgenroth (1999) implied that during hopping leg stiffness is adjusted primarily by modulating the ankle joint angle. The results of Arampatzis et al. (1999) suggest that in running the knee joint angle is more important than the ankle joint angle in controlling the leg stiffness. Therefore, documenting the joint angles of the lower limb during ground contact would inform any alterations in stiffness presented during running.

2.4.1. Vertical stiffness

Vertical stiffness is a measure of resistance of the body to vertical displacement after application of ground reaction force (Brughelli and Cronin, 2008b). It is often used to describe linear movements that occur in only the vertical direction during activities such as hopping, jumping and running (Butler et al., 2003). Previous research has suggested that vertical stiffness values should be accompanied by other biomechanical variables as during running the movement of the body is in all three planes and not just in the vertical direction (Brughelli and Cronin, 2008b). Vertical stiffness is often calculated by one of three methods (Table 2.3, Equations 2, 4 and 5). McMahon and Cheng (1990) developed the simplest method, the maximal ground reaction force is divided by the vertical displacement of the CM during contact with the ground, Table 2.3, Equation 2. The vertical displacement of the CM during contact is determined from the double integration of the vertical force curve as described by Cavagna (1975). This method assumes that the vertical position of the CM at initial touchdown is similar to that at take-off, resulting in an integration of the constant equal to zero. The vertical velocity is then integrated to produce the vertical trajectory of the centre of mass. The vertical displacement of the CM is determined from the difference between the maximum and minimum of this curve. CM displacement using this method has been evaluated using a force platform, but previous research has also determined this from full body kinematic analysis using video-based systems (Arampatzis et al., 1999).

The mathematical model proposed by Cavagna, Franzetti, Heglund, and Willems (1988) differs from that of McMahon and Cheng (1990) by utilising body mass and the period of oscillation not the vertical displacement of the centre of mass. Therefore, Cavagna et al. (1988) method used the vertical ground reaction force, the body mass, and the period of oscillation to quantify K_{vert} (Table 2.3 Equation 3). This method assumes the vertical force curve to be a sine wave, with a peak occurring at during mid-stance. However, this method does not account for the impact peak that occurs at initial touchdown (Butler et al., 2003). The period of oscillation is then used to determine the time to the mid-stance of the vertical ground reaction force curve (Cavagna et al., 1988). This method has previously been used to examine hopping in time with a metronome; where the frequency of the activity is constant (Farley, Blickhan, Saito, & Taylor, 1991). The period of oscillation is then equal to the frequency of the activity.

Where the frequency of the activity is inconsistent, McMahon et al. (1987) K_{vert} method has been proposed (Table 2.3 Equation 4). This method uses contact and flight time between successive contacts, to calculate the natural frequency of oscillation rather than the period of oscillation determined in Cavagna et al. (1988). Methods proposed by Cavagna et al. (1988) and McMahon et al. (1987) have been employed during hopping and jumping activities rather than running. Running research has favoured McMahon and Cheng (1990) mathematical model which quantifies K_{vert} by dividing the maximal ground reaction force by the vertical displacement of the CM during ground contact.

Stiffness studies have favoured McMahon and Cheng (1990) method in quantifying K_{vert} during running (Table 2.3 Equation 2); however, the methodologies used to determine CM displacement does vary considerably between studies. Previous literature has used force plate, pressure sensor or accelerometer technology to calculate maximum ground reaction force and modelled CM displacement (Girard, Racinais, Kelly, Millet, & Brocherie, 2011b; Hobara et al., 2010a; Morin, Dalleau, Kyrolainen, Jeannin, & Belli, 2005; Morin, Jeannin, Chevallier, & Belli, 2006). Moritz and Farley (2004) determined vertical stiffness by quantifying ground reaction force using a force platform but did not specify how CM displacement was determined. Morin et al. (2005) method modelled both maximum ground reaction force and CM displacement from independent variables such as contact time and flight time (Table 2.3 Equation 5, 6, 7 and 8). These differences in how maximal ground reaction force and vertical displacement of the CM are quantified would have implications on the K_{vert} values presented.

Table 2.3 Summary of models used to calculate vertical stiffness

Equation		Studies which use this model
$K_{vert} = F_{max} / \Delta y$	[Equation 2]	McMahon and Cheng (1990) calculation used to determine K_{vert}
$K_{vert} = m\left(\frac{2\pi}{P}\right)^2$	[Equation 3]	Cavagna et al. (1988) calculation used to determine K_{vert}
$K_{vert} = m\omega_0^2$	[Equation 4]	McMahon et al. (1987) calculation used to determine K_{vert}
$K_{vert} = F_{max} / \Delta y$	[Equation 5]	Morin et al. (2005) calculation used to determine K_{vert}
$\Delta y = \frac{F_{max} t_c^2}{m\pi^2} + g\frac{t_c^2}{8}$	[Equation 6]	Morin et al. (2005) method used to determine Δy for K_{vert} calculation
$t_f = \frac{t_c + T_f}{2} - t_c$	[Equation 7]	Morin et al. (2005) method used to determine t_f for K_{vert} calculation
$F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c} + 1\right)$	[Equation 8]	Morin et al. (2005) method used to determine F_{max} for K_{vert} calculation

K_{vert}, vertical stiffness ($kN \cdot m^{-1}$); F_{max}, maximal vertical ground reaction force (kN); Δy, vertical displacement of the centre of mass (m); t_c, contact time (s); t_f, flight time (s); m, body mass (kg); P, period of the vertical vibration; $\omega_{0,}$ natural frequency of oscillation; g, acceleration of gravity; T_f, time taken from take-off to initial touchdown of the same leg point of force translation distance (m)

The majority of research has estimated CM displacement by double integration of vertical acceleration as described by McMahon and Cheng or by Cavagna (Cavagna, 1975; Dutto & Smith, 2002; Farley & Gonzalez, 1996; He, Kram, & McMahon, 1991; Morin et al., 2005; Slawinski et al., 2008). Serpell, Ball, Scarvell, and Smith (2012) presented a qualitative analysis of both methods described by McMahon and Cheng (1990) and Cavagna (1975) and concluded that 'no argument can be made regarding which method is better'. This was surmised by examining the K_{vert} standard deviation conducted by Morin et al. (2005) using the method outlined by Cavagna (1975) and Hunter and Smith (2007) using McMahon and Cheng (1990) method. Across both studies the absolute K_{vert} and standard deviations were similar (37.70 kN·m^{-1} ± 8.80 kN·m^{-1} and 36.50 kN·m^{-1} ± 5.40 kN·m^{-1} respectively).

Research that has quantified K_{vert} using McMahon and Cheng (1990) model (Table 2.3 Equation 2) either choosing to model ground reaction force or CM displacement, or both, have produced results similar to studies where ground reaction force and CM were directly measured (Morin et al., 2005). This observation suggests that modelling K_{vert} may provide a suitable alternative where direct measurement is not possible, such as during training and competition (Serpell et al., 2012). This is supported by Morin et al. (2005) who revealed a small bias of between 0.67% and 6.93% for results when ground reaction force and CM displacement were estimated by mathematical modelling opposed to when measured directly.

2.4.2. Vertical stiffness and performance

Vertical stiffness strongly influences performance as evaluated by running velocity, step frequency, step length, contact and flight time, Figure 1.3 (He et al., 1991; Kuitunen et al., 2002; Morin et al., 2005). In addition, some studies reported decreases in K_{vert}

during prolonged or exhausting treadmill runs at a constant velocity of induced self-paced field races (Dutto & Smith, 2002; Hobara et al., 2010a; Hunter & Smith, 2007). Less is known of the lower limb neuromuscular behaviour at higher running velocities or on the impact of maintaining a higher running velocity. Morin et al. (2006) reported that changes in K_{vert}, step frequency and displacement of the CM during ground contact were significantly related to changes in mean and maximal running velocity achieved over 100 m. These changes in the lower limb neuromuscular behaviour were linked with the fatigue effects on performance time during maximal sprint running. Hobara et al. (2010a) built on the findings of Morin et al. (2006) by measuring K_{vert} continuously over an entire 400 m race. The authors indicated that K_{vert} decreased due to the onset of fatigue, which potentially could be a limiting factor in performance. A significant positive linear relationship was found between K_{vert} and step frequency. No correlation between K_{vert} and step length was reported. An increase in K_{vert} would enable the spring-mass system to recoil in a shorter time, which is beneficial for quicker absorption and generation of power and kinetic energy during ground contact (Hobara et al., 2010a).

Potentially a high K_{vert} could be achieved by increasing the activity of the lower limb muscles. In the case of hopping, an increase in triceps surae muscle activity in the pre- and early post-landing phase was reported to be crucial for higher K_{vert} (Hobara, Kanosue, & Suzuki, 2007). Research has suggested that a higher K_{vert} could also be reported by adjusting the initial touchdown joint angles (Farley, Han Houdijk, Van Strien, & Louie, 1998). If the leg is more extended at initial touchdown, the ground reaction forces will be more closely aligned with each joint, simultaneously decreasing the joint moments while increasing stiffness. McMahon et al. (1987) reported that running with greater knee flexion (a term the authors defined as 'groucho running') reduces K_{vert}. Further physiological and biomechanical investigation is needed to identify the regulation of the lower limb neuromuscular behaviour and its impact on performance time (Hobara et al., 2010a).

2.4.3. Leg stiffness

Vertical stiffness only takes into account the motion in the vertical direction. During running, at initial touchdown the leg contacts the ground at an angle and the CM is not directly over the foot. To accommodate this McMahon and Cheng (1990) developed the spring-mass model for calculating K_{leg} which would take into account the velocity (υ), time of contact (initial touchdown [TD] to toe off [TO]), initial length of the leg (L_0) and the maximal vertical ground reaction force, Figure 2.4. This model requires the accurate measurement of running velocity (McMahon & Cheng, 1990).

Leg stiffness is a measure of resistance to change in leg length after application of internal or external forces (Butler et al., 2003). Leg stiffness is not always clearly defined with a number of studies explicitly stating an intention to investigate K_{leg} where in actual fact they were estimating K_{vert}. That is, they stated they were measuring K_{leg} but estimated it as the quotient of ground reaction force and CM displacement (Table 2.3, Equation 2). Or, they used other models which relied on CM displacement to measure K_{leg} rather than measuring change in leg length (Arampatzis, Schade, Walsh, & Bruggemann, 2001; Dalleau et al., 1998; Dutto & Smith, 2002; Farley et al., 1998; Granata, Padua, & Wilson, 2002a; Granata, Wilson, & Padua, 2002b; Hobara, 2008; Hobara et al., 2010b; Hobara et al., 2007; Hobara et al., 2010c; Pruyn et al., 2012a, 2012b). Some specifically noted CM displacement was only measured during ground contact (Farley et al., 1998; Granata et al., 2002a; Hobara et al., 2010c). The tasks required of participants in those studies varied from single or double leg hopping (Arampatzis et al., 2001; Granata et al., 2002a; Hobara et al., 2010b) to drop jumps (Arampatzis et al., 2001; Hobara et al., 2010b) and overground running (Bret, Rahmani, Dufour, Messonnier, & Lacour, 2002). Leg stiffness is not the same as K_{vert} and therefore should not be measured in the same manner.

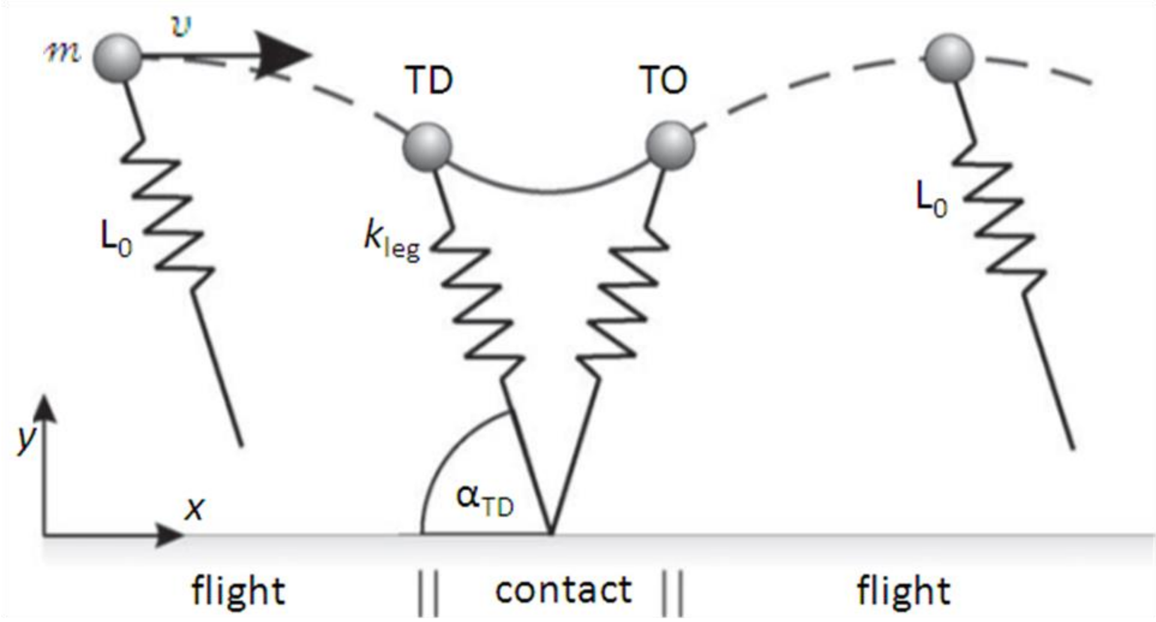


Figure 2.4 Spring-mass model for calculating leg stiffness during running McMahon and Cheng (1990)

McMahon and Cheng (1990) calculate leg stiffness by using Equation 9, the maximum vertical ground reaction force (F_{max}) is divided by the change in vertical leg length (ΔL). Vertical ground reaction force was measured directly from a force platform and the change in vertical leg length was calculated from running velocity and initial leg length (Table 2.4). Leg stiffness was calculated as the ratio of maximum vertical ground reaction force to the maximum change in leg length, which was measured during contact from the CM to the foot (Brughelli & Cronin, 2008b).

$$K_{leg} = F_{max}/\Delta L \qquad \text{[Equation 9]}$$

The Morin et al. (2005) K_{leg} method used initial leg length and running velocity to calculate the change in vertical leg length. Running velocity was measured with a laser distance measurement (LDM) device, and the initial leg length was measured from the greater trochanter to the ground. The results of Morin et al. (2005) were compared with that of a reference method (McMahon & Cheng, 1990). The K_{leg} values of Morin et al. (2005) were found to range from 0.67% to 6.93% less than those of McMahon and Cheng (1990) and thus were reported to be acceptable (Brughelli & Cronin, 2008b). The advantage of using the Morin et al. (2005) mathematical model is that K_{leg} values can be calculated without the use of force plates or force transducers. Another proposed method for calculating K_{leg} was described by Arampatzis et al. (1999). Vertical ground reaction force was measured with a force plate with K_{leg} subsequently being calculated; the results were compared with those of McMahon and Cheng (1990). However, Arampatzis et al. (1999) measured the change in vertical leg length (a two segment model from the hip joint to the knee joint to the ankle joint) with a high-speed video, and reported higher mean K_{leg} values (>35 kN/m) compared to McMahon (<20 kN/m) (He et al., 1991; McMahon & Cheng, 1990; Morin et al., 2005). The differences between these two studies could be explained by either a difference in sampling frequency of cameras used (thus underestimations of segment displacement) or by differences in the measurements of leg length.

2.4.4. Leg length

Only three previous studies that have determined K_{leg} have measured the actual change in vertical leg length, the majority of studies use estimates (Grimmer, Ernst, Gunther, & Blickhan, 2008; Rapoport, Mizrahi, Kimmel, Verbitsky, & Isakov, 2003; Stafilidis & Arampatzis, 2007). Where leg length was measured it was considered to be the distance between the hip joint and the distal point of the leg. Increased measurement accuracy from those studies measuring leg length may be assumed, however each study adopted different methods for determining leg length. Each considered the distal end of the leg at different points; one marked it as a point on the foot (Grimmer et al., 2008), another considered it the point of force application from ground reaction force

(Stafilidis & Arampatzis, 2007) or simply the measured distance perpendicular to the ground (Rapoport et al., 2003). Only Stafilidis and Arampatzis (2007) and Grimmer et al. (2008) measured the change in vertical leg length during running using three-dimensional motion capture system capturing between 240Hz and 250Hz. During running the change in vertical leg length has been illustrated by either the point of force application between initial touchdown and when maximum ground reaction force is reached (Stafilidis & Arampatzis, 2007); or the vertical excursion of the hip relative to the ground (Morin et al., 2005; Rapoport et al., 2003). Rapoport et al. (2003) is the only study to measure leg length perpendicular to the ground. Variation in results, as suggested by standard deviation of the mean, was in the range of 4% to 28% (Grimmer et al., 2008; Rapoport et al., 2003).

The majority of K_{leg} studies have estimated (not measured) the change in leg length during running in order to determine K_{leg} (Arampatzis et al., 1999; Avogadro, Kyrolainen, & Belli, 2004b; Blum, Lipfert, & Seyfarth, 2009; Dutto & Smith, 2002; Hobara et al., 2010a; Morin et al., 2006; Morin, Samozino, & Peyrot, 2009b; Morin, Samozino, Zameziati, & Belli, 2007; Slawinski et al., 2008). Several methods to estimate change in leg length have been suggested which are reasonably similar (Table 2.4, Equations 10 and 11), two differed considerably (Table 2.4, Equations 12 and 13). Morin et al. (2005) demonstrated how the estimated change in leg length, although similar, is not the same as the measured value. Studies that estimated initial leg length did so either by muliplying by a constant value (0.53) and height (Hobara et al., 2008; Morin et al., 2005; Morin et al., 2006; Morin et al., 2009b) or by calcuating the vertical distance from the ground to the greater trochanter during standing (Arampatzis et al., 1999; Farley & Gonzalez, 1996; He et al., 1991; Slawinski et al., 2008). Potentially research that estimated initial leg length (by muliplying a constant value (0.53) and height) poses several anthropometric problems which have implications on the leg length values presented. It is well documented that athletes at the highest level of performance do not possess typical anthropometric profiles and are often considered the extremes of the general population (Bejan, Jones, & Charles, 2010; Watts, Coleman, & Nevill, 2012). Therefore applying a constant value (0.53) may not be representative of the athletic population in question, which may lead to an over- or underestimation of initial leg length and errors in subsequent calculations of K_{leg}.

Watts et al. (2012) indicated that athletes at the highest level of performance have become taller, although variations exist between athletes (based on place of origin). A comparison of African and Caucasian distance runners revealed that relative leg length of African distance runners was considerably longer compared to their Caucasian counterparts (Larsen, Christensen, Nolan, & Sondergaard, 2004). This research also reported longer tibial length in absolute terms in the African distance runners than the Caucasians despite the fact their stature was smaller. Bejan et al. (2010) suggested that it is the height which the CM falls from which is indicative of high-levels of sprinting performance. The location of the CM is dependent upon the morphology of the body, thus an athlete with longer leg length and narrower circumferences of body segments (e.g. the shanks) will result in a higher position of the CM. Taylor and Beneke (2012) and Beneke, Taylor, and Leithäuser (2011) support this by stating that a taller stature would facilitate a longer step length coupled with longer contact times resulting in further distances travelled during ground contact.

These findings are not reflected in how initial leg length is estimated within the leg stiffness literature (Arampatzis et al., 1999; Avogadro et al., 2004b; Dutto & Smith, 2002; Farley & Gonzalez, 1996; He et al., 1991; Hunter & Smith, 2007; Morin et al., 2005; Morin et al., 2009b; Morin et al., 2007; Slawinski et al., 2008). Despite evidence suggesting that measured change in leg length is not equal to estimated change in leg length, it should be pointed out that research has suggested that at higher constant velocities variation in K_{leg} decreases coupled with an increase in stride frequency and decrease in contact time. Change in leg length also increased at higher constant velocities. These results suggest that when power requirements are greater (e.g. when accelerating, jumping for distance or height, or when performing a single leg hop as opposed to a double leg hop, etc.), leg stiffness variation is also greater possibly due to increased contact time. Change in leg length will concurrently decrease, and therefore it can be assumed that metabolic energy expenditure is greater (Blum et al., 2009).

In summary, results from studies which have measured K_{leg} highlight an inconsistency in terminology use, showing that the terms K_{vert}, and K_{leg} are often used interchangeably. Nevertheless, the best method for modelling K_{leg} appears to be the quotient of ground reaction force and change in leg length (Equation 9); however the application of this model is restricted due to constraints of current methodologies and data collection environments. In some instances K_{vert} will equal K_{leg} (e.g. when change in leg length is estimated from vertical jumps or hops); however, they are not the same. Future research will need to determine and measure change in leg length. The method by which leg length is measured requires additional consideration because current methods are inconsistent and somewhat inaccurate in determining initial leg length of athletes at highest level of performance or from different places of origin. Furthermore, there appears to be an element of task dependency on variation in results which also requires exploration.

Table 2.4 Summary of models used to estimate change in leg length to determine leg stiffness

Equation		Studies which use this model
$\Delta L = L_0 - \sqrt{L_0^2 - \left(\frac{\upsilon t_c}{2}\right)^2} + \Delta y$	[Equation 10]	Avogadro, Chaux, Bourdin, Dalleau, and Belli (2004a); Hunter and Smith (2007); Morin et al. (2005); Morin, Samozino, and Peyrot (2009a); Morin et al. (2006); Where L_0 = 0.53 x height
$\Delta L = L - \sqrt{L_0^2 - \left(\frac{\upsilon t_c - d}{2}\right)^2} + \Delta y$	[Equation 11]	Morin et al. (2007);Hobara et al. (2010a) Where L_0 = distance from greater trochanter to ground
$\Delta L = \Delta y_c + L\,(1 - \cos\theta)$ $\theta = \sin^{-1}\left(\frac{\upsilon t_c}{2L}\right)$	[Equation 12]	Arampatzis et al. (1999); Dutto and Smith (2002); Farley and Gonzalez (1996); He et al. (1991); Slawinski et al. (2008)
$\Delta L = L_0 + \frac{F_{max}}{m}\left(\frac{t_c}{\pi}\right)^2 - \frac{g}{8}t_c^2 - L_0 \sin\alpha_{TD}$ $F_{max} = mg\frac{\pi}{4}\left(\frac{1}{DF}\right)$ $DF = \frac{t_c}{2(t_c + t_f)}$	[Equation 13]	Blum et al. (2009)

F_{max}, maximal vertical ground reaction force (kN); ΔL, displacement of the leg spring (m); Δy, vertical displacement of the centre of mass (m); L_0, initial length of the leg spring (m); υ, forward speed (m·s^{-1}); t_c, contact time (s); t_f, flight time (s); m, body mass (kg); d, point of force translation distance (m); α_{TD}, leg angle relative to x-axis at initial touchdown (°)

2.4.5. *Leg stiffness and performance*

There are many questions that remained unanswered concerning the relationship between K_{leg} and performance. In some studies, K_{leg} remained constant during running at different speeds (He et al., 1991); however, it has also been suggested that K_{leg} is adjusted to meet the changes in demands of a specific task (Farley & Gonzalez, 1996; Farley & Morgenroth, 1999). Contradictory to the previous studies by He et al. (1991) K_{leg} has been reported to increase during running as running velocity increases (Arampatzis et al., 1999). Only, Morin et al. (2005) has examined K_{leg} during moderate maximum running velocities; however, no significant alteration in K_{leg} was reported. No change in the K_{leg} can be explained as the change in leg length also increases with running velocity, thus the increase in maximal ground reaction force with velocity is offset by the increase in change in leg length and therefore K_{leg} does not alter. These differences in K_{leg} patterns can be partly explained by different calculation methods which were discussed earlier in this chapter (Arampatzis et al., 1999).

Of the current K_{leg} research, only a handful of papers have conducted research on higher-level athletes. Little is known about the effects of training on K_{leg}, as previous research has focussed on power-trained athletes as opposed to endurance-trained athletes. The majority of K_{leg} research has been conducted during treadmill protocols reporting running velocities ranging from 2 to 5 $m{\cdot}s^{-1}$ during short runs and often do not allow for direct comparison of running velocities across specific populations (Dutto & Smith, 2002; He et al., 1991; Morin et al., 2005). Therefore, before conclusions can be drawn concerning K_{leg} and the effects of running velocity and overall performance more studies are required to examine across a range of ability levels to establish the differentiating factors. In addition, the effect of training on K_{leg} has not yet been determined in any homogenous population (e.g. middle-distance athletes).

2.5 Importance of performance data

The goal of competitive distance running is to run a given distance in the least amount of time, a successful performance outcome is often determined by maintaining a high running velocity (Anderson, 1996; Leskinen et al., 2009). High performance running is reliant on skill and precise timing in which all movement has purpose and function (Anderson, 1996). Capturing of high performance running data often takes place away from the laboratory setting on synthetic athletic tracks during training sessions or competitive races. Documenting the gait and spring-mass characteristics of athletes during training and competition would allow for comparison of various ability levels. At present there is limited research available that documents the differentiating biomechanical factors associated with performance over a range of ability levels. For these factors to be identified, biomechanical studies must investigate the gait and spring-mass characteristics across a range of homogenous ability levels from regional- national- and international-level middle-distance athletes.

Competition-based biomechanical data capture informs the development of athletes in training, by allowing for the identification of differentiating biomechanical factors associated with performance. During training athletes can look to modify their gait and spring-mass characteristics in order to reduce their performance time and maintain a higher running velocity. To facilitate these changes in gait coaches may require real-time feedback on gait characteristics, such as running velocity or contact times. In contrast, the coach may also require a more in depth analysis post-training or competition in order to assess the technical aspects of running gait that includes; the movement of an athletes' CM or speed of individual limbs during the flight phase. These scenarios pose unique challenges for the sport biomechanist both in terms of their ability to collect reliable and accurate data away from the laboratory setting on synthetic athletic tracks and, wherever possible reducing the necessary processing time.

Research is yet to establish the most appropriate methods using currently available biomechanical systems to collect data away from the laboratory setting on synthetic athletic tracks. Contemporary data collection and methodologies employed must be relevant to the sport (e.g. track and field athletics) as this influences the coaches' acceptance of the subsequent findings (Spinks, 1997).

A possible reason for the lack of empirical evidence is that traditionally research has been undertaken through universities, using complex automated biomechanical systems, within controlled laboratory environments. University-based research is often focused on increasing the fundamental body of biomechanical knowledge rather than focusing on performance lead investigations. By using complex automated systems, laboratory-based research has accurately determined biomechanical parameters during a controlled running or jumping protocol (Popovich & Kulig, 2011; Saunders, Schache, Rath, & Hodges, 2005; Snyder, Earl, O'Connor, & Ebersole, 2009; Willson, Kernozek, Arndt, Reznichek, & Scott Straker, 2011). Whilst the use of automated systems in collecting biomechanical data offers great accuracy (Richards, 1999), their use is restricted to the laboratory due to the intrusive and restrictive nature of the systems, which require markers to be placed on individual athletes. For example an automated system would not permit a capture area large enough to monitor an 800 m or 1500 m performance during training away from the laboratory setting on synthetic athletic tracks.

In longitudinal studies requiring extended periods of data collection, over several weeks of training, Exell (2010) reported that many athletes were reluctant to wear markers, due to the perceived negative effects on performance. Exell (2010) found that when athletes wore markers they were conscious of trying not to displace them. If a marker was displaced it could fall off the athlete, which interrupts the data collection and disrupts the training session. Kearney (1999) concurred with this statement and suggested that highly-trained athletes were often unwilling to change their training or competition set-up or schedule for the sake of research. To further compound this issue, many coaches are reluctant to engage their athletes in research that is based away from training environments. This is due to the potential for injury, time demands placed on the athlete, and there is often little reward or recognition for such commitment in terms of performance outcome data (Williams & Kendall, 2007). Williams and Kendall (2007) concluded that more research should be based within a training and competition environment. This would require specific biomechanical systems but would provide coaches and sport biomechanists with training and competition performance measures, thereby increasing the performance data available and its acceptance by coaches. Documentation of performance would inform coaching practice and enable specific athletic development to reduce performance time.

2.6. Techniques used to investigate gait characteristics

It is important that any data collected in a biomechanical investigation are accurate and relevant for addressing the specific research questions. When attempting to collect data during training and competition, the sport biomechanist often has less control over the environment due to restrictions to access and protocol. Once collected, raw data in biomechanical research studies are seldom instantly reported. In order to yield meaningful, accurate data which can be used for descriptive purposes or in a theoretical model, these data must be processed. Aspects of raw data processing which are particularly important for dynamic human movements such as running include the appropriate smoothing of noise and the application of data acquired. The main measurement issues to be considered for all biomechanical parameters are validity and reliability (O'Donoghue, 2012). The validity of a biomechanical system depends on its reliability and its relevance. The relevance of a biomechanical system is how well the system reports specific gait characteristics. Reliability is concerned with the constancy of measurement for a given biomechanical parameter (O'Donoghue, 2012). Very often it is not possible to determine the accuracy of a biomechanical system; as the ‘true’ value may not be known. In these instances, research often reports the comparison of different biomechanical systems in measuring each gait characteristic, none of which can be taken as 100 per cent accurate (O'Donoghue, 2012).

There are numerous biomechanical systems available for collecting the data necessary to analyse running performance. Whilst some offer potentially higher levels of accuracy, their use can be limited by the environment in which they must operate. Therefore in order to obtain accurate training and competition data during middle-distance performances without altering the athlete’s typical environment, the choice of appropriate biomechanical system is an important issue.

2.6.1 Comparison of treadmill and overground running

Studies have examined the biomechanics of running in a wide range of individuals, ranging from the sedentary to international-level distance runners (Derrick et al., 2002; Morin et al., 2005; Williams et al., 1987). The convenience of treadmills makes them ideal biomechanical tools for investigating human movement (Schache et al., 2001). Treadmills provide a standardised and reproducible running environment, where running velocity and gradient can be controlled and the required calibration volume for capturing kinematic data is considerably reduced. Furthermore, the treadmill also allows a greater number of gait cycles to be captured and ensures that continuous movement kinematics are obtained (Sinclair et al., 2013). For the treadmill to be accepted as a useful biomechanical tool, it must be demonstrated that it does not impede the natural patterns of movement.

There is not a clear consensus within the literature on how gait characteristics differ during treadmill running compared to overground. The majority of these studies have utilised treadmill-based running protocols that instigate maximum efforts to the point of exhaustion (Abt et al., 2011; Avogadro, Dolenec, & Belli, 2003; Candau et al., 1998; Derrick et al., 2002; Dutto & Smith, 2002; Millet et al., 2011). It has been proposed that gait characteristics of treadmill running are similar to overground, provided that running velocity remains constant (Sinclair et al., 2013). Numerous studies have reported biomechanical differences between overground and treadmill running; concluding that the gait characteristics exhibited during treadmill running cannot be applied to overground running (Frishberg, 1983; Sinclair et al., 2013; Wank & Schmidtbleicher, 1998). Matsas, Nicholas, and McBurney (2000) proposed that significant differences observed between treadmill and overground running were due to the lack of participant familiarisation, and concluded that differences may disappear following an appropriate familiarisation period. More recent research has rejected this claim as a number of significant differences have been observed despite the utilisation of a familiarisation period (Sinclair et al., 2013).

The kinematic differences that have been reported between overground and treadmill running may be attributed to the different mechanical properties of the two running surfaces. Research suggests that distance runners adjust their gait and spring-mass characteristics to accommodate to difference surface stiffness's allowing them to maintain their running velocity in all conditions (Maquirriain, 2012; Schache et al., 2001). Research has noted the differences between overground and treadmill running in both the sagittal plane and transverse plane (Sinclair et al., 2013). Overground running has been associated with increased peak hip flexion and flexion angle at initial touchdown when compared to treadmill running (Schache et al., 2001; Sinclair et al., 2013). These findings may be attributable to the reduced step length that have been observed during treadmill running (Wank & Schmidtbleicher, 1998).

Since running velocity can be fixed on a treadmill; individuals may have altered their gait characteristics in an attempt to maintain running velocity as they were unable to slow down (Dierks, Davis, & Hamill, 2010). Therefore, gait characteristics during treadmill running may not provide a 'true' reflection of K_{vert} and K_{leg} (Schache et al., 2001). Due to the potential impact of treadmills on K_{vert} and K_{leg} (in response to changes in the gait characteristics), all data collected and reported as part of this thesis will be completed during overground running.

2.6.2 Video camera

Traditionally, qualitative and quantitative assessment of human movement has been derived from panning or fixed video (25Hz to 50Hz) during training and competition, as this allowed for greater freedom (Enomoto & Michiyoshi, 2012; Exell, Irwin, & Kerwin, 2007; Mann & Herman, 1985; Salo et al., 2011). A possible reason for their extensive application is that video cameras can be positioned away from the athlete enabling a larger field of view; whilst providing an image size big enough to provide detail on the athletes' movement patterns (Cassidy, Stanley, & Bartlett, 2006).

The two main drawbacks of using video for analysing movement patterns are the resolution of the image, which restricts the digitising accuracy when compared with high-speed video, and the sampling rate of 50 Hz, which makes them unsuitable for the quantitative study of very fast movement patterns (Bartlett, 2007). Bezodis et al. (2008) and Salo et al. (2011) demonstrated that for fast movements, such as sprinting, high-speed video (with a sampling frequency between 100Hz and 300Hz) are needed to quantitatively assess biomechanical parameters over time intervals, e.g. contact time (which can be less than 0.100s). High-speed video can also be used to digitise video images to calculate spatial coordinates of body landmarks, with the only equipment required at the time of data collection being the video cameras (mounted on tripods) and a calibration object, Figure 2.5. The majority of published research pertaining to the documentation of gait and spring-mass characteristics have utilised video in order to analyse human movement (Morin et al., 2006).

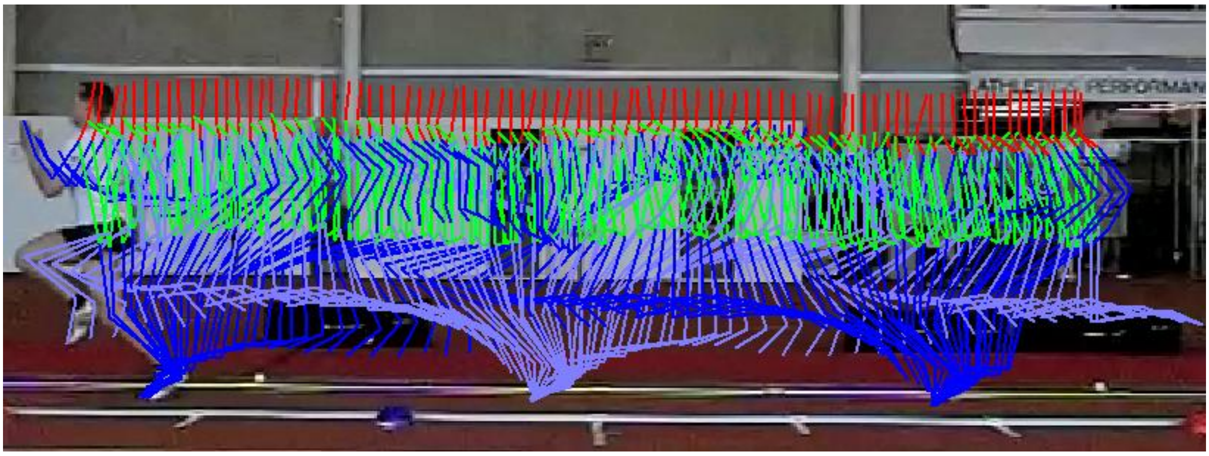


Figure 2.5 Example of high-speed video (300Hz) with whole body digitisation

2.6.3 Optojump

Many biomechanical parameters may be sensitive to variations in velocity, including step length and step frequency (Dugan & Bhat, 2005; Farley & Gonzalez, 1996; Mann & Herman, 1985; Novacheck, 1998). This has given rise to biomechanical systems such as Optojump that provides real-time data on contact time, flight time, step length and step frequency with no impedance to the athlete (Lehance, Croisier, & Bury, 2005). This system is easy to set-up and consists of two parallel bars (one receiver and one transmitter unit) that transmit an infrared light 1 to 2 mm above the floor, allowing for athlete-surface interaction, Figure 2.6 (Bosquet, Berryman, & Dupuy, 2009; Debaere, Jonkers, & Delecluse, 2012; Glatthorn et al., 2011). Contemporary biomechanical systems such as Optojump are often preferred during training due to their unobtrusive nature and ability to provide real-time information to inform the coaching process. This system cannot be used in competition due to the rules enforced by the International Association of Athletics Federations ("Competition Rules," 2012-2013).

Scientific literature has demonstrated the reliability of the Optojump system in quantifying jump height derived from flight time during hopping and jumping (ICCs ranging between 0.982-0.989) and running reporting a coefficient of variation (CV) of 3% (Glatthorn et al., 2011; Lehance et al., 2005). As of yet no research has provided a comprehensive breakdown of how Optojump compares to video for contact time, flight time, step length, step frequency and velocity. Therefore, the measurement of agreement for Optojump and video must be established, without this biomechanical parameters quantified from one biomechanical system cannot be compared to the other (e.g. training data captured by Optojump cannot be compared to competition data captured by high-speed video).

Figure 2.6 Optojump system A) positioned on the side bars of a treadmill B) modular system (available from 2 m to 100 m) on an synthetic athletics track

2.6.4 Laser distance measurement device

In competitions, coaches are routinely provided with precise finishing times captured by photofinishing cameras. Although end-to-end timing data from such devices can be very accurate, they do not provide the coach with a complete speed profile that covers the entire race. In training, similar issues are experienced, as optical sensor-based timing gates provide coaches with convenient and rapidly accessible information on end-to-end timing data, from which an average velocity can be calculated (Harrison, Jensen, & Donoghue, 2005; Yeadon, Kato, & Kerwin, 1999). End-to-end timing data is limited by; the start distance of the athlete behind the lights, foot position, first step strategy and height of timing light gates (Cronin & Templeton, 2008). An alternative system is the laser distance measurement (LDM) device it provides a non-obstructive method of determining distance-time and velocity-time data during running in real-time and can be captured during training and competition (Harrison et al., 2005; Lopez, Padulles, & Olsson, 2011).

The LDM device is limited to line of sight, straight-line measurement but can be placed either behind the start line (tracking the rear of athlete) or behind the finish line (tracking the front of athlete). As of yet no research has examined the reliability or validity of LDM device position, e.g. compared tracking athletes from the front and rear. Previous research has positioned LDM devices behind the start line (tracking the rear of athlete) and not behind the finish line (tracking the front of athlete); however, the rationale for this has never been justified (Bruggemann, Koszewski, & Muller, 1999; Harrison et al., 2005). It has been inferred that there are advantages for both positions, if the LDM device is positioned behind the start line this allows the operator to track the athlete from the rear which subjectively appears to be easier. When the LDM device is positioned by the finish line this means the operator can track the athlete from the front which infers greater accuracy during the 'business' end of the event, e.g. last 30m of a

100m race, as the size of the object is larger (easier to track the athlete). Another possible limiting factor when using LDM devices is that they can only capture data from one athlete at a time, this often restricts their use in competition to field events such as long jump where athlete's velocity can be determined one at a time.

The accuracy of velocity data obtained by LDM devices has previously been compared to those derived from video (Arsac & Locatelli, 2002; Harrison et al., 2005) and optical sensor-based timing gates (di Prampero et al., 2005; Morin et al., 2006). Based on the findings of Harrison et al. (2005) the LDM device is not able to measure the relative and rapid changes in velocity and acceleration that are likely to occur during the stride cycle. These rapid changes in velocity and acceleration could be determined by high-speed video; however, this would require digitisations of multiple video frames of the whole body and further processing. Despite this, Harrison et al. (2005) stated that LDM devices produce reliable measures of distance-time and velocity-time during running when compared to video. This has facilitated the use of LDM devices in elite level competitions (Bruggemann et al., 1999) and in biomechanical research (Bezodis et al., 2008; Exell, 2010). The use of the LDM device in training and competition to quantify an athletes' velocity is supported by biomechanical studies which have consistently identified velocity as an important determinant of success in jumping and sprint running (Linthorne, 2008).

2.7 Final Summary of Research Area

Performance environment and technologies

Competition-based biomechanical data capture informs the development of athletes in training, by allowing for the identification of differentiating gait and spring-mass characteristics associated with performance. The best means by which the gait and spring-mass characteristics of middle-distance athletes could be determined is in competition. Literature has identified specific differences in gait characteristics between sprint and endurance athletes (Bushnell & Hunter, 2007), but the differences in gait characteristics between middle-distance athletes and ability levels within the same event (e.g. international- compared to national-level middle-distance athletes) is less apparent. To capture biomechanical data during competition and training, research must first document the validity of a range of biomechanical technologies that could be used away from the laboratory environment on a synthetic athletics track. There are numerous biomechanical systems available for collecting the data necessary to analyse running performance. Whilst some offer potentially higher levels of accuracy, their use can be limited by the environment in which they must operate.

Only a limited set of information is available concerning the gait characteristics of international-level athletes, and very little has been reported on step length and step frequency of middle-distance athletes (Cavanagh et al., 1985; Huxley et al., 2013; Leskinen et al., 2009; Mann et al., 1984; Salo et al., 2011). Past research has tended to evaluate the impact of step length and step frequency on recreational participants running at velocities between 3.00 and 5.00 $m \cdot s^{-1}$ (Derrick et al., 2002; Federations, 2012-2013; Queen et al., 2006). The 2012 London Samsung Diamond League 800 m final was won in a time of 1:44.49, during this race the athletes achieved average running velocities of between 6.00 and 8.00 $m \cdot s^{-1}$. New research on international-level middle-distance athletes is therefore critical to identify how higher running velocities are achieved in terms of step length and step frequency. Small changes in gait characteristics can result in large gains in running velocity and ultimately influence performance time (Chapman et al., 2011). The performance time achieved is a consequence of how an athlete modifies their gait and lower limb neuromuscular behaviour to maintain a high running velocity (Chapman et al., 2011)

Methodologies used to estimate lower limb neuromuscular behaviour (e.g. K_{vert} and K_{leg}) through determining F_{max}, change in leg length and CM displacement vary considerably between studies. Leg stiffness is not always clearly defined with a number of studies explicitly stating an intention to investigate K_{leg} where in actual fact they were estimating K_{vert}. Limited studies have compared gold standard direct measurements (by a force platform) and estimations (by mathematical modelling) in determining K_{vert} and K_{leg}. Only one study has documented the sensitivity of K_{vert} and K_{leg} measured directly by force platforms compared to estimations by mathematical modelling (Morin et al., 2005). These authors deemed estimations (by mathematical modelling) in determining K_{vert} and K_{leg} values acceptable (Morin et al., 2005). Gait and spring-mass characteristics achieved at each running velocity were omitted from this study; therefore, the impact of increasing running velocity on each gait and spring-mass characteristics used to estimate stiffness (by mathematical modelling) in unknown. Further physiological and biomechanical investigation is needed to identify the regulation of the lower limb neuromuscular behaviour and its impact on performance time (Hobara et al., 2010a). Past research has suggested that joint angles may facilitate in the understanding of how lower limb neuromuscular behaviour (e.g. K_{vert} and K_{leg}) is altered to achieve a high running velocity (Kuitunen et al., 2002).

The majority of studies have used estimations of K_{leg}, with only 3 studies measuring actual change in vertical leg length (Grimmer et al., 2008; Rapoport et al., 2003; Stafilidis & Arampatzis, 2007). Potentially research that estimated initial leg length (by muliplying a constant value (0.53) and height) poses several anthropometric problems which have implications on the leg length values presented. It is well documented that athletes at the highest level of performance do not possess typical anthropometric profiles and are often considered the extremes of the general population (Bejan et al., 2010; Watts et al., 2012). Therefore applying a constant value (0.53) may not be representative of the athletic population in question, which may lead to an over- or underestimation of initial leg length and errors in subsequent calculations of K_{leg}.

There are many questions that remained unanswered concerning the relationship between gait and spring-mass characteristics and middle-distance performance time. Little is known about the effects of training on gait and spring-mass characteristics, as previous research has focussed on power-trained athletes as opposed to endurance-trained athletes.

2.8 Statement of Purpose

The aim of this thesis was to initially establish a valid means of measuring gait and spring-mass characteristics away from the laboratory environment (e.g. on an outdoor 400 m synthetic athletics track), and then use this to provide a biomechanical evaluation of middle-distance running during competition and training in order to identify gait and spring-mass characteristics that influence performance time.

In order to achieve this aim the thesis had the following objectives:

- Determine the validity of digital (50Hz) and high-speed camera (300 Hz) compared to Optojump and LDM in obtaining contact time, flight time, step length, step frequency and running velocity on a synthetic athletics track (chapter 3)
- Assess the validity of mathematical models in determining K_{vert} and K_{leg} during running to the gold standard direct measurement (using a force platform, chapter 4).
- Establish how mathematical models (using only high-speed video) compared to the gold standard direct measurement (using a force platform) in responding to an increase in running velocity (chapter 4)

- Report the gait and spring-mass characteristics across a range of ability levels, from regional- national- and international-level middle-distance athletes, to establish potential differences in contact time, flight time, step length, step frequency, running velocity, K_{vert} and K_{leg} (chapter 5).
- To investigate gait and spring-mass characteristics and their relationship to performance time (chapter 5).
- Document the gait and spring-mass characteristics in regional-level athletes during a single speed endurance training session (chapter 6).
- Document the gait and spring-mass characteristics in regional-level athletes during 4 week speed endurance training block (chapter 6)

The thesis attempted to answer the following research questions:

I. Are field based biomechanical technologies valid in determining gait and spring-mass characteristics?
II. Are mathematical models (estimations based on high-speed video data only) a valid measure in determining K_{vert} and K_{leg} during running compared to the gold standard direct measurement (using a force platform)?

Previous research has been unclear how comparable mathematical models are to the gold standard direct measurement when determining K_{vert} and K_{leg} during running(Arampatzis, Knicker, Metzler, & Bruggemann, 2000; Morin et al., 2005). Therefore it is of interest to provide a detailed comparison of mathematical models (using only high-speed video) to direct measurement.

III. How do gait and spring-mass characteristics compare between ability levels and what biomechanical parameters are related to middle-distance performance time?

Three studies have documented the gait characteristics of middle-distance athletes during official races (Hayes & Caplan, 2012; Leskinen et al., 2009; Skof & Stuhee, 2004).

There is paucity in the biomechanical literature depicting how gait and spring-mass characteristics differ across middle-distance athlete ability levels when maintaining a high running velocity. A study was conducted to investigate the gait and spring-mass characteristics across a range of ability levels, from regional- national- and international-level middle-distance athletes during middle-distance competition.

IV. How do gait and spring-mass characteristics vary during a single speed endurance training and a training block?

Training is designed to stimulate adaptions in physiological and biomechanical parameters to influence performance time by developing greater aerobic capacity, greater muscular power generation, as well as improved lower limb neuromuscular behaviour and shorter contact times (Iaia & Bangsbo, 2010; Smith, 2003). Although the lower limb neuromuscular behaviour during ground contact has been widely investigated the effects of high-intensity training (e.g. speed endurance training) on gait and spring-mass characteristics remains poorly understood. A study was conducted to examine the effects of speed endurance training on gait and spring-mass characteristics in regional-level athletes during training on a synthetic athletics track.

CHAPTER 3: THE APPLICATION OF A VIDEO CAMERA SYSTEM FOR QUANTIFYING GAIT CHARACTERISTICS

3.1. Introduction

The qualitative and quantitative assessment of human movement has traditionally been derived from panning or fixed video (25Hz to 50Hz) (Enomoto & Michiyoshi, 2012; Exell et al., 2007; Graham-Smith & Lees, 2005; Mann & Herman, 1985; Salo et al., 2011). Bezodis et al. (2008) and Salo et al. (2011) suggested that for fast movements, such as high velocity running, high-speed video with a sampling frequency between 100Hz and 300Hz are required to quantitatively assess gait characteristics. Few published studies have provided a comparison of traditional (e.g. video-based) and contemporary biomechanical systems (e.g. Optojump and LDM device) in quantifying gait characteristics at high running velocities (Glazier & Irwin, 2001; Harrison et al., 2005; Ogueta-Alday, Morante, Rodrı´guez-Marroyo, & Garcı´a-Lo´ pez, 2013). Digital (50Hz) and high-speed camera (300 Hz), Optojump and LDM devices can be used away from the laboratory setting on synthetic athletic tracks; however limited research is available documenting their validity of quantifying contact time, flight time, step length, step frequency and running velocity during high velocity running.

Traditional video-based systems (digital [50Hz] and high-speed camera [300 Hz]) are often preferred, as the only equipment required at the time of data collection is a video cameras (mounted on tripods) and a calibration object (for more information refer to chapter 2, section 2.6) making it ideal for data collection away from the laboratory setting on synthetic athletic track. High-speed video can also be used to digitise video images to calculate spatial coordinates of body landmarks.

Along with high-speed video, Optojump and LDM device have been developed to allow for the collection of accurate data without the large processing time associated with traditional techniques (Exell, 2010). Optojump and LDM devices can be used to collect data away from the laboratory setting on synthetic athletic tracks with minimal processing time (Lopez et al., 2011). Contemporary biomechanical systems, such as Optojump, are often preferred during training due to their increased ability to provide real-time information. In these instances contemporary biomechanical systems are often used instead of video-based systems (digital [50Hz] and high-speed camera [300 Hz]). Traditional methods, such as video, are still necessary to quantify gait characteristics during competition as they offer a non-intrusive approach which adhere to the rules and regulations outlined by the IAAF ("Competition Rules," 2012-2013). This demonstrates the limited applicability of certain biomechanical systems to be utilised away from the laboratory setting on synthetic athletic tracks. As contemporary biomechanical systems, such as Optojump, cannot be used in both training and competition environments. It is of interest to establish the validity of these different biomechanical systems so that they can be confidently used to quantify gait characteristics away from the laboratory setting on synthetic athletic tracks.

Numerous biomechanical studies have utilised Optojump and/or LDM device to determine gait characteristics during high velocity running (Debaere, Jonkers, & Delecluse, 2013; Harrison & Bourke, 2009; Slawinski et al., 2008). Few published studies have provided a comparison of traditional (e.g. video) and contemporary biomechanical systems (e.g. Optojump and LDM device) in quantifying gait characteristics at high running velocities (Glazier & Irwin, 2001; Harrison et al., 2005; Ogueta-Alday et al., 2013). Recent treadmill research compared Optojump to high-speed video (sampling frequency 1,200 Hz) at velocities between 2.78 $m\cdot s^{-1}$ and 6.11 $m\cdot s^{-1}$ (Ogueta-Alday et al., 2013). The authors concluded that high-speed video was sensitive for detecting small differences in contact time (<0.020 s) compared to Optojump when the running speed increased and when the type of foot strike patterns changed. Research is yet to compare video and Optojump at high running velocities (~ 8.00 m·s^{-1}) during overground running.

Unlike Optojump the LDM device has been compared to video during overground running at higher velocities (> 8.00 m·s^{-1}) (Arsac & Locatelli, 2002; Harrison et al., 2005). During the Athens 1997 World Championship 100 m finals the average difference between LDM device compared to 50 Hz video was 0.10 m·s^{-1} ± 0.06 m·s^{-1} for one athlete (Arsac & Locatelli, 2002). An average difference of 0.10 m·s^{-1} during the World Championship 100 m final is a considerable margin when considering this value from a performance perspective, as during the 2013 World Championship 100 m gold and silver medal position were separated by less than 0.08 m·s^{-1}. This would suggest that the LDM device and 50 Hz video would not be able to separate the gold and silver 100 m medallists at the recent World Championships. A more detailed comparison of LDM device was undertaken by Harrison et al. (2005) who compared the LDM to video (using sampling frequencies of 50 Hz and 100 Hz) over a 3 m capture zone. These results showed a high intraclass correlation coefficient (>0.99) for repeated static measures at all distances ranging from 10 m to 70 m using the LDM device. In the running trials, the intraclass correlation coefficient results demonstrated that all LDM, 50 Hz and 100 Hz video produced reliable estimates of average velocity within the defined 3 m measurement zone (1 contact) at running velocities between 4.60 m·s^{-1} and 7.50 m·s^{-1}. Research is yet to document how the position of the LDM device (e.g. tracking from the rear compared to tracking from the front) influences the values presented at velocities greater than 8.00 m·s^{-1} for more than 1 contact. Due to the constraints of the training and competition environment it is sometimes necessary to place the LDM device behind the start line (tracking the rear of athlete) or behind the finish line (tracking the front of athlete). Research is yet to detail the impact of LDM device position (e.g. tracking the rear of athlete versus tracking the front of athlete) and how this may influences the values presented. A greater understanding of the relationship between video, Optojump and LDM device in determining gait characteristics is required.

The aim of this investigation was to quantify the validity of digital (50Hz) and high-speed camera (300 Hz) against Optojump and laser distance measurement (LDM) device in determining contact time, flight time, step length, step frequency and running velocity on a synthetic athletics track (away from the laboratory environment). Through focusing on a cohort of track athletes, it was hypothesised that in accordance with previous research (Harrison et al., 2005; Lehance et al., 2005) that a digital (50Hz) and high-speed camera (300 Hz) compared to Optojump and LDM device would provide a valid measure of contact time, flight time, step length, step frequency and running velocity during high running velocity on a synthetic athletics track. This study investigates the differences between LDM device position (e.g. tracking from the rear compared to tracking from the front) and the intra-operator reliability of gait and spring-mass characteristics determined by video. This would mean that any of these biomechanical technologies could be used during training and competition to provide a valid measure of gait and spring-mass characteristics.

3.2. Method

3.2.1. Participants

Following written informed consent fifteen athletes (mean ± SD age: 23 ± 4 years; stature: 1.77 ± 0.10 m; mass: 71 ± 11 kg) volunteered to participate in this study as part of their normal training session. The Local Research Ethics Committee and UK Athletics approved biomechanical investigations which did not involve any invasive procedures to be undertaken during training sessions. In order to remain unobtrusive no markers were attached to the athletes included in this study or throughout this thesis. All participants were track athletes (mean ± SD time in discipline: 7 ± 4 years) and were all based at the UK Athletics, High Performance Athletics Centre. Athletes had extensive experience of multiple-sprint running. As such no familiarisation period was required. The information was also used by the coach and athlete for monitoring purposes. Following approval from the University of Salford Manchester Research, Innovation and Academic Engagement Ethical Approval Panel the experimental methodology was performed in accordance with the Declaration of Helsinki.

3.2.2. Data collection

All multiple-sprints were conducted on a 130 m indoor synthetic athletic track. All athletes wore closely-fitting clothes and their own running spikes. The athletes performed 3 x 60 m maximal straight-line sprints interspersed by 7 to 10 minutes of passive recovery. Biomechanical data were captured for the last 30 m of each 60 m straight-line sprint (30 m to 60 m; Figure 3.1).

One gait cycle was identified from the initial touchdown of one foot to the initial touchdown of the same foot (e.g. left to left). The instants of initial touchdown and take-off were critical reference points in determining contact and flight time. Contact time (t_c; s) was identified as initial touchdown to take-off, and flight time ($t_{f;}$ s) was determined as take-off to touchdown. Initial touchdown was defined as the first frame in which the foot had made clear contact with the ground and take-off was defined as the first frame in which the foot had clearly left the ground. Step length (S_l; m) was measured as the distance between the tip of two subsequent foot contacts (e.g. left to right). Step frequency (S_f; Hz) was calculated as:

$$S_f = 1 / (t_c + t_f)$$

Velocity (υ; $m{\cdot}s^{-1}$) was calculated for each step:

$$\upsilon = S_f \times S_l$$

Biomechanical parameters were quantified for the` fastest run achieved by each athlete (in total 15 runs were analysed) all using panning digital video camera recorder, high-speed video cameras, Optojump system and LDM devices. A tripod-mounted panning digital video camera recorder (HVR-A1E, Sony, Japan) sampling at 50 Hz set at a height of 2 m and positioned 9.25 m away from the centre of the running lane. Two high-speed video cameras (EX-F1, Casio, Japan) were positioned 9.50 m from the centre of the running lane and 1.10 m above the track surface. Each high-speed video camera provided a 6 m field of view (with a 2 m overlap), sampling at 300 Hz, a shutter speed of 1/1000 s, and were manually focused. A 1.07 m x 1.20 m calibration object was placed in both high-speed video cameras field of view (in the centre of the running lane in the sagittal plane). All camera footage was taken perpendicular to the running direction in accordance with previous research (Cavanagh et al., 1985; Mero & Komi, 1985).

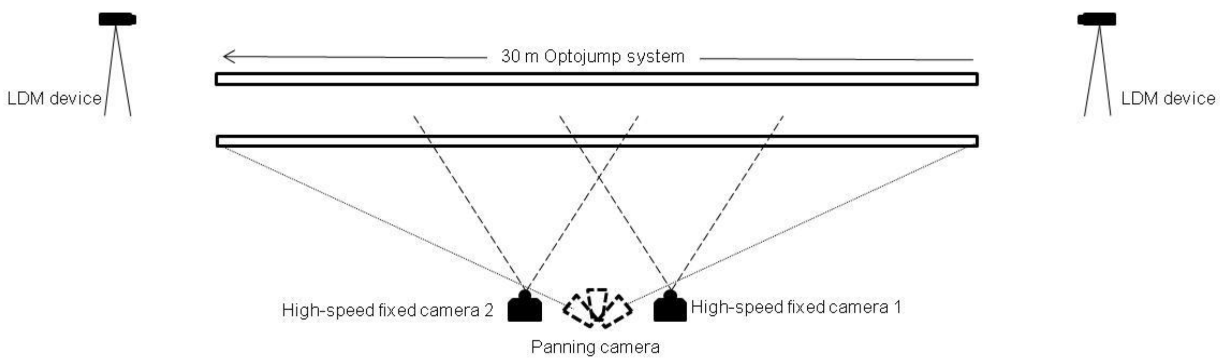


Figure 3.1 Illustration of the last 30 m of each 60 m straight-line sprint (30 m to 60 m) where data were collected

One metre marks (0.15 m in length) were positioned on both sides of the lane border perpendicular to the lane. The 1 m markings enabled a large field of view and image size of the athlete to be maintained in the panning digital video, which increased the accuracy of foot position (for measurement of step length). In addition these 1 m markings also enabled the panning digital video to be calibrated at each point of interest and reduce the effect of parallax errors. The point of interest was midstance for each contact. Midstance was identified half way between initial touchdown and take-off (when both knees were together). The position of the foot relative to the 1 m markers was determined from which step length was subsequently calculated.

Biomechanical parameters were monitored by the Optojump system (Microgate, Bolzano, Italy), which consisted of 60 x 1 m parallel bars (consisting of 30 receivers and 30 transmitters; equating to the system spanning 30 m in total) that were positioned on the synthetic athletic track, allowing for athlete-surface interaction. Each bar contains 100 infrared light emitting diodes (LED at a sampling frequency of 100Hz). Optojump bars were connected to a personal computer, and the proprietary software (Optojump software, version 1.5.1.0) allowed for biomechanical parameters to be quantified with a precision of 0.001s.

Two LDM devices (LDM-300C, Jenoptik, Germany) were used to obtain linear distance measures during all trials at a sampling frequency of 100 Hz. Both LDM devices derived split times at 42 to 47 m, 47 to 52 m and 42 to 52 m. These splits were used as they replicated the field of view in each of the high-speed cameras therefore replicating the same data collect zones. A static measurement validity test was performed on the LDM device with the zero point corresponding to the 30 m line. A zero point of 30m was chosen to correspond with all the other biomechanical technologies used in this study. The raw LDM device data were truncated 50 data points after displacement exceeded 0 m (Wood, 1982). Front and rear LDM devices were placed on tripods corresponding approximately to the height of the athlete's CM. The rear LDM device captured velocity from the rear of the athlete; whilst, the front LDM device recorded velocity from the front of the athlete.

3.2.3 Data Analysis

Running velocity is determined differently by high-speed camera, Optojump and LDM devices.

Table 3.1 outlines the methods used to determine velocity. High-speed video data were digitised at 300 Hz using a 18-point model in Quintic Biomechanics (Quintic Consultancy Ltd, 9.03 version 17). The 18-point model comprising of the shoulder, hip, elbow, wrist, tip of the finger, knee, ankle, toe on each side of the body, and top of the head and base of the neck. The CM was determined in accordance with de Leva (1996) using the 18-point model.

The fastest run of each athlete was digitised three times on separate days to determine the level of measurement error introduced to the calculation by the digitisation process. The intra-operator error was assessed by randomly selecting five athletes who participated in this study and digitising each of their runs three times. The intra-operator error for several key biomechanical parameters was reported in terms of standard error of the mean (SEM, Table 3.2). The SEM quantifies how precisely you know the 'true' mean of the population and takes into account both the value of the standard deviation and the sample size. The SEM, by definition, is always smaller than the standard deviation. Biomechanical parameters selected for the intra-operator error analysis were deemed to be important, as these parameters would be referred to in subsequent studies within this thesis.

Table 3.1 Methods used to determine velocity

Biomechanical systems	Method used to determine velocity
High-speed video camera[a]	By averaging the resultant of the horizontal and vertical velocities of the CM at touchdown, maximum knee flexion and take-off (average velocity)
High-speed video camera[b]	By multiplying step length and step frequency (velocity for each step)
High-speed video camera[c]	By identifying the maximum resultant of the horizontal and vertical velocities of the CM at either touchdown, maximum knee flexion and take-off (peak velocity)
Optojump	By multiplying step length and step frequency (velocity for each step)
LDM device[a]	By identifying either 42 to 47 m, 47 to 52 m and 42 to 52m splits on the data trace (average velocity)
LDM device[b]	By identifying individual points on the data trace (peak velocity)

LDM, laser distance measurement.

Table 3.2 Intra-operator error values for several key biomechanical variables reported in terms of standard error of the mean (SEM)

	1	2
Biomechanical parameters	**Standard Error of the Mean**	**Represents**
υ (m·s^{-1})	0.02	< 0.1 m·s^{-1}
t_c (s)	0.001	< 1 frame*
t_f (s)	0.003	~ 1 frame*
S_l (m)	0.01	~ 1 cm
S_f (Hz)	0.6	< 1 Hz
L_0 (m)	0.01	~ 1 cm
ΔL (m)	0.01	~ 1 cm
Δy (m)	0.01	~ 1 cm
CM-ankle distance (m)	0.02	~ 2 cm
Joint angles (°)	1.86	< 2 °

υ, running velocity determined by averaging the resultant of the horizontal and vertical velocities of the CM at touchdown, maximum knee flexion and take-off (high-speed camera[a]); t_c, contact time (s); t_f, flight time (s); S_l, step length (m) ; S_f, step frequency (Hz); L_0, initial leg length; ΔL, displacement of the leg spring (m); Δy, displacement of the centre of mass; CM, centre of mass. *when using a sampling frequency of 300Hz high-speed camera.

All trajectories were filtered using a low-pass Butterworth (second order filter in the forward and reverse direction resulting in a forth order filter overall) with a cut-off frequency of 11 Hz. A 11 Hz cut-off frequency was determined to be the optimal following the completion of a residual analysis (Klous, Muller, & Schwameder, 2010) and a qualitative evaluation of the data. All digitised data were exported from Quintic Biomechanics and processed through Microsoft Office Excel 2007. The biomechanical parameters were calculated on the basis of the exported x and y coordinates.

To calculate step length from 30 to 60 m, foot placement distances derived from the tape markings were taken from the panning digital video. High-speed video captured contact time, flight time, and step length for all athletes between 42 m and 52 m of the 60 m straight-line sprint. Step frequency and velocity was subsequently calculated. Optojump measured contact time, flight time and step length and subsequently calculated step frequency and velocity.

Statistical analyses were performed using Statistical Package for the Social Sciences version 17.0 (SPSS, 2012). Standard statistical methods were used for the calculations of means and standard deviations. Normal distribution of the data was verified by the Shapiro-Wilk test and homogeneity of variance was verified by the Levenne test. To assess the agreement between each biomechanical technique, Bland-Altman graphical method and limits of agreement were calculated instead of statistical significance. The focus of this study is not whether the difference is statistically significant but, rather, whether such differences are practically meaningful or not. The number of individual observations identified on the Bland-Altman plots represents the number of individual trials compared. For example, if 30 individual flight times were compared between two biomechanical methods, there would be 30 individual observations on the Bland-Altman plot. The Bland-Altman method calculates the mean difference between two methods of measurement (the 'bias'), and 95% limits of agreement as the mean difference (1.96 SD). It is expected that the 95% limits include 95% of differences between the two measurement methods.

This study reported the intraclass correlation coefficient, and confidence limits for each biomechanical variable (contact time, flight time, velocity, step length, step frequency, peak and average CM velocity). An intraclass correlation coefficient > 0.70 was considered as a minimum acceptable reliability (Baumgartner & Chung, 2001). The presentation of the 95% limits of agreement is for visual judgement of how well two methods of measurement agree. The smaller the range between these two limits the better the agreement is. Therefore, these statistical analyses will quantify the measurement of agreement of five biomechanical systems measuring contact time, flight time, step length, step frequency and velocity. The findings will identify how each biomechanical system compares to another and if these biomechanical systems can be used interchangeably.

3.3. Results

The mean and standard deviation of video (digital [50Hz] and high-speed camera [300 Hz]) compared to Optojump and LDM in obtaining each gait characteristics are presented in Table 3.3. Each biomechanical system demonstrated highly comparable values with some variation in the mean. Mean contact time (0.112 s) and step length (2.09 m) quantified by Optojump and high-speed video were the same. Mean flight time determined by Optojump and high-speed video provided similar values of 0.121 s and 0.120 s respectively. Step length values determined by the panning digital video, high-speed video and Optojump were identical (2.09 m ± 0.13 m). Both the panning digital video and high-speed video determined step length by identifying individual foot placement distances from 1 m markings, perpendicular to the track, this method demonstrated a mean difference of 0.03 m ± 0.01 m. Figure 3.2 presents a Bland-Altman plot illustrating the systematic bias and 95% limits of agreement between the Optojump and high-speed video when quantifying step frequency.

Table 3.3 Mean [± SD] velocity, contact time, flight time, step length, step frequency, peak velocity and average velocity quantified by five biomechanical systems

	1	**2**	**3**	**4**	**5**
	High-speed video camera	**Digital video camera**	**Optojump**	**Front LDM device**	**Rear LDM device**
Biomechanical parameters	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**
υ ($m \cdot s^{-1}$)	8.99 [0.62][b]		8.96 [0.60]		
t_c (s)	0.112 [0.007]		0.112 [0.007]		
t_f (s)	0.120 [0.008]		0.121 [0.008]		
S_l (m)	2.09 [0.13]	2.09 [0.13]	2.09 [0.13]		
S_f (Hz)	4.33 [0.18]		4.31 [0.19]		
Peak υ ($m \cdot s^{-1}$)	9.428 [0.524][c]			9.346 [0.545][b]	9.157 [0.527][b]
Average υ ($m \cdot s^{-1}$)	8.926 [0.493][a]			9.016 [0.522][a]	8.994 [0.525][a]

υ, running velocity, t_c, contact time (s); t_f, flight time (s); m, body mass (kg); S_l, step length; S_f, step frequency; LDM device, laser distance measurement device; High-speed camera[a], average velocity determined by averaging the resultant of the horizontal and vertical velocities of the CM at touchdown, maximum knee flexion and take-off; High-speed camera[b], velocity for each step determined by multiplying S_l and S_f; High-speed camera[c], peak velocity determined by identifying the maximum resultant of the horizontal and vertical velocities of the CM at either touchdown, maximum knee flexion and take-off; LDM device[a], average velocity determined by identifying either 42 to 47 m, 47 to 52 m and 42 to 52m splits on the data trace; LDM device[b], peak velocity determined by identifying individual points on the data trace.

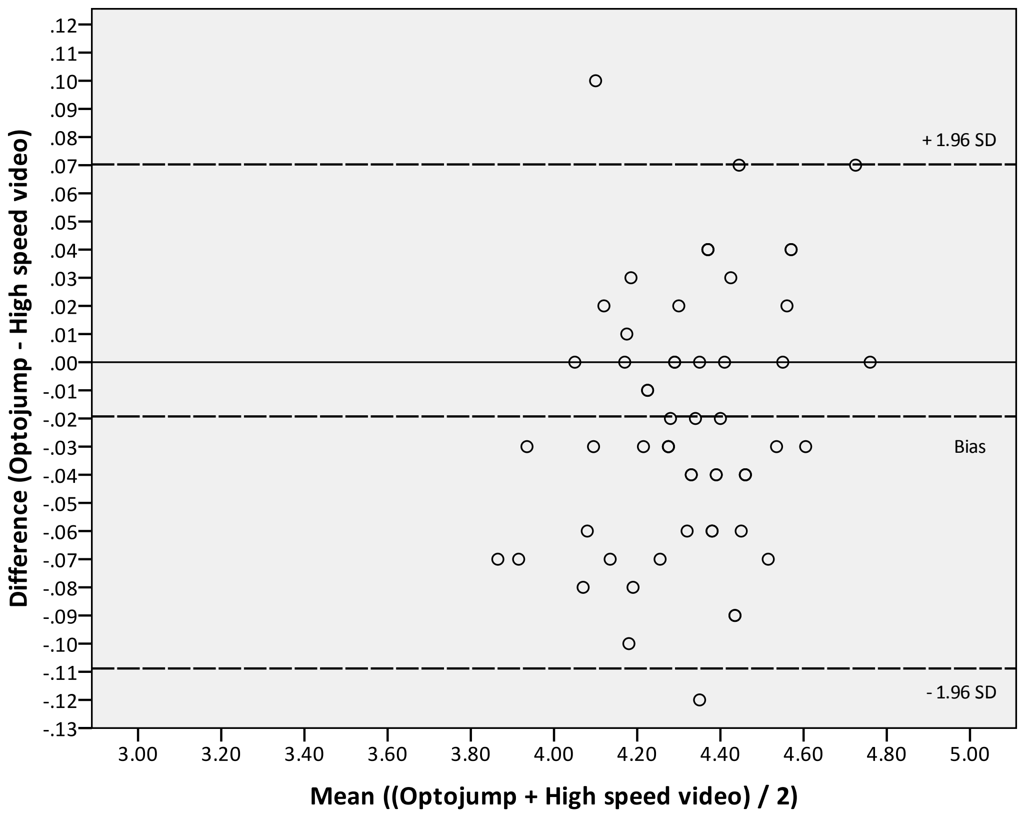


Figure 3.2 Bland-Altman plot comparing step frequency derived from the Optojump and high-speed video during running. Dash lines represent bias and 95% limits of agreement

To investigate further the validity of the gait and spring-mass characteristics reported by Optojump and high-speed video an intraclass correlation coefficient and confidence limits were determined, see Table 3.4. All biomechanical parameters reported an intraclass correlation coefficient of greater than 0.980 which is deemed as an almost perfect agreement. Contact time and flight time for Optojump and high-speed video reported confidence limits of 0.978-0.992 and 0.967-0.989 respectively. Velocity and step frequency reported the largest range of confidence limits (0.983-0.994 and 0.974-0.991, respectively); however, all variables reported confidence limits with in minimal range. The coefficient of variation values stated for contact time (0.79%) flight time (0.23%), velocity (1.12%), step length (0.54%) and step frequency (0.92%). The lowest intraclass correlation coefficient was reported for flight time. Figure 3.3 presents a Bland-Altman plot illustrating the systematic bias and 95% limits of agreement between the Optojump and high-speed video when quantifying flight time.

Table 3.4 Intraclass correlation coefficient and 95% confidence intervals of Optojump and high-speed video in determining biomechanical parameters

	1	
	Optojump versus high-speed video[b]	
Biomechanical parameters	**ICC**	**95% CI**
υ ($m \cdot s^{-1}$)	0.990	0.983-0.994
t_c (s)	0.987	0.979-0.992
t_f (s)	0.981	0.967-0.989
S_l (m)	0.995	0.992-0.997
S_f (Hz)	0.985	0.974-0.991

υ, running velocity, t_c, contact time (s); t_f, flight time (s); m, body mass (kg); S_l, step length; S_f, step frequency; LDM device, laser distance measurement device; running velocity was determined from step frequency multiplied by step length; ICC, intraclass correlation coefficient; CI, confidence limits; High-speed camera[b], velocity for each step determined by multiplying S_l and S_f.

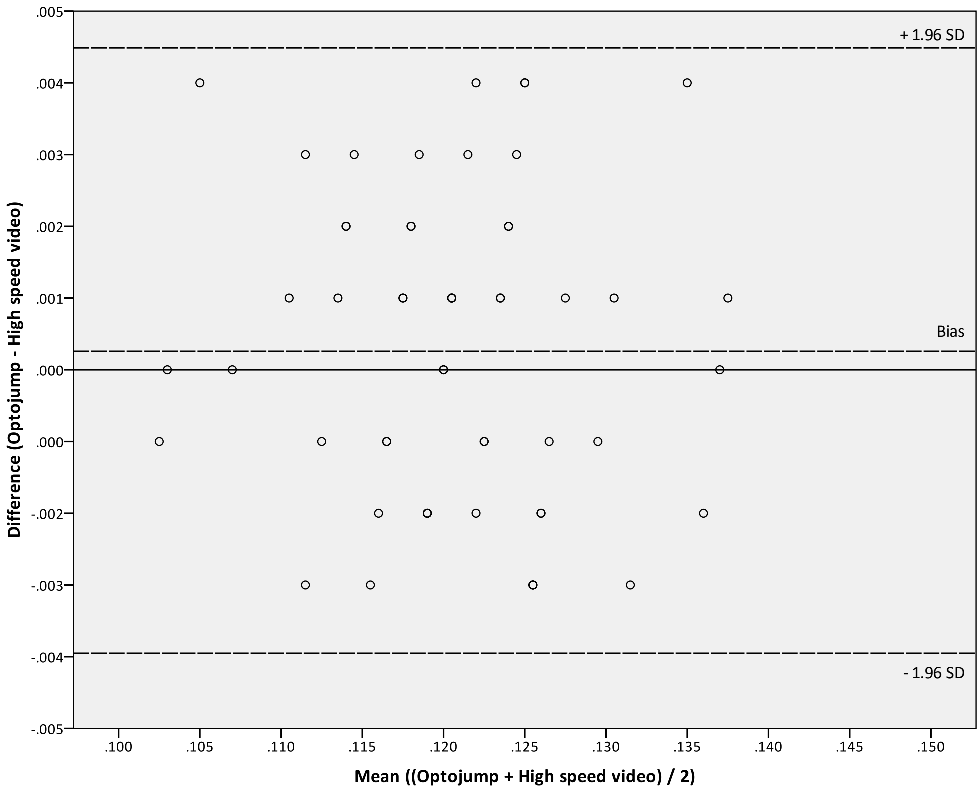


Figure 3.3 Bland-Altman plot comparing flight time derived from the Optojump and high-speed video during running. Dash lines represent bias and 95% limits of agreement

The mean difference of average velocity for front and rear LDM devices was 0.022 ± 0.039 m·s^{-1}. Front LDM device and high-speed video reported a higher mean difference of 0.090 ± 0.110 m·s^{-1} in average velocity compared to rear LDM device and high-speed video (0.068 ± 0.108 m·s^{-1}). The coefficient of variation values reported for average velocity was less than 0.99%. Figure 3.4 presents a Bland-Altman plot illustrating the systematic bias and 95% limits of agreement between the front and rear LDM devices when quantifying average velocity. Rear LDM device consistently presented lower average and peak velocity values compared to front LDM device.

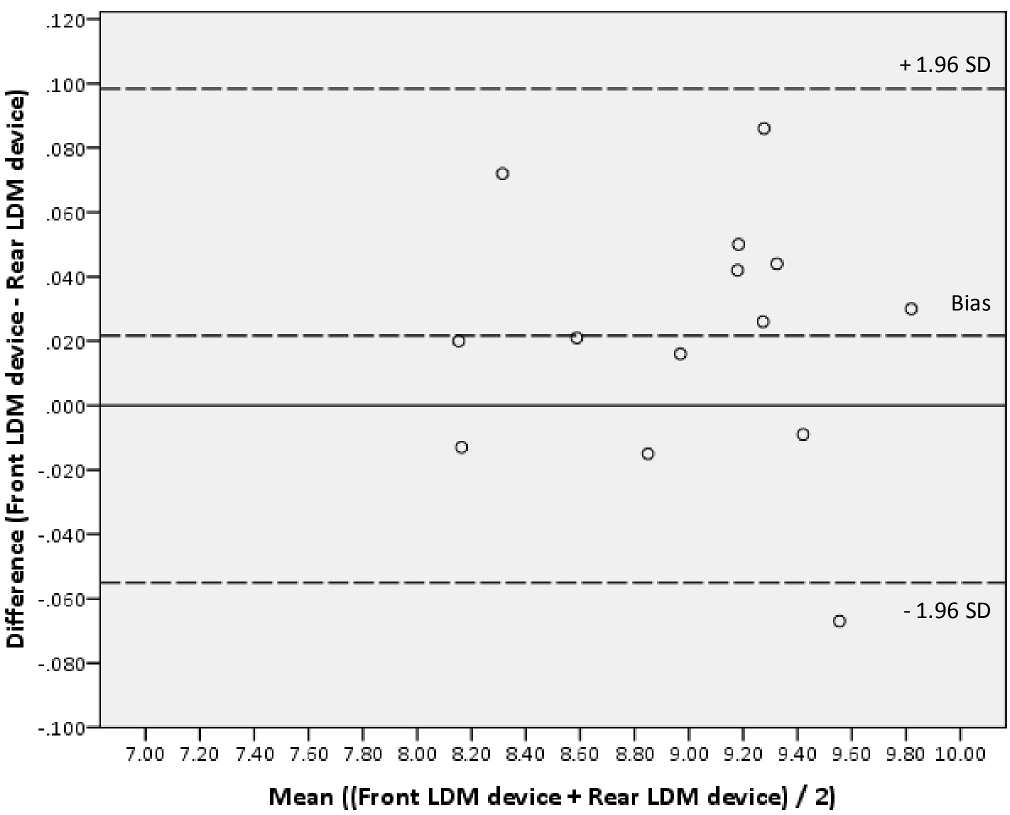


Figure 3.4 Bland-Altman plot comparing average velocity derived from front and rear laser distance measurement devices during running. Dash lines represent bias and 95% limits of agreement

Variation was reported in the peak velocity quantified by high-speed video, front and rear LDM devices, see Table 3.3 and Table 3.5. Peak velocity for front LDM device and high-speed video reported a lower mean difference than rear LDM device and high-speed video (0.082 ± 0.131 $m \cdot s^{-1}$ and 0.271 ± 0.071 $m \cdot s^{-1}$ respectively). The mean difference of peak velocity for front and rear LDM devices was 0.189 ± 0.115 $m \cdot s^{-1}$. The coefficient of variation values reported for peak velocity determined by front LDM device versus high-speed video (1.34%) and rear LDM device versus high-speed video (2.92%). The relationship between peak velocity values derived front LDM device and high-speed video and 95% limits of agreement are present in Figure 3.5.

Table 3.5 Intraclass correlation coefficient, 95% confidence intervals and coefficient of variation of front laser distance measurement device, rear laser distance measurement device and high-speed video determining peak and average velocity.

	1			2		
	Front LDM device versus high-speed video			Rear LDM device versus high-speed video		
Biomechanical parameters	**ICC**	**95% CI**	**CV**	**ICC**	**95% CI**	**CV**
Peak υ ($m{\cdot}s^{-1}$)	0.985	0.985-0.995	1.34%	0.995	0.986-0.999	2.92%
Average υ ($m{\cdot}s^{-1}$)	0.988	0.963-0.996	0.99%	0.989	0.965-0.996	0.74%

LDM device, laser distance measurement device; ICC, intraclass correlation coefficient; CI, confidence limits; CV, coefficient of variation; peak and average running velocity was determined by high-speed video using the 18-point model; peak and average running velocity was determined by LDM by individual points/splits on the data trace.

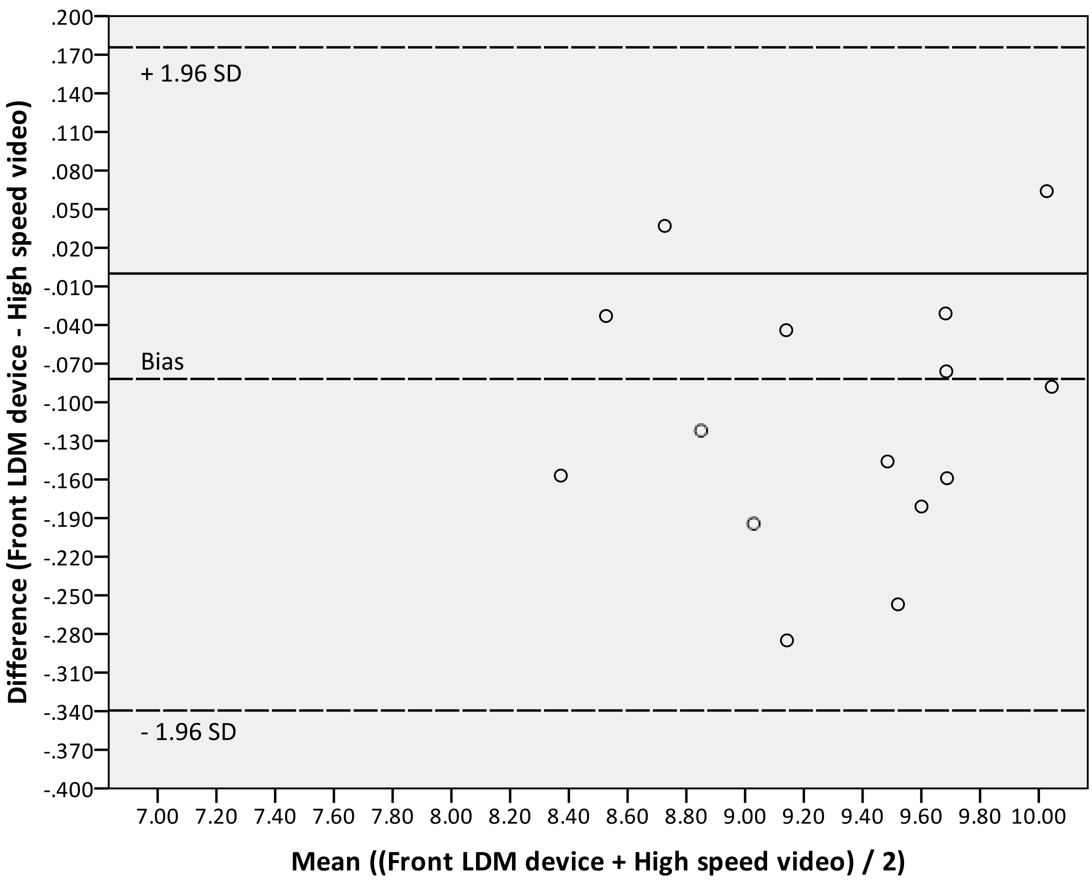


Figure 3.5 Bland-Altman plot comparing peak velocity derived from front laser distance device and high-speed video during running. Dash lines represent bias and 95% limits of agreement.

3.4. Discussion

The aim of this investigation was to quantify the measure of agreement of video (digital [50Hz] and high-speed camera [300 Hz]) compared to Optojump and LDM devices in obtaining contact time, flight time, step length, step frequency and running velocity. Through focusing on a cohort of track athletes, it was hypothesised that in accordance with previous research (Harrison et al., 2005; Lehance et al., 2005), that a digital (50Hz) and high-speed camera (300 Hz) compared to Optojump and LDM device would provide a valid measure of contact time, flight time, step length, step frequency and running velocity during high running velocity on a synthetic athletics track. All gait characteristics observed throughout this study were similar to those previously reported for track athletes (Mann et al., 1984; Salo et al., 2011). The findings from this study identified that gait characteristics determined by video were comparable to those reported by Optojump and LDM devices. Also the scatter plots illustrated homoschedascity (e.g. the bias between the methods was not influenced by the overall magnitude of measurement) further supporting the validity between methods.

Whilst variations in gait characteristics were observed between each biomechanical system, these were deemed to be valid for each parameter investigated (intraclass correlations >0.980). This meant that gait and spring-mass characteristics could be determined from video (digital [50Hz] and high-speed camera [300 Hz]), Optojump and LDM devices during both training and competition. Data collected from the Optojump system showed a difference in the mean flight time of 0.001s compared to high-speed video. The differences elicited by Optojump and high-speed video may be explained in part by the sampling frequencies employed by each system (100Hz compared to 300Hz, respectively). The variation in sampling frequency of a biomechanical system has considerable implications, particularly at high running velocities. A low sampling frequency can lead to gross under or over estimations of initial touchdown and take-off events which will affect the derived gait characteristics. The potential for a key event to be under- or over-estimated increases as the sampling frequency decreases, if each key event (e.g. point of initial touchdown) is out by three or four data points this could have severe implications on the derived data. For example, a camera that has a sampling frequency of 120 frames per second for 0.100 second will only give 12 frames that can be digitised. This can lead to gross under-estimations of segment or CM displacement as only 12 frames will be used to inform the movement of the body (Brughelli & Cronin, 2008b).

Another possible explanation for the differences in data obtained from Optojump and high-speed video is the method used to determine contact and flight time (e.g. the identification of initial touchdown and take-off key events). Optojump identifies initial touchdown and take-off events by a break in the LEDs which are positioned along the parallel bars just above the ground surface. Therefore, the Optojump system may consider the athlete to be in contact with the ground due to the break in the LEDs; however, the athlete may not have physically made contact with the ground. Initial touchdown is determined in high-speed video to be the first frame in which the foot has made clear contact with the ground. Take-off is identified through high-speed video as the first frame in which the foot has clearly left the ground. Despite these differences findings from this study acknowledge that contact and flight times quantified by Optojump and high-speed video have a comparable measurement error equivalent to less than one video frame (<0.003s). There was variation in the reported step frequency, as a consequence to a variation in flight time between Optojump and high-speed video which accounts for the discrepancy in derived running velocity. These findings concurred with those of Ogueta-Alday et al. (2013) stating that both Optojump and high-speed footage is valid and sensitive enough to detect small changes in gait characteristics during running. Sport biomechanists can now confidently use high-speed video and Optojump away from the laboratory setting on synthetic athletic tracks to quantify gait characteristics that influence an athlete's ability to maintain running velocity (Figure 1.2).

It has been well-documented that running velocity is defined as the product of step length and step frequency (Salo et al., 2011). The maintenance of a high running velocity is therefore the result of an optimal combination of step length and step frequency (Salo et al., 2011). This study contradicts the conclusions of Glazier and Irwin (2001) who stated that step length estimates obtained from Optojump lacked sufficient validity. The present study reported no difference in step length between Optojump and video. This contradicted the findings of Glazier and Irwin (2001) who reported between 0.04 m and 0.23 m in variance in step lengths for one participant obtained by Optojump compared to video. Differences in methods used to quantify step lengths from video may account for these discrepancies between the current study and that of Glazier and Irwin (2001). The present study compared three methods of quantifying step length; panning digital video, high-speed video and Optojump. These three biomechanical systems reported identical mean step length values, without impeding the athlete. Both the panning digital video and high-speed video determined step length by identifying individual foot placement distances from 1 m markings placed perpendicular to the track. Future uses for this method in the identification of foot placement are supported by the high intraclass correlation coefficient and confidence limits values as well as the low coefficient of variation values (Table 3.3).

A comparison of velocity values quantified by high-speed video, front LDM device and rear LDM device reported a high intraclass correlation coefficient (≥0.984) signifying that these three biomechanical systems provide a valid measure of velocity. These findings concur with those of Harrison et al. (2005) who report an intraclass correlation coefficient of greater than 0.980 when comparing LDM device and video-based average running velocity data (Table 3.5). These findings are important as it confirms that running velocity can be determined by high-speed video and LDM devices. Bruggemann and Glad (1990) and Bezodis (2009) concurred with this and advocated the use of LDM devices and high-speed video to quantify running velocities. During training either high-speed and LDM devices can be used to quantify running velocity, whereas, during competition only high-speed cameras can be used due to the restrictions of the environment. When compared against front and rear LDM devices the high-speed video reported a larger range of confidence limits (Table 3.5). There were also variations between the rear and front LDM devices with the rear LDM device consistently presenting lower mean and peak running velocity values. Harrison et al. (2005) stated that variations between LDM devices and high-speed video may be explained by the different methods each of the systems obtains displacement measurements. High-speed video quantifies CM velocity by utilising a whole body model which derives CM and subsequently running velocity of the body as a whole (Cronin & Templeton, 2008). In contrast, the LDM devices determine running velocity from the horizontal displacement of the athlete; the accuracy of which is determined by the sport biomechanists ability to continually track the athlete. The displacement data acquired by the LDM device relates to the motion of a point on the surface of an athlete (typically in the lumbar/stomach region), which depending on the position of the LDM device could influence the accuracy of data collection.

The difference in how running velocity is determined may also help explain the variation of peak running velocity quantified by high-speed video, front and rear LDM devices. The mean difference in the peak velocity for the front LDM device and rear LDM device was lower than that reported for the high-speed video (Table 3.5). These variations in the peak running velocity exhibited by LDM devices could also be due to the subjective nature of selecting the peak from the trace. Nevertheless the peak values obtained from both LDM devices were deemed valid.

To interpret rapid changes in velocity and acceleration using a whole body model high-speed video is recommended; however, this requires considerable post-session processing time. In cases where average velocity or split times are the preferred outcome LDM devices should be employed. For instance, during a long jump run up average approach velocities between 11 m to 6 m and 6 m to 1 m from the board help determine if an athlete is slowing down into the board/take off. Findings demonstrate that average velocity values were valid when determined from all biomechanical systems.

A limitation of the LDM device is it is constrained to a straight-line measurement only (line of sight) but can be placed either behind the start line (tracking the rear of athlete) or behind the finish line (tracking the front of athlete). This is the first study to examine the consistency and repeatability of the LDM device position giving a comparison of from the front and rear when tracking athletes. Bruggemann et al. (1999) and Harrison et al. (2005) reported running velocities quantified by LDM devices which were positioned behind the start line (tracking the rear of the athlete), the rationale for this was never justified but may be due to the practicalities imposed by data collection. Results from this study demonstrated that LDM devices positioned behind the start line (tracking the rear of athlete) and behind the finish line (tracking the front of athlete) produced consistent and valid velocity values.

This study allows for the justification to use LDM devices in either position enabling the sport biomechanist to determine the most appropriate placement of the device. For example, during long jump it may be more practical for the sports biomechanist to position the LDM device at the end of the sand pit (tracking the front of the athlete); this will allow the runway to be kept clear as well as allowing a larger image size of the athlete as they approach the take-off board. In contrast, it may be more practical when examining running velocity on a track for the sports biomechanist to position the LDM device behind the start line (tracking the rear of the athlete) so to allow appropriate deceleration distance after the athlete has crossed finishing line. Another example of appropriate LDM device positioning is during pole vault, where the LDM device should be located at the rear of the athlete so to avoid tracking errors as the pole is lowered in the final stages of the run up.

3.5. Conclusions

The aim of this investigation was to quantify the validity of digital (50Hz) and high-speed camera (300 Hz) compared to Optojump and LDM device in obtaining contact time, flight time, step length, step frequency and running velocity in the field. The main findings from this study were that gait characteristics obtained from digital (50Hz) and high-speed camera (300 Hz) were comparable to Optojump and LDM devices. Bland-Altman plots indicate that bias is minimal for each gait and spring-mass characteristics and scatterplots revealed homoscedasticity. This facilitates the quantification of gait and spring-mass characteristics during training and competition with any of these biomechanical systems. Findings from the present study demonstrated that contact and flight times quantified by Optojump and high-speed video have an acceptable amount of measurement error; which was equivalent to less than one video frame ($\geq$ 0.003s). Through the use of video this study has confirmed that gait characteristics can be documented away from the laboratory setting (e.g. training and competitive races). This allows coaches and sport biomechanists to confidently capture gait characteristics using only video during a running performance. This had previously not been possible but now allows for the assessment of gait characteristics and lower limb neuromuscular behaviour to be documented during training and competition.

Lower limb neuromuscular behaviour has been suggested to influence running velocity and performance time, Figure 1.1 and Figure 1.3 (Brughelli & Cronin, 2008b; Butler et al., 2003). Collection of stiffness data had previously required force platforms which were not always deemed appropriate to use away from a laboratory. It is now possible to estimate an athlete's stiffness using mathematical models from characteristics such as; body mass, running velocity, leg length and contact and flight time (Morin et al., 2005). Only one study has provided a comparison of estimations (by mathematical modelling) to direct measurements (by a force platform) for determining stiffness (Morin et al., 2005). This study however lacked clarity. Therefore, more detailed research is required to provide a comparison of stiffness values obtained through mathematical modelling (estimations based on high-speed video data only) and direct measurement (using a force platform).

CHAPTER 4: ASSESSMENT OF SPRING-MASS CHARACTERISTICS: VALIDATION OF METHODS IN MIDDLE-DISTANCE RUNNING

4.1. Introduction

Simple mathematical models have been used to determine the essential features of sagittal plane motion during running (Blickhan, 1989; McMahon & Cheng, 1990). These models represent the leg as a massless spring that compresses on contact with the ground; often referred to as the spring-mass model (Avogadro et al., 2004a; Morin et al., 2005). The compression of the leg results in a displacement of the CM; with the model depicting this displacement as it sweeps through an arc during the contact phase (Brughelli & Cronin, 2008a). This compression can be reported as vertical (K_{vert}) and leg (K_{leg}) stiffness. Vertical stiffness is the resistance of the body to vertical displacement (CM displacement, Figure 2.3) after application of ground reaction force during the contact phase (Brughelli & Cronin, 2008a). Whereas, K_{leg} is the resistance to the change in leg length after application of ground reaction forces during the contact phase (Butler et al., 2003). The gold standard for measuring K_{vert} and K_{leg} is the direct measurement of the spring-mass model through the use of a force platform (Arampatzis et al., 2000; Morin et al., 2005). Vertical and leg stiffness can also be estimated by mathematical modelling, these are often used when the gold standard direct measurement (using a force platform) is not possible or deemed appropriate (Morin et al., 2005). It remains unclear how comparable mathematical models (using only high-speed video) are to the gold standard direct measurement (using a force platform) when estimating stiffness during running.

There is paucity in the comparisons between the gold standard direct measurement and mathematical models in determining stiffness (refer to the review of literature section

2.4 for more information). Significant discrepancies in reporting K_{leg} and its response to running velocity have been shown between Arampatzis et al. (1999) and McMahon and Cheng (1990) mathematical models. The majority of running research has employed Morin et al. (2005) mathematical model to estimate K_{vert} and K_{leg} during velocities of 6.00 m·s^{-1} to 12.19 m·s^{-1} (He et al., 1991; Hobara et al., 2010a; Morin et al., 2006; Morin, Tomazin, Edouard, & Millet, 2011c; Taylor & Beneke, 2012). This mathematical model has been validated by comparing stiffness values measured to the gold standard direct measurement (e.g. force platform) to those estimated through mathematical modelling during running velocities of 3.33 m·s^{-1} to 7.00 m·s^{-1} (Morin et al., 2005). Morin et al. (2005) reported a percentage difference of 0.67% for maximal vertical ground reaction forces and 6.93% for the displacement of CM when comparing the gold standard direct measurement to the estimation (by mathematical modelling). Estimations of maximal vertical ground reaction forces are based on the sine function previously used by Dalleau, Belli, Viale, Lacour, and Bourdin (2004) to model the force-time curve (for more details refer to chapter 2). The sine function requires the measurement of; initial leg length, running velocity, body mass, contact and flight time to estimate maximal vertical ground reaction forces.

The accuracy of the sine function (to model the force-time curve) improves at higher velocities during treadmill running; with the percentage difference ranging from 11.7% at 3.33 m·s^{-1} to 1.7% at 6.67 m·s^{-1} (Morin et al., 2005). The percentage difference of the sine function fitting the force-time curve was constant; however, the influence of increasing running velocity from 6.00 m·s^{-1} to maximal did significantly influence K_{vert}. To the contrary, this velocity effect on bias was not observed during overground running (Morin et al., 2005). The sensitivity of K_{vert} and K_{leg} measured by the gold standard direct measurement compared to estimations by mathematical modelling has been documented during treadmill (5%) and overground running (3%), which the authors deemed acceptable (Morin et al., 2005). Findings from this study were limited to mean error bias, K_{vert} and K_{leg} values only. Gait and spring-mass characteristics achieved at each running velocity were omitted from this study; therefore, the impact of increasing running velocity on each gait and spring-mass characteristics used to estimate stiffness (by mathematical modelling) in unknown.

There are several key assumptions in Morin et al. (2005) mathematical model which have only been investigated in the original research article (Morin et al., 2005). These assumptions include that; the maximum compression of the limb will occur at the same time that the CM reaches its lowest position; velocity and displacement of CM are equivalent before; and after mid-stance and leg length at the moment of ground contact is equal to the initial leg length while standing. The initial leg length while standing is determined by muliplying the athletes height to a constant value (0.53). It is also assumed that the flight time remains constant during a single gait cycle (e.g. flight time is the same on the left and right). Until research presents the validity of estimations (by mathematical modelling) and the gold standard direct measurement (by a force platform) for determining stiffness; the full importance of K_{vert} and K_{leg} will remain unknown.

The primary aim of this study is to assess the validity of stiffness values obtained through mathematical modelling (estimations based on high-speed video data only) in determining K_{vert} and K_{leg} during running to the gold standard direct measurement (using a force platform). It was hypothesised that estimations (by mathematical modelling) would allow for the documentation of stiffness when the gold standard direct measurement of stiffness was not possible. The secondary aim was to establish the validity of mathematical models (using only high-speed video) to the gold standard direct measurement (using a force platform) in responding to an increase in running velocity. Based on previous findings it was hypothesised that a mathematical model (using only high-speed video) and the gold standard direct measurement (using a force platform) would allow for valid estimations of stiffness at a range of velocities.

4.2. Method

4.2.1. Participants

Following written informed consent six distance runners (mean ± SD age: 24 ± 4 years; stature: 1.82 ± 0.08 m; body mass: 71.83 ± 6.15 kg) volunteered to participate in this study as part of their normal training session. The University of Salford Manchester Research, Innovation and Academic Engagement Ethical Approval Panel and UK Athletics approved biomechanical investigations which did not involve any invasive procedures to be undertaken during training sessions. All participants were distance runners who regularly competed (mean ± SD time in discipline: 9 ± 3 years) and were all based at the UK Athletics High Performance Institute. Athletes had extensive experience of running at predetermined running velocities as such no familiarisation period was required. The information was also used by the coach and athlete for monitoring purposes. All experimental methodology was performed in accordance with the Declaration of Helsinki.

4.2.2 Data Collection

Pilot testing was undertaken to establish a protocol which would minimise the impedance to the athletes and, enable the most repeatable measurements to be taken. All athletes wore closely-fitting clothes and their own running spikes. The athletes performed runs at 5.00 $m \cdot s^{-1}$, 6.50 $m \cdot s^{-1}$ and 8.50 $m \cdot s^{-1}$ (+/- 10%) interspersed by 7 to 10 minutes of passive recovery. An illustration of biomechanical set-up can be seen in Figure 4.1. Gait and spring-mass characteristics were quantified using high-speed video cameras, force platforms and timing gates. Two high-speed video cameras (EX-F1, Casio, Japan), sampling at 300 Hz, were positioned 9.50 m from the centre of the running lane and 1.10 m above the track surface. Refer to data collection 3.2.2 for more information on camera set-up and calibration.

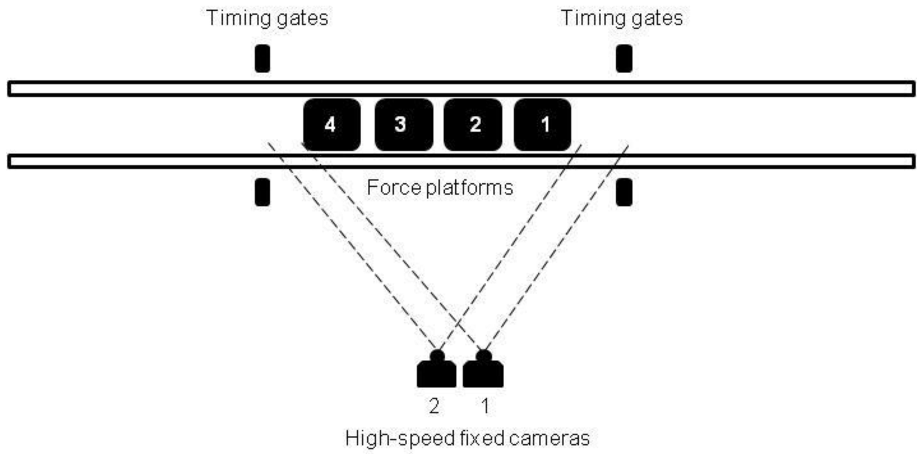


Figure 4.1 An illustration of biomechanical set-up

The system used consisted of four individual force plates (600 x 400 x 35 mm) connected in series, covered with 0.014 m thick tartan track (Altro Mondo Sportflex). The use of four force platforms meant that ground reaction forces of between one and two contacts could be quantified per run (depending on the step length and the separated distance of the first foot contact from the entrance of the force plate area). All force platforms (Kistler, model 9286BA, Kistler Instruments, Winterthur, Switzerland) were interfaced with a computer and were used to record the vertical components of the ground reaction force. Instacal was used to configure each of the force platforms. The force signals were sampled at 1200 Hz. All force platforms measured body weight reporting a typical error of ± 3.64 N calculated in accordance with Hopkins (2000). Recorded forces were normalised to the body weight of the distance runners. Leg length was measured as the great trochanter to ground distance in a standing position in accordance with previous literature (Morin et al., 2005).

Average running velocity was measured by using two pairs of timing gates for each run (Brower Timing Systems, Draper, UT). Previous investigations using timing gates have found typical errors of between 1% and 2%, this was deemed acceptable (Cronin & Templeton, 2008). Timing gates were placed at 10 and 15 m from the start line, this allowed all participants to have a rolling start before entering the timing gates. Details of this equipment and appropriate set-up where in accordance with previous research (Cronin & Templeton, 2008). Athletes were instructed to begin their run from a static position. Split times were recorded from a wireless receiver accurate to 0.001s. Average running velocity was derived during data collection from the timing gates by dividing the displacement of the athlete (measured distance; 5 m) by the time taken to travel the given distance (split time). Average running velocity provided by timing gates allowed for each successful run to be classified as either 5.00m·s^{-1}, 6.50m·s^{-1}, 8.50m·s^{-1} (+/- 10%) or unsuccessful.

Gait characteristics (including step length, step frequency, contact and flight time; see data collection 3.2.2 for more information) and were quantified for each successful run achieved at 5.00m·s^{-1}, 6.50m·s^{-1} and 8.50m·s^{-1} in line with previous K_{vert} and K_{leg} research (Morin et al., 2005). A range of +/- 10% was implemented to provide clear distinct running velocities (with no overlap). These ranges represented three well-defined running velocities that were easily recognisable to the athletes included in this study. Running velocities were recognised as; 5.00 m·s^{-1} as “tempo - 5 minute mile pace”, 6.50 m·s^{-1} as “1500 m pace” and 8.50 m·s^{-1} as “fast”. A trial was deemed successful if the athlete was able to strike the force platform, at one of the three predetermined running velocities, without noticeably or consciously altering their stride pattern. If an athlete was deemed to be targeting the force platform or appeared to be shortening or reaching for the force platform the trial was excluded from the study. Trials were also discounted if the athletes missed the force platform or if their foot was placed on the edge of the platform. To help prevent athletes altering their stride pattern; athletes were not told whether the trial was successful or not in accordance with Abendroth-Smith (1996).

4.2.3 Data Analysis

A typical example of the vertical component of the ground reaction force measured during a run is presented in Figure 4.2. Each trial included at least one ground contact on a force platform. Maximal vertical ground reaction forces (F_{max}) were measured for each contact (amplitude of the active peak, Figure 4.2 point B).

High-speed video data were imported into Quintic Biomechanics (Quintic Consultancy Ltd, 9.03 version 17) and manually digitised (for more detailed information concerning data analysis refer to section 3.2.2). Measurement error and intra-operator error has previous been investigated for gait and spring-mass characteristics parameters have been reported elsewhere (for more details refer to chapter 3). Stiffness values were calculated for each contact (that coincided with athlete striking the force platform). Vertical stiffness was calculated using methods A to E for each contact (Table 4.1 and Figure 4.3). Method A determines K_{vert} through the gold standard direct measurement (force platform); whereas methods B, C, D and E report estimates of stiffness (by mathematical modelling; using a high-speed camera).

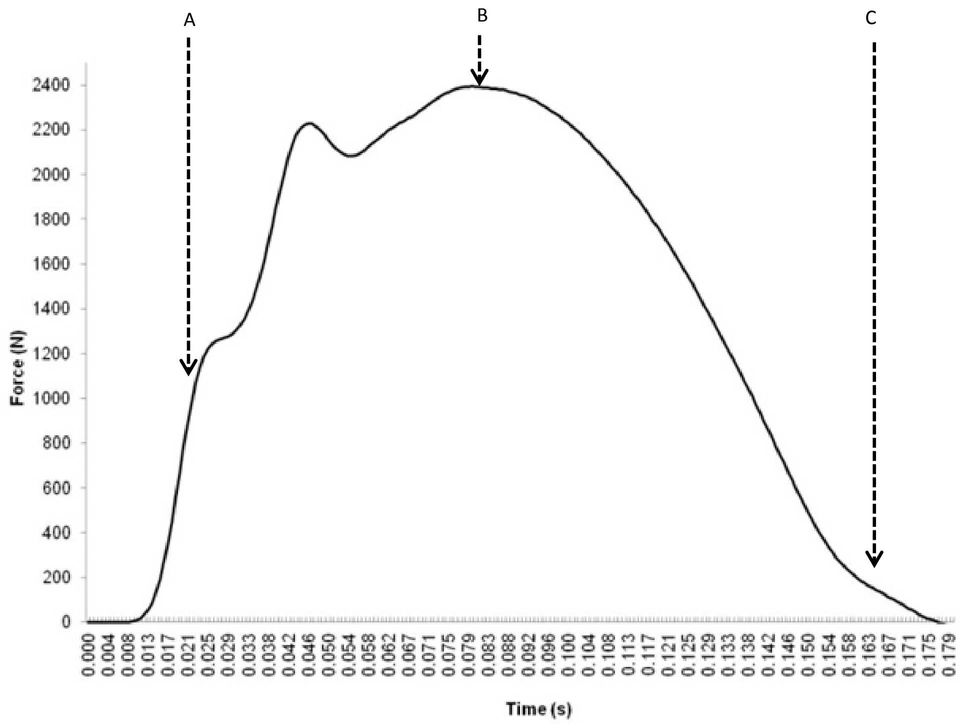


Figure 4.2 Typical example of the vertical ground reaction force measured during a run A) initial touchdown, B) maximum knee flexion and C) take-off

Leg stiffness was calculated using methods F to J for each contact with method 1 and 5 to determine initial leg length (Table 4.2 and 4.3 and Figure 4.4). Method F determines K_{leg} through the gold standard direct measurement (force platform); whereas methods G, H and J estimates stiffness (by mathematical modelling; using a high-speed camera). Methods 1 to 5, in Table 4.3, highlight the diverse manner in which previous research has examined displacement relative to a particular point, whether this is by the measurement of the CM to ankle CM or the double integration of the vertical acceleration over time (Dapena & Chung, 1988; McMahon & Cheng, 1990). Average running velocity used in methods G and H was determined through the digitisation of high-speed video instead of timing gates; this facilitated accurate measurement of running velocity for each contact. The accurate measurement of running velocity is critical as literature has identified running velocity as one of the gait characteristics that influence K_{vert} and K_{leg} values (Morin et al., 2005; Morin, Tomazin, Samozino, Edouard, & Millet, 2011d).

Table 4.1 Input parameters, equations of vertical stiffness and required calculations for methods A to E

Method	Study	Parameters Required	Equipment	Calculations	
A	McMahon and Cheng (1990) gold standard direct measurement	F_{max}, Δy	Force platform	$K_{vert} = F_{max} / \Delta y$	$F_{max} =$ determined during contact $\Delta \gamma =$ determined by double integration of the vertical acceleration over time
B	Morin et al. (2005)	Δy, t_c, T_f, t_f, m	High-speed camera	$K_{vert} = F_{max} / \Delta y$	$\Delta \gamma = \frac{F_{max} t_c^2}{m\pi^2} + g\frac{t_c^2}{8}$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $t_f = \frac{t_c + T_f}{2} - t_c$
C	Morin et al. (2005)**	Δy, t_c, t_f, m	High-speed camera	$K_{vert} = F_{max} / \Delta y$	$F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $\Delta \gamma =$ determined by digitised 18-point model (min and max CM displacement)
D	Morin et al. (2005)**	Δy, t_c, t_f, m	High-speed camera	$K_{vert} = F_{max} / \Delta y$	$F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $\Delta \gamma =$ determined by digitised 18-point model (min and max CM to ankle joint displacement)
E	Morin et al. (2005)**	Δy, t_c, t_f, m	High-speed camera	$K_{vert} = F_{max} / \Delta y$	$F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$ $\Delta \gamma =$ determined by digitised 18-point model (min and max CM to foot CM displacement)

** F_{max} derived using Morin et al. (2005) with Δy derived by another means; K_{vert}, vertical stiffness ($kN \cdot m^{-1}$); F_{max}, maximal vertical ground reaction force (kN); Δy, vertical displacement of the centre of mass (m); t_c, contact time (s); t_f, flight time (s); T_f, time from take-off to initial touchdown of same leg; m, body mass (kg)

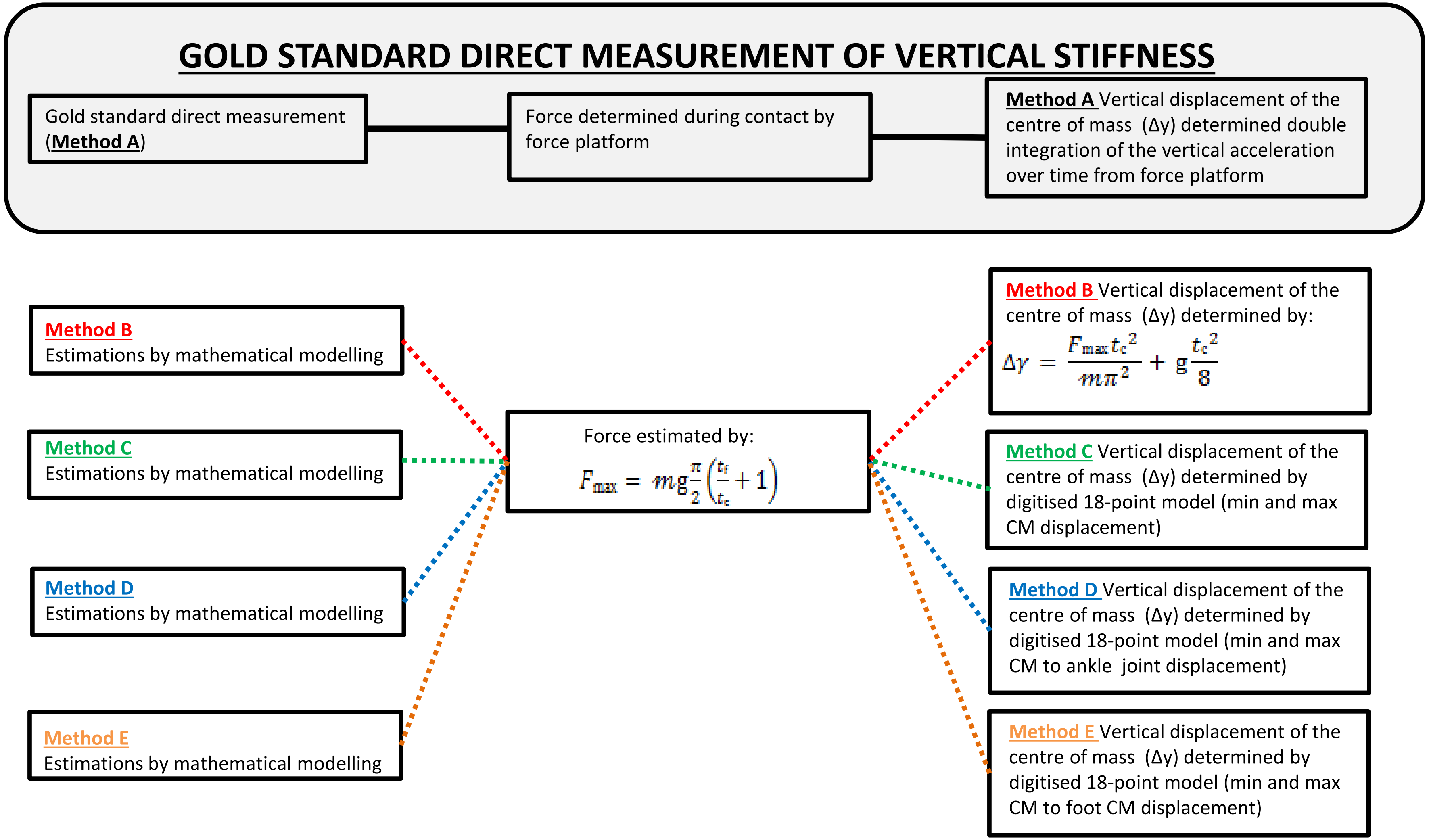


Figure 4.3 Diagram to illustrate the differences in calculations between the gold standard direct measurement for vertical stiffness (Method A) compared to estimations by mathematical modelling (Methods B, C, D and E)

Table 4.2 Input parameters, equations of leg stiffness and required calculations for methods F to J

Method	Study	Parameters Required	Equipment Required	Calculations	
F	McMahon and Cheng (1990) gold standard direct measurement	F_{max}, ΔL	Force platform	$K_{leg} = F_{max}/\Delta L$	$F_{max} =$ determined during contact $\Delta L = \Delta y + L_0(1\ cos -\ \theta)$ $\theta = \sin^{-1}\left(\frac{\upsilon t_c}{2L_0}\right)$
G	Morin et al. (2005)	L_0, υ, t_c, t_f, Δy, m	High-speed camera	$K_{leg} = F_{max}/\Delta L$	$\Delta L = L_0 - \sqrt{L_0^2 - \left(\frac{\upsilon t_c}{2}\right)^2} + \Delta y$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c} + 1\right)$
H	Morin et al. (2007) and Morin et al. (2005)	L_0, υ, t_c, t_f, d, Δy, m	High-speed camera	$K_{leg} = F_{max}/\Delta L$	$L = L_0 - \sqrt{L_0^2 - \left(\frac{\upsilon t_c - d}{2}\right)^2} + \Delta y$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c} + 1\right)$
J	Mcmahon and Cheng (1990) and Morin et al. (2005)**	L_0, t_c, t_f, m	High-speed camera	$K_{leg} = F_{max}/\Delta L$	$\Delta L = \Delta y + L_0(1\ cos -\ \theta)$ $\theta = \sin^{-1}\left(\frac{\upsilon t_c}{2L_0}\right)$ $F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c} + 1\right)$

** F_{max} derived using Morin et al. (2005) with ΔL derived by McMahon and Cheng (1990); K_{leg}, leg stiffness ($kN{\cdot}m^{-1}$); F_{max}, maximal vertical ground reaction force (kN); ΔL, displacement of the leg spring (m); Δy, vertical displacement of the centre of mass (m); L_0, initial length of the leg spring (m); υ, forward speed ($m{\cdot}s^{-1}$); t_c, contact time (s); t_f, flight time (s); m, body mass (kg); d, point of force translation distance (m); α_{TD}, leg angle relative to x-axis at initial touchdown (^{o})

Table 4.3 Input parameters required to determine initial leg length methods 1 and 5 (methods used in leg stiffness calculations)

Method	Study	Parameters Required	Calculations/Measurement
1	McMahon and Cheng (1990); Morin et al. (2005) gold standard direct measurement	h	$L_0 = 0.53h$
2	Morin et al. (2007) and (Morin et al., 2013)	L_0	L_0 = vertical distance from the greater trochanter to ground while standing
3	[not yet examined in the K_{leg} research]	L_0	L_0 = vertical distance from the CM to ground at initial touchdown
4	[not yet examined in the K_{leg} research]	L_0	L_0 = vertical distance from the CM to the foot CM at initial touchdown
5	[not yet examined in the K_{leg} research]	L_0	L_0 = vertical distance from the CM to the ankle joint at initial touchdown

h, athlete height (m); L_0, initial length of the leg spring (m)

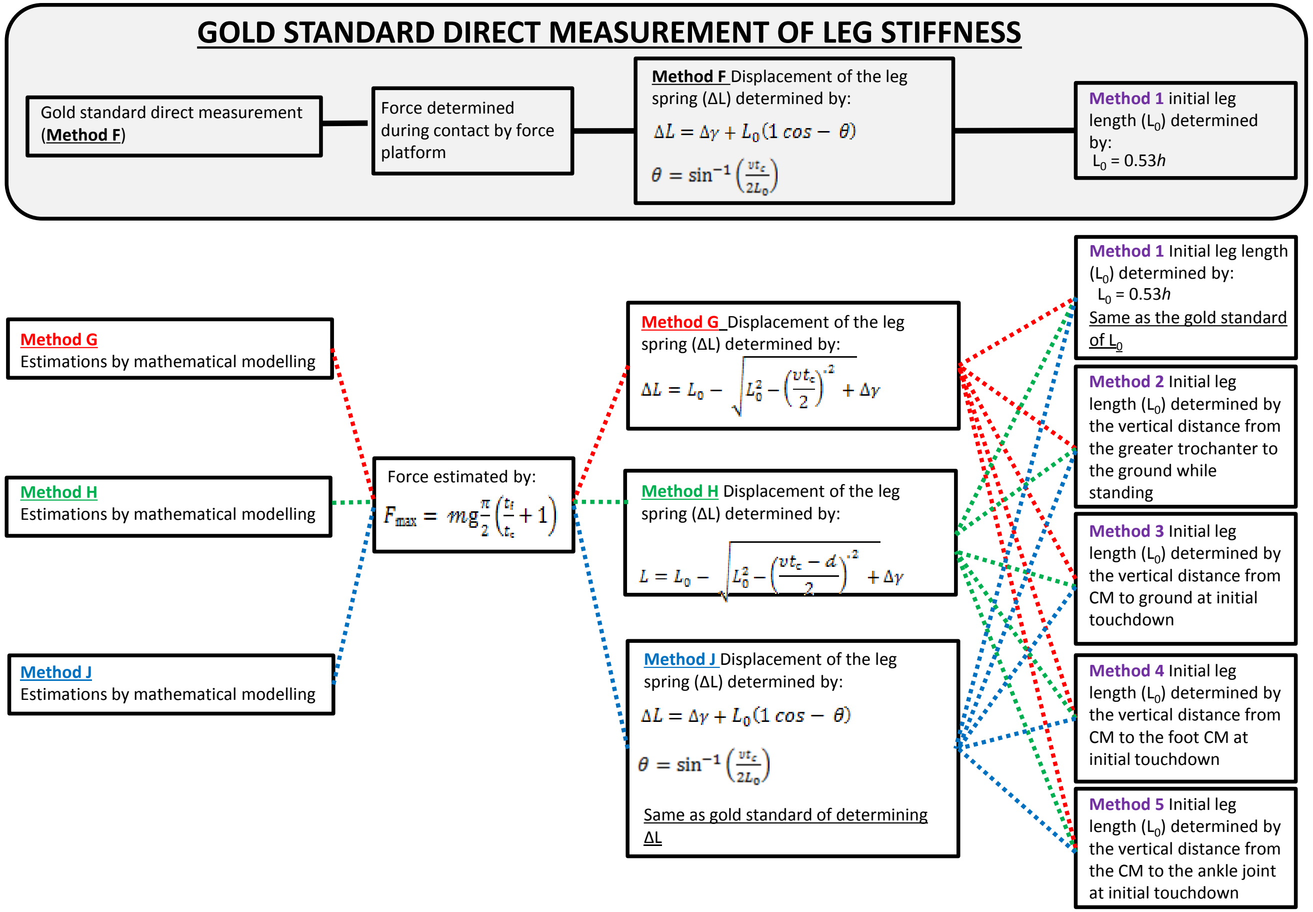


Figure 4.4 Diagram to illustrate the differences in calculations between the gold standard direct measurement for leg stiffness (Method F) compared to estimations by mathematical modelling (Methods G, H, and J). To determine change in initial leg length (L_0) methods 1 to 5 were compared across leg stiffness methods G, H and J.

The focus of this study is to identify K_{vert}, K_{leg} and L_0 estimation methods (by mathematical modelling) that are not significantly different from the gold standard direct measurement (using a force platform) during tempo, 1500m pace and fast running conditions. This would mean that these estimations (by mathematical modelling) could be used to determine K_{vert}, K_{leg} and L_0 when direct measurement is not possible. Statistical analyses were performed using Statistical Package for the Social Sciences version 19.0 (SPSS, 2012). Standard statistical methods were used for the calculations of means and standard deviations for all individual contacts. Normal distribution of the data was verified by the Shapiro-Wilk test and homogeneity of variance was verified by the Levenne test. Separate 5 by 3 factorial analysis of variance (ANOVA; $p \leq 0.05$) were conducted to analyse the effects of K_{vert} methods (A, B, C, D, and E) on running velocity (tempo, 1500 m pace and fast) for each gait and spring-mass characteristics. The gold standard direct measurement (using a force platform) in determining K_{vert} was Method A; Methods B, C, D and E depicted estimations (by mathematical modelling) of K_{vert}. A Bonferroni post hoc were performed to establish differences between the gold standard direct measurement (by a force platform) and estimations (by mathematical modelling using a high speed camera) at each running velocity. Paired samples t-tests were conducted to evaluate flight time measured directly (t_f) and when calculated (from T_f and contact time) for each running velocity.

Additional, 4 by 3 factorial analysis of variance (ANOVA; $p \leq 0.05$) were conducted to analyse the effects of K_{leg} methods (F, G, H and J) on running velocity (tempo, 1500 m pace and fast) for each gait and spring-mass characteristics. A Bonferroni post hoc were performed to establish differences between the gold standard direct measurement (by a force platform) and estimations (by mathematical modelling using a high speed camera) at each running velocity. The gold standard direct measurement (using a force platform) in determining K_{leg} was Method F; Methods G, H and J reported estimations (by mathematical modelling) of K_{leg}.

The same athlete was compared across each condition; tempo, 1500 m pace and fast. Bonferroni post-hoc tests were conducted where appropriate to reduce the risk of type II errors. In order to determine how body weight may influence F_{max}, K_{vert} and K_{leg} a one-way sensitivity analysis was completed. The one-way sensitivity analysis permitted the modification of body weight by a given amount and examined the impact that the changes had on the F_{max}, K_{vert} and K_{leg}.

4.3. Results

In total 32 contacts were analysed in this study. Each running velocity condition clearly represented 3 distinct groups with no overlap. No significant differences in the measured or derived flight time values and subsequent calculations of F_{max} and stiffness (calculated from T_f and t_c) were reported during tempo, 1500 m pace or fast conditions (p>0.05, Table 4.4).

Table 4.4 Mean [± SD] running velocity, contact and flight time used to estimate K_{vert} and Kleg in all the velocity conditions

Biomechanical parameters	1 "Tempo" n = 10 Mean [± SD]	2 "1500m pace" n = 12 Mean [± SD]	3 "Fast" n = 10 Mean [± SD]
υ ($m \cdot s^{-1}$)	5.28 [0.21]*	6.52 [0.38]*	8.19 [0.48]*
t_c (s)	0.186 [0.016]*	0.158 [0.015]*	0.148 [0.013]*
t_f (s)	0.155 [0.015]	0.145 [0.010]	0.137 [0.009]
t_f (s)†	0.155 [0.010]	0.146 [0.008]	0.136 [0.008]
T_f (s)	0.496 [0.030]	0.450 [0.026]	0.420 [0.026]

υ, running velocity; t_c, contact time; t_f, flight time; T_f, time from take-off to initial touchdown of same leg; t_f†, calculated from T_f and t_c. * significant difference in gait characteristic between tempo, 1500m pace and fast running velocities ($p<0.005$).

A 5 by 3 factorial ANOVA for F_{max} revealed significant differences between methods and running velocities (p=0.0001, Table 4.5). However, in the fast running velocity condition no differences in F_{max} were reported between the gold standard direct measurement (Method A) and estimations (by mathematical modelling Method B, C, D and E, p>0.05). The factorial ANOVA for Δy and K_{vert} revealed significant differences between methods and running velocities (p=0.003 and p=0.039, respectively). Only method E (estimation by mathematical model) did not differ in Δy and K_{vert} from the gold standard direct measurement during tempo, 1500m pace and fast running velocity conditions (p>0.05). No significant interaction effect was reported between methods and running velocities for F_{max}, Δy and K_{vert} (p>0.05).

Table 4.5 Mean [± SD] of biomechanical parameters used in methods A to E used to determine vertical stiffness during all conditions

	1	2	3	4	5
	Gold standard direct measurement (Method A)	**Method B**	**Method C**	**Method D**	**Method E**
Biomechanical parameters	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**
"Tempo"					
F_{max} (kN)	2.35 [0.19]	2.04 [0.17] *	2.04 [0.17] *	2.04 [0.17] *	2.04 [0.17] *
Δy (m)	0.074 [0.014]	0.043 [0.007] *	0.056 [0.012]	0.055 [0.021]	0.082 [0.020]
K_{vert} (kNm^{-1})	32.57 [5.79]	48.89 [9.49] *	38.60 [10.60]	40.37 [11.51]	25.94 [4.79]
"1500m pace"					
F_{max} (kN)	2.23 [0.25]	2.06 [0.15] *	2.06 [0.15] *	2.06 [0.15] *	2.06 [0.15] *
Δy (m)	0.063 [0.010]	0.031 [0.006] *	0.037 [0.010] *	0.041 [0.016] *	0.067 [0.016]
K_{vert} (kNm^{-1})	36.27 [7.83]	68.71 [12.05] *	59.18 [17.20] *	58.23 [24.76] *	32.48 [8.44]
"Fast"					
F_{max} (kN)	2.30 [0.35]	2.14 [0.11]	2.14 [0.11]	2.14 [0.11]	2.14 [0.11]
Δy (m)	0.063 [0.021]	0.027 [0.005] *	0.034 [0.003] *	0.040 [0.018] *	0.063 [0.024]
K_{vert} (kNm^{-1})	41.06 [16.54]	80.99 [13.63] *	62.92 [8.71]	61.59 [23.74]	42.63 [18.45]

F_{max}, maximal vertical ground reaction force (kN); Δy, vertical displacement of the centre of mass (m); K_{vert} vertical stiffness ($kN \cdot m^{-1}$). *significant difference ($p<0.05$) between gold standard direct measurement and method of K_{vert}

A 4 by 3 factorial ANOVA for ΔL and K_{leg} revealed significant differences between methods and running velocities (*p*=0.001 and *p*=0.0001, respectively; Table 4.5). However, in the tempo, 1500m pace and fast running velocity condition no differences in ΔL and K_{leg} were reported between the gold standard direct measurement (Method A) and estimations (by mathematical modelling Methods J, p>0.05). No significant interaction effect was reported between methods and running velocities for F_{max}, ΔL and K_{leg} (p>0.05).

Table 4.6 Mean [± SD] of biomechanical parameters used in methods F to J used to determine leg stiffness during all conditions

Biomechanical parameters	1 Gold standard direct measurement (Method F) Mean [± SD]	2 Method G Mean [± SD]	3 Method H Mean [± SD]	4 Method J Mean [± SD]
"Tempo"				
F_{max} (kN)	2.35 [0.19]	2.04 [0.17] *	2.04 [0.17] *	2.04 [0.17] *
ΔL (m)	0.220 [0.030]	0.190 [0.041]	0.176 [0.017] *	0.196 [0.0172]
K_{leg} (kNm^{-1})	10.79 [1.39]	11.15 [1.97]	11.67 [9.88] *	10.44 [0.83]
"1500m pace"				
F_{max} (kN)	2.23 [0.25]	2.06 [0.15] *	2.06 [0.15] *	2.06 [0.15] *
ΔL (m)	0.221 [0.034]	0.184 [0.033]	0.163 [0.027] *	0.182 [0.025]
K_{leg} (kNm^{-1})	10.82 [1.30]	11.15 [1.97]	12.93 [2.16] *	11.48 [1.53]
"Fast"				
F_{max} (kN)	2.30 [0.35]	2.14 [0.11]	2.14 [0.11]	2.14 [0.11]
ΔL (m)	0.264 [0.057]	0.228 [0.041] *	0.206 [0.044]	0.218 [0.039]
K_{leg} (kNm^{-1})	9.15 [2.64]	9.63 [1.86]	10.78 [2.38] *	10.11 [1.98]

F_{max}, maximal vertical ground reaction force (kN); ΔL, displacement of the leg spring (m); K_{leg}, leg stiffness ($kN \cdot m^{-1}$) *significant difference (p<0.05) between gold standard direct measurement and method of K_{leg}

A 4 by 3 factorial ANOVA for L_0 revealed significant differences between methods and running velocities (*p*=0.001 and *p*=0.0001, respectively; Table 4.5). However, in the tempo, 1500m pace and fast running velocity condition no differences in ΔL and K_{leg} were reported between the gold standard direct measurement (Method A) and estimations (by mathematical modelling Methods J, p>0.05). No significant interaction effect was reported between methods and running velocities for F_{max}, ΔL, and K_{leg} (p>0.05).

There was a significant difference in L_0 determined using the gold standard direct measurement (Method 1) and estimations (by mathematical modelling Methods 2, 3, 4, and 5) which were used in the calculation of K_{leg} (Table 4.7, p=0.0001). Post-hoc comparisons of L_0 reported only method 5 for determining L_0 did not differ from the gold standard direct measurement (Method 1) (p>0.05). No significant difference in L_0 was reported across all 3 running conditions (p<0.05). Results from the one-way sensitivity analyses completed as part of this study are presented in Appendix C.

Table 4.7 Mean [± SD] of methods 1 to 5 to determine initial leg length (used in leg stiffness calculations)

	1	2	3	4	5
	Gold standard direct measurement (Method 1)	Method 2	Method 3	Method 4	Method 5
Biomechanical parameters	Mean [± SD]	Mean [± SD]	Mean [± SD]	Mean [± SD]	Mean [± SD]
L_0 (m)	0.96 [0.04]	0.95 [0.05] *	1.14 [0.13] *	1.02 [0.04] *	0.96 [0.03]

L_0, initial length of the leg spring (m) *significant difference (p<0.05) between gold standard direct measurement and method of L_0

4.4. Discussion

This study has demonstrated that to quantify K_{vert} method E, which was based on Morin et al. (2005) mathematical model was the most representative of the gold standard direct measurement (method A). This mathematical method calculated F_{max} by quantifying flight time directly and Δy as the vertical displacement of the CM through a digitised 18-point model (difference between the maximum and minimum CM to foot displacement). To quantify K_{leg} method J, which was based on McMahon and Cheng (1990) and Morin et al. (2005) was deemed the most representative of the gold standard direct measurement (method F). This mathematical method calculated F_{max} by quantifying flight time directly. The same calculation was used to determine ΔL in both method J and the gold standard direct measurement (method F). Based on this study's findings the original hypothesis that estimations (by mathematical modelling) would allow for the documentation of K_{vert} and K_{leg} when the gold standard direct measurement of stiffness was not possible was accepted.

This is only the second study to compare several methods of estimation (by mathematical modelling) to the gold standard direct measurement (by a force platform) in determining stiffness. All spring-mass characteristics observed throughout this study were similar to those previously reported during running velocities between 5.28 $m \cdot s^{-1}$ and 8.19 $m \cdot s^{-1}$ (Girard, Micallef, & Millet, 2011a; Mann & Hagy, 1980; Morin et al., 2005; Slawinski et al., 2008). The contact time presented in this study were lower than previously stated in K_{vert} and K_{leg} research, this could be explained in part by the higher running velocities achieved and the distance runners used in this study (Hobara et al., 2010a; Morin et al., 2006). Previous research has reported contact times of 0.212 s and 0.227 s for running velocities between 5.25 $m.s^{-1}$ and 5.28 $m.s^{-1}$ (Girard, Millet, Slawinski, Racinais, & Micallef, 2010; Slawinski et al., 2008). This velocity range is similar to the mean velocity in the tempo condition where mean contact time was less at 0.186 s (± 0.016 s). In comparison during the fast condition this study reported a mean contact time of 0.148 s (0.013 s). The differences reported in contact time could alter the estimations of F_{max} and subsequently the estimation of K_{vert} and K_{leg} (Table 4.2 and Table 4.3). Previous research has determined that the influence of contact time is important as it is a key parameter in the estimation of K_{vert} and K_{leg} (Morin et al., 2005).

Based on the findings of this study it would be recommended that any gait and spring-mass characteristic that can be measured should be, so reducing the likelihood of error. This will allow for subtle changes in gait characteristics over the course of a training session or race to be identified. Method E estimates (by mathematical modelling) F_{max} measuring flight time directly; whereas method B derived time of flight from T_f and contact time (Table 4.1). In this study there were no significant differences in measured and derived flight time across all three running conditions.

Across all three running conditions method E, which was based on Morin et al. (2005) mathematical model with Δy determined by digitised 18-point model (difference between the maximum and minimum CM to foot displacement) was the most representative of gold standard direct measurement (method A) in quantifying K_{vert}. This is the first study to determine Δy in this manner when quantify K_{vert}. The gold standard direct measurement (method A) ascertains Δy by determining the double integration of vertical acceleration over time using a force platform. The majority of previous research has determined Δy by the equation in method B (Hobara et al., 2010a; Hunter & Smith, 2007; Morin et al., 2007). Findings in this study do not support the use of this equation in determining Δy as it was significantly different to the gold standard direct measurement (method A) during the tempo and 1500 m pace running conditions. Utilising method E to estimate (by mathematical modelling) would facilitate the capture of stiffness data during training and competition, using only a fixed calibrated high-speed camera to quantify K_{vert}, F_{max} and Δy.

Higher mean Δy of 0.063 m to 0.74 m was demonstrated in this study for the gold standard direct measurement (method A) compared to previous research which has reported displacements between 0.023 m to 0.040 m (Girard et al., 2011a; Hobara et al., 2010a; Morin et al., 2007). A possible reason for the differences reported in Δy could be explained by the type and level of the athletic population utilised in the study. It has been suggested that higher-level athletes present smaller variations in Δy compared to recreational runners (Anderson, 1996). The comparison of Δy across ability levels is yet to be investigated in middle-distance athletes. The influence of running technique on variability in the gait cycle was studied by Nakayama et al. (2010), who found that long term running training can produce a stable and consistent gait cycle, due to a decrease in variability in inter-limb coordination. This has potential impact on training and competition stiffness research and how spring-mass characteristics are defined, in particular Δy, ΔL and L_0.

Morin et al. (2005) stated that ΔL was not a crucial parameter for improving the accuracy of the estimations of K_{leg}. This study does not concur with this statement and is the only study to propose another means of determining ΔL. A key assumption used in previous estimations (by mathematical modelling) in determining K_{leg}, is that the leg length at the moment of ground contact is equal to the L_0 whilst standing (Morin et al., 2011d). Initial leg length has been determined by either; muliplying a constant value (0.53) and athlete height (Hobara et al., 2008; Morin et al., 2005; Morin et al., 2006; Morin et al., 2009b; Winter, 1979); or by measuring the vertical distance from the ground to the greater trochanter whilst the athlete is standing (Arampatzis et al., 1999; Farley & Gonzalez, 1996; He et al., 1991; Slawinski et al., 2008).

Previous research has not measured the actual length of the leg at the moment of ground contact and presented this value as initial leg length. This poses several issues as recent research has suggested that international-level athletes do not possess typical anthropometric profiles and are often considered the extremes of the general population (Bejan et al., 2010; Watts et al., 2012). This is further compounded by research which reported a comparison of African and Caucasian distance runners revealing that the relative leg length of African distance runners was considerably longer compared to their Caucasian counterparts (Larsen et al., 2004). Longer tibial length, in absolute terms, was noted in the African distance runners when compared to the Caucasians despite the fact their stature was smaller. This may suggest that applying a constant value (0.53) may not be representative of the athletic population, which may lead to an over- or under-estimation of L_0 and errors in subsequent estimations of ΔL and K_{leg} values. Based on this study's findings it is suggested that L_0 is determined at point of ground contact by measuring the vertical distance from the CM to the ankle joint (Method 5).

The secondary aim was to establish the validity of mathematical models (using only high-speed video) to the gold standard direct measurement (using a force platform) in responding to an increase in running velocity. Based on study findings the hypothesis is accepted that a mathematical model (using only high-speed video) and the gold standard direct measurement (using a force platform) would allow for comparable estimations of stiffness at a range of velocities. This study found no significant interactions between method E and method J and the gold standard direct measurement (method A and F) with running velocity. These findings concur with previous research that has reported that K_{leg} does not differ with an increase in running velocity (He et al., 1991; Morin et al., 2005). Research concerning K_{vert} and running velocity is less clear (for more information refer to chapter 2).

As expected, shorter flight and contact time were reported as running velocity increased, supporting previous running research (Farley, Glasheen, & McMahon, 1993; Mann & Hagy, 1980; Weyand et al., 2000b). This study reported significant differences in F_{max} during tempo and 1500 m pace conditions between the gold standard direct measurement (using a force platform; method A) and estimated (by mathematical modelling; method B, C, D, E, G and H). No significant differences were reported between gold standard direct measurement and estimation of F_{max} during the fast condition. When estimating (by mathematical modelling) method (B, C, D, E, G and H) estimated 86%, 92% and 93% of F_{max} measured by the force platform during tempo, 1500 m pace and fast conditions respectively. These findings support Morin et al. (2005) who stated that the estimation of F_{max} improved at higher velocities. Based on these findings, the full importance of K_{vert} and K_{leg} can be investigated in training and competition using high-speed video only.

4.5. Conclusions

The gold standard for measuring K_{vert} and K_{leg} is the direct measurement of the spring-mass model through the use of a force platform (Arampatzis et al., 2000; Morin et al., 2005). Vertical and leg stiffness can also be estimated by mathematical modelling, these are often used when the gold standard direct measurement is not possible or deemed appropriate (Morin et al., 2005). The aim of this study was to assess the validity of stiffness values obtained through mathematical modelling (estimations based on high-speed video data only) in determining K_{vert} and K_{leg} during running to the gold standard direct measurement (using a force platform).

This study has demonstrated that to quantify K_{vert}, method E based on Morin et al. (2005) mathematical model was the most representative of the gold standard direct measurement (method A). This mathematical method calculated F_{max} by quantifying flight time directly and Δy as the vertical displacement of the CM through a digitised 18-point model (difference between the maximum and minimum CM to foot displacement). To quantify K_{leg} method J, based on McMahon and Cheng (1990) and Morin et al. (2005) was deemed the most representative of the gold standard direct measurement (method F). This mathematical method calculated F_{max} by quantifying flight time directly. The same calculation was used to determine ΔL in both method J and the gold standard direct measurement (method F). Based on this study's findings the original hypothesis that estimations (by mathematical modelling) would allow for the documentation of K_{vert} and K_{leg} when the gold standard direct measurement of stiffness was not possible was accepted. Findings also reported no significant interactions between method E and method J and the gold standard direct measurement (method A and F) with running velocity.

4.6. Summary of techniques used to investigate gait and spring-mass characteristics

Chapter 3 identified that gait characteristics determined by video were comparable to those reported by Optojump and LDM devices. Findings demonstrated that contact and flight times quantified by Optojump and high-speed video have an acceptable amount of measurement error; which was equivalent to less than one video frame (≥0.003s). Step frequency was different between Optojump and high-speed video, as a consequence to the variation in flight time and the discrepancy in derived running velocity. All three methods of quantifying step length (panning digital video, high-speed video and Optojump) reported identical mean step length values, without impeding the athlete. Findings support those of Bruggemann and Glad (1990) and Bezodis (2009) in advocating the use of LDM device and high-speed video to quantify running velocity in competitive races, training and biomechanical research.

Chapter 4 developed on from chapter 3 and demonstrated that to quantify K_{vert}, method E based on Morin et al. (2005) mathematical model was the most representative of the gold standard direct measurement (method A). This mathematical method calculated F_{max} by quantifying flight time directly and Δy as the vertical displacement of the CM through a digitised 18-point model (difference between the maximum and minimum CM to foot displacement). To quantify K_{leg} method J, based on McMahon and Cheng (1990) and Morin et al. (2005) was deemed the most representative of the gold standard direct measurement (method F). This mathematical method calculated F_{max} by quantifying flight time directly. The same calculation was used to determine ΔL in both method J and the gold standard direct measurement (method F). Results also suggested that L_0 should be quantified at point of ground contact by measuring the vertical distance from the CM to the ankle joint (Method 5). Based on this study's findings the original hypothesis that estimations (by mathematical modelling) would allow for the documentation of K_{vert} and K_{leg} when the gold standard direct measurement of stiffness was not possible was accepted. Findings also reported no significant interactions between method E and method J and the gold standard direct measurement (method A and F) with running velocity.

Through the use of video chapters 3 and 4 support the documentation of gait and spring-mass characteristics away from the laboratory setting (e.g. training and competitive races). The ability to capture gait and spring-mass characteristics using only video, has provided the potential to examine aspects of an athlete's running performance that previously had not been possible. The concept of lower limb neuromuscular behaviour has been suggested to influence running velocity and performance time (Brughelli & Cronin, 2008b; Butler et al., 2003). These relationships can now be explored in more detail across a range of middle-distance ability levels, from regional- national- and international-level athletes, to establish the differentiating factors associated with middle-distance performance.

CHAPTER 5: COMPARISON OF GAIT CHARACTERISTICS EXHIBITED DURING COMPETITION FOR INTERNATIONAL- NATIONAL- AND REGIONAL-LEVEL MIDDLE-DISTANCE ATHLETES

5.1. Introduction

Previous research has identified physiological factors (e.g. running economy) that are associated with performance success in middle-distance running (Foster & Lucia, 2007; Lucia et al., 2006). There is paucity in the biomechanical literature depicting how the gait and spring-mass characteristics differ across middle-distance athlete ability-levels when maintaining a high running velocity. It is important to determine and quantify the biomechanical parameters that influence performance time to inform the development of middle-distance athletes (Iaia et al., 2009; Le Meur et al., 2013; Morin et al., 2011b; Quinn, 2009; Thiel et al., 2012). Performance time can be quantified by running velocity and distance which are influenced by multiple biomechanical factors (Figure 1.3).

Middle-distance athletes are faced with a unique challenge of generating high running velocities while making movements as economical as possible (Williams & Cavanagh, 1987). The maintenance of a high running velocity is the result of an optimal combination of step length and step frequency (Salo et al., 2011). Research based on international-level 400 m athletes reported that a higher running velocity was maintained by longer step lengths, rather than an increase in step frequency (Hanon & Gajer, 2009; Hunter et al., 2004; Taylor & Beneke, 2012). From a physiological and biomechanical perspective the 400 m is more representative of sprinting than middle-distance running, therefore the gait characteristics and metabolic cost of middle-distance running are likely to differ (Anderson, 1996; Hanon & Gajer, 2009).

Small changes in gait characteristics can result in large gains in running velocity and ultimately influence performance time (Chapman et al., 2011). The performance time achieved is a consequence of how an athlete modifies their gait and lower limb neuromuscular behaviour to maintain a high running velocity (Chapman et al., 2011). At present the changes in gait characteristics and the lower limb neuromuscular behaviour associated with different middle-distance ability-level performances are largely unknown. Identifying the gait and spring-mass characteristics across differing middle-distance ability levels is important, but athletes are rarely available in the same place and at the same time. Only data collected during competition would provide this level of information and provide insight into how middle-distance athletes maintain a high running velocity (Hayes & Caplan, 2012; Leskinen et al., 2009; Skof & Stuhee, 2004).

Three studies have documented the gait characteristics of middle-distance athletes during official races (Hayes & Caplan, 2012; Leskinen et al., 2009; Skof & Stuhee, 2004). The foot strike patterns and ground contact times during middle-distance performances were documented by Hayes and Caplan (2012). The rationale for this research was based on previous findings that identified a relationship between ground contact time and performance (Chapman et al., 2011; Hobara et al., 2010a). Hayes and Caplan (2012) using British Miler Club competitors of varying abilities reported a high correlation between ground contact time and mean running velocity for the men's 1500 m (r = -0.601; p < 0.001), whereas the men's 800 m displayed only a moderate relationship (r = -0.361; p = 0.002). This suggests that contact time helps to explain 36% of the variance in 1500 m mean running velocity compared to only 13% of the variance in 800 m mean running velocity. In contrast, Leskinen et al. (2009) reported that contact time did not differ between 1500 m international- and national-level middle-distance athletes (p > 0.05).

The differences in the study findings could in part be explained by the contact times recorded and the ability-level of the athletes used (Hayes & Caplan, 2012; Leskinen et al., 2009). In both these studies the mean running velocity was similar; 6.36 $m \cdot s^{-1} \pm 0.23$ $m \cdot s^{-1}$ (Hayes & Caplan, 2012) and 6.40 $m \cdot s^{-1} \pm 0.10$ $m \cdot s^{-1}$ (Leskinen et al., 2009). There was a difference in mean contact time 0.172 s ± 0.016 s versus 0.150 s ± 0.006 s, Hayes and Caplan (2012) and Leskinen et al. (2009) respectively. Only Hayes and Caplan (2012) reported the mean performance time of 1500 m athletes included in the study (3:59.9 ± 00:08.8), no mean performance time was presented in Leskinen et al. (2009) study. A good indication of the ability-level of an athlete included in research is performance time. Without the documentation of performance time it is difficult to determine the calibre of the athlete and therefore the gait characteristics reported may not be representative of 'true' competitive performance.

The performance time and gait characteristics have been collected simultaneously in a single athlete case study on the female indoor 800 m world record holder Jolanda Ceplak (Skof & Stuhee, 2004). This athlete achieved a running velocity of 7.10 $m \cdot s^{-1}$ with a step length of 1.97 m and a step frequency of 3.60 Hz (Skof & Stuhee, 2004). This step length was achieved by a faster plantarflexion velocity and knee extension velocity enabling the athlete to produce greater propulsive ground reaction forces (Skof & Stuhee, 2004). It is suggested that hip extension velocity in the pre-activity and braking phases of the step can reduce knee flexion at the beginning of the ground contact (Leskinen et al., 2009). Effective hip extension before the ground contact enables initial touchdown to be located as close as possible to the vertical line drawn from the CM of the body (Farley & Ferris, 1998). Both these characteristics have been positively associated with preparing the athlete for ground contact (Farley & Ferris, 1998; Leskinen et al., 2009).

The vertical displacement of Jolanda Ceplak's CM was 0.08 m, this was comparable to female athletes of similar ability-levels (Skof & Stuhee, 2004). Centre of mass to ankle distance at initial touchdown was 0.32 m for Jolanda Ceplak, which minimised the loss of horizontal velocity during the braking phase of ground contact (Skof & Stuhee, 2004). Female counterparts reported similar CM to ankle distance at initial touchdown of 0.27 m (Jarmila Kratochvilova) and 0.28 m (Marita Koch) at running velocities of 8.12 $m \cdot s^{-1}$ and 7.77 $m \cdot s^{-1}$ respectively (Skof & Stuhee, 2004). At initial touchdown Jolanda Ceplak reported an ankle angle of 70^{o} this was comparable to athletes of similar ability-levels (Skof & Stuhee, 2004). Skof and Stuhee (2004) concluded that whilst running at 7.10 $m \cdot s^{-1}$ the CM to ankle distance is longer with a smaller ankle angle at initial touchdown during middle-distance running compared to sprinting. This supports research which has suggested that sprinters and distance runners exhibit significant differences in gait and spring-mass characteristics whilst running at the same velocity (Brughelli & Cronin, 2008b). Research is yet to document the correlation between performance time and the CM to ankle distance and angle at touchdown.

Therefore, the aim of this study was to investigate the effects of athlete ability-level (e.g. international-, national- and regional-level athletes) on gait and spring-mass characteristics during competition. By identifying differences in gait and spring-mass characteristics between athlete ability-levels it is hoped that the findings would provide new information to inform coaches in technique training of middle-distance athletes. Based on previous research it was hypothesised that K_{vert} and K_{leg} would be lower in international-level athletes compared to national- and regional-level athletes. Research based on international-level 400 m athletes has reported that a higher running velocity was maintained by longer step lengths, which would result in lower levels of stiffness (Hanon & Gajer, 2009; Hunter et al., 2004; Taylor & Beneke, 2012). It was hypothesised that gait and spring-mass characteristics would correlate to performance time.

5.2. Method

5.2.1. Participants

Thirty male middle-distance athletes (15 x 800 m and 15 x 1500 m) volunteered for the study. Athletes were split into one of three groups; international- national- or regional-level (refer to Table 2.1 for more information). Each athlete-level group consisted of 10 middle-distance athletes (5 x 800 m and 5 x 1500 m). Mean ± standard deviation (SD) for physical characteristics and performance best (PB) times are presented in Table 5.1. Physical characteristics for international-level athletes was acquired through All-Athletics.com (All-Athletics.com, 2012). Following approval from the University of Salford Manchester Research, Innovation and Academic Engagement Ethical Approval Panel the experimental methodology was performed in accordance with the Declaration of Helsinki.

Table 5.1 Mean [± SD] physical characteristics and performance best (PB) times of the middle-distance athletes included in this study

	International-level athletes	**National-level athletes**	**Regional-level athletes**
	Mean [± SD]	**Mean [± SD]**	**Mean [± SD]**
Age (years)	23 [1]	25 [4]	25 [3]
Mass (kg)	63.79 [4.34]	67.66 [4.63]	68.41 [7.20]
Height (m)	1.80 [0.09]	1.84 [0.06]	1.83 [0.03]
800 m athlete PB (min:sec.millisec)	1:43.08 [0:00.50]	1:45.14 [0:00.93]	1:48.62 [0:04.02]
1500 m athlete PB (min:sec.millisec)	3:30.91 [0:01.83]	3:37.57 [0:01.85]	3:46.55 [0:04.81]

5.2.2. Data Collection

Performance profile

The middle-distance performance of each athlete was examined during their appearance at either the London or Birmingham Samsung Diamond League events, UK Athletics Trials/UK and England Championships 2012. Where athletes competed and data was obtained on more than one occasion (e.g. an athlete competed at both the UK Athletics Trials and Birmingham Samsung Diamond League); only the athlete's quickest performance was included. There was no overlap in performance times between international- national- and regional-level athletes. All competition data was collected on synthetic athletic tracks that were certified by the International Association of Athletics Federations (IAAF). Competition temperature ranged between 14 °C and 20 °C with a mean wind reading of less than 1 $m{\cdot}s^{-1}$.

Middle-distance events, such as the 800 m and 1500 m, have been contested at every major athletics championship since 1896 (Miller, 2012). The 800 m is the shortest middle-distance event and is run over 2 laps of a 400 m track. Athletes make standing starts from staggered positions and run in lanes until the start of the back straight (end of the first bend), which is when they can break for the inside. The 1500 m is contested over 3 and three-quarter laps of a 400 m track. This consists of a bunched standing start where athletes can break immediately for the inside. Due to the nature of both the 800 m and 1500 m starts, the second 100 m interval (on the back straight for 800 m) and the first 100 m interval (on the back straight for 1500 m) was not selected for analysis in this study. For previous research on the influence of running a curved bend on gait characteristics see Quinn (2009). Only gait characteristics on the straight sections of the track (e.g. home and back straight) were examined in this study. Running performance was determined for each athlete using the official timing system (Omega, Swatch Group, Swiss).

Gait characteristics

Two high-speed video cameras (EX-F1, Casio, Japan) were positioned 10-12 m outside of the running track (distance from track dependent on advertising boards and space available) and 1.10 m above the track surface. One high-speed video camera was placed on the home straight (40 m before the finish line) and the other was placed on the back straight (20 m before the 200 m start line in lane 1), see Figure 5.1. A 1.07 m x 1.20 m calibration object was placed in both high-speed video cameras field of view (in the centre of the running lane in the sagittal plane). Each high-speed video camera provided a 6 m field of view, sampling at 300 Hz, with a shutter speed of 1/1000 s, and were manually focused. This field of view permitted each high-speed video camera to capture at least 2 contacts. Previous research has presented 2 to 4 contacts, which was deemed representative of each lap (Le Meur et al., 2013; Rabita et al., 2011).

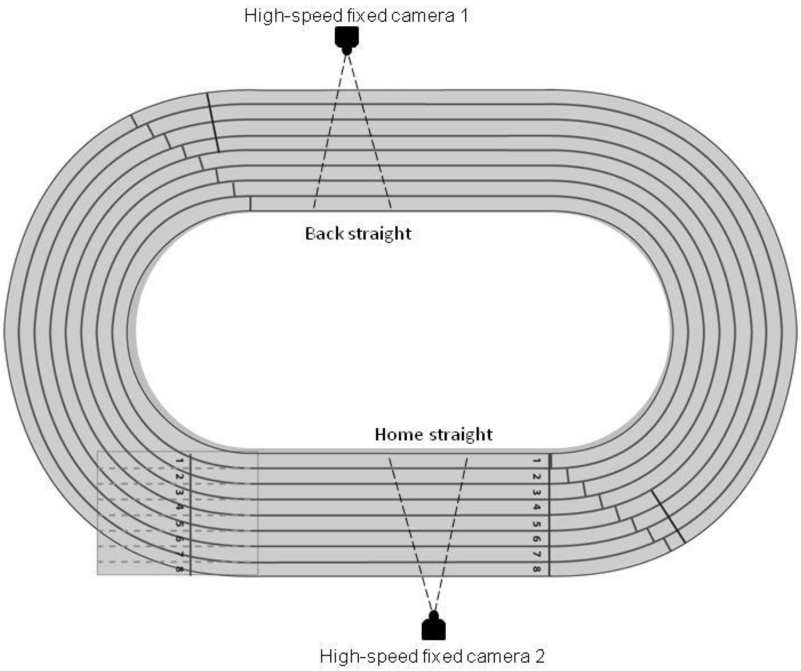


Figure 5.1 Location of each high-speed video camera on an outdoor 400 m synthetic athletics track during competition

Gait characteristics including step length, step frequency, contact time and flight time were determined from the high-speed video cameras placed on the home and back straights (see data collection 3.2.2 for more information). From this the fastest 2 consecutive contacts were identified (determined by multiplying step length and step frequency). All data presented in this study are taken from the fastest 2 consecutive contacts, which were analysed twice and then averaged for each athlete.

Trunk, hip, knee and ankle angles were quantified at initial touchdown, maximum knee flexion and take-off during the race (Figure 5.2). Trunk angle was reported relative to a vertical line going upwards through the mid-point of the hip joints (e.g. negative value reporting an inclined backwards and a positive value indicating inclined forwards). Hip joint angle was calculated from the thigh to the trunk (e.g. flexed hip represented by a value less than 180°). Knee joint angle was calculated from the thigh to the lower leg (e.g. smaller the angle the more flexion). Ankle angle was determined from the lower leg to the foot (e.g. greater the angle the more plantarflexion). Centre of mass to ankle distance describes the body position relative to the foot (horizontal distance). The CM to ankle angle is measured between a line connecting the CM and ankle to the downward vertical (e.g. positive value when ankle is in front of the CM and negative value when the CM is in front of ankle). Vertical take-off velocity was reported at take-off the rate at which the CM moves upwards at an angle of 90° to the ground. Extension velocity was determined as the rate at which a joint straightens; a movement which returns a body segment to the anatomical position from a flexed position. Flexion velocity was determined as the rate at which a joint bends so that the bones forming the joint are brought closer together. In this study hip, knee and ankle joint flexion and extension velocities were reported.

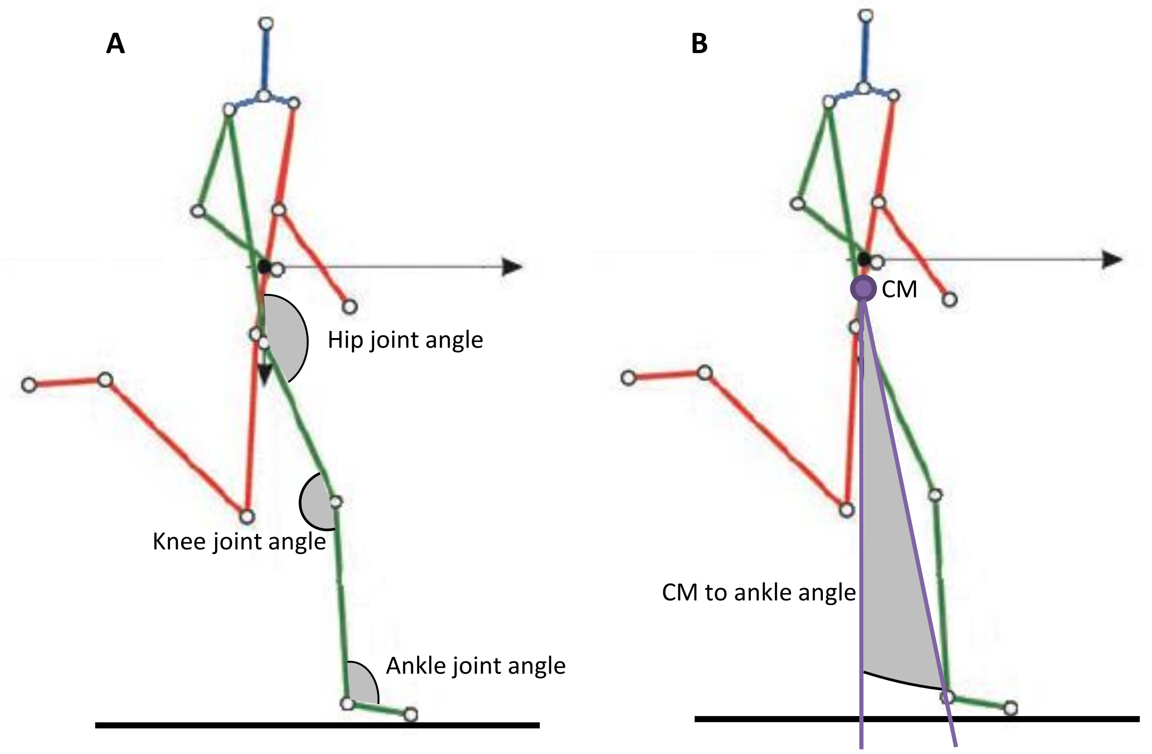


Figure 5.2 (A) location of each joint angle (B) centre of mass (CM) angle

Vertical and leg stiffness (as well as associated variables vertical displacement of the CM [Δy], displacement of the leg spring [ΔL], initial length of the leg spring [L_0] and maximal vertical ground reaction force [F_{max}]) were calculated in accordance with the findings of Chapter 4, Table 5.2). Due to the impact of body mass in deriving F_{max} and subsequently K_{vert} and K_{leg} these variables are also reported as a ratio (refer to Chapter 4). The body mass multiplied by gravity component (mg; e.g. body weight [BW]) was removed from the calculation of F_{max}, K_{vert} and K_{leg} (Table 5.2). These relative measures will be presented as F_{max}/BW ($N \cdot BW^{-1}$); K_{vert}/BW ($N \cdot m^{-1} \cdot BW^{-1}$); and K_{leg}/BW ($N \cdot m^{-1} \cdot BW^{-1}$) to allow for comparison between athlete-levels and because of the accuracy physical characteristics for international-level athletes from All-Athletics.com (All-Athletics.com, 2012) could not be determined.

Table 5.2 Spring-mass characteristics calculations

Biomechanical parameter	Required parameters	Calculations
F_{max}	m, t_c, t_f	$F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right)$
Δy	determined by the digitised 18-point model (min and max CM to foot CM displacement)	
K_{vert}	$F_{max}, \Delta\gamma$	$K_{vert} = F_{max} / \Delta y$
L_0	determined by the vertical distance from the CM to the ankle joint at initial touchdown	
ΔL	$\Delta\gamma, L_0, t_c$	$\Delta L = \Delta\gamma + L_0(1\, cos - \theta)$ $\theta = \sin^{-1}\left(\frac{vt_c}{2L_0}\right)$
K_{leg}	$F_{max}, \Delta L$	$K_{leg} = F_{max} / \Delta L$

F_{max}, maximal vertical ground reaction force (kN); Δy, vertical displacement of the centre of mass (m); K_{vert}, vertical stiffness (kN·m^{-1}); L_0, initial leg length; ΔL, displacement of the leg spring (m); K_{leg}, leg stiffness (kN·m^{-1}); t_c, contact time (s); t_f, flight time (s); m, body mass (kg).

5.2.3. Data Analysis

High-speed video data were imported into Quintic Biomechanics (Quintic Consultancy Ltd, 9.03 version 17) and manually digitised (for more detailed information concerning data analysis refer to section 3.2.2). Measurement error and intra-operator error has previously been investigated for gait and spring-mass characteristics parameters have been reported in chapter 3.

Statistical analyses were performed using Statistical Package for the Social Sciences version 17.0 (SPSS, 2012). Means and standard deviations for international- national- and regional-level athletes are displayed separately. Normal distribution of the data was verified by the Shapiro-Wilk test and homogeneity of variance was verified by the Levenne test. A one-way between groups ANOVA (p ≤0.05) was performed on each gait and spring mass characteristic to detect differences between international- national- and regional-level athletes. Tukey's post-hoc tests were conducted as appropriate. The relationship between performance time and gait and spring-mass characteristics were examined by a linear regression analysis, using Pearson's correlation coefficients (*r*). Strength of correlation was interpreted as; *r* >0.9 nearly perfect, 0.7 to 0.9 very high, 0.5 to 0.7 high, 0.3 to 0.5 moderate, 0.1 to 0.3 small and 0.1 or less trivial (Hopkins, 2002). The coefficient of determination was also calculated to determine the level of variance between athlete-level and gait and spring-mass characteristics. The coefficient of determination was calculated by squaring the Pearson's correlation coefficients (*r*) to provide a percentage of variance (%) between performance time and gait and spring-mass characteristics.

5.3. Results

Performance profile

Significant differences in 800 m performance time were found between athlete levels ($F_{2,57} = 111.462$ $p = 0.0001$). Post hoc comparison revealed a difference in 800 m performance time between all athlete levels ($p = 0.0001$). The mean performance time for the international- national- and regional-level 800 m athletes was 1:45.05 ± 0:00.94, 1:47.78 ± 0:00.37 and 1:50.95 ± 0:01.53 respectively. Each 800 m athlete cohort (international- national- and regional-level) was deemed homogenous based upon their performance time values (co-efficient of variation 0.90%, 0.68% and 1.38%, respectively).

Significant differences in 1500 m performance time were found between athlete-levels ($F_{2,57} = 21.874$ $p = 0.0001$). Post hoc comparison revealed a difference in 1500 m performance time between international- national- and regional-level athletes (p = 0.0001). The mean performance time for the international- national- and regional-level

1500 m athletes was 3:35.19 ± 0:0041, 3:37.57 ± 0:00.44 and 3:49.84 ± 0:07.14 respectively. Each 1500 m athlete cohort (international- national- and regional-level) was deemed homogenous based upon their performance time values (co-efficient of variation 0.19%, 0.20% and 3.11%, respectively).

Gait Characteristics

Running velocity differed between athlete-levels ($F_{2,117} = 18.972$ $p = 0.0001$, Table 5.3). Lower mean running velocities were reported in regional-level athletes compared to international- and national-level ($p = 0.001$). Significant differences in step length were found between athlete levels ($F_{2,117} = 5.653$ $p = 0.001$). Regional-level athletes reported shorter mean step length compared to international- ($p = 0.004$) and national-level athletes ($p = 0.048$).

Table 5.3 Comparison of mean [± SD] gait and spring-mass characteristics during competition.

Biomechanical parameters	1 International Mean [± SD]	2 National Mean [± SD]	3 Regional Mean [± SD]
υ ($m{\cdot}s^{-1}$)	7.65 [0.54]	7.63 [0.37]	7.04 [0.56] **
t_c (s)	0.154 [0.011]	0.154 [0.007]	0.153 [0.009]
t_f (s)	0.140 [0.014]	0.140 [0.014]	0.141 [0.013]
S_l (m)	2.17 [0.19]	2.15 [0.09]	2.07 [0.15] **
S_f (Hz)	3.41 [0.15]	3.41 [0.18]	3.41 [0.20]
L_0 (m)	0.92 [0.03]	0.97 [0.02] *	0.96 [0.04] *
ΔL (m)	0.24 [0.01]	0.22 [0.01] *	0.21 [0.02] *
Δy (m)	0.08 [0.01]	0.07 [0.01] *	0.07 [0.01]
F_{max}/BW	3.01 [0.21]	3.00 [0.17]	3.02 [0.14]
K_{vert}/BW	41.50 [11.92]	47.82 [10.57] *	43.46 [8.15]
K_{leg}/BW	13.13 [1.68]	13.85 [1.60]	14.89 [1.87]

υ, running velocity($m{\cdot}s^{-1}$); t_c, contact time (s); t_f, flight time (s); S_l, step length; S_f, step frequency; L_0, initial leg length; ΔL, displacement of the leg spring (m); Δy, vertical displacement of the centre of mass (m); F_{max}/BW, maximal vertical ground reaction force relative to body weight ($N{\cdot}BW^{-1}$); K_{vert}/BW, vertical stiffness relative to body weight ($N{\cdot}m^{-1}{\cdot}BW^{-1}$); K_{leg}/BW, leg stiffness relative to body weight ($N{\cdot}m^{-1}{\cdot}BW^{-1}$);*significant difference ($p<0.05$) between athlete-level and international-level; **significant difference in regional-level compared to national-level and international-level

Mean trunk angle at initial touchdown was higher in international- compared to national-level athletes (Table 5.4, p = 0.037). National-level athletes reported a larger mean hip angle at initial touchdown compared to international-level athletes (p = 0.041). International-level athletes had a smaller mean hip angle at maximum knee flexion compared to national-level athletes (p = 0.001) and regional-level athletes (p = 0.019). At maximum knee flexion a significantly lower mean knee angle was reported in international-level athletes compared to national- (p = 0.037) and regional-level (p = 0.003). Significant differences in mean ankle angle at initial touchdown were found between athlete levels ($F_{2,117}$ = 10.910 p = 0.0001). Post hoc comparison revealed a significantly larger mean ankle angle in international-level athletes compared to national- (p = 0.0001) and regional-level athletes (p = 0.0001).

Table 5.4 Comparison of mean [± SD] joint angles and centre of mass (CM) to ankle angle and distance during competition

Biomechanical parameters	1 International Mean [± SD]	2 National Mean [± SD]	3 Regional Mean [± SD]
Trunk angle at TD (°)	8.0 [2.3]	6.8 [2.7] *	7.8 [2.0]
Trunk angle at MKF (°)	10.8 [2.5]	10.2 [3.0]	10.3 [2.4]
Trunk angle at TO (°)	6.9 [3.6]	6.4 [3.3]	5.7 [2.0]
Hip angle at TD (°)	137.2 [9.0]	141.0 [4.9] *	140.3 [6.2]
Hip angle at MKF (°)	149.8 [6.9]	156.8 [8.4] *	155.2 [10.0] *
Hip angle at TO (°)	200.0 [6.7]	203.1 [5.5]	198.7 [9.2]
Knee angle at TD (°)	150.9 [7.0]	155.4 [5.1]	154.1 [6.4]
Knee angle at MKF (°)	129.8 [6.7]	136.0 [6.2] *	138.3 [7.6] *
Knee angle at TO (°)	161.7 [11.0]	162.1 [5.9]	160.4 [13.2]
Ankle angle at TD (°)	119.0 [6.4]	112.6 [4.2] *	111.6 [6.3] *
Ankle angle at MKF (°)	89.5 [9.2]	88.2 [4.0]	91.9 [10.3]
Ankle angle at TO (°)	135.3 [4.5]	133.2 [4.4]	134.3 [7.2]
CM to ankle distance at TD (m)	0.27 [0.3]	0.27 [0.01]	0.24 [0.1]
CM to ankle angle at TD (°)	16.4 [2.5]	16.3 [2.5]	19.3 [6.7]

TD, touchdown; MKF, maximum knee flexion; TO, take off;*significant difference (p<0.05) between athlete-level and international-level.

Significant differences in mean sweep of the leg during contact (Θ) were found between athlete levels ($F_{2,117} = 19.020$ $p = 0.01$). A significantly higher sweep of the leg during contact was reported in international-level athletes compared to national- ($p = 0.015$) and regional-level ($p = 0.0001$). No significant difference in vertical take-off velocity was reported between athlete-levels ($p > 0.05$). Significantly higher mean hip extension velocity was reported between international- and regional-level athletes (761 ± 115 deg/s versus 673 ± 90 deg/s, $p = 0.015$). International-level athletes reported higher mean knee flexion and extension velocities compared to regional-level athletes ($p = 0.015$, $p = 0.002$, respectively). International-level athletes demonstrated a higher mean ankle dorsiflexion velocity compared to national- ($p = 0.012$) and regional-level ($p = 0.0001$).

Spring-mass characteristics

International-level athletes reported higher mean Δy and lower K_{vert}/BW compared to national-level athletes (Table 5.3, $p = 0.005$ and $p = 0.039$, respectively). Mean L_0 was significantly different between athlete levels ($F_{2,117} = 10.126$ $p = 0.01$). Post hoc comparison revealed a lower mean L_0 for international-level athletes compared to both national- ($p = 0.0001$) and regional-level ($p = 0.003$). Mean ΔL differed significantly between athlete levels ($F_{2,117} = 11.461$ $p = 0.037$). International-level athletes demonstrated larger ΔL compared to national- ($p = 0.021$) and regional-level athletes ($p = 0.0001$).

Relationship between performance time and gait and spring-mass characteristics

There was a strong negative significant correlation between 800 m performance time and running velocity and step length ($r = -0.659$, $p < 0.001$ and $r = -0.537$, $p < 0.001$, respectively; Table 5.5). Running velocity helps to explain 43% of the variance in 800 m performance time but only 3% of the variance between the 1500 m. Change in leg length and 800m performance time reported a strong positive significant correlation (r = 0.583, p < 0.001); whereas 1500m performance time did not (r = 0.283, p>0.005). All gait and spring-mass characteristics and 1500 m performance time demonstrated small correlations that were not significant (r <0.300, p>0.005).

Table 5.5 Correlation coefficients between performance time and gait and spring-mass characteristics

	1		2	
	800 m performance time		1500 m performance time	
Biomechanical parameters	Person Correlation Coefficient (r)	Percentage of Variance (%)	Person Correlation Coefficient (r)	Percentage of Variance (%)
υ ($m \cdot s^{-1}$)	-0.659***	43%	0.160	3%
t_c (s)	-0.359	13%	0.231	5%
t_f (s)	0.284	8%	0.160	3%
S_l (m)	-0.537**	29%	0.110	1%
S_f (Hz)	0.253	6%	-0.263	7%
L_0 (m)	0.583***	34%	0.284	8%
ΔL (m)	-0.304	9%	0.202	4%
Δy (m)	0.177	3%	0.171	3%
F_{max}/BW	-0.389*	15%	0.099	< 1%
K_{vert}/BW	-0.262	7%	-0.183	3%
K_{leg}/BW	0.026	< 1%	-0.178	3%
Hip angle at TD (°)	0.230	5%	0.147	2%
Knee angle at TD (°)	0.174	3%	0.127	2%
Ankle angle at TD (°)	0.046	< 1%	0.022	< 1%
CM to ankle distance at TD (m)	-0.138	2%	-0.038	< 1%
CM to ankle angle at TD (°)	-0.044	< 1%	-0.009	< 1%

υ, running velocity, t_c, contact time (s); t_f, flight time (s); S_l, step length; S_f, step frequency; L_0, initial leg length; ΔL, displacement of the leg spring (m); Δy, vertical displacement of the centre of mass (m); F_{max}, maximal vertical ground reaction force (kN); F_{max}/BW, maximal vertical ground reaction force relative to body weight ($N \cdot BW^{-1}$); K_{vert}/BW, vertical stiffness relative to body weight ($N \cdot m^{-1} \cdot BW^{-1}$); K_{leg}/BW, leg stiffness relative to body weight ($N \cdot m^{-1} \cdot BW^{-1}$). *p<0.05; ** p<0.01; ***p<0.001.

5.4. Discussion

The main findings of this study were that international-level athletes achieved a lower performance time as a consequence of a longer step length and lower K_{vert} and K_{leg}. These findings concur with a past competition-based study that suggested that longer step lengths were associated with a significant reduction in K_{vert}, K_{leg} and performance time (Taylor & Beneke, 2012). These authors also suggested that longer step length would lead to an increase in contact times, although in the present study longer step lengths were found these did not occur with changes in contact time.

In this middle-distance population it could be suggested that step length is the dominant determinant of running velocity and a lower performance time; as step frequency in this study did not differ between athlete-levels. Data from this study suggests step length accounts for 29% of the variance in 800 m performance time. Step length is achieved through the contribution of take-off distance, flight distance and landing distance (Hay, 1993). When reporting take-off distance the extent to which the athlete extends the support leg (whilst in contact with the ground) is an important characteristic and consequently impacts on the step length. The extent to which the athlete extends the support leg is often determined in K_{leg} research by the sweep of the leg during contact (Θ) and L_0. The current study suggests that L_0 explains 34% of the variance in 800 m performance times.

Significant differences in mean Θ and L_0 were found between athlete-levels, with international-level athletes reporting a higher mean Θ and lower L_0 compared to their less able counterparts. These gait characteristics were associated with greater ankle plantarflexion and higher ankle dorsiflexion velocity at initial touchdown; and during contact a greater amount of knee flexion (at maximal knee flexion) and larger ΔL for international-level athletes. This could imply that the international-level athletes CM travelled faster during ground contact. This explains why international-level athletes reported a higher Δy and mean Θ. These findings concur with those of Taylor and Beneke (2012) who reported that an international-level athlete had a higher Δy compared to his competitors. This suggests that international-level athletes can run at greater velocities but with lower limb stiffness. These findings infer that international-level athletes have a greater level of compliance thereby facilitating the storage and utilisation of elastic energy during the stretch-shortening cycle (Brughelli & Cronin, 2008a).

The stretch-shortening cycle is typically characterised by an eccentric muscular contraction (or stretch) followed immediately by a concentric muscular contraction (Harrison et al., 2004). Utilizing a stretch immediately before a concentric contraction has been shown to augment the concentric phase resulting in increased force production and power output (Cavagna et al., 1968). This increase in force production could translate in to an increase in flight distance and subsequently a longer step length (Harrison et al., 2004). Although it was beyond the scope of this study to examine force production directly, the current results suggested that there was a moderate negative significant correlation between estimated F_{max}/BW and 800 m performance time. This would indicate that as performance time increases there is a reduction in F_{max}/BW.

Running velocity differed between athlete ability-levels; however, no differences were reported between international- and national-level athletes. Running velocity helped to explain 43% of the variance in 800 m performance time but only 3% of the variance between the 1500 m. During competition athletes may run with a slower than ideal pace with varied tactics, the variations in pace will alter performance time. Tactics could explain why the running velocity only explained 3% of the variance in the performance time for the longer events (e.g. 1500 m). Thiel et al. (2012) suggested that in some high-standard competitions the finishing place was a more important outcome than performance time. The original hypothesis that K_{vert} and K_{leg} would be lower in international-level athletes compared to national- and regional-level athletes was accepted. As international-level athletes achieved a lower performance time through longer step lengths, resulting in lower levels of stiffness. Our findings reported high running velocities for international-level athletes which were associated with lower K_{vert}/BW and K_{leg}/BW which differed from those of He et al. (1991) and Morin et al. (2005). Research suggests that there may be an ideal range of stiffness that allows one to optimise performance of a specific skill (e.g. middle-distance running) while minimising the negative impact on performance time (Butler et al., 2003). To the authors knowledge this is the first study to document the gait and spring-mass characteristics across three distinct athlete ability levels during competition (*n*=30). Previous competition research has only documented up to 11 athletes (Leskinen et al., 2009; Skof & Stuhee, 2004), whereas the current study included 30 middle-distance athletes.

Limitations

Comparing gait and spring-mass characteristics in the present investigation to other published data poses some challenges. The majority of the current literature has been completed using participants that are recreationally active or specialise in sprint events or team sports (Hobara et al., 2010a; Hobara et al., 2008; Hobara et al., 2010c). This is the first study to include athletes that a have achieved accolades in international competition. Due to the competitive nature of middle-distance events the majority of high calibre athletes train behind closed doors. It would be practically impossible to collect gait and spring-mass characteristic data on these athletes with in a laboratory environment. This means that the only method of gait and spring-mass characteristic data captured can be during competition. This has implications on the data presented.

Using middle-distance athletes competing in 800 m and 1500 m races as study participants offers a number of challenges. The nature of the 800 m and 1500 m race as a timed, outdoor event means that many factors cannot be controlled in the manner preferred for laboratory studies. Set up and operation of measurement equipment outside the laboratory environment provides technical obstacles, while the loss of capacity for repeating failed trials limits the completeness of the data set. However, studying middle-distance athletes within an actual race provides a unique opportunity to study international- national- and regional-level athletes performing in a competitive environment to the limit of their endurance capacity.

Due to the nature of this study it was not possible to quantify the body mass of each international-level athlete on race day. Therefore to quantify physical characteristics, data was acquired through All-Athletics.com (All-Athletics.com, 2012). To reduce the impact of any discrepancies in body mass, F_{max} and subsequently calculated K_{vert} and K_{leg} were reported relative to body weight (therefore removing the need of body mass). By comparing these values relative to body weight it is possible to identify the impact of the variables involved in the calculation of F_{max}, K_{vert} and K_{leg}. This provides a rare glimpse of the gait and spring-mass characteristics and facilitates the comparison of three clearly defined middle-distance cohorts during competition. Studies have suggested that middle-distance athlete's exhibit significantly longer contact times and shorter step lengths compared to sprint athletes whilst running at the same velocities (Bushnell & Hunter, 2007; Saunders et al., 2004). Therefore, estimations of K_{vert} and K_{leg} using Morin et al. (2005) models could differ considerably depending on the athletic population investigated and the sampling frequency employed to determine contact time (for more information on the importance of sampling frequency refer to Chapter 3).

Finally, caution is needed when interpreting the correlation results presented in this study, as a cause-and-effect relationship cannot be inferred from this statistical approach. Further, studies are needed to corroborate these findings and to prove the existence of an-actual cause-and-effect relationship between gait and spring-mass characteristics at varying athlete-levels.

5.5. Conclusions

The aim of this study was to investigate the effects of athlete ability-level (e.g. international-, national- and regional-level athletes) on gait and spring-mass characteristics during competition. By identifying differences in gait and spring-mass characteristics between ability-levels at high running velocities and establish their relationship to performance time. The main findings of this study were that international-level athletes achieved a lower performance time as a consequence of a longer step length and lower K_{vert} and K_{leg}. A longer step length could be attributed to the international-level athletes exhibiting a greater level of knee flexion (lower knee angle) at initial touchdown and maximal knee flexion. This resulted in a significantly higher ΔL being reported for international-level athletes compared to national- and regional-level athletes. This suggests that international-level athletes have a greater level of compliance; thereby facilitating the storage and utilisation of elastic energy during the stretch-shortening cycle. This reduction in stiffness was a consequence of the longer step length, international-level athletes showed significantly lower K_{vert} and K_{leg} values compared to national- and regional-level athletes. The original hypothesis that K_{vert} and K_{leg} would be lower in international-level athletes compared to national- and regional-level athletes, due to the increased step length was accepted.

By documenting the gait and spring-mass characteristics during competition it is possible to establish how performance time can be reduced. This chapter suggests that by increasing their step length an athlete could improve their running velocity and performance time.

CHAPTER 6: GAIT CHARACTERISTICS OF REGIONAL-LEVEL DISTANCE ATHLETES DURING TRAINING

6.1. Introduction

The previous chapter findings infer that international-level athletes have a greater level of compliance thereby facilitating the storage and utilisation of elastic energy during the stretch-shortening cycle (Brughelli & Cronin, 2008a). However, as runners become exerted and fatigue develops over the course of a run, the effectiveness of the protective neuromuscular mechanism of muscle diminishes (Radin, 1986) along with the tolerance to repeated stretch-shortening cycles (Hayesetal et al., 2004; Komi, 2000; Skof and Strojnik, 2006). Fatigue can have considerable influence on lower extremity mechanics. With altered neuromuscular function, a reduction in the transfer of mechanical energy between eccentric and concentric muscle contractions can occur (Mizrahi etal.,2000a, 2000b) along with slower muscle reaction times (Mizrahi et al., 2001). This creates problems when running as the ability to maintain desired angular displacements during the stance phase becomes compromised as runners become exerted (Komi, 2000). Thus, it is likely that changes in joint motion will occur over the course of a single training session and over a block of training.

Training is designed to stimulate adaptions in physiological and biomechanical parameters including greater aerobic capacity, greater muscular power generation, as well as improved lower limb neuromuscular behaviour and shorter contact times (Iaia & Bangsbo, 2010; Smith, 2003). Although the lower limb neuromuscular behaviour during ground contact has been widely investigated the effects of high-intensity training (e.g. speed endurance training) on gait and spring-mass characteristics remains poorly understood. Evidence suggests that the development of an athlete's performance in competition is achieved through training (Skof & Stuhee, 2004).

Speed endurance training is defined by: 1) repetitions should last from 30 seconds up to 2-3 minutes as opposed to 5 to 10 seconds for speed drills and 2) rest intervals between repetitions is reduced to prevent complete recovery (Iaia et al., 2009). To inform speed endurance training the majority of research has focused on the physiological demands required in middle-distance events, commonly examining anaerobic threshold and maximal oxygen uptake (Daniels and Daniels 1992). Previous studies have reported high but similar maximal oxygen uptake values in Kenyan and European distance runners (Saltin et al. 1995). Despite this Kenyan distance runners have a higher success rate during competitions; in 2012 male Kenyan athletes represented 30% and 50% of athletes in IAAF 800 m and 1500 m top ten year rankings, respectively. Research and IAAF data clearly demonstrate that middle-distance Kenyan athletes have the capacity to maintain a higher running velocity over long distances (Enomoto & Michiyoshi, 2012; Saltin et al., 1995b). Subsequently research attention has shifted to determine other possible factors to differentiate athlete ability level and performance time (Figure 1.3). Iaia et al. (2009) demonstrated that in trained athletes an alteration from regular endurance to speed endurance training reduced energy expenditure during submaximal running. This 4 week block of speed endurance training was shown to improve running economy; however this could not be attributed to physiological changes and may indicate that gait and spring-mass characteristics could be responsible (Iaia, 2009). Biomechanical research has yet to establish whether gait and spring-mass characteristics change during speed endurance training in regional-level middle distance athletes (at running velocities of 6.00 $m{\cdot}s^{-1}$).

To date, studies have investigated how recreational distance participants attempt to maintain running velocities between only 2.78 $m{\cdot}s^{-1}$ and 5.07 $m{\cdot}s^{-1}$ over prolonged periods (Girard et al., 2011a; Morin et al., 2011c). For relatively low running velocities (between 2.78 m·s^{-1} and 3.33 m·s^{-1}), during a 24 hour treadmill run or 166 km mountain ultra-marathon run, an increase in K_{vert} and K_{leg} is associated with an increase in step frequency (Morin et al., 2011b; Morin et al., 2011c). At moderate velocities (4.03 ± 0.36 m·s^{-1}) a decrease in K_{vert} and K_{leg} was observed between the beginning and the end of an exhaustive run (Dutto & Smith, 2002). Running to exhaustion on an indoor track at velocities from 5.01 m·s^{-1} to 5.07 m·s^{-1} has been associated with a reduction in K_{leg} but no change in K_{vert} (Rabita et al., 2011). There is paucity in the middle-distance research that documents the changes in gait and spring-mass characteristics associated with high-levels of performance during training. Therefore, the aim of this study was to investigate the changes in gait and spring-mass characteristics associated with high-levels of performance (reported in Chapter 5) in regional-level athletes during speed-endurance training sessions.

6.2. Method

6.2.1. Participants

Following written informed consent ten middle-distance athletes (mean ± SD age: 26 ± 2 years; stature: 1.85 ± 0.05 m; mass: 67.70 ± 8.18 kg) were included in the present study. All participants were middle-distance athletes (time in discipline: 9 ± 3 years) and were all based at the UK Athletics, High Performance Athletics Centre. The information collected was also used by the coach and athlete for monitoring purposes. Following approval from the University of Salford Manchester Research, Innovation and Academic Engagement Ethical Approval Panel the experimental methodology was performed in accordance with the Declaration of Helsinki. UK Athletics approved biomechanical investigations which did not involve any invasive procedures to be undertaken during training.

6.2.2. Data Collection

Athletes completed a 30 day training block (consisting of 6 track sessions and 2 gym session every 7 days) measurements were taken at day 0 and day 30, this was in accordance with Iaia et al. (2009). Training sessions involved completing nine consecutive 400 m runs (total distance covered 3600 m) with a recovery of 30 s between each 400 m run. All 400 m runs were completed on an outdoor 400 m synthetic athletic track between January and February 2012. Session data was collected from the first 3 x 400 m runs (BEG) and the last 3 x 400 m runs (END). This selection was determined due to the homogeneity of 400 m performance times. Mean 400 m performance time (of all 9 x 400 m runs) at day 0 and day 30 was 67.93 s ± 2.16 s and 64.97 ± 2.04 s respectively (over 3600 m). Each athlete completed three countermovement jumps (CMJ) on day 0 and day 30 pre- and post-training, using a force platform (Kistler, model 9286BA, Kistler Instruments, Winterthur, Switzerland; refer to section 4.2.2 for more information). A CMJ was used to asses fatigue and was included in this study as pilot testing revealed that drop jump technique was inconsistent in this athlete population. The athletes ran with no verbal encouragement and each 400 m performance time was recorded by the coach (using a stop watch). All athletes wore closely-fitting clothes and their own running spikes.

Performance profile

The performance profile for each athlete was determined by measuring each 400 m performance time. This was measured using a panning digital video camera recorder (HVR-A1E, Sony, Japan) sampling at a frequency of 50 Hz positioned in the home straight. By using a panning digital video and adjusting the zoom it is possible to maintain a larger image size of the athletes. This increased the accuracy of measurement whilst permitting a larger panning field of view. The running velocity for each 400 m run and 100 m interval was determined by dividing the running distance by running time of the interval using the panning digital video.

Gait characteristics

All data presented in this study are taken from the fastest 100 m interval, which for all athletes was on the home straight. Two high-speed video cameras (EX-F1, Casio, Japan) were positioned 9.50 m from lane 8 (outside of the running track) and 1.10 m above the track surface, placed on the home straight of the outdoor 400 m synthetic athletics track (20 m before the finish line), see Figure 6.1. This camera position permitted the capture of gait and spring-mass characteristics with clear visualisation of each athlete and to avoid capturing athletes slowing down towards the finish line.

Each high-speed video camera provided a 6 m field of view (with a 2 m overlap), sampling at 300 Hz, a shutter speed of 1/1000 s, and were manually focused. This field of view enabled at least 4 contacts for each 400 m run. Previous research has presented 2 to 4 contacts per lap (400 m) to be captured, which was deemed representative of each run (Le Meur et al., 2013; Rabita et al., 2011). A 1.07 m x 1.20 m calibration object was placed in both high-speed video cameras field of view (in the centre of the running lane in the sagittal plane). All camera footage was taken perpendicular to the running direction in accordance with previous research (Cavanagh et al., 1985; Mero & Komi, 1985).

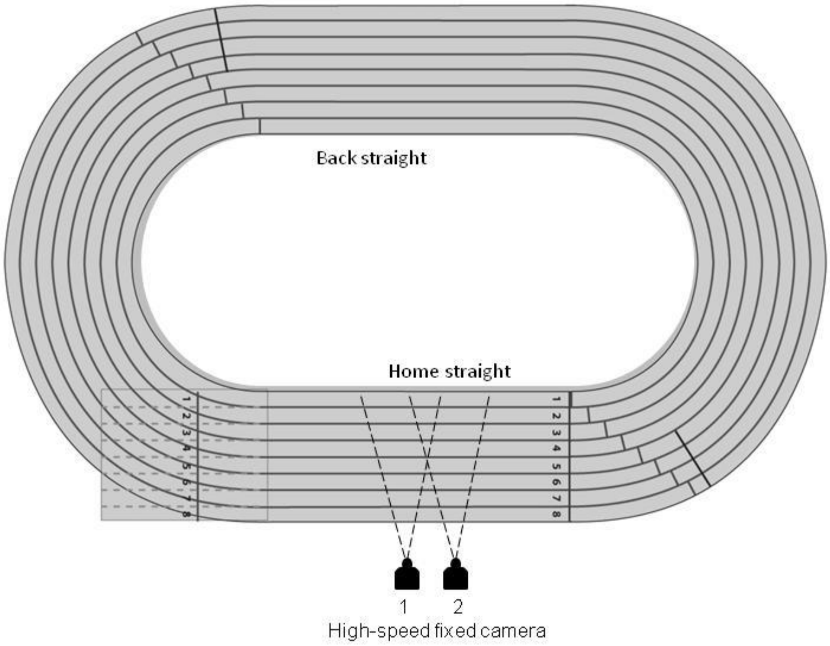


Figure 6.1 Location of high-speed video cameras on the outdoor 400 m synthetic athletics track during training

Gait and spring mass characteristics, including contact time, flight time, step length and step frequency were determined from the two high-speed video cameras placed on the home straight (see data collection 3.2.2 for more information). All data presented in this study are taken from the fastest 2 consecutive contacts (repetition 1, 2, 3 [BEG = 6 contacts] and 7, 8, 9 [END = 6 contacts]). Each contact was analysed twice. An average of 12 contacts per athlete was taken for analysis of the BEG and 12 contacts per athlete was taken for analysis of the END. In total 24 contacts were analysed per athlete (Degache et al., 2013; Morin et al., 2005; Williams, Davis, Scholz, Hamill, & Buchanan, 2004). The running velocity was reported as an average of resultant speed at initial touchdown, maximum knee flexion and take-off for each contact in accordance with previous stiffness research (Morin et al., 2006; Morin, Samozino, & Edouard, 2011a; Morin et al., 2011b; Morin et al., 2009b; Morin et al., 2007; Morin et al., 2011c). Findings reported in Chapter 5 supported that the documentation of running velocity and the position and movement of the leg joints during the contact phase. Therefore, this chapter will also document the angles of the trunk, hip, knee and ankle at initial touchdown, maximum knee flexion and take-off on day 0 and day 30.

Trunk angle was reported relative to a vertical line going upwards through the mid-point of the hip joints (e.g. negative value reporting an inclined backwards and a positive value indicating inclined forwards). Hip joint angle was calculated from the thigh to the trunk (e.g. flexed hip represented by a value less than 180^{o}). Knee joint angle was calculated from the thigh to the lower leg (e.g. smaller the angle the more flexion). Ankle angle was determined from the lower leg to the foot (e.g. greater the angle the more plantarflexion). Centre of mass to ankle distance describes the body position relative to the foot (horizontal distance). The CM to ankle angle is measured between a line connecting the CM and ankle to the downward vertical (e.g. positive value when ankle is in front of the CM and negative value when the CM is in front of ankle, Figure 5.2). Vertical and leg stiffness (as well as associated variables Δy, ΔL, initial leg length and F_{max}) were calculated in accordance with the findings of Chapter 4 (Table 5.1).

6.2.3. Data Analysis

High-speed video footage was manually digitised in Quintic Biomechanics software (Quintic Consultancy Ltd, 9.03 version 17) for more detailed information concerning data analysis refer to section 3.2.2. Ground contacts were manually digitised for each 400 m. Measurement error and intra-operator error has previously been investigated for several key biomechanical parameters and reported in section 3.2.3. Gait characteristics considered in this thesis showed minimal measurement errors and therefore confirmed the high reliability of the digitising process with regard to the overall group of athletes.

Statistical analysis was performed using Statistical Package for the Social Sciences version 17.0 (SPSS, 2012). All data are reported as means ± standard deviations. Normal distribution of the data was verified by the Shapiro-Wilk test and homogeneity of variance was verified by Levenne test. A 2 x 2 factorial ANOVA ($p \leq 0.05$) was performed to compare gait and spring-mas characteristics BEG at day 0 to END at day 0 (for the single training session) and BEG at day 0 to BEG at day 30 and END at day 0 to END at day 30 (for the training block).

6.3. Results

Single training session

For the single training session a comparison was completed between BEG and END at day 0. Increase in step frequency was reported from BEG to END at day 0 ($F_{3,7} = 12.922$, $p = 0.016$). Countermovement jump flight time decreased from BEG to END at day 0 (Table 6.1, t = 5.09, $p = 0.0001$). Height jumped during the CMJ decreased from BEG to END at day 0 (0.47 m ± 0.02 m and 0.38 m ± 0.01 m, respectively, t = 8.08, $p = 0.007$). A decrease in maximal vertical ground reaction force was reported during CMJ from BEG to END at day 0 but this did not reach a level of significance (Table 6.1, $p > 0.05$, respectively).

Table 6.1 Mean (± SD) countermovement jump performance at day 0 and day 30

	1	2	3	4
	Day 0	Day 0	Day 30	Day 30
	BEG	END	BEG	END
Biomechanical parameters	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**
Flight time (s)	0.605 [0.003]	0.555 [0.009]	0.608 [0.011]	0.591 [0.003]
Maximal vertical ground reaction force (kN)	1.69 [0.10]	1.55 [0.08]	1.87 [0.05]*	1.69 [0.08]
Jump height (m)	0.47 [0.02]	0.38 [0.01]	0.38 [0.01]	0.042 [0.02]

* = $p < 0.05$ BEG day 0 versus BEG day 30

Training block

For the training block, gait and spring-mas characteristics were compared at BEG at day 0 to BEG at day 30 and END at day 0 to END at day 30. There was a trend for a reduction in performance time during the training block but this did not reach statistical significance (Table 6.2, $p > 0.05$).

Table 6.2 Mean (± SD) 400 m performance times at day 0 and day 30

	1		2	
	Day 0		Day 30	
	BEG	END	BEG	END
Biomechanical parameters	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**
400 m performance time (s)	66.51 [2.88]	67.38 [2.90]	64.94[1.72]	65.41[1.99]

Gait and spring-mass characteristics from day 0 to day 30 are reported in Table 6.3. Mean flight time and step frequency increased ($F_{3,7} = 23.021$, $p = 0.018$ and $F_{3,7} = 12.922$, $p = 0.003$, respectively) whereas contact time decreased ($F_{3,7} = 4.246$, $p = 0.041$) from BEG day 0 to BEG day 30. Increases in F_{max}/BW were reported at END day 0 to day 30 ($F_{3,7} = 6.403$, $p = 0.014$). Reductions in K_{vert}/BW were reported at BEG day 0 to BEG day 30 ($F_{3,7} = 58.253$, $p = 0.045$).

Table 6.3 Mean [± SD] gait and spring-mass characteristics at the beginning (BEG) and end (END) at day 0 and day 30

	1	2	3	4
	Day 0	Day 0	Day 30	Day 30
	BEG	END	BEG	END
Biomechanical parameters	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**
υ ($m \cdot s^{-1}$)	5.84 [0.20]	6.09 [0.34]	6.25 [0.24]	6.13 [0.12]
t_c (s)	0.190 [0.008]	0.178 [0.024]	0.164 [0.010]*	0.165 [0.011]
t_f (s)	0.139 [0.012]	0.137 [0.015]	0.155 [0.016]*	0.157 [0.013]
S_l (m)	1.88 [0.05]	1.91 [0.08]	1.92 [0.11]	1.91 [0.07]
S_f (Hz)	3.02 [0.07]	3.32 [0.05]	3.25 [0.09]	3.29 [0.07]
L_0 (m)	0.92 [0.04]	0.91 [0.05]	0.91 [0.04]	0.91 [0.05]
ΔL (m)	0.21 [0.02]	0.21 [0.03]	0.20 [0.01]	0.20 [0.02]
Δy (m)	0.07 [0.02]	0.07 [0.02]	0.07 [0.01]	0.07 [0.01]
F_{max} (kN)	1.74 [0.18]	1.79 [0.22]	1.90 [0.13]	1.96 [0.21]
F_{max}/BW ($kN \cdot m^{-1} \cdot BW^{-1}$)	2.73 [0.12]	2.81 [0.21]	2.83 [0.09]	3.08 [0.22]#
K_{vert} ($kN \cdot m^{-1}$)	28.24 [3.46]	25.51 [4.22]	28.92 [4.76]	26.84 [3.85]
K_{vert}/BW ($kN \cdot m^{-1} \cdot BW^{-1}$)	49.89 [6.78]	40.39 [8.02]	45.69 [9.15]*	42.70 [8.22]
K_{leg} ($kN \cdot m^{-1}$)	8.17 [1.05]	8.81 [2.84]	10.01 [1.12]	9.95 [1.24]
K_{leg}/BW ($kN \cdot m^{-1} \cdot BW^{-1}$)	12.84 [1.45]	13.91 [4.98]	15.78 [1.68]	15.80 [2.73]

υ, running velocity, F_{max}, maximal vertical ground reaction force (kN); Δy, vertical displacement of the centre of mass (m); K_{vert}, vertical stiffness ($kN \cdot m^{-1}$);); F_{max}/BW, maximal vertical ground reaction force relative to body weight ($N \cdot BW^{-1}$); K_{vert}/BW, vertical stiffness relative to body weight ($N \cdot m^{-1} \cdot BW^{-1}$); K_{leg}/BW, leg stiffness relative to body weight ($N \cdot m^{-1} \cdot BW^{-1}$); L_0, initial leg length; ΔL, displacement of the leg spring (m); K_{leg}, leg stiffness ($kN \cdot m^{-1}$); t_c, contact time (s); t_f, flight time (s); m, body mass (kg); S_l, step length; S_f, step frequency; * = $p < 0.05$ BEG day 0 versus BEG day 30; # = $p < 0.05$ END day 0 versus END day 30.

Centre of mass to ankle angle at initial touchdown decreased during the training block (Table 6.4, $p < 0.010$). Hip angle at initial touchdown significantly increased from BEG day 0 to day 30 ($F_{3,7} = 5.230$, $p = 0.018$). Ankle angle at initial touchdown had increased at BEG from day 0 to day 30 ($F_{3,7} = 4.841$, $p = 0.026$). No significant changes at the trunk and knee were reported during contact from day 0 to day 30 ($p > 0.05$). Countermovement jump maximal vertical ground reaction force increased from END day 0 to day 30 (Table 6.1, t = 5.32, $p = 0.010$). Height jumped during CMJ increased from 0.38 m ± 0.01 m and 0.42 m ± 0.02 m from END day 0 to day 30 (t = 3.02, $p = 0.013$).

Table 6.4 Mean [± SD] gait characteristics at initial touchdown (TD), maximum knee flexion (MKF) and take-off (TO) at the beginning (BEG) and end (END) at day 0 and day 30

	1	2	3	4
	Day 0	Day 0	Day 30	Day 30
	BEG	END	BEG	END
Biomechanical parameters	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**	**Mean [± SD]**
Trunk angle at TD (°)	7.6 [1.8]	6.7 [2.1]	7.3 [2.6]	6.5 [1.6]
Trunk angle at MKF (°)	11.2 [2.9]	9.7 [2.9]	11.3 [1.9]	10.1 [2.4]
Trunk angle at TO (°)	7.8 [3.2]	5.4 [3.1]	7.8 [3.0]	7.6 [2.6]
Hip angle at TD (°)	143.3 [6.8]	144.4 [8.1]	149.6 [7.9]*	149.7 [5.5]#
Hip angle at MKF (°)	153.8 [6.2]	155.5 [8.1]	153.6 [5.2]	158.7 [3.9]
Hip angle at TO (°)	199.2 [8.0]	200.0 [13.8]	196.8 [7.5]	199.1 [5.7]
Knee angle at TD (°)	161.0 [7.9]	161.5 [7.5]	165.3 [7.1]	162.9 [5.4]
Knee angle at MKF (°)	134.1 [5.2]	135.6 [8.1]	133.7 [3.0]	135.3 [3.1]
Knee angle at TO (°)	162.2 [4.5]	163.0 [8.7]	161.4 [4.7]	164.4 [2.9]
Ankle angle at TD (°)	110.6 [4.8]	114.7 [4.4]	116.2 [3.4]*	116.1 [9.1]
Ankle angle at MKF (°)	91.7 [6.9]	92.4 [6.9]	92.2 [6.5]	94.3 [8.9]
Ankle angle at TO (°)	136.9 [4.9]	134.9 [12.2]	135.4 [8.6]	135.4 [6.9]
CM to ankle distance at TD (m)	0.23 [0.02]	0.21 [0.03]	0.23 [0.02]	0.21 [0.04]
CM to ankle angle at TD (°)	17.3 [1.1]	16.7 [1.7]	14.4 [1.2]*	10.3 [1.7]#

TD, touchdown; MKF, maximum knee flexion; TO, take-off; CM, centre of mass; * = $p < 0.05$ BEG day 0 versus BEG day 30; # = $p < 0.05$ END day 0 versus END day 30.

6.4. *Discussion*

The aim of this study was to investigate the changes in gait and spring-mass characteristics associated with high-levels of performance (reported in Chapter 5) in regional-level athletes over the course of a training session and training block. The main findings of this study were that regional-level athletes maintained running velocity over the single training session and training block by significantly increased step frequency and a reduction in K_{vert}/BW. Whereas the previous study demonstrated that international-level athletes achieved a greater running velocity through a longer step length and lower K_{vert} and K_{leg}.

Changes in gait and spring-mass characteristics during single training session

Regional-level athletes' performance time increased during the single training session but this did not reach a level of significance. Changes in the performance time were coupled with a decrease in CMJ performance (Table 6.1). Both these parameters could indicate the onset of fatigue after the single training session (END at day 0). In contrast, running velocity during the last 100 m was not significantly different during the single training session (Table 6.3). This suggests that the running velocity achieved over the last 100 m is not representative of the total performance time. This supports Thiel et al. (2012) claims that 400 m lap splits do not present the 'true' degree of variation within a lap. Consequently 400 m performance time provides an overview of running velocity, to actually establish running velocity achieved during runs smaller intervals need to be determined in future research.

The performance time presented in this study was associated with an increase in step frequency. It has been suggested that a more rapid turnover of the limbs during swing time (e.g. flight time) may be the preferred strategy to increase step frequency (Kratky & Muller, 2013). Findings from this study do not support this as flight time during the training session did not change (ranged from 0.137 s to 0139 s). Weyand, Sternlight, Bellizzi, and Wright (2000a) stated that there may be a minimum time of flight required to recover the lower limb for the next step. This suggests that the recovery of the limb (during flight time) may not be the determining factor associated with changes in performance time, rather alterations during ground contact may be more important (e.g. the contact portion of the step). During a single training session athletes may have made small modifications to their gait characteristics (e.g. contact time) but these changes were not of a high enough magnitude to be significant.

The contact portion of the step is the only phase during a running cycle in which the athlete can produce F_{max} to influence running velocity (Nummela et al., 2007). No significant changes in F_{max} or F_{max}/BW were reported during the single training session. This concurs with Dutto and Smith (2002) who stated that athletes maintain F_{max} when attempting to maintain running velocity. During the single training session, changes were reported in CM to ankle angle at initial touchdown which may have attributed to the maintenance of ΔL and Δy. This is the first study to document CM to ankle distance and joint angles at initial touchdown alongside stiffness value (K_{vert} and K_{leg}). The advantage of documenting the K_{vert} and K_{leg} is its simplicity in studying the lower limb neuromuscular behaviour during ground contact by using just one spring. The spring-mass system does provide some insight into the position of lower limb at initial touchdown but does not detail the CM to ankle distance or joint angles of the hip, knee and ankle at initial touchdown and during ground contact. Past research has suggested that these parameters may assist in the understanding of how lower limb neuromuscular behaviour is altered during running (Kuitunen et al., 2002). Research has often omitted these gait characteristics and only reported ΔL and Δy (Morin et al., 2005); the reason for this omission is unknown.

Previous research has reported significant increases in ΔL and Δy which attributed to the decrease in K_{vert} and K_{leg} (Dutto & Smith, 2002; Slawinski et al., 2008). During the single training session K_{leg} remained constant which concurs with previous running literature (He et al., 1991). No changes were reported in K_{vert} during the single training session, suggesting that middle-distance athletes may have made small modifications to Δy and F_{max}/BW in order to achieve a higher running velocity. The spring-mass characteristics reported during the single training session do not concur with previous research which reported a reduction in K_{vert} during the development of fatigue (Hobara et al., 2010a; Morin et al., 2011c; Slawinski et al., 2008). A possible reason for the disparity may be that the athletes included in this study did not exhibit high enough levels of fatigue as mean performance time only reduced by 0.87 s over the single training session. This suggests that gait characteristics and lower limb neuromuscular behaviour do not alter over a single training session when performance time does not significantly increase.

Therefore proposed explanations for not finding any changes in performance time over a single training session could be associated with variations in environmental factors, tactics, athlete physical characteristics, equipment and surface, as presented in Figure 1.1.

Changes in gait and spring-mass characteristics during training block

Over the training block the performance time and running velocity did not alter, this could be due to environmental factors and or tactics employed by the athletes (Figure 1.1). Wind direction may have changed from day 0 to day 30 with the athletes having to overcome a head-wind on the home straight or back straight on the 400 m run. The CMJ performance improved from the END of day 0 to day 30 which could imply an improvement in athlete training status and the ability to delay the onset of fatigue. Speed-endurance training facilities the maintenance of aerobic capacity whilst improving intense short-duration-repeated high-intensity exercise performance (Iaia & Bangsbo, 2010). To monitor changes during speed-endurance training sessions physiological research has documented alterations in lactate threshold and heart rate (Iaia & Bangsbo, 2010; Iaia et al., 2009). It was beyond the scope of this study to report the physiological changes during speed-endurance training block although it is acknowledged that these may occur. The remit of this study was to focus on changes in gait and spring-mass characteristics in response to a block of speed-endurance training. Past research suggests in order to attain a high-level performance middle-distance athletes must delay the onset of fatigue to maintain a high running velocity (Kadono, Ae, Suzuki, & Shibayama, 2013).

Running velocity did not change over the training block but the gait characteristics associated in maintaining the running velocity did. Contact time decreased and flight time increased over the training block, these alterations in gait characteristics were associated with an increase in step frequency. Biomechanical research has concluded that during ground contact the development of higher step frequency is associated with faster force production (Brughelli et al., 2011; Weyand et al., 2000b). Findings from this study also reported a significant increase in F_{max}/BW during the training block. This suggests that the athletes were able to exert higher ground reaction forces during ground contact which may benefit subsequent competitive performance. Hasegawa et al. (2007) suggested that athletes who demonstrated shorter contact times achieved a higher finishing position during a half marathon race. This would suggest that the regional-level athletes over this training block made positive modifications to their flight and contact time in order to positively impact on competitive performance.

Research suggests that the contact portion of the step attributes to the differences in the resultant running velocity and subsequent step length and step frequency (Chapman et al., 2011; Hunter et al., 2004). The CM to ankle distance of initial touchdown has been suggested as a critical determinant of performance as it increases step length (Mann, 2010). Sprinting studies have suggested that a decrease in CM to ankle distance at initial touchdown reduced the horizontal braking forces that are associated with an increase in running velocity (Mann, 2010; Mann & Hagy, 1980; Mann & Herman, 1985; Mann et al., 1984). In the current study no change in CM to ankle distance at initial touchdown was reported during the training block and subsequently there were no increases in running velocity or step length. It has been suggested that through conditioning and repetition in training, athletes may randomly select a step length and step frequency combination that is the most optimal for the individual athlete (Cavanagh & Williams, 1982).

Decreases in contact time have been coupled with reductions in K_{vert} (Morin et al., 2005; Slawinski et al., 2008). The findings of this study concur with this as a reduction in K_{vert}/BW was reported over the training block. This in part could be explained by the significant changes in F_{max}/BW during the training block. Past research has suggested that no change in K_{leg} could be explained as the change in leg length also increases with running velocity (Butler et al., 2003). Thus the increase in F_{max} with velocity is offset by the increase in leg length and therefore K_{leg} does not alter. Data from this study reported no change in running velocity, K_{leg}, K_{leg}/BW, Δy and ΔL over the training block. Increases in hip angle and ankle angle were associated with alterations in CM to ankle angle at initial touchdown.

Over the training block the CM to ankle angle decreased whereas the CM to ankle distance did not change, this would suggest that the CM may be higher at touchdown. The decrease in CM to ankle angle during the training block potentially influenced the position of the lower limb at initial touchdown and subsequently the running velocity achieved. Findings from this study suggest that small variations in gait and spring-mass characteristics were not significant in isolation but in combination may cause a subsequent change in CM position at touchdown. To understand more how and why the CM to ankle angle decreased during training future research should examine both the lower limb position during contact and recovery (flight). It was beyond the scope of this study to examine the position of the lower limb during recovery (flight).

Limitations

This is the first study to include regional-level athletes during an actual training session rather than reporting findings from a predetermined protocol. This study therefore allows for a greater level of ecological validity. It would be practically impossible to collect gait and spring-mass characteristic data on these athletes within a laboratory environment. Access to regional-level athletes is limited and therefore this information would inform coaches and sport biomechanists of what is required to develop middle-distance running technique and improve performance.

Documenting middle-distance athletes during specific training sessions offers a number of challenges. The nature of the middle-distance training as outdoor event means that many factors cannot be controlled in the manner preferred for laboratory studies. Set up and operation of measurement equipment outside the laboratory environment provides technical obstacles, while the loss of capacity for repeating failed trials limits the completeness of the data set. Salo et al. (2011) suggested that training studies should be undertaken to account for how athletes prepare for competition.

Despite positive changes in gait and spring-mass characteristics no improvement was noted in training performance time (associated with an increase in running velocity) this may have been due to the constraints of data capture during the training session. As part of this study no physiological markers of fatigue were reported, only CMJ were used to assess the impact of fatigue on K_{vert} and $K_{leg.}$ Due to inconsistences in jump technique in the middle-distance athletes only CMJ could be employed, this is a limitation as past research has used other jump tests which was not possible in this study.

6.5. Conclusions

The aim of this study was to investigate the changes in gait and spring-mass characteristics associated with high-levels of performance (reported in Chapter 5) in regional-level athletes. This investigation documented the maintenance of running velocity during a single speed endurance training session and over a 4 week speed endurance training block. The findings from the single training session showed that only step frequency altered, with no difference in performance time, running velocity, contact time, flight time and step length. Over the training block the performance time and running velocity did not alter, this could be attributed to environmental factors and or tactics employed by the athletes (Figure 1.1). The CMJ performance improved over the training block implying an improvement in athlete training status although no changes in running velocity were evident. Despite this gait characteristics associated in maintaining the running velocity did differ with contact time decreasing and flight time increasing over the training block, these alterations were associated with an increase in step frequency. Variations in gait and spring-mass characteristics were not significant in isolation but in combination may cause a subsequent reduction in lower limb neuromuscular behaviour (e.g. K_{vert} and K_{leg}).

This chapter suggests that regional-level athletes maintain running velocity during speed endurance training by increasing step frequency. This approach contradicts findings from the previous chapter that suggests that a longer step length is associated with an increase in running velocity and reduced performance time during competition. This would imply that regional-level athletes should instead focus on step length rather than step frequency in a training scenario.

CHAPTER 7: DISCUSSION

7.1. Introduction

Traditionally, middle-distance events have been considered primarily from a metabolic perspective (Daniels & Daniels, 1992; Jung, 2003). Paavolainen et al. (1999) reported an intuitive link between physiological and biomechanical aspects of middle-distance running, with 54% of the variation in running economy attributed to gait and spring-mass characteristics (Anderson, 1996; Saunders et al., 2004). Within the literature, several biomechanical parameters have been proposed to influence performance time and the maintenance of a high running velocity, Figures 1.1 and 1.3 (Iaia et al., 2009; Le Meur et al., 2013; Morin et al., 2011a; Quinn, 2009; Thiel et al., 2012). Small changes in gait and spring-mass characteristics can result in large gains in running velocity and ultimately influence performance time (Chapman et al., 2011). When it comes to documenting the gait and spring-mass characteristics associated with homogenous populations (e.g. middle-distance athletes) the published research is less clear.

To date, running research has established that more experienced runners possess a freely chosen step length that minimises submaximal oxygen consumption, these step lengths are larger than less experienced or novice runners (Bailey & Messier, 1991; Daniels & Daniels, 1992). The process by which an experienced runner determines their step length and step frequency is currently unknown. It has been suggested that through conditioning and repetition in training athletes may randomly select a step length and step frequency combination that is the most optimal for that individual athlete (Cavanagh & Williams, 1982). Literature has tended to evaluate the impact of step length and step frequency on recreational participants running at velocities between 3.00 and 5.00 $m \cdot s^{-1}$ (Derrick et al., 2002; Federations, 2012-2013; Queen et al., 2006). Only a handful of studies have analysed the impact of step length and step frequency on maintaining a high running velocity between 6 and 8.00 $m \cdot s^{-1}$ (Hayes & Caplan, 2012; Leskinen et al., 2009; Skof & Stuhee, 2004).

At running velocities greater than 4.00 $m \cdot s^{-1}$ research suggests that contact time significantly relates to competitive performance, this may be due to the greater neuromuscular demands of running at higher running velocities (Oliver & Stembridge, 2011). Hayes and Caplan (2012) identified a large negative relationship between contact and performance time in both 800 m and 1500 m competitive races. Comparative data of international- and national-level middle distance athletes demonstrated similar contact times during the 2005 World Championship men's 1500 m final (Leskinen et al., 2009). Research suggests that the difference between middle-distance athlete-levels may not be contact time, rather the ability of the athletes to modify their lower limb neuromuscular behaviour during ground contact without simultaneously increasing their metabolic cost or contact time. Until this thesis no study had documented flight time of middle-distance athletes during competition. Potential influences of flight time on middle-distance performance time have been inferred from studies based away from the synthetic athletics track environment. A decrease in flight time is a consequence of a decrease in the lower limb stiffness due to the reduction in the system's capacity to generate force rapidly and/or to tolerate impact forces (Hobara et al., 2010a).

Vertical stiffness has been shown to increase with running velocity and is an important factor in maintaining running velocity (Hobara et al., 2010a; Morin et al., 2005). These studies suggest that changes in K_{vert} are due to the onset of fatigue. Dutto and Smith (2002) investigated the effects of exhaustion on lower limb neuromuscular behaviour during treadmill running and reported that as participants became fatigued K_{vert} decreased. In an synthetic athletics track environment, Morin et al. (2006)

demonstrated that K_{vert} decrease during repetitive maximal 100 m sprints. Therefore it has been suggested that K_{vert} decreases under fatigue, which could be a limiting factor in maintaining a high running velocity (Hobara et al., 2010a). Previous research has contended that K_{vert} is not an appropriate measure during running and that K_{leg} would be more suitable variable. This is due to the fact that K_{vert} does not take into account the angle of the leg at initial touchdown, the change in leg length, resting leg length or velocity (Brughelli & Cronin, 2008a). Leg stiffness which encompasses the angle of the leg at initial touchdown, the change in leg length, resting leg length and velocity, has been deemed by several authors to be a more appropriate measure during running (Brughelli & Cronin, 2008a).

The ability to maintain gait and spring-mass characteristics during running was strongly correlated to length of time and distance covered. Changes in K_{leg} provided a better prediction than metabolic predictors, accounting for 75% of the variance in distance covered and 68% of the variance in performance time. Farley and Gonzalez (1996) manipulated step frequency and found that as it decreased both step length and contact time increased while K_{leg} decreased. More recently, Morin et al. (2007) were able to differentiate the effects of change in step frequency and contact time on K_{leg}. These authors found that 96% of changes in K_{leg} were accounted for by changes in contact time. In some studies, K_{leg} remained constant during running at different speeds (He et al., 1991); however, it has also been suggested that K_{leg} is adjusted to meet the changes in demands of a specific task (Farley & Gonzalez, 1996; Farley & Morgenroth, 1999). Only, Morin et al. (2005) has examined K_{leg} during moderate maximum running velocities; however, no significant alteration in K_{leg} was reported. No change in the K_{leg} could be explained as the change in leg length also increases with running velocity. Therefore the increase in maximal ground reaction force with velocity is offset by the increase in leg length and therefore K_{leg} does not alter.

Inconsistencies among gait and spring-mass characteristics research previously reported may be a consequence of the different nature, intensity, duration, type of exercise, participants included and the equipment used (e.g. treadmill) (Girard et al., 2010). Accordingly this thesis investigated the following objectives assess:

(i) the validity of gait and spring-mass characteristics captured from a range of biomechanical technologies that could be used away from the laboratory environment on an synthetic athletics track (chapter 3)

(ii) evaluate the stiffness values obtained through mathematical modelling (estimations based on high-speed video data only) compared to direct measurement (using a force platform, chapter 4)

(iii) identify the effects of athlete ability-level (e.g. international-, national- and regional-level athletes) on gait and spring-mass characteristics during competition (chapter 5)

(iv) identify the effects of speed endurance training on gait and spring-mass characteristics in regional-level athletes (chapter 6)

7.2. Experimental findings and recommendations

Through investigating a cohort of fifteen athletes, the aim of chapter 3 was to assess the validity of digital (50Hz) and high-speed camera (300 Hz) compared to Optojump and LDM device in obtaining contact time, flight time, step length, step frequency and running velocity on a synthetic athletics track (away from the laboratory environment). The main findings from this study were that gait characteristics obtained from digital (50Hz) and high-speed camera (300 Hz) were comparable to Optojump and LDM devices. This meant that gait and spring-mass characteristics could be determined from video (digital [50Hz] and high-speed camera [300 Hz]), Optojump and LDM devices during both training and competition. Bland-Altman plots indicate that bias is minimal for each gait and spring-mass characteristics and scatterplots revealed homoscedasticity. According to the data presented in this study, each gait and spring-mass characteristics had good reproducibility, as differences between the biomechanical systems were small. The current study's findings demonstrated that contact and flight times quantified by Optojump and high-speed video have an acceptable amount of measurement error; which was equivalent to less than one video frame (≥ 0.003s). Through the use of video this study has confirmed that gait characteristics can be documented away from the laboratory setting (e.g. training and competitive races). This allows coaches and sport biomechanists to confidently capture gait characteristics using only video during a running performance. Due to the unforeseen constraints of both training and competition, this thesis gait and spring-mass characteristics data was solely captured from video (digital [50Hz] and high-speed camera [300 Hz]).

The gold standard for measuring K_{vert} and K_{leg} is the direct measurement of the spring-mass model through the use of a force platform (Arampatzis et al., 2000; Morin et al., 2005). Vertical and leg stiffness can also be estimated by mathematical modelling, these are often used when the gold standard direct measurement is not possible or deemed appropriate (Morin et al., 2005). The aim of chapter 4 was to assess the validity of stiffness values obtained through mathematical modelling (estimations based on high-speed video data only) in determining K_{vert} and K_{leg} during running to the gold standard direct measurement (using a force platform).

Through the analysis of 32 contacts chapter 4 demonstrated that to quantify K_{vert}, method E based on Morin et al. (2005) mathematical model was the most representative of the gold standard direct measurement (method A). This mathematical method calculated F_{max} by quantifying flight time directly and Δy as the vertical displacement of the CM through a digitised 18-point model (difference between the maximum and minimum CM to foot displacement). To quantify K_{leg} method J, based on McMahon and Cheng (1990) and Morin et al. (2005) was deemed the most representative of the gold standard direct measurement (method F). This mathematical method calculated F_{max} by quantifying flight time directly. The same calculation was used to determine ΔL in both method J and the gold standard direct measurement (method F). Based on this study's findings the original hypothesis that estimations (by mathematical modelling) would allow for the documentation of K_{vert} and K_{leg} when the gold standard direct measurement of stiffness was not possible was accepted. Findings also reported no significant interactions between method E and method J and the gold standard direct measurement (method A and F) with running velocity.

Chapter 3 and 4 supported the use of video in the documentation of gait and spring-mass characteristics in training and competition environments (e.g. away from a laboratory setting). The ability to capture gait and spring-mass characteristics using only video, has provided the potential to investigate aspects of performance (Figure 1.1 and Figure 1.3) that previously had not been possible. This relationship was explored through the aims of chapter 5. The aim of this chapter was to investigate the effects of athlete ability-level (e.g. international-, national- and regional-level athletes) on gait and spring-mass characteristics during competition. By identifying differences in gait and spring-mass characteristics between athlete ability-levels it is hoped that our findings would provide new information to inform coaches in technique training of middle-distance athletes. The main findings of this study were that international-level athletes achieved a lower performance time as a consequence of a longer step length and lower K_{vert} and K_{leg}. These findings concur with a past competition-based study that suggested that longer step lengths were associated with a significant reduction in K_{vert}, K_{leg} and performance time (Taylor & Beneke, 2012).

In this middle-distance population it could be suggested that step length is the dominant determinant of running velocity and a lower performance time; as step frequency in this study did not differ between athlete-levels. Data from this study suggests step length accounts for 29% of the variance in 800 m performance time. Step length is achieved through the contribution of take-off distance, flight distance and landing distance (Hay, 1993). When reporting take-off distance the extent to which the athlete extends the support leg (whilst in contact with the ground) is an important characteristic and consequently impacts on the step length. The extent to which the athlete extends the support leg is often determined in K_{leg} research by the sweep of the leg during contact (Θ) and L_0. The current study suggests that L_0 explains 34% of the variance in 800 m performance times. This reinforces the conclusions of chapter 4 which stated that initial leg length (Method 5) was an important factor in determining stiffness of the lower limb. By documenting initial leg length using method 5 it enabled the difference in anthropometric profiles, tibial length and position of lower limb at initial touchdown to be reported.

Significant differences in mean Θ and L_0 were found between athlete-levels, with international-level athletes reporting a higher mean Θ and lower L_0 compared to their less able counterparts. These gait characteristics were associated greater amount of knee flexion during contact (at maximal knee flexion) and larger ΔL for international-level athletes. This could imply that the international-level athletes CM travelled faster during ground contact. This explains why international-level athletes reported a higher Δy and mean Θ. These findings concur with those of Taylor and Beneke (2012) who reported that an international-level athlete had a higher Δy compared to his competitors. This suggests that international-level athletes can run at greater velocities but with lower limb stiffness. These findings infer that international-level athletes have a greater level of compliance thereby facilitating the storage and utilisation of elastic energy during the stretch-shortening cycle (Brughelli & Cronin, 2008a). The stretch-shortening cycle is typically characterised by an eccentric muscular contraction (or stretch) followed immediately by a concentric muscular contraction (Harrison et al., 2004). Utilizing a stretch immediately before a concentric contraction has been shown to augment the concentric phase resulting in increased force production and power output (Cavagna et al., 1968). This increase in force production could translate in to an increase in flight distance and subsequently a longer step length (Harrison et al., 2004).

However, as runners become exerted and fatigue develops and progresses over the course of a run, the effectiveness of the protective neuromuscular mechanism of muscle diminishes (Radin, 1986) along with the tolerance to repeated stretch-shortening cycles (Hayesetal et al., 2004; Komi, 2000; Skof and Strojnik, 2006). Fatigue can have considerable influence on lower extremity mechanics. With altered neuromuscular function, a reduction in the transfer of mechanical energy between eccentric and concentric muscle contractions can occur (Mizrahi etal.,2000a, 2000b) along with slower muscle reaction times (Mizrahi et al., 2001). This creates problems when running as the ability to maintain desired angular displacements during the stance phase becomes compromised as runners become exerted (Komi, 2000). Thus, it is likely that changes in joint motion will occur over the course of a run. Chapter 6 investigated the changes in gait and spring-mass characteristics associated with high-levels of performance (reported in Chapter 5) in regional-level athletes during speed endurance training. This investigation documented the maintenance of running velocity during a single speed endurance training session and over a 4 week speed endurance training block.

The findings from the single training session showed that only step frequency altered, with no difference in performance time, running velocity, contact time, flight time and step length. Performance time and running velocity did not change over the training block but the gait characteristics associated in maintaining the running velocity did. Contact time decreased and flight time increased over the training block, these alterations in gait characteristics were associated with an increase in step frequency. Decreases in contact time have been coupled with reductions in K_{vert} (Morin et al., 2005; Slawinski et al., 2008). The findings from this study reported a significant increase in

F_{max}/BW during the training block. This suggests that the athletes were able to exert higher ground reaction forces during ground contact which may benefit subsequent competitive performance. Hasegawa et al. (2007) suggested that athletes who demonstrated shorter contact times achieved a higher finishing position during a half marathon race. This would suggest that the regional-level athletes over this training block made positive modifications to their flight and contact time in order to positively impact on competitive performance.

Data from this study reported no change in running velocity, K_{leg}, K_{leg}/BW, Δy and ΔL over the training block. Small variations in these gait and spring-mass characteristics were not significant in isolation but in combination may cause a subsequent reduction in K_{vert}/BW. This highlights the importance of documenting both joint angles and spring-mass characteristics to provide a more comprehensive overview of how athletes modify the position of the lower limb during ground contact. During training athletes reported changes in hip angle, ankle angle, CM to ankle angle at initial touchdown which potentially influenced running velocity and reduce performance time. The decrease in CM to ankle angle during the training block potentially influenced the position of the lower limb at initial touchdown and subsequently the running velocity achieved.

Over the training block the performance time and running velocity did not alter, this could be due to environmental factors and or tactics employed by the athletes (Figure 1.1). The CMJ performance improved from the END of day 0 to day 30 which could imply an improvement in athlete training status and the ability to delay the onset of fatigue. Speed-endurance training facilitates the maintenance of aerobic capacity whilst improving intense short-duration-repeated high-intensity exercise performance (Iaia & Bangsbo, 2010). To monitor changes during speed-endurance training sessions physiological research has documented alterations in lactate threshold and heart rate (Iaia & Bangsbo, 2010; Iaia et al., 2009). It was beyond the scope of this study to report the physiological changes during speed-endurance training block although it is acknowledged that these may occur.

This chapter suggests that regional-level athletes maintain running velocity during speed endurance training by increasing step frequency. This approach contradicts findings from the previous chapter that suggests that a longer step length is associated with an increase in running velocity and reduced performance time during competition. This would imply that regional-level athletes should instead focus on step length rather than step frequency in a training scenario. The findings of both chapters 5 and 6 from this thesis provide new insight into the proposed explanations for the success of middle-distance athletes (Figure 1.1 and Figure 1.3). Research has already suggested biomechanical parameters that may influence performance time (Le Meur et al., 2013; Morin et al., 2011b; Quinn, 2009; Quinn, Manley, Aziz, Padham, & MacKenzie, 2011). Until this thesis there was paucity of studies documenting gait and spring-mass characteristics of middle-distance athletes of varying abilities in competition and regional-level athletes in training. Only Leskinen et al. (2009) had reported gait characteristics across differing middle-distance ability-levels during competitive performances. Therefore it can be assumed that this thesis adds to the body of biomechanical knowledge and informs fellow researchers of the important aspects of reducing performance time.

7.3. Limitations to the Doctoral investigations

Whilst this body of work makes a significant contribution to providing coaches and sport biomechanics with a greater understanding of gait and spring-mass characteristics of middle-distance athletes, as with any research, it is important to acknowledge that it is not without its limitations given the complexity of the area and the restrictive nature of the competition and training environment.

A key aim of this thesis was to document the stiffness values obtained through mathematical modelling during competition and training as direct measurement of stiffness was not possible. To facilitate this, comparisons of stiffness values obtained through mathematical modelling (estimations based on high-speed video-based data only) and direct measurement (using a force platform) were completed. Based on the findings of Chapter 4 it was suggested that mathematical modelling would allow the documentation of stiffness in middle-distance athletes. At moderate running velocities achieved by long distance athletes (≥ 3000 m) the findings of this thesis support the application of gait and spring-mass characteristics determined by video only in both training and competition. This thesis does not support the general application of stiffness values obtained through mathematical modelling in all athlete populations. For this to occur the literature must provide a more extensive comparison of stiffness values obtained through mathematical modelling (estimations based on high-speed video-based data only) and direct measurement (using a force platform) in a variety of homogenous athlete cohorts.

The use of international- national- and regional-level middle-distance (800 m and 1500 m) athletes presented several methodological difficulties. The potential sample population that could be included in this thesis was limited to those athletes that pertain to one of three groups. Participant groups were homogenous and included 800 m and 1500 m male middle-distance athletes only (refer to section 5.3). Power calculations based on data presented in Leskinen et al. (2009) were used to justify the sample size of the current thesis (Research, 2011). The sample size utilised within this thesis ranged from 10 to 30 athletes.

The nature of middle-distance competitive races and training environment as a timed outdoor event means that many factors cannot be controlled in the manner preferred for laboratory studies. Set up and operation of measurement equipment outside the laboratory environment provides technical obstacles, while the loss of capacity for repeating failed trials limits the completeness of the data set. Studying middle-distance athletes within an actual race provides a unique opportunity to document athletes of different-levels performing in a competitive manner to the limit of their endurance capacity.

7.4. Future research directions

The aim of this thesis was to provide a biomechanical evaluation of middle-distance running during competition performance and document these gait characteristics during training. Future research should aim to apply these methods to other sporting activities (e.g. longer-distance events) to enable a more comprehensive understanding of the running mechanics. The spring-mass mathematical models and the methods used to determine gait characteristics are incorporated in the first body of work (Chapters 3 and 4) progressing current methods for use within the field to investigate running mechanics away from laboratory settings. As such, whilst distance running mechanics has been the focus of numerous biomechanical investigations, only one study (single case study of indoor 800 m world record holder Jolanda Ceplak) has reported running mechanics exhibited during a women's middle-distance competitive race (Skof & Stuhee, 2004). More research is needed to investigate the gait and spring-mass characteristics of female athletes and identify potential differences between genders during middle-distance events. Future research should also determine the gait and spring-mass characteristics exhibited during longer distance competitive races (e.g. 5,000 m and 10,000 m).

Similar to the work of Leskinen et al. (2009), data presented in Chapter 5 outlined the gait and spring-mass characteristics exhibited during competition of international-, national- and regional-level athletes and, their relationship to performance. Documenting the gait and spring-mass characteristics of international-level athletes provided an insight into the key biomechanical variables that potentially differentiate running performance. Future research should look to assess training interventions and how these impact the key biomechanical variables that facilitate the maintenance of a high running velocity and improve running performance. Studies should focus on how gait and spring-mass characteristics may be influenced by the recovery of the lower limb during flight. Continued investigations into the recovery and position of the lower limb during running could provide additional insight into the application of 'front side' running mechanics. As 'front side' running mechanics have been previously linked to high-levels of sprinting performance (Mann, 2010). Research is yet to document 'front side' running mechanics in middle-distance running.

To the author's knowledge this body of work is the first to investigate running at a high velocity and, document the contribution of the lower limb during ground contact by reporting both gait and spring-mass characteristics together. The majority of previous research examining the neuromuscular behaviour of the lower limb during ground contact (stiffness regulation) has only reported running velocity step length and step frequency (Hobara et al., 2010a; Le Meur et al., 2013; Taylor & Beneke, 2012). Future studies should provide more of an overview of the lower limb position at initial touchdown and during ground contact to enable conclusions to be drawn on how stiffness regulation influences parameters associated with reduction in performance time.

Future research should look to increase data capture to include the flight phase of running gait, as the majority of stiffness research has focused solely on ground contact

(Blum et al., 2009; Butler et al., 2003; Dalleau et al., 1998; Degache et al., 2013; Dumke, Pfaffenroth, McBride, & McCauley, 2010). This is supported by studies that have suggested that an increase in step length has been associated with the capacity of the hip extensors and knee flexors to slow the lower leg during the swing phase (De Lucca & Melo, 2012). Hanon, Thepaut-Mathieu, and Vandewalle (2005) reported that the hamstrings fatigue before other leg muscles during high-speed running. Hamstring fatigue could result in decreased step length and thereby increase contact time and reduce the time available to recover the lower limbs during the flight phase (Hayes & Caplan, 2012). Electromyography (EMG) studies investigating muscle fatigue and its effect on gait and spring-mass characteristics would provide much needed insight. These investigations would enable the relationship between K_{vert} and K_{leg} with other measures of stiffness (e.g. tendon and musculotendinous) to be explored and the mechanisms of these changes to be observed.

7.5. Concluding statement

The aim of this thesis was to initially establish a valid means of measuring gait and spring-mass characteristics away from the laboratory environment (e.g. on an outdoor 400 m synthetic athletics track), and then provide a biomechanical evaluation of middle-distance running during competition and training in order to identify gait and spring-mass characteristics that influence performance time. The main findings of this thesis was that international-level athletes achieved a lower performance time as a consequence of a longer step length and lower K_{vert} and K_{leg}. Whereas, regional-level athletes maintain running velocity during speed endurance training by increasing step frequency. Data from this thesis implies that regional-level athletes should focus on step length rather than step frequency in a training scenarios in order to maintain running velocity.

APPENDIX B – ETHICS FORM

College Ethics Panel

Ethical Approval Form for Post-Graduates

Name of Student: Claire Bridgman

Name of Supervisor: Dr Philip Graham-Smith and Dr Paul Brice

School: School of Health Sciences

Course of study: PhD programme

Name of Research Council or other funding organisation (if applicable):

1a. Title of proposed research project

BIOMECHANICAL EVALUATION OF DISTANCE RUNNING DURING TRAINING AND COMPETITION

1b. Is this Project Purely literature based?

NO

2. Project focus

The aim of this thesis was to provide a biomechanical evaluation of distance running during competition performance, to investigate differences in gait characteristics between levels of performances and changes as a consequence of training.

3. Project objectives

Therefore the research aims were to:

(I) Evaluate various technologies available for use in the competition and training environment to quantify gait characteristics (contact time, flight time, step length, step frequency and velocity) and to examine the differences in output. (Comparison of Optojump, video analysis using standard camcorders and high-speed video cameras, and Laveg (LDM speed measuring device).

(II) Compare the data output of vertical stiffness and leg stiffness obtained through mathematical modelling (estimations based on high-speed video-based data only) to direct measurement (using a force platform) across a range of running speeds.

Findings from these studies will then inform the methodologies subsequently used to quantify gait and spring-mass characteristics in competition and training. During competition the research aims were to determine how:

(III) International-level athletes gait and spring-mass characteristics differed from their national- and regional-level counterparts.

The gait and spring-mass characteristics associated with higher-levels of performance (e.g. international-level athletes) should be documented in training. Research aim was to quantify the:

(IV) Gait and spring-mass characteristics associated with higher-levels of performance during training (within single session and over a training block)

4. Research strategy

(For example, outline of research methodology, what information/data collection strategies will you use, where will you recruit participants and what approach you intend to take to the analysis of information / data generated)

All athletes included in this PhD research will be track and field athletes and will be based at the UK Athletics Loughborough High Performance Athletics Centre. Athletes will participate in this research as part of their normal training session.

All data will be collected during training and competition with no impedance to the athlete. This aim of this research is to monitor the athletes at no point will there be any intervention or implementation of any protocol outside the athletes usual training activities. The information collected for this research will also be made available the coach and athlete for monitoring purposes.

During training session data will be captured using the following biomechanical technologies. A digital video camcorder (HVR-A1E, Sony, Japan) and high-speed video cameras (EX-F1, Casio, Japan) will be used to collect video for quantitative and qualitative analysis. All camera footage was taken perpendicular to the running direction in accordance with previous research (Cavanagh et al., 1985, Mero and Komi, 1985).

To quantify step length white tape, 0.15 m in length, will be placed perpendicular to the lane border at 1 m intervals on both sides of the running lane (throughout the field of view). These white tape markings allow for the position of the foot (and thereby step lengths) to be calculated from video analysis using the Quintic Biomechanics software.

Temporal running kinematics (such as contact and flight time) will be monitored by an optical acquisition system (Optojump, Microgate, Bolzano, Italy). This system consists of 60 x 1 m parallel bars (30 receivers and 30 transmitters; equating to the system spanning 30m in total) that will be positioned on the synthetic athletic track, allowing for athlete-surface interaction. Each bar contains 32 infrared light emitting diodes (LED), resulting in a system accuracy of 0.031 m at a sampling frequency of 1000 Hz. Optojump bars were connected to a personal computer, and the proprietary software (Optojump software, version 1.5.1.0) allowed for temporal kinematic quantification with a precision of 0.001 s.

Laser distance measurement (LDM) devices (LDM-300C, Jenoptik, Germany) will be used to obtain linear distance measures during athletes training sessions. The LDM devices will be placed on tripods corresponding approximately to the height of the athlete’s centre of mass (COM). Data output includes average speed of the athlete throughout a specific range and instantaneous speed.

Kistler force plates sampling at 1200Hz (Kistler Instruments 9287BA, Switzerland) were used to collect kinetic data of running during training. The kinetic data was analysed using Bioware software to determine force loading characteristics and through additional processing techniques to quantify parameters such as vertical and leg stiffness (which are thought to relate to running economy).

The data collected will be used for routine monitoring of athlete performance and development.

5. What is the rationale which led to this project?

(For example, previous work – give references where appropriate. Any seminal works must be cited)

Whilst research into the biomechanics of running has gained substantial interest over the last 40 years there is surprisingly a lack of information within specific populations (e.g. middle-distance athletes). The literature has identified differences in gait characteristics between sprint and endurance athletes (Bushnell & Hunter, 2007), but differences in gait characteristics between athletes of different performance levels within the same event (e.g. international- compared to national-level middle-distance athlete) is not well established. It is therefore not clear whether biomechanical factors can differentiate between performance level.

Coaches and sport biomechanists devote substantial time and resource implementing training sessions to develop running technique and improve competition performance (Paton & Hopkins, 2005). Training is therefore a prerequisite for all athletes to facilitate the process of continuous adaptation required for competition. There is limited research documenting kinematics and the relationship with running performance and lower limb neuromuscular behaviour during training that can be related to competition performance.

Past research has tended to evaluate the impact of gait and spring-mass characteristics on recreational participants running at velocities between 3 and

5 $m \cdot s^{-1}$ (Derrick et al. 2002; Queen et al. 2006; Padulo et al. 2012). This is significantly lower than typical velocities of elite performers. For example at the 2012 London Samsung Diamond League 800 m final, the race was won in a time of 1:44.49, during this race the athletes achieved average running velocities of between 6 and 8 $m \cdot s^{-1}$. New research on international-level middle-distance athletes is therefore critical to document how higher running velocities are achieved in terms of gait and spring-mass characteristics. The best means by which the gait and spring-mass characteristics of international-level middle-distance athletes could be determined is in competition.

6. **If you are going to work within a particular organisation do they have their own procedures for gaining ethical approval**

(For example, within a hospital or health centre?)

NO

If YES – what are these and how will you ensure you meet their requirements?

7. **Are you going to approach individuals to be involved in your research?**

NO (delete as appropriate)

If YES – please think about key issues – for example, how you will recruit people? How you will deal with issues of confidentiality / anonymity? Then make notes that cover the key issues linked to your study

Athletes will be monitored during their training sessions at the UKA Loughborough High Performance Centre.

8. **More specifically, how will you ensure you gain informed consent from anyone involved in the study?**

Whilst data will be collected as part of routine monitoring of performance, the athletes were all informed of the purpose of the data collection and its use, both verbally and through an information sheet. All athletes were provided with at least 48 hour notice of sessions that would be recorded. A participant information sheet and consent form was constructed to highlight the use for research purposes (appendix 1).

9. **How are you going to address any Data Protection issues?**

See notes for guidance which outline minimum standards for meeting Data Protection issues

All data will be collected and stored under the strictest of guidelines and according to the data protection act. Each athlete will be numerically coded and the data will only be discussed amongst lead investigators and relevant UK Athletics member of staff. Researcher, supervisors and UK Athletics head of performance would have access to the part identifiers. Data will be stored in a performance database for monitoring performance across athlete's careers. All paper data will be secured by lock in the Biomechanics cupboard. Electronic data will be stored on a hard-drive and Claire Bridgman's (researcher) PC under password protection. There is no intention to complete any further secondary analysis of the data.

10. Are there any other ethical issues that need to be considered? For example - research on animals or research involving people under the age of 18.

NO

11. (a) Does the project involve the use of ionising or other type of "radiation"

NO

(b) Is the use of radiation in this project over and above what would <u>normally</u> be expected (for example) in diagnostic imaging?

NO

(c) Does the project require the use of hazardous substances?

NO

(d) Does the project carry any risk of injury to the participants?

NO

(e) Does the project require participants to answer questions that may cause disquiet / or upset to them?

NO

If the answer to any of the questions 11(a)-(e) is YES, a risk assessment of the project is required and must be submitted with your application.

12. How many subjects will be recruited/involved in the study/research? What is the rationale behind this number?

This research will comprise of only endurance athletes. Athletes will be based at Loughborough High Performance Athletic Centre. The number of athletes involved in this research will vary depending on training and competition status and a minimum of 10 athletes has been set. This is based on a realistic estimate of how many subjects can be recruited whilst still maintaining a high criteria of elite athlete status, the time consuming nature of the data processing involved with these procedures, and the need to adequately explore relationships through statistical analysis.

13. Please state which code of ethics has guided your approach (e.g. from Research Council, Professional Body etc.).

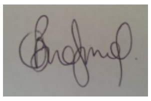
Please note that in submitting this form you are confirming that you will comply with the requirements of this code. If not applicable please explain why.

British Association of Sport & Exercise Sciences

Remember that informed consent from research participants is crucial, therefore all documentation must use language that is readily understood by the target audience.

Projects that involve NHS patients, patients' records or NHS staff, will require ethical approval by the appropriate NHS Research Ethics Committee. The University College Ethics Panel will require written confirmation that such approval has been granted. Where a project forms part of a larger, already approved, project, the approving REC should be informed about, and approve, the use of an additional co-researcher.

I certify that the above information is, to the best of my knowledge, accurate and correct. I understand the need to ensure I undertake my research in a manner that reflects good principles of ethical research practice.

Signed by Student 

Print Name CLAIRE BRIDGMAN

Date 1/07/2014

In signing this form I confirm that I have read this form and associated documentation.

I have discussed and agreed the contents with the student on ____________________
(Please insert date of meeting with student)

Signed by Supervisor ____ P Graham ___________________

Print Name __Dr Philip Graham-Smith______________

Date ___01/07/14_________________________

College Ethics Panel:	**Ref No:** *Office Use Only*
Application Checklist	

Name of Applicant: CLAIRE BRIDGMAN

The checklist below helps you to ensure that you have all the supporting documentation submitted with your ethics application form. This information is necessary for the Panel to be able to review and approve your application. Please complete the relevant boxes to indicate whether a document is enclosed and where appropriate identifying the date and version number allocated to the specific document (*in the header / footer*), Extra boxes can be added to the list if necessary.

Document	Enclosed? (indicate appropriate response)				Date	Version No
Application Form	Mandatory			If not required please give a reason		
Risk Assessment Form	~~Yes~~	No	Not required for this project	Project is observational based on athlete and coaching practise		
Participant Invitation Letter	~~Yes~~	No	Not required for this project	All athletes are part of UKA world class performance programme		
Participant Information Sheet	Yes	~~No~~	Not required for this project	See attached (app 1)		
Participant Consent Form	Yes	~~No~~	Not required for this project	See attached (app 1)		
Participant Recruitment Material – e.g. copies of posters, newspaper adverts, website, emails	~~Yes~~	No	Not required for this project	All athletes are part of UKA world class performance programme and will undertake their normal day to day activities.		
Organisation Management Consent / Agreement Letter	~~Yes~~	No	Not required for this project	Project funded by UKA		
Research Instrument – e.g. questionnaire	~~Yes~~	No	Not required for this project	Observational study with no interventions		
Draft Interview Guide	~~Yes~~	No	Not required for this project	No interviews		
National Research Ethics Committee consent	~~Yes~~	No	Not required for this project	Local ethics approval required		
Note: If the appropriate documents are not submitted with the application form then the application will be returned directly to the applicant and will need to be resubmitted at a later date thus delaying the approval process						

INFORMATION SHEET FOR PARTICIPANTS

BIOMECHANICAL EVALUATION OF DISTANCE RUNNING DURING TRAINING AND COMPETITION

Principal Investigator: CLAIRE BRIDGMAN

You are being invited to take part in a PhD research study as a co-project between UK Athletics and the University of Salford. Before you decide whether you want to take part, it is important for you to understand why the research is being done and what your participation will involve. Please take time to read the following information. Ask us if there is anything that is not clear or if you would like more information.

What is the purpose of the study?

The aim of this thesis is to provide a biomechanical evaluation of distance running during competition performance and document these gait and spring-mass characteristics during training. This will aid in the understanding of how middle-distance velocities are achieved and to inform the training methods adopted by coaches.

Do I have to take part?

Whilst you have an obligation to be monitored as part of your athlete development, it is up to you to decide whether or not you wish to participate. You will be provided with at least 48 hour notice of any sessions that will be recorded. All data will be collected during your routine training sessions or in competition and there will be no interference to yourself or the training programme as a whole. If you do agree you will be asked to sign a consent form. You are still free to withdraw at any time and without giving a reason. If the decision is made to withdrawn athletes will not be included in the final thesis. A decision to withdraw will not affect your rights/any future treatment/service you receive.

What will happen to me if I take part?

All data will be collected during your routine training sessions at Loughborough Athletics centre. Video data will be collected during training sessions throughout the season. The cameras will be placed at the side of the running track so as not to interfere with your session. Kinetic data will be collected of your runs using a Kistler force plate sampling at 1200Hz. The data will be used to form studies within this PhD thesis and may be presented or published at a later date.

Are there any risks/benefits involved?

You will not be expected to undertake any activities that do not form part of your normal training or competition routines and as such there will be no additional risk of injury.

Will my taking part in the study be kept confidential?

Confidentiality will be maintained throughout the study. The data acquired will not be personally identifiable to the subject, shared with any third party, or stored for unrelated analysis.

Contact details of Researcher

For further details please contact Claire Bridgman

c.f.bridgman@edu.salford.ac.uk

UNITED KINGDOM ATHLETICS

Consent Form

Title of Project: BIOMECHANICAL EVALUATION OF DISTANCE RUNNING DURING TRAINING AND COMPETITION

Name of Chief Researcher: CLAIRE BRIDGMAN

Please Initial

- I confirm that I have been given and have read and understood the athlete information sheet for the above study and have asked and received answers to any questions raised

  ____

- I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason and without my rights or future service being affected in any way

  ____

- I understand that the researchers will hold all information and data collected securely and in confidence and that all efforts will be made to ensure that I cannot be identified as a participant in the study (except as might be required by law) and I give permission for the researchers to hold relevant personal data and to present and publish findings.

  ____

- I agree to take part in the above study

  ____

______________________________	___________________________	_________________
Name of Subject	Signature	Date

_____________________________	__________________________	________________
Name of Witness	Signature	Date
_____________________________	__________________________	________________
Name of Researcher	Signature	Date

One copy for the subject; one for the researcher

APPENDIX C – SENSITIVITY ANALYSIS

In order to determine how body weight may influence F_{max}, K_{vert} and K_{leg} a one-way sensitivity analysis was completed. The one-way sensitivity analysis permitted the modification of body weight by a given amount and examined the impact that the changes had on the F_{max}, K_{vert} and $K_{leg.}$ Results from the one-way sensitivity analysis are presented in Table A.1.

Table A.C.1 Body weight (BW) sensitivity analysis

Biomechanical parameters	1 Actual Value *n* = 1	2 Absolute Difference *n* = 1
Actual body weight (BW, kg)	73.61	-
Actual F_{max} (kN)	**2.10**	**-**
+ 1% of BW (kg)	74.35	0.74
Impact on F_{max} (kN) of +/- 1% of BW	**2.12**	**0.02**
+ 5% of BW (kg)	77.29	3.68
Impact on F_{max} (kN) of +/- 5% of BW	**2.20**	**0.10**
+ 10% of BW (kg)	80.97	7.36
Impact on F_{max} (kN) of +/- 10% of BW	**2.31**	**0.21**
Actual K_{vert} (kNm^{-1})	**35.50**	**-**
+ 1% of BW (kg)	74.35	0.74
Impact on K_{vert} (kNm^{-1}) of +/- 1% of BW	**35.85**	**0.35**
+ 5% of BW (kg)	77.29	3.68
Impact on K_{vert} (kNm^{-1}) of +/- 5% of BW	**37.28**	**1.78**
+ 10% of BW (kg)	80.97	7.36
Impact on K_{vert} (kNm^{-1}) of +/- 10% of BW	**39.05**	**3.55**
Actual K_{leg} (kNm^{-1})	**10.10**	**-**
+ 1% of BW (kg)	74.35	0.74
Impact on K_{leg} (kNm^{-1}) of +/- 1% of BW	**10.21**	**0.11**
+/- 5% of BW (kg)	77.29	3.68
Impact on K_{leg} (kNm^{-1}) of +/- 5% of BW	**10.61**	**0.51**
+/- 10% of BW (kg)	80.97	7.36
Impact on K_{leg} (kNm^{-1}) of +/- 10% of BW	**11.11**	**1.01**

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