BIOMECHANICAL ANALYSIS OF ELITE RACE WALKING

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ABSTRACT

The aim of this study was to provide a comprehensive analysis of key biomechanical variables in race walking through the analysis of elite athletes in both competitive and laboratory settings. Video data from two 3CCD camcorders of athletes competing over 10 km (juniors only), 20 km, and 50 km were collected at three international competitions. For the 20 km and 50 km events, multiple recordings were made to identify if kinematic changes occurred. In addition, synchronised high-speed video, electromyography and ground reaction force data were collected of 20 elite race walkers in a laboratory setting and combined to calculate joint moments, power and work. The key discriminants with regard to better performances were long step lengths and high cadences, and the contribution made by flight distance to step length (approximately 13%) was particularly important, regardless of race distance or age category. Step length ratio was a better predictor of optimum step length than absolute values and a ratio of about 70% was found in the fastest athletes. Although reductions in step length and flight distance were a major cause of decreased speed over both 20 km and 50 km, many gait variables did not alter greatly, showing that these elite athletes were able to maintain their techniques despite fatigue. The foot position ahead of the body at initial contact (approximately 20% of stature) need not be detrimental to fast walking if the athlete has the strength to overcome the potentially negative effects; instead, it can be beneficial to increase this distance in achieving a greater step length and could be a key area for women in particular to develop. The hip muscles were the main source of energy generation, with both flexors and extensors doing more positive work than any other muscle group (22.4 ± 7.1 J and 42.3 ± 10.1 J respectively), although the ankle plantarflexors also generated considerable energy before toe-off (16.4 ± 3.8 J). A hip extensor moment that occurred during late swing and early stance helped maintain forward momentum as it reduced the braking peak force and duration of the negative anteroposterior force. The knee had little involvement in energy generation because of its predominant role as a rigid lever during stance, and absorbed considerable energy during swing (–46.4 ± 9.5 J). However, its abnormal movement that was dictated by the race walking rule also had an important role in maintaining contact with the ground and reducing vertical forces so that visible loss of contact was avoided. The study was the first to analyse in such depth the biomechanics of elite male and female race walkers across all competitive distances and its results could be used to develop a technical manual for this Olympic event and greatly impact on coaching practice.

DECLARATION

I confirm that the thesis is my own work; and that all published or other sources of material consulted have been acknowledged in notes to the text or the bibliography.

I confirm that the thesis has not been submitted for a comparable academic award.

ACKNOWLEDGEMENTS

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I want to give special thanks to the international coaches who helped to arrange for so many of their athletes to travel to Leeds, in particular Michael Lane, National Event Coach (Ireland) who has consistently supported the work done for this study. The feedback on the data and interpretation from all coaches who got involved was extremely useful in directing the study's path. I would also like to thank Dr Ian Richards who was also a great help in arranging data collection and travel, especially at the 7th European Cup Race Walking in Royal Leamington Spa.

Thank you to all the athletes who took part in the studies, and especially those who had to travel great distances to volunteer their time and efforts. The study was greatly enhanced by the quality of these world-class athletes. In addition, I would like to thank the members of staff and students at Leeds Metropolitan University who assisted with data collection.

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CHAPTER 1

INTRODUCTION

1.1 History of race walking

Race walking is part of the athletics programme at the Olympic Games and all other major athletics championships. Competitions are held over 20 km for men and women, and 50 km for men only. Races for junior men and women (under 20 years of age) are held over 10 km. Race walking was first introduced to the Olympic Games in London in 1908 (Lassen, 1990), after its growth from 'pedestrian' races for cash wagers that became popular in 18th century Britain (Kozloff, 2004). These races operated under unregulated definitions of walking and gradually fell out of favour, being eventually replaced by modern race walking (Osterhoudt, 2000).

Early Olympic races were held over various distances, and in 1956 the men's 20 km road race joined the 50 km race that had first appeared in 1932 (Marlow, 1990). Performances improved relatively steadily until large improvements started to occur with the emergence in the 1970s of the Mexican race walkers (Bondarenko & Korobov, 1986; Lassen, 1990) who achieved great walking speeds through exaggerated gaits, with features such as walking with the feet in a straight line (Payne & Payne, 1981) and large degrees of pelvic rotation (Hopkins, 1978). Before this, race walking generally looked much like normal walking but at a faster pace (Figure 1.1).

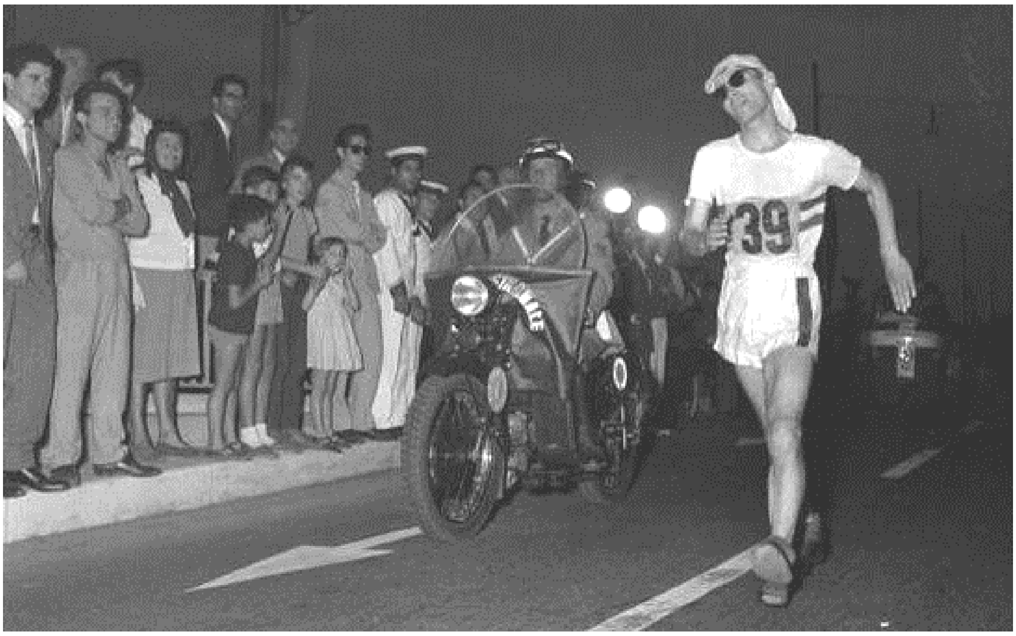


Figure 1.1. Don Thompson (Great Britain) leading the 50 km walk at the 1960 Olympic Games (Australian Olympic Committee, n.d.). His winning time of 4:25:30 was a Games record at the time.

It was not until the 1992 Olympic Games that a race walking event for women was introduced, held over 10 km (Levin, 1992), although this event had appeared previously at the International Association of Athletics Federations (IAAF) World Championships in 1987 (Burrows & Fitzgerald, 1990). The competitive distance for women was increased to 20 km at the 2000 Olympics, but as yet there is no 50 km championship race for women.

1.2 Elite performances in race walking

The current World Records for the senior and junior championship distances are shown in Table 1.1 below, as well as the qualifying standards used for the 2012 Olympic Games and the 2012 World Junior Championships. An athlete must be at least 18 years old to compete over the 20 km distance, and 19 to compete over 50 km (IAAF, 2014). Competing nations are entitled to send three athletes to the Olympic Games if all have achieved the 'A' standard, or one athlete with a 'B' standard if no one else from that nation is sent with the 'A' standard. There is a single qualifying standard for the World Junior Championships and most other underage championships.

Table 1.1. World Records and the qualifying standards for senior (h:min:s) and junior (min:s) championship distances in 2012.

	World Record	Olympic 'A' standard	Olympic 'B' standard	World Junior standard
Men's 20 km	1:17:16	1:22:30	1:24:30	
Women's 20 km	1:25:02	1:33:30	1:38:00	
Men's 50 km	3:34:14	3:59:00	4:09:00	
Junior men's 10 km	37:44			44:20
Junior women's 10 km	41:57			51:00

1.3 Definition of race walking

According to IAAF Rule 230.1, "Race walking is a progression of steps so taken that the walker makes contact with the ground, so that no visible (to the human eye) loss of contact occurs. The advancing leg must be straightened (i.e. not bent at the knee) from the moment of first contact with the ground until the vertical upright position" (IAAF, 2014). The 'vertical upright position' was a term introduced by the IAAF in 1972, and is considered to be the moment when the whole body centre of mass

(CM) passes over the foot (Figure 1.2 (IAAF, 1972)). For convenience, this instant has been termed midstance instead (although it is worth pointing out that this term is sometimes used to describe a phase of the gait cycle rather than a single moment (e.g. Levine et al., 2012)). It is important to note from the wording of the rule that loss of contact with the ground is judged by the human eye, which is incapable of detecting very short periods of flight. For this reason, while measurements made with high-speed cameras or force plates might record brief flight times, this does not mean that non-legal race walking has taken place.

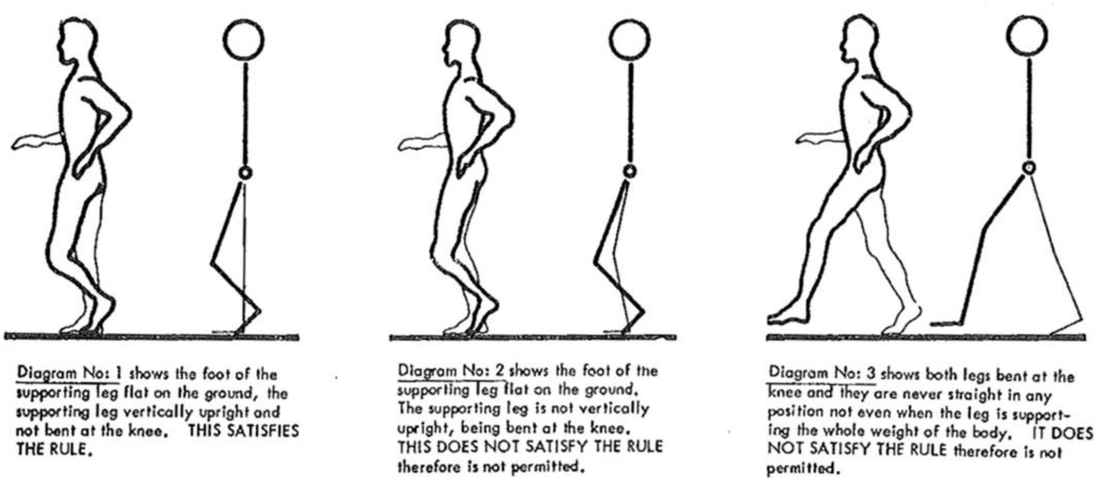


Diagram No: 1 shows the foot of the supporting leg flat on the ground, the supporting leg vertically upright and not bent at the knee. THIS SATISFIES THE RULE.

Diagram No: 2 shows the foot of the supporting leg flat on the ground. The supporting leg is not vertically upright, being bent at the knee. THIS DOES NOT SATISFY THE RULE therefore is not permitted.

Diagram No: 3 shows both legs bent at the knee and they are never straight in any position not even when the leg is supporting the whole weight of the body. IT DOES NOT SATISFY THE RULE therefore is not permitted.

Figure 1.2. Diagrams from 'Guidance for Walking Judges' showing legal and non-legal technique (IAAF, 1972).

Race walking is a form of locomotive gait not dissimilar to normal walking or running, but nonetheless the rule regulating it and the attempts by competitors to move as quickly as possible result in some noticeable differences (Figures 1.3 and 1.4). In general, initial contact is made on the lateral heel, and toe-off concludes from the hallux, with higher pressures experienced on the lateral side of the foot compared with normal walking (Villarroya et al., 2009). The knee is extended from initial contact until beyond midstance in race walking, whereas it flexes slightly in normal walking (Levine et al., 2012). More exaggerated pelvic and shoulder girdle movements tend to occur in race walking, giving it its distinctive appearance. The elbows are flexed at just less than a right angle, similar to a distance runner's posture, and the shoulders move through a much greater range of movement than in normal walking.

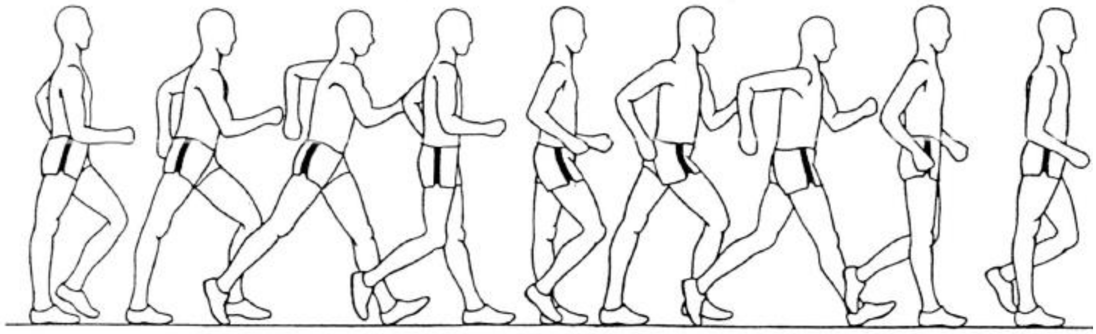


Figure 1.3. Illustration of a typical race walking gait cycle (Laird, 1996).

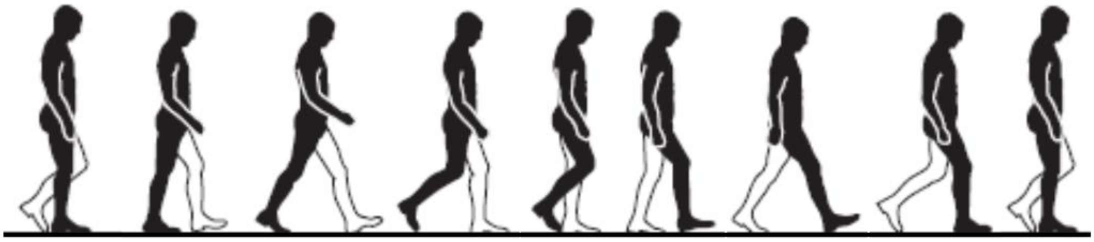


Figure 1.4. Illustration of a normal walking gait cycle (adapted from Rose & Gamble, 2005).

The current rule that defines race walking was first introduced in 1995; before this, the straightened leg requirement was only applicable at the vertical upright position. This in effect meant that athletes were permitted to have a flexed knee from initial contact until midstance. In fact, Fruktov et al. (1984) reported that some athletes in their study on race walkers had initial contact angles ranging from 172° to 179°. The 1995 rule change might have resulted in altered race walking techniques (Hoga et al., 2006), and hence some measurements reported before 1995 must be treated with caution with regard to comparisons made with more recent studies.

To ensure athletes are complying with Rule 230.1, qualified judges are positioned around the course to scrutinise the walking techniques used. If a judge observes an athlete exhibiting loss of contact or a bent knee, a red card is sent to the Chief Judge (IAAF, 2014). Three red cards from three different judges lead to disqualification. Before issuing a red card, if a judge is not completely satisfied that a walker is complying with the rule, the athlete is shown a yellow paddle indicating the offence (Figure 1.5). Showing a yellow paddle used to be known as a 'caution' as it is used to alert the athlete to the strong possibility of receiving a red card if technique is not altered satisfactorily. Although the concept of the yellow paddle is to advise athletes to alter their technique to avoid receiving red cards, many athletes do not pay attention to them as they don't count towards disqualification, and many even continue with their race plan when they have been awarded red cards (Vernillo et al., 2011).

Figure 1.5. A judge shows a yellow paddle indicating loss of contact at the Olympic Games in London (Solis, 2012).

1.4 Prior biomechanical research in race walking

Because race walking is a highly technical event with a specific defining rule (Schiffer, 2008), a number of gait variables are essential to success. Understanding the optimisation and balance between these variables is invaluable to coaches and athletes seeking to improve technique and reduce the possibility of disqualification. Despite this, there has been surprisingly little research conducted on the biomechanics of elite race walking. Various authors have discussed possible important variables in race walking, although most published articles are based on coaches' opinions. In addition, Russian coach Korolyov (1990) is of the opinion that most race walking studies have limited practical value as they fail to take into consideration the difference between training and competitive performances, or the influence of fatigue. It is difficult to recruit high calibre race walkers for research studies (Saunders et al., 2010) because its technical requirements mean fewer athletes compete compared with sprinting or distance running and thus what scientific research has been conducted has tended to test very few participants.

Because there are relatively few elite race walkers, and because women's competitive race walking is quite new, most currently available studies have been conducted on male athletes who are below international standard. In fact, before the inclusion of a race walking event for women in the 1992 Olympics, there were only two studies published on the physiology of women's race walking (Yoshida et al., 1989; Yoshida et al., 1990) and one on biomechanics (Huajing & Lizhong, 1991), and few have been published since then. There has also been little research on junior athletes, even though Vallance (2005) reports that the 1990, 1992, 1996 and 1998 world junior men champions at 10,000 m all progressed to be the top ranked 20 km walker in the world at some point in time; hence, studies of elite junior walkers could provide a key to the development of elite senior walkers (Douglass & Garrett, 1984) and give an indication of technical peculiarities of younger athletes.

Past research on the biomechanics of race walking has tended to be confined to laboratory tests only, or took place before the current race walking rule was introduced. With respect to the most notable previous research in competition, Hoga et al. (2003) videoed 28 elite walkers in six championship races held in Japan with a sampling rate of 60 Hz. This study has the largest sample size found in the literature; however, only one camera was used for two-dimensional (2D) analysis. Douglass & Garrett (1984) also recorded in competition; their participants were eight junior men (in two separate 10 km races) and the recording was also made with only one camera (48 Hz) as the athletes walked round the bend on a 400 m track (the athletes were analysed on more than one occasion to measure for possible fatigue effects). In a case study of an elite athlete, Polozkov & Papanov (1982) analysed Maurizio Damilano, Olympic 20 km champion in 1980 in Moscow, 250 m from the finish of that race, using one camera (40.7 Hz). Finally, Knicker & Loch (1990) conducted a study on the effects of fatigue on the gait parameters of male walkers competing over 35 km, although this was limited to five athletes, of whom only one participant was measured on more than two occasions (partially due to having to choose which athletes to analyse in advance because of the cinematography methods employed). Knicker & Loch's (1990) study also used only one camera (100 Hz), and hence all four previous studies conducted in competition were limited in terms of participant numbers, only testing men, and not having access to three-dimensional (3D) data. Furthermore, three of these studies were conducted before the rule change of 1995 which limits the application of their findings to present-day competitors.

Kinematic studies have also been conducted in laboratory conditions, usually with high-speed frame rates ranging from 100 to 200 Hz, although Brisswalter et al.'s (1996, 1998) studies used a single 50 Hz camera to measure the effects of fatigue in national-standard race walkers before and after a long training session. Sample sizes in these laboratory studies ranged from one non-elite man (White & Winter, 1985) to 12 non-elite men (Hoga et al., 2006). Small sample sizes are common to many prior studies; in fact, between all kinematic studies (laboratory and competition), a total of 85 men and only nine women have been analysed (some studies did not report whether the participants were male or female). In addition, several recent studies (e.g. Donà et al., 2009; Preatoni et al., 2010) focus more on variability during the race walking gait cycle (in order to study variability itself rather than the technique) as opposed to the variables associated with competitive success, and thus these studies are limited in their practical application to race walkers and their coaches. Therefore, as with competition studies, research that has taken advantage of laboratory conditions is very limited to date.

While there have been some, albeit limited, studies on race walk kinematics, very few studies of value have been conducted on important kinetic variables (e.g. Fenton, 1984; Cairns et al., 1986). In previous research, 36 men and six women have been tested using force plates to measure ground reaction forces (GRF) although some only used these data for the further calculation of joint moments, and did not describe or analyse the GRFs themselves. One such study tested a single non-elite man (White & Winter, 1985) and one of the other studies tested 12 men (Hoga et al., 2006). As a result, only two studies (Cairns et al., 1986; Preatoni et al., 2006) have measured these variables for female race walkers, but unfortunately neither study reported the women's results separately from the men's, despite the potential of gender differences affecting interpretation. As well as there being a paucity of GRF research in race walking, even fewer studies have analysed muscle activity patterns using electromyography (EMG) (Murray et al., 1983; Padulo et al., 2012a). Murray et al.'s (1983) study collected EMG data on two race walkers, comparing muscular activity in normal walking with race walking, while Padulo et al.'s (2012a) study compared EMG patterns of five leg muscles between race walking at 0° inclination and uphill at 2° and 7°. Neither of these studies was conducted on elite athletes (confusingly, Murray et al. (1983) described their participants as "Olympic" race walkers when in fact they had not competed at the Olympics) or included women, and nor were their EMG results combined with any measurements of joint moments or powers that could have informed the analysis of muscle activity. As a result, those studies on joint moments and powers, and those using EMG, are not complete in their descriptions of elite race walking. More thorough measurements and analyses of GRFs and muscle activity in a large group of elite athletes are therefore still essential for a full understanding of the pattern of muscle activation and the internal dynamics of the key joints in race walking.

Although previous research has given some insights into the mechanics of successful race walking, substantial gaps remain in the current knowledge of the event because of the limitations discussed above. In summary, these include:

- A very small number of studies overall with few participants in each;
- A lack of studies on elite athletes (e.g. Olympic competitors);
- Very few studies on women or junior athletes;
- Many of the studies are from before 1995 when the current race walking rule was introduced;
- Only 2D studies have been conducted in competition, with the result that important race walking parameters such as pelvic and shoulder girdle rotations have not been properly measured or evaluated;
- The effects of fatigue have not been measured in elite walkers over the different competition distances of 20 km and 50 km to identify if changes occur, when they occur, and what their importance to performance might be;
- GRF and EMG data collection has been negligible resulting in a lack of understanding of the mechanisms that underlie important parameters;
- Limited data have been collected of muscle moments, powers and work that can add to the information provided by the EMG data.

Despite the fact that the correction and optimisation of technique is of great importance to the athlete, there has been little research on elite race walking, and what research has been conducted has adopted very limited methodologies. Coaches and athletes must frequently rely on anecdotal evidence to develop and modify technique, with little regard for any scientific basis or analysis, or by comparing race walking with, for instance, distance running. Of course, this situation is not unique to race walking (Hawley et al., 1997), but its technical idiosyncrasies heighten the importance of a scientific foundation for the training methods adopted. Because the topic has been so under-researched, new and full research on a larger number of elite male and female race walkers across both junior and senior age groups in laboratory and competitive situations is therefore crucial to understanding the event for biomechanists, athletes, and coaches. In particular, assessment of muscular activity using EMG and internal kinetics measurements would be a major development in understanding the dynamics involved in this unique form of gait.

1.5 Purpose and prospects of the research

The purpose of this research was to provide a comprehensive analysis of the biomechanics of elite race walking by measuring and identifying key variables in determining success, and which could ultimately contribute to a technical manual. This involved analysis of men and women, junior and senior athletes, and 20 km and 50 km athletes. Competitive performances were analysed to investigate the variables associated with faster race walking, as well as any changes that occurred with variations in speed. In addition to kinematic data, kinetic variables were measured in a laboratory setting to investigate important features of elite race walking that cannot be measured in competition. The collection and analysis of these kinetic data within the laboratory was combined with high speed video and EMG data collection to provide a clear picture of lower limb muscle recruitment patterns, muscle moments, and their power absorption and generation.

The prospects for this study's results are manifold: the results will be of great interest to the scientific community, particularly those who are interested in gait, as it will map the biomechanical 'profile' of race walking from a large range of possible factors (kinematic, kinetic, EMG, inverse dynamics); more importantly, the results will interest those directly involved in the Olympic event of race walking. The main implications for athletes and coaches relate to training: analyses of elite athletes assist in identifying which biomechanical aspects are most important (and those that might have no importance at all), and what values are typically found in elite performers; how these variables vary with fatigue; and whether different training approaches might be appropriate if the athlete is male or female, junior or senior, or competes over 20 km or 50 km. Currently, there is virtually no understanding of how the key leg muscles instigate or are affected by race walking technique; given the uniqueness and abnormality of the gait used, this understanding might be of profound importance in developing training regimens (particularly with regard to strength and conditioning), in understanding why specific injuries occur, and in confirming or contradicting current coaching practices and beliefs.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Race walking is an event that requires both physical endurance (Hilliard, 1986) and technical ability, although psychological factors are also important in coping with the event's demands (Clingman & Hilliard, 1990; Yukelson & Fenton, 1992). From a biomechanical point of view, success in competitive race walking is primarily due to having a faster average walking speed than other competitors. The two main factors that influence race walking speed are step length and cadence (Knicker & Loch, 1990), similar to other athletic events such as sprinting (Kersting, 1999). However, race walking speed is restricted by the two unique elements of the event's rule, and as a result an athlete can only manipulate step length and cadence to a certain degree before this rule is infringed. Success in competition therefore depends not only on walking speed but also on the athlete's ability to maintain a gait pattern in keeping with the rule. Race walking is thus markedly different from normal walking, being a function of the rule that governs it (Cairns et al., 1986), as well as being very different from running.

Race walking is a complicated, technical event and appreciating the biomechanics involved goes far beyond its basic components of step length, cadence, and the need to adhere to Rule 230.1. To help understand what biomechanical factors might be important in any sporting activity, the use of hierarchical (or deterministic) models has been advocated to help identify meaningful variables and build theoretical linkages between them (Chow & Knudson, 2011). As examples, Figure 2.1 below shows a basic hierarchical model for sprint running (Hay & Reid, 1988) and Figure 2.2 shows a long jumping model (Hay, 1993).

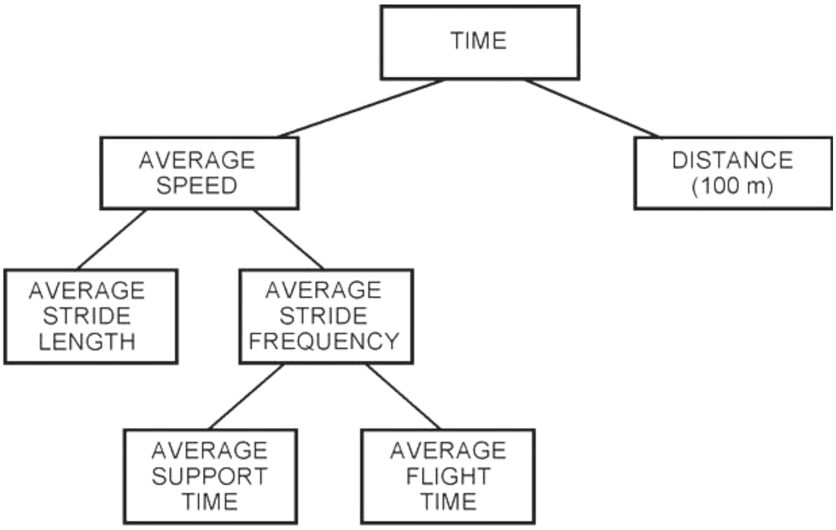


Figure 2.1. Basic hierarchical model of sprint running (Hay & Reid, 1988).

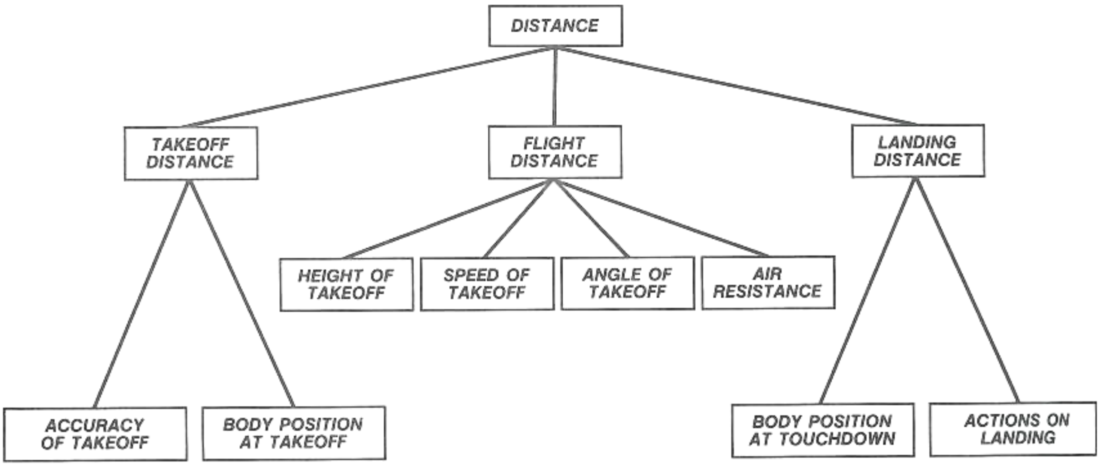


Figure 2.2. Hierarchical model of basic factors in long jumping (Hay, 1993).

2.2 Hierarchical model of race walking

Figure 2.3 below shows a model for race walking that is similar to the running models, with some additions that take into account variables of particular interest. The hierarchical model is based on technical knowledge of gait, biomechanical principles, and previous models (e.g. Paradisis and Cooke (2001)), and represents all the important factors in the biomechanics of race walking (external factors such as gravity and air resistance have been excluded). The usage of the hierarchical model is fundamental to understanding the role of the variables measured in this and other studies, and is something very practical for coaches. It allows an appreciation of the interrelationships between variables, identifies areas for athletic development, and highlights potential limits on performance.

Two of the most important aspects of the hierarchical model of race walking are of course the inclusion of knee extension from initial contact to midstance and no visible loss of contact. This means that the main criterion of success is not speed *per se*, or any other performance criterion, but the actual race result that relies on legal technique being adopted to the satisfaction of the judges. Flight time, a determinant of cadence, has been linked by a dashed line to show that it is related to the first part of the rule; and the knee angle, an aspect of posture, has similarly been linked to the second part of the rule. Notwithstanding the importance of adhering to the two aspects of Rule 230.1 in competitive success, the two main components of race walking speed as shown in the model are step length and cadence. Each of these is further broken down; step length into four components, and cadence into contact time and flight time.

Breaking down the variables in this way can aid researchers and coaches of race walking to understand specific areas that might be of interest (e.g. long step lengths might be considered ‘good’ by a coach, but if flight distance is too great a contributor, this might be of concern). The achievement of these basic gait variables might be due to other factors in the hierarchical model, such as physique or posture, the latter of which can be affected by upper and lower limb angles, and by movements such as pelvic rotation, which is considered important in normal walking (Inman et al., 1981) and a distinguishing feature of race walking. Aside from kinematics, the corresponding kinetic factors are also relevant and included in the model. For example, the amount of anteroposterior force applied during stance affects the change in velocity (or the extent to which a constant velocity is maintained). The model is partially expanded at its base in alluding to key neuromuscular factors affecting the production of force (Korhonen et al., 2009) that have largely been ignored in prior research on elite race walking. Previous literature on most of the key variables shown in Figure 2.3 is reviewed below, and referred to in the model by the appropriate section number. Some aspects of the model have not been analysed to date and thus do not have a section number associated with them.

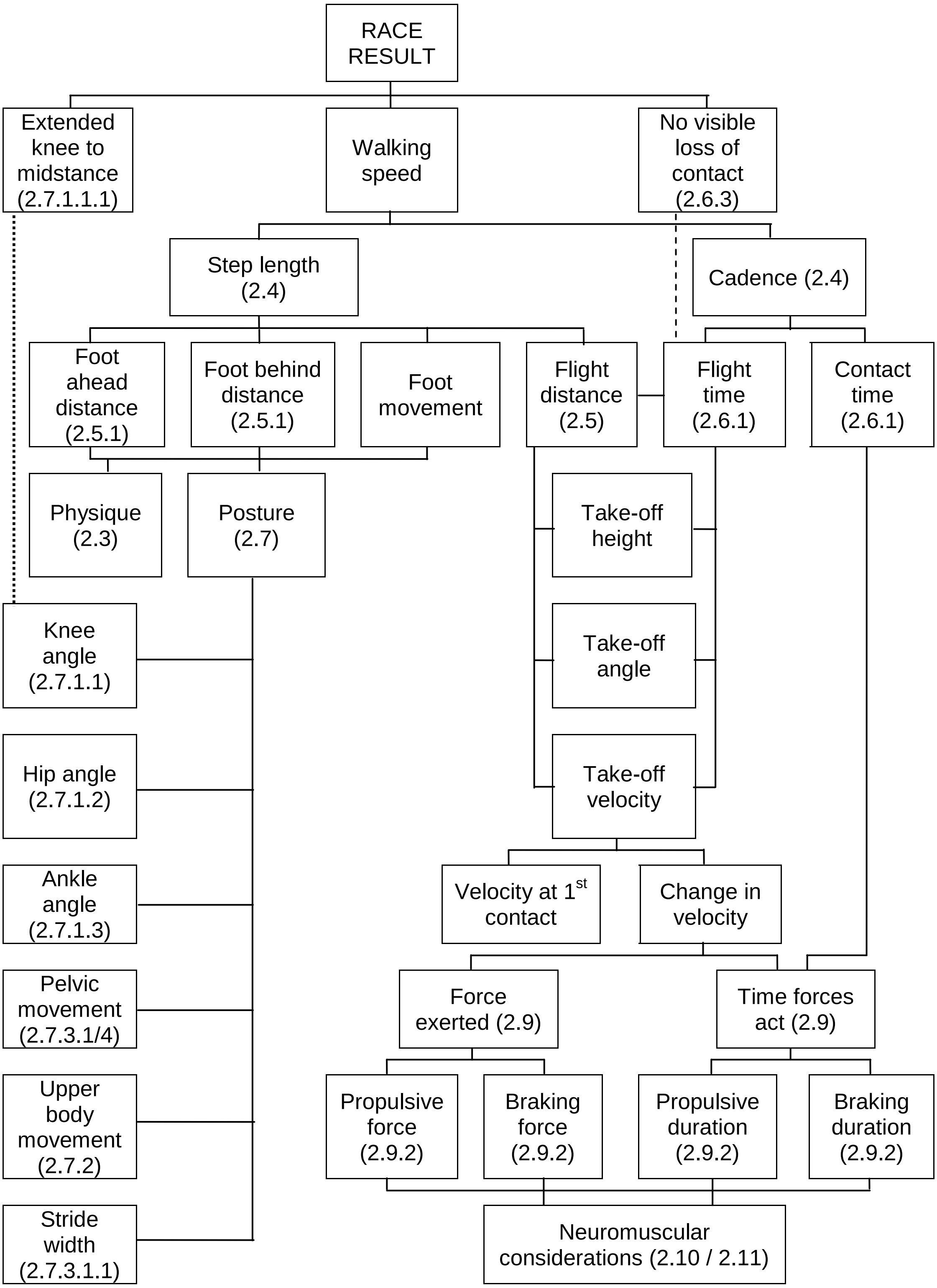


Figure 2.3. Hierarchical model of race walking; the information in parentheses refers to the section of the literature review that deals with that topic.

2.3 Physiques of race walkers

2.3.1 Leg length relationships

Race walkers have similar anthropometric characteristics to other elite endurance-trained athletes, and in particular, long-distance runners (Franklin et al., 1981; Ruhling & Hopkins, 1990). Taller people generally have longer legs, and longer legs should theoretically allow taller race walkers to have longer step lengths (Erdmann, 2007) (Figure 2.4), and indeed Douglass & Garrett (1984) did find that step length in male junior race walkers increased with leg length.

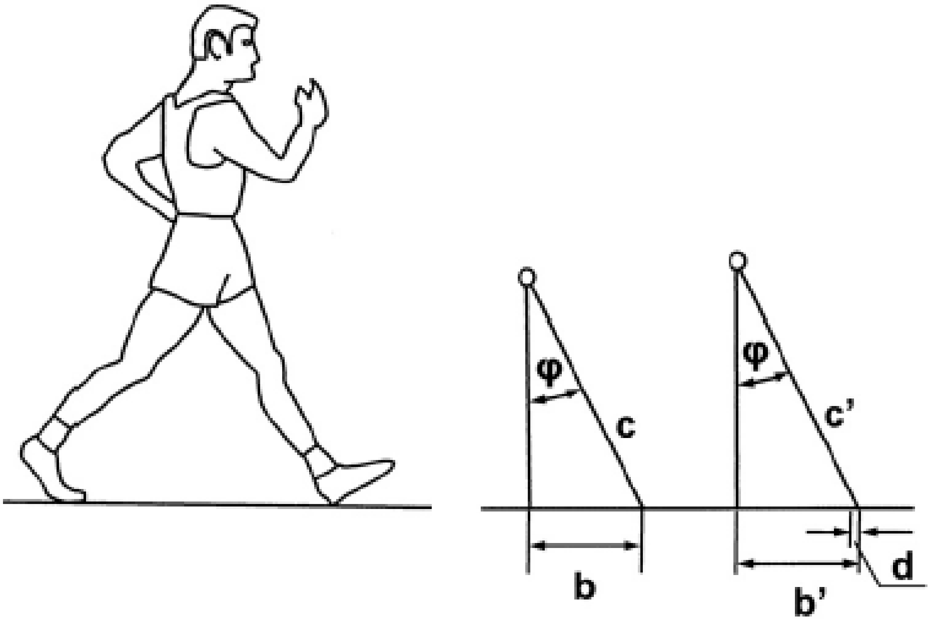


Figure 2.4. An athlete with a longer lower limb (c') than a rival (c) will theoretically achieve a longer half-step (b') with the same hip flexion angle (φ) (Erdmann, 2007).

Based on mathematical modelling, Trowbridge (1981) considered leg limb length the key factor determining maximum speed achievable by a race walker, although he also considered that the 'effective' leg length of a walker could be increased through pelvic rotation. In Figure 2.5, L_A represents the actual length of a race walker's leg; while L_{EFF} is the increased, 'effective' leg length achieved with pelvic rotation ('a' represents the resulting distance between the hip joints caused by this pelvic rotation). Step length can thus be calculated as [2 x (L_A x cosθ) + a] (Trowbridge, 1981). In the diagram, θ represents the angle between the leg and the ground and is assumed to be the same for both legs at double support (and L_A is assumed to be the same for both the front and rear legs).

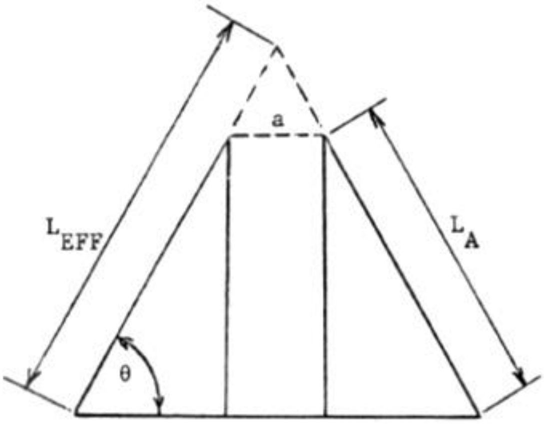


Figure 2.5. The effective leg length of a race walker (L_{EFF}) could be longer than its actual length (L_A) by means of pelvic rotation.

While Trowbridge's model has been used as evidence that elite race walkers cannot possibly achieve their typical competitive speeds without loss of contact (e.g. Barrow, 2012), its weaknesses include an assumption that the push-off leg is straight (which is what allows θ to be equal for both legs), even though race walkers only need to maintain a straightened knee until midstance. Trowbridge's model was not based on actual race walking joint kinematics, and the future measurement of these variables will therefore be useful in explaining how race walkers actually achieve their step lengths and hence their speeds. With regard to suggestions about the contribution of pelvic rotation, Erdmann (2007) believes that an athlete who rotates the pelvis 10° more than another competitor gains about 0.5 cm per step, which could provide a substantial advantage over the course of a race. However, there is no evidence to support this claim and in fact it might be counterproductive to have such great magnitudes of pelvic rotation. Past studies have not focussed on this variable, partly because of 2D kinematic methodologies, and this is clearly an area requiring further study. Erdmann (2007) also considers there to be an optimum leg length, as he believes very long legs would have too great a moment of inertia about the hip to maintain a sufficiently high cadence. However, longer-legged athletes might have an advantage in terms of avoiding loss of contact that provides them with a technical benefit over shorter athletes who can achieve higher cadences but not attain the same step lengths without considerable flight times. It must therefore always be kept in mind that race walking is not a straightforward example of achieving high speeds in order to succeed, and the risk of disqualification must always be considered when assessing key variables such as step length and cadence.

2.3.2 Reported anthropometric measurements

A number of authors have reported heights and masses of world-class race walkers (although none were of female competitors). Schmolinsky (1996) details the characteristics of the top eight finishers in the men's 20 km race at the 1972 Olympics: their ages ranged from 20 to 36 years, their heights from 1.77 m to 1.87 m, and their masses from 62 to 78 kg. More recently, Raković et al. (2008b) reports the characteristics of elite male race walkers competing in 20 km and 50 km races held in 1999: the means for the 20 km walkers were 27 years (± 4), 1.77 m (± .05) and 66 kg (± 6); while the means for the 50 km walkers were 28 years (± 5), 1.77 m (± .06) and 65 kg (± 5). No differences were found between 20 and 50 km walkers. With regard to past biomechanical and physiological research, the characteristics of race walking participants are shown below in Tables 2.1 (men) and 2.2 (women).

Table 2.1. Mean (± *s*) anthropometric characteristics of male race walkers.

Authors	N	Age (yr)	Height (m)	Mass (kg)
Brisswalter et al. (1998)	9	30 (± 4)	1.76 (± .05)	70 (± 5)
Čillík & Pupiš (2005)	1	27	1.75	61
Donà et al. (2009)	4	N/A	1.81 (± .09)	64 (± 2)
Farley & Hamley (1979)	20	30 (± 4)	1.78 (± .04)	69 (± 3)
Franklin et al. (1981)	9	27 (± 8)	1.79 (± .08)	69 (± 6)
Hagberg & Coyle (1983; 1984)	8	29 (± 3)	1.80 (± .03)	70 (± 3)
Hoga et al. (2006)	12	21 (± 3)	1.72 (± .04)	56 (± 3)
Hoga et al. (2003)	28	24 (± 4)	1.71 (± .05)	59 (± 4)
Ljunggren & Hassmén (1991)	4	27 (± 8)	1.78 (± .04)	68 (± 5)
Murray et al. (1983)	2	24 (± 1)	1.89 (± .05)	68 (± 3)
Marchetti et al. (1982)	4	23 (± 4)	1.73 (± .10)	60 (± 7)
Pavei et al. (2011)	6	18 (± 2)	1.76 (± .04)	63 (± 5)
Polozkov & Papanov (1982)	1	23	1.83	70
Reilly et al. (1979)	25	21 (N/A)	1.80 (± .02)	66 (± 2)
Rodano & Santambrogio (1987)	3	N/A	1.79 (± .03)	67 (± 1)
Schmolinsky (1996)	8	31 (N/A)	1.81 (N/A)	71 (N/A)
Thorstensson et al. (1977)	7	27 (± 3)	1.78 (± .02)	65 (± 1)
White & Winter (1985)	1	21	1.66	63

It can be seen in Table 2.1 that those male race walkers who have been analysed are predominantly between 1.71 and 1.81 m, which included junior walkers in the study of Pavei et al. (2011). In general, the athletes had body masses between 60 and 70 kg for men, and between 51 and 56 kg for women. While these data are informative in their own right, their usefulness has not been fully exploited in terms of analysing the possible effects of physique on race walking technique, or in normalising results (e.g. of step length), and future research should therefore consider these data in evaluating aspects of technique.

Table 2.2. Mean (± *s*) anthropometric characteristics of female race walkers.

Authors	N	Age (yr)	Height (m)	Mass (kg)
Ávila et al. (1998)	4	21 (± 6)	1.64 (± .09)	55 (± 8)
Donà et al. (2009)	3	N/A	1.67 (± .05)	51 (± 7)
Dunster et al. (1993)	12	N/A	1.65 (± .06)	56 (± 4)
Neumann et al. (2008)	4	16 (N/A)	1.69 (± .04)	56 (± 4)
Yoshida et al. (1989)	8	20 (± 2)	1.62 (± .06)	51 (± 6)
Yoshida et al. (1990)	5	19 (± 1)	1.60 (± .05)	50 (± 3)

2.4 Step length and cadence

Step length is defined as the distance between successive foot contacts from a specific instant on the gait cycle on one foot to the equivalent instant on the other foot (e.g. Knicker & Loch, 1990). The term 'stride length' is often used interchangeably with 'step length' (e.g. Enomoto et al., 2008). However, 'stride length' is frequently used in biomechanics literature to refer to the distance between a specific instant on the gait cycle on one foot to the equivalent instant on the same foot (e.g. Cavanagh & Kram, 1989) (Figure 2.6). Hence, a stride refers to two successive steps (Levine et al., 2012) and this distinction is retained here. Cadence refers to the frequency of steps occurring during the walking action (Marais & Pelayo, 2003; Levine et al., 2012) although some authors prefer the equivalent term 'step frequency' (e.g. Hoga et al., 2006). It is believed that once step length has been maximised to the point where it is on the threshold of visible loss of contact, increasing speed in race walking is dependent on increasing cadence (Cairns et al., 1986; Swan et al., 1997), similar to how faster speeds (> 7 m/s) are achieved in sprinting (Mero et al., 1992).

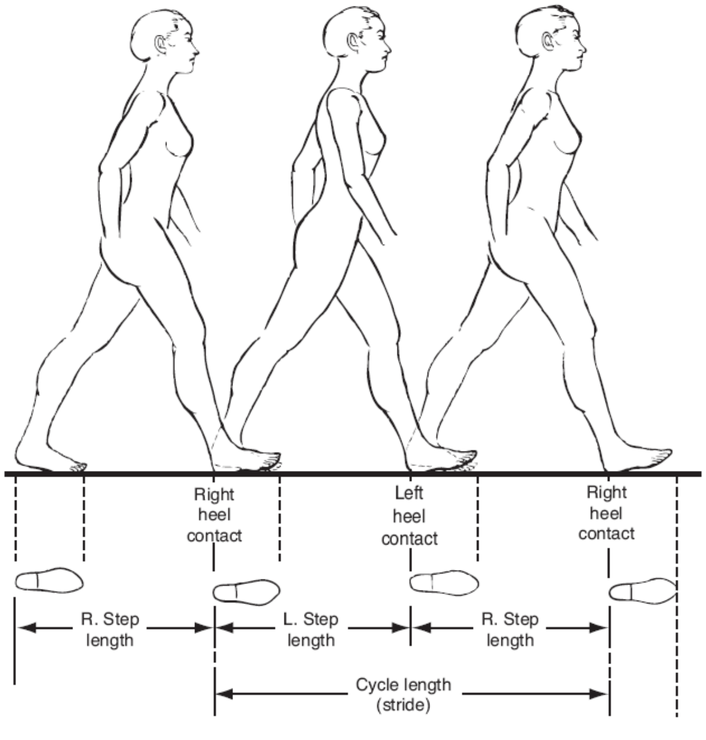


Figure 2.6. Visual depictions of step and stride in walking (Rose & Gamble, 2005).

As shown in the hierarchical model in Figure 2.3, race walking speed is considered the product of step length and cadence. It is therefore not surprising to find that coaching articles have concentrated on these two variables (e.g. Markham, 1989;

Huajing & Lizhong, 1991) and step length is described by Payne & Payne (1981, p.366) as being of “obsessive concern to every race walker”. However, despite this coaching focus and their importance to race walking performance, relatively few biomechanical studies have reported data for these two variables. Therefore, unlike other Olympic athletic events such as sprinting or distance running, there is little or no understanding of the relative significance of these key variables, let alone the importance of neuromuscular factors affecting them. By contrast, studies on the relationships between kinematics, kinetics and EMG activity in running have been numerous and date back many decades (e.g. Sprague & Mann, 1983; Mero & Komi, 1987; Cavanagh, 1990), and the role of muscle fibre type on sprinting mechanical characteristics is well established (e.g. Mero et al., 1992). It is remarkable that step length and cadence have been given so little attention in race walking given the additional constraints on technique, and regrettably this means that much race walking research has low external validity for coaches. Table 2.3 below summarises the main findings of the small number of studies that have included relevant descriptive data on step length and cadence. The number of male participants in this and successive tables is indicated by the ♂ symbol; the number of female participants by the ♀ symbol (their results were not reported separately in the original studies). Mean step length ranged from 1.15 to 1.25 m, and cadence from 2.83 to 3.39 Hz, with the shortest step length and highest cadence reported for the same elite individual (Polozkov & Papanov, 1982) (all other participants in the studies included in Table 2.3 were not at elite standard).

Table 2.3. Mean (± *s*) race walking speeds, step lengths and cadences.

Authors	N (♂ / ♀)	Speed (km/h)	Step length (m)	Cadence (Hz)
Cairns et al. (1986)	8 / 2	13.07 (± .54)	1.19 (± .15)	3.08 (± .28)
Hoga et al. (2006)	12 / 0	14.08 (± .61)	1.23 (± .06)	3.17 (± .17)
Lafortune et al. (1989)	6 / 4	14.15 (± .65)	1.25 (± .05)	3.26 (± .16)
Murray et al. (1983)	2 / 0	12.05 (± .49)	1.18 (± .08)	2.83 (± .09)
Polozkov & Papanov (1982)	1 / 0	14.04	1.15	3.39
Rodano & Santambrogio (1987)	3 / 0	12.32 (± .69)	N/A	3.11 (± .15)

2.4.1 Step length correlations

With regard to the analysis of step length and cadence, Hoga et al. (2003) reported that race walking speed in 28 elite male athletes was correlated with step length, but there was no correlation between walking speed and cadence. However, in a separate study of 11 male non-elite athletes walking over 50 m in laboratory conditions, Hoga et al. (2002) found a correlation not only between walking speed and step length, but also between speed and cadence. There is little other research on these key variables and thus there is a clear lack of scientific understanding of the importance of step length and cadence beyond their position in the hierarchical model, and this means that coaching suggestions have little or no evidence to support them. For example, because of the lack of actual data on women, Huajing & Lizhong (1991) could only hypothesise that successful elite female walkers would have optimal step lengths between 1.10 and 1.16 m long, and optimal cadences between 3.42 and 3.58 Hz; no measurements have been subsequently conducted to verify these hypotheses. Two other studies that reported these basic kinematic data (Cairns et al., 1986; Lafortune et al., 1989) did include female participants, but their data were not separated from the men’s, despite the possible effects of differences in stature and muscular qualities. There is therefore a need to identify the role of these two fundamental gait variables and their relationship with other important variables specific to race walking across all categories of competition (junior / senior, male / female, 20 km / 50 km). While step length and cadence are the two fundamental components of gait speed, it is possible that different athletes will rely on one factor more than another, achieve them in a different manner (e.g. cadence could be increased by reducing either contact time or flight time), or experience different changes with fatigue. A large-scale analysis of race walking technique in elite athletes in competition will provide useful scientific information closer to the standard of what is already well-established in other forms of competitive gait (e.g. Mero et al., 1992), and hence improve the research-based evidence that race walk coaches can use in practice.

2.4.2 Step length ratio

Step lengths presented as absolute values can be useful but are often impractical to researchers and coaches as they have been found to vary with leg length (Douglass & Garrett, 1984). Despite the fact that presenting step length as normalised data allows easier comparisons between athletes, and might be instructive in terms of allowing coaches to adopt individualised recommendations, very few studies have actually adopted this useful means of analysis. Murray et al. (1983) reported the mean step length as a percentage of body height (referred to in this study as step length ratio) for the two national-standard male athletes they tested (with ratios of 60.5% and 64.5% respectively), and Polozkov & Papanov (1982) measured a single race walking stride of Maurizio Damilano (Italy) as he won the 1980 Olympic 20 km title in Moscow (Figure 2.7). At the distance of analysis, 250 m before the finish, Damilano's step length was 1.15 m (Table 2.3), equivalent to 62.8% of his stature (Polozkov & Papanov, 1982). However, Damilano might have had a considerably different gait pattern compared with earlier in the competition, especially considering he was more than a minute ahead of the silver medallist and was able to "walk freely for the last segment of the race" (Polozkov & Papanov, 1982, p.23). As with absolute step length, Hoga et al. (2003) reported that race walking speed was correlated with step length ratio but no other relationships were reported. These few data show that there is a gap in understanding this important aspect, and further research is required not only to ascertain cadences and absolute step lengths in elite race walking, but also typical step length ratios that need to be evaluated for their importance in biomechanical and coaching terms (e.g. with respect to correlations with other key kinematic and kinetic variables).

Figure 2.7. Maurizio Damilano (Italy) wins the 1980 Olympic 20 km race (Associazione Italiana della Marcia, 2010).

2.4.3 Changes in step length and cadence with changes in speed

As in any other form of gait, changes in step length and cadence lead to alterations in speed (Douglass & Garrett, 1984; Padulo et al., 2012b). For example, De Angelis & Menchinelli (1992) measured the step lengths and cadences of 10 men and six women of international standard at a range of speeds, and apart from being used to identify the speed where visible loss of contact occurred (Table 2.5), their data are also useful in identifying how both step length and cadence change as walking velocity increases. At 12 km/h, the men had a mean step length of 1.02 m and a mean cadence of 3.23 Hz, which increased to 1.18 m and 3.49 Hz respectively at 15 km/h. At 12.65 km/h, the women had a mean step length and cadence of 1.01 m and 3.47 Hz respectively, which increased to 1.09 m and 3.62 Hz at 14.1 km/h. The changes for the men represented a 16% increase in step length and an 8% increase in cadence (for a 25% increase in walking speed); for the women the 8% increase in step length and 4% increase in cadence led to an 11% increase in speed.

Despite the apparent usefulness of these results, De Angelis and Menchinelli’s (1992) study was conducted in an artificial setting (the speeds used for testing were pre-defined and the walkers were paced by auditory signals), and more externally valid results might be found in competition. For example, race walkers might experience varied walking speeds, step lengths and cadences over the course of a race depending on factors such as race tactics and fatigue. That fatigue might have an effect on endurance athletes like race walkers is not unexpected, and indeed decreases in pace have been found from halfway onwards in World Championship races (Hanley, 2013a) (Figures 2.8 and 2.9). These speed decreases were more obvious in the men’s 50 km races, and were particularly noticeable after 35 km (although some athletes started slowing earlier than this), and highlight the need for measurement of kinematic variables over the course of such a long-distance event.

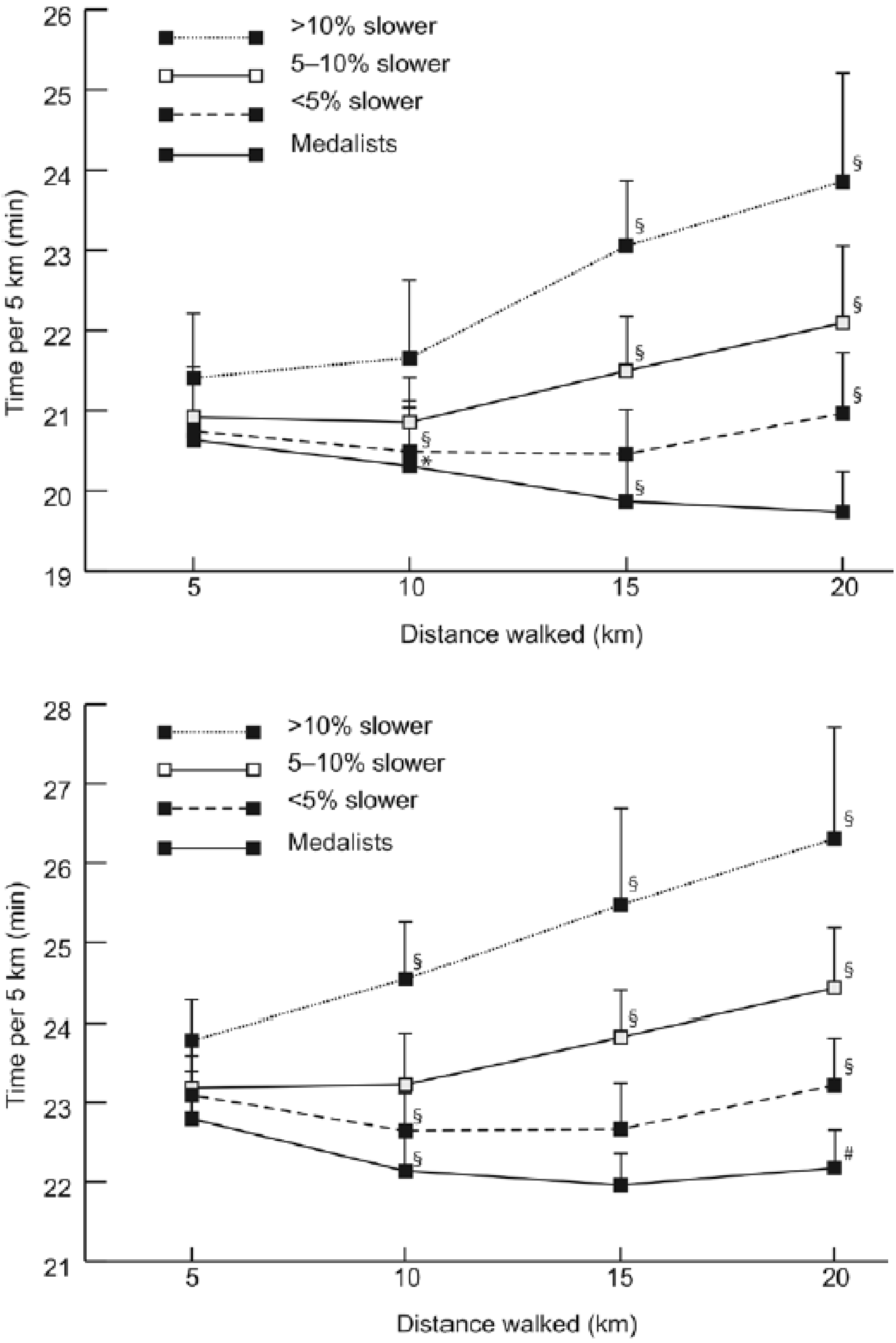


Figure 2.8. Most 20 km men (top figure) and women (bottom figure) tend to start quickly and slow progressively through the race, particularly after halfway (Hanley, 2013a).

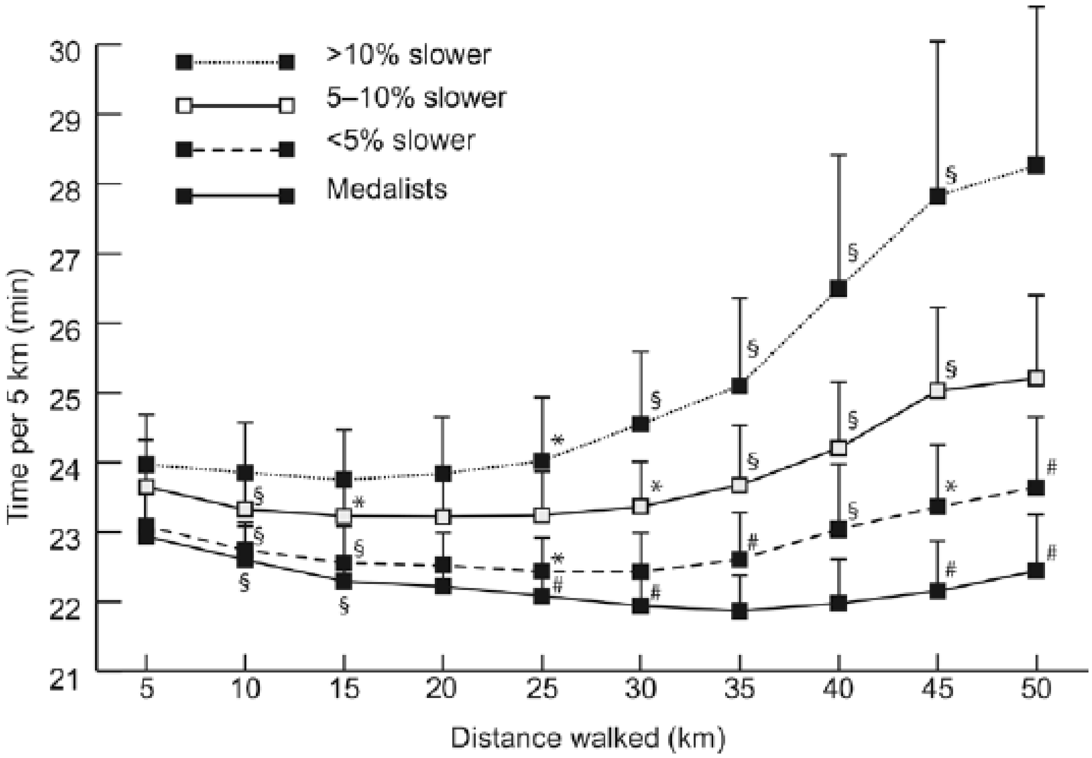


Figure 2.9. 50 km walkers tend to speed up gradually over the first half of the race and then slow after this distance (Hanley, 2013a).

To observe if kinematic changes did occur with the onset of fatigue, Knicker & Loch (1990) designed a research study to measure particular variables in male race walkers at repeated distances during a 35 km race. Unfortunately, because of measurement issues and participants not completing the race, only four athletes were measured more than once, and only one athlete on the four occasions that were planned. The one athlete who was measured at four distances in the race had a mean step length that decreased from 1.10 m after 5 km to 1.05 m after 35 km. Knicker & Loch (1990) state that cadence did not decrease and so the main cause of slowing down during the race was attributed to shortened step length. Nonetheless, Knicker & Loch's (1990) findings are clearly limited by their sample size and this in turn limits their application to race walkers in general (and especially those competing over the longer, championship distance of 50 km).

Douglass & Garrett (1984) also measured at multiple distances during competition, and their study on eight international junior male athletes likewise showed that cadence varied little; instead, step length and the ability to maintain it are considered by the authors to be the main determinants of success. However, while mean step length for the right leg was consistent at about 0.80 m, mean step length for the left leg decreased from 0.79 m (± .04) at 450 m to 0.76 m (± .03) at 6,450 m. Douglass & Garrett (1984) do not define how they measured step length, but the shortness of these steps when compared with those in Table 2.3 suggests they might have measured from the toe of the rear foot to the heel of the front foot (rather than using the same gait event on both feet). The fact that the races were videoed at the midpoint of the first bend on a standard 400 m athletics track partly accounts for the discrepancy between left and right step lengths (Douglass & Garrett, 1984) and shows the unsuitability of this camera positioning for analysing race walking. High-standard races are held on long, straight roads that only feature a turn every 500 or 1000 m and thus placing cameras on a straight section is crucial in analysing race walking gait.

Research on changes in gait has also been conducted in laboratory settings; to measure any effects of fatigue caused by a 50 km race walker's typical training session, Brisswalter et al. (1996; 1998) measured race walking kinematics in nine men using a treadmill moving at 12 km/h, both before and after a three-hour walk performed on a 400 m track, and paced throughout at 12 km/h (Figure 2.10).

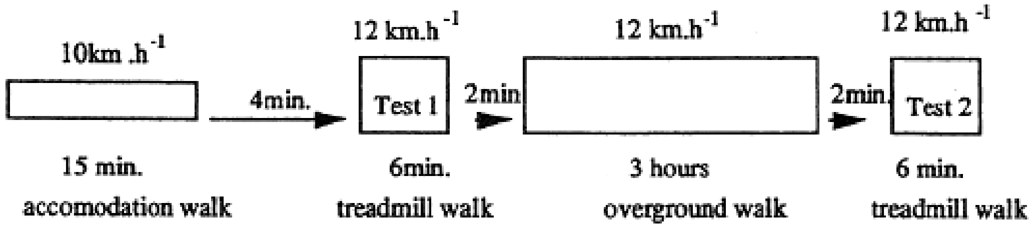


Figure 2.10. The fatigue protocol adopted by Brisswalter et al. (1996).

Similar to earlier research (Farley & Hamley, 1979), there was an increase in energy cost, but no general alterations occurred in the few gait kinematics measured. Mean step length did not differ between pre-testing (0.94 m) and post-testing (0.92 m), and neither did knee angle at midstance (mean of 179° both pre- and post-test). However, although treadmills have certain advantages when analysing gait (e.g. the belt can be set at a predetermined speed (Riley et al., 2007)), gait kinematics can be considerably different when walking on a treadmill compared with walking overground (Alton et al., 1998; Sinclair et al., 2013). Consequently, these results might not be replicated in a competitive setting, especially given that pacing is not controlled in the same way in competition (Hanley, 2013a) and elite 50 km athletes typically walk faster than 12 km/h.

Race walking is an endurance event and the fatigue aspect cannot be neglected if endeavouring to understand the event’s technical demands. While there have been attempts to measure the effects of fatigue (or to measure changes in key variables with speed), methodological limitations restrict these findings in terms of their usefulness to coaches or scientists interested in race walking, and in general the standard of understanding of fatigue effects on technique is very low. Measurements of fatigue effects are required to fill the large knowledge gaps highlighted above with new research on women, on competitive performances over the two Olympic distances of 20 km and 50 km (the latter of which might be considerably different from 20 km or even 35 km), on larger numbers of elite athletes, and with an analysis of more key variables. Such findings might not only aid the biomechanists who interact with the athletes and coaches but also those who are interested in physiological factors such as decreased work output or reduced economy.

2.5 Position of the foot in relation to the centre of mass

Step length is the sum of four different distances in race walking (Figure 2.11). At initial contact, the athlete strikes with the heel, and the distance from the CM to the foot centre of mass is the first of these distances (in the hierarchical model, this distance is termed ‘foot ahead’). The body then rolls forwards over the foot until toe-off. The distance the foot centre of mass moves from its horizontal position at initial contact to toe-off is the second distance contributing to step length (‘foot movement’). The distance from the CM to the foot centre of mass at toe-off is the third of the four distances, and is termed ‘foot behind’ in the hierarchical model. Finally, the athlete will typically have a brief flight period during which the CM will travel a relatively short distance (the fourth and final distance) before initial contact occurs on the other foot and the gait cycle is repeated.

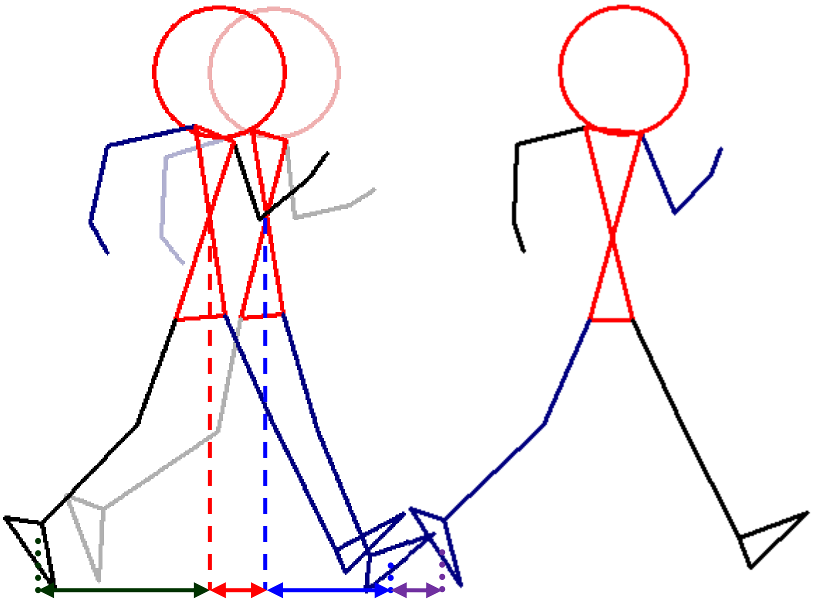


Figure 2.11. The four distances that contribute to step length. The green arrow represents the foot behind distance, the red arrow represents the flight distance, the blue arrow represents the foot ahead distance, and the purple arrow represents the foot movement distance.

2.5.1 Foot ahead and foot behind

The two largest components of step length are the foot ahead and foot behind distances. These positions of the support foot in relation to the athlete’s CM are important in maintaining forward momentum. From a coaching viewpoint, Summers (1991) suggests that the optimum foot position at initial contact is theoretically directly under the CM (i.e. a foot ahead distance approaching zero) because he assumes it will result in considerably reduced braking forces. However, this suggestion seems likely to be counterproductive as such a short foot ahead distance would reduce step length considerably. Summers (1991) does however suggest that a foot ahead distance of up to 30 cm would not necessarily be disadvantageous because the race walker's forward momentum would be great enough to make any braking forces unnoticeable. Using a similar rationale, and with the disadvantage of a lack of prior research, Huajing & Lizhong (1991) predicted that a key technical factor for future successful women walkers would be a foot ahead distance shorter than 10 cm, but as with their predictions for step length, there were no subsequent measurements carried out on elite walkers and the validity of this estimate is as yet untested.

During late stance, the foot behind distance is considered important by coaches in generating step length and forward propulsion (Schmolinsky, 1996). Summers (1991) states that walkers increase step length and speed by increasing their 'drive', i.e. the proportion of time spent in propulsion between midstance and toe-off, as he believes that the foot ahead position during early stance only provides stabilising assistance and that it is the thrust from the push-off leg that moves the body forward. By contrast, Villa (1990) claims that athletes should try to reduce the amount of time spent between midstance and toe-off in order to avoid upward rather than forward propulsion. It was proposed that this could be achieved through powerful hip flexion movements in the late stages of stance (Villa, 1990). It must be noted that both Summers (1991) and Villa (1990) based their recommendations entirely on coaching observations rather than biomechanical measurements and as with step length and cadence, these could be incorrect and misleading for coaches; new research findings on different categories of race walkers will be able to support or challenge these suggestions for both the foot ahead and foot behind distances.

In terms of actual measurements, only one study analysed these two key elements of step length. Lafortune et al. (1989) measured the foot ahead distance in 10 non-elite race walkers as 0.40 m (± .04) and the foot behind distance as 0.55 m (± .03). They compared these values (measured at race pace) with those achieved when the athletes walked at their 'maximum controlled velocity' (15.88 km/h (± .86)). The foot ahead distance (0.39 ± .04 m) did not differ but the foot behind distance did increase to 0.56 m (± .03) ($p < .05$). These differences of 1 cm for both distances were probably too small to be meaningful given measurement errors, but nevertheless the authors attribute the decrease in foot ahead distance to an increase in hip extension velocity before contact, while the increase in foot behind distance is believed to have provided extra propulsion before the next step (Lafortune et al., 1989). It is thus suggested, similar to the concept proposed by Summers (1991), that if the foot ahead distance is too large, it can cause too great a braking impulse for the effective maintenance of race walking speed (Lafortune et al., 1989). However, because a mean race walking speed of 15.88 km/h is faster than the current men’s 20 km World Record (and thus beyond the normal competitive capabilities of the non-elite race walkers who participated), it is unclear how valid these results are with regard to real competitive performances. Further measurements of both foot ahead and foot behind distances will serve to improve understanding of these key components of step length in terms of their typical magnitudes and their associations with other variables, and will ultimately provide meaningful recommendations for coaches. Such measurements might also benefit from being normalised using stature so that further analysis can take place and individualised recommendations can be provided to athletes.

2.6 Step time

2.6.1 Contact time and flight time

Cadence is determined by the time taken to complete each successive step, and in turn this step time can be broken down into contact time and flight time. Because step time is the reciprocal of cadence, a shorter step time (usually associated with a shorter contact time rather than a shorter flight time) is unsurprisingly associated with higher walking speeds (Cairns et al., 1986).

Theoretically, there should be no flight phase during race walking, although previous research during competition found it to be as high as 0.07 s (Knicker & Loch, 1990). Korolyov (1990) reported flight times at the 1983 IAAF World Championships of between 0.02 and 0.06 s for male 20 km walkers and between 0.01 and 0.04 s for 50 km walkers. However, it was believed that the athletes themselves were unlikely to notice any flight phases because of their relative brevity (Korolyov, 1990). Table 2.4 shows the step, contact, and flight times as reported in a number of studies, all of which were conducted in laboratory settings. It is clear that the athletes with the fastest mean race walking speeds recorded shorter step times, shorter contact times, and longer flight times. However, given the importance of achieving very short flight times in race walking, it is surprising that so little detailed data have been provided in most of these studies.

Table 2.4. Mean (± *s*) step time, contact time, and flight time values.

Authors	N (♂ / ♀)	Speed (km/h)	Step time (s)	Contact time (s)	Flight time (s)
Cairns et al. (1986)	8 / 2	13.07 (± .54)	0.34 (± .06)	0.34 (± .06)	< 0.04
Hoga et al. (2002)	11 / 0	13.93 (± .61)	0.32 (N/A)	0.27 (N/A)	0.05
Lafortune et al. (1989)	6 / 4	14.15 (± .65)	0.31 (± .01)	0.28 (± .02)	0.03
Murray et al. (1983)	2 / 0	12.05 (± .49)	0.35 (± .01)	0.34 (± .01)	< 0.01
Preatoni et al. (2006)	2 / 2	10.26 (± 1.44)	0.36 (± .04)	N/A	N/A
Rodano & Santambrogio (1987)	3 / 0	12.32 (± .69)	0.32 (± .16)	N/A	N/A

While there is no prescribed limit of what constitutes loss of contact except as a subjective ‘visible’ occurrence, reporting typical flight times of elite athletes and those tested in laboratory studies is invaluable to the coach (and judge) who is interested in appreciating what actual flight durations occur, and to the researcher of race walking who is keen to ensure external validity. Knicker & Loch’s (1990) study on the effects of fatigue on race walking kinematics found that mean contact times were 0.27 s and mean flight times 0.04 s. The authors found no changes in these values for the very small number of athletes measured and concluded that individual walking rhythms are maintained despite fatigue, with the main cause of slowing down being decreased step length (Knicker & Loch, 1990). However, further studies are required to properly determine the effects of fatigue on contact time and flight time, as well as to identify the athletes who might experience longer flight times (e.g. shorter athletes, 20 km competitors) and if any other kinetic or kinematic variables are associated with temporal variables.

2.6.2 Maintenance of double support

One of the aims of some early research was to find the speed at which race walkers no longer encounter double support, but instead undergo a flight phase (visible or not) (Neumann et al., 2006). This was because before 1995 the race walking rule required that “unbroken contact with the ground is always maintained” (IAAF, 1972, p.3) and judges therefore had to observe a period of double support during each stride. From a coaching point of view, Hopkins (1985) believes that walkers cannot maintain double support at speeds greater than 13 to 14 km/h, although based on mathematical models, Trowbridge (1981) calculates that double support is still possible in tall athletes walking at speeds up to 14.85 km/h (with the proviso that cadence would have to be at least 3.41 Hz). It seems to make sense therefore that shorter athletes begin to lose contact with the ground at a much slower speed (Zatsiorsky et al., 1994), although this has not been demonstrated in race walking to date. Korolyov (1990) calculated that a top class walker with a velocity of 16.20 km/h (faster than the current men’s World Record for 20 km) would need to reduce step length to 1.03 m and achieve a corresponding cadence of 4.37 Hz in order to maintain double support. This high value for cadence is generally only found in elite 100 m and 200 m sprinting (Kersting, 1999) and would be very difficult for endurance athletes like race walkers to achieve or maintain. The current wording of the race walking rule is more lenient as double support no longer has to be observed, and because most elite walkers do have very short loss of contact durations, permitting very short periods of flight is normal when testing athletes in research. For example, Witt & Gohlitz (2008) used flight times of greater than 0.05 s as indicative of ‘human eye visible loss of contact’. However, it is worth pointing out that the results of some previous studies must be treated with caution as they tested using race walking speeds much faster than the current World Record for 20 km (e.g. Lafortune et al., 1989; Korolyov, 1990), and the World Records at the time would have been even slower. Testing participants should be based on their competitive ability over the standard distances and not beyond this; flight time is certainly one variable that might be misleading if measured during unrealistically fast race walking and so safeguards must be put in place to ensure valid testing occurs.

2.6.3 Visible loss of contact

A flight phase is one feature that distinguishes running from normal walking (Dugan & Bhat, 2005), and Rule 230.1 is an attempt to maintain this difference. The position of flight time in the hierarchical model of race walking (Figure 2.3) is important not just because of its effect on cadence and flight distance, but also because of its bearing on the final race result (because of the risk of disqualification). Research by Knicker & Loch (1990) has already been discussed with regard to its findings on race walking kinematics in competition. Their research was in fact two-fold, with the other part conducted in a laboratory setting to identify how long flight times had to last before a loss of contact was detectable to the human eye. It was found that flight phases were difficult to detect in competitive athletes walking slower than 13.5 km/h. Similar research conducted by De Angelis & Menchinelli (1992) found that flight times were recorded in all 10 international-standard men and six international-standard women, and at all speeds used in testing (Table 2.5).

Table 2.5. Mean (± *s*) flight times during race walking (De Angelis & Menchinelli, 1992).

Speed (km/h)	Men: Flight time (s)	Women: Flight time (s)
12.00	0.030 (± .013)	
12.65	0.033 (± .011)	0.039 (± .004)
13.30	0.036 (± .008)	0.041 (± .004)
14.10	0.040 (± .007)	0.045 (± .004)
15.00	0.043 (± .006)	

Knicker & Loch (1990) and De Angelis & Menchinelli (1992) both concluded that the judges present in their studies were unable to observe loss of contact if it lasted less than 40 milliseconds (0.04 s). However, there were very few judges actually assessed. The first study (Knicker & Loch, 1990) had one international judge and two national judges, and the other used “a coach of long-standing international experience” (De Angelis & Menchinelli, 1992, p.87). Unfortunately, these very small sample sizes mean that it is impossible to make any general assumptions about what duration of flight time will attract the judges’ attention. It could therefore be useful to measure values for flight times in a large range of qualified athletes (i.e. those not disqualified under Rule 230.1) that can give an indication of what flight times are considered acceptable during junior and senior competition and hence inform coaching and judging.

2.6.4 Stance to swing ratio

Two temporal measurements used to analyse gait are stance (or contact) time as described above, and swing time. The purpose of the swing phase is to reposition the leg from the instant of toe-off to initial contact (Novacheck, 1998) and it is important that the foot is able to clear the ground and therefore avoid dragging. With regard to the hierarchical model in Figure 2.3, the stance phase relates to contact time and the foot ahead, foot behind and foot movement distances, whereas the swing phase relates to flight time and flight distance. The ratio of the gait cycle spent in stance compared with swing during normal walking is usually greater than 50:50 (Figure 2.12) because of double support, and previously the ratio has been reported as 62:38 and 54:46 (Mann & Hagy, 1980; Li et al., 1999). By contrast, there is always a flight period in running when both legs are at opposite ends of the swing phase (Novacheck, 1998) and typical stance:swing ratios in running range between 22:78 and 36:64, dependent on speed (Mann & Hagy, 1980; Novacheck, 1998).

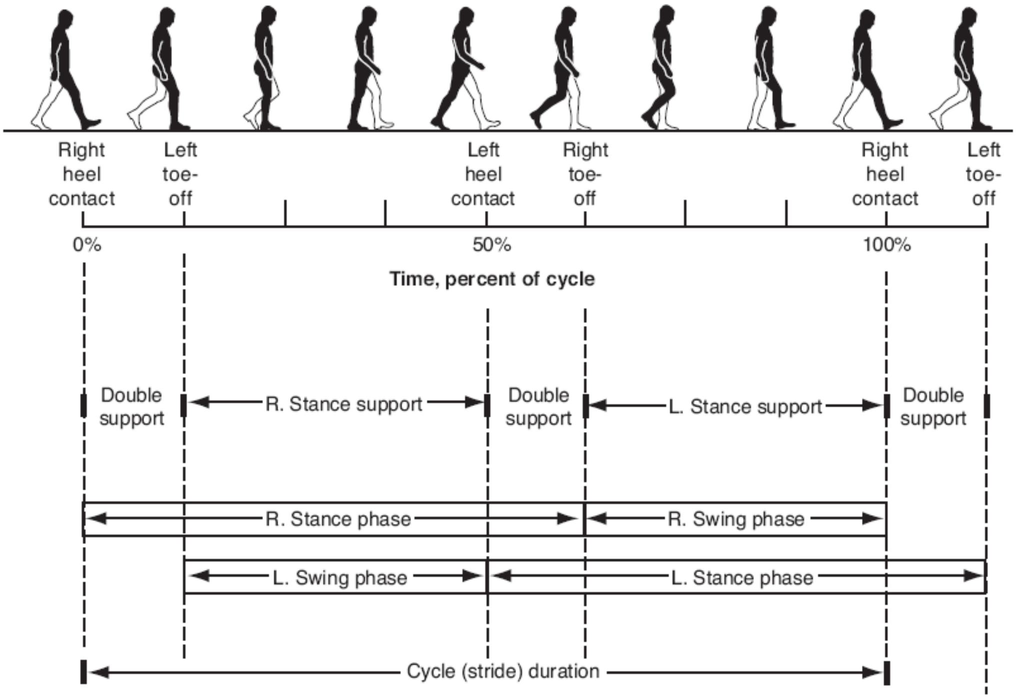


Figure 2.12. Time dimensions of a normal walk gait cycle (Rose & Gamble, 2005).

As mentioned above, flight times also frequently occur in race walking but their brevity means that simultaneous swing times for both legs are very short (Cairns et al., 1986). As with normalising step length, the usage of a ratio (stance:swing) might be useful when comparing athletes, and in describing relationships between key variables. Murray et al. (1983) found that the stance:swing ratios in two male walkers with very short flight times (< .005 s) were 51:49 and 50:50 respectively. Cairns et al. (1986) similarly reported that at competitive speeds, race walkers exhibited almost equally long stance and swing phases. These studies were conducted before the rule change of 1995 and are indicative of a race walking pattern of trying to be certain of double support (and of non-elite athletes). More recent research by Villarroya et al. (2009) found a much shorter stance:swing ratio of 42:58 in four male and four female athletes race walking at 11.51 km/h (± 1.68), but it is difficult to tell from this laboratory study if similar values would be found in competition (e.g. due to the lack of any flight time data). As is typical of previous race walking research, no elaboration was given with regard to any gender differences found (Villarroya et al., 2009). Further studies with larger sample sizes of elite race walkers in competition will contribute greatly in improving scientific knowledge of this and other under-researched temporal variables, and will go much further than previous research by assessing any effects of fatigue and by comparing between men and women, juniors and seniors, and 20 km and 50 km competitors, that in turn will contribute to and inform coaching practice.

2.7 Posture

2.7.1 The lower limb joints

Race walking, as with all other forms of locomotion, requires angular motion at particular joints for linear motion of the CM to occur. There is a direct link between step length, the position of the foot, and the joint angles of the entire lower limb, and hence the study of angular motion is of paramount importance in race walking (Ruhling & Hopkins, 1990). Cairns et al. (1986) believe that the differences in angular kinematics at the ankle, knee and hip between running and race walking are necessary to attain increased gait velocity within the rules and to avoid too much vertical displacement of the CM. In their single-subject study, White & Winter (1985) found the greatest rates of change in angular displacements for the lower limb joints in race walking occurred at the initial and late stages of stance and especially during the swing phase. Each of the main lower limb joints (hip, knee and ankle) will be discussed below in terms of brief descriptions of movements with current coaching understanding and suggestions, details of any actual scientific measurements of the joint angles and their role in race walking, and consequently any gaps or limitations in the research that need to be filled.

2.7.1.1 The knee joint

2.7.1.1.1 The straightened knee rule in race walking

The knee is in many ways the most important joint to measure and assess in race walking because the strictly-enforced rule that it must be straightened at initial contact until the ‘vertical upright position’ has a visible effect on the gait mechanics of all lower limb joints. However, as with flight time, judging of the knee’s straightness is entirely subjective, and as a result the definition of this rule and its implementation are not without controversy (Lassen, 1990; Osterhoudt, 2000; Westerfield, 2007). This is partly because of the complexity of the knee joint’s movements in dynamic gait (Lafortune et al., 1992) but also because of different interpretations of the definition of ‘straightened’ (Westerfield, 2007). It must be remembered that before 1995 race walkers were only required to have a straightened knee at the vertical upright position, and this makes any research conducted on knee angles in race walking before this largely redundant in terms of understanding knee mechanics or its effects on other joint mechanics. In this study, the term ‘straightened’ has been used to describe a fully extended (or hyperextended) knee (≥ 180°) to retain consistency with the wording of the IAAF rule, although it must be stressed that does not necessarily equate to what a judge would consider to be an acceptable degree of straightness.

2.7.1.1.2 Knee angle during stance

Complete straightness at the knee is atypical in normal walking, fast walking, and jogging (White & Winter, 1985; Ruhling & Hopkins, 1990; Takeuchi et al., 2009) where instead the knee is slightly flexed at initial contact with a small degree of further flexion during midstance (Kersting, 1999). By contrast, race walking is quite a marked variation of natural, ordinary walking (Marín, 1990) and as such is a learned skill (Neumann et al., 2008) that takes time to develop (and hence might be noticeably different between junior and senior race walkers).

Several coaches suggest that the knee aspect of Rule 230.1 is what differentiates the event from running (Korolyov, 1990) rather than no visible loss of contact, and slows the athlete down by making race walking more difficult (i.e. less efficient) than running. For example, Schmolinsky (1996) suggests that if a straightened knee at initial contact was not required by the rules then a flexed knee would reduce the braking effect of the foot landing ahead of the body. Similarly, Laird (2000) suggests that it is because flexed knees promote the use of the quadriceps femoris muscle group and result in a running motion that they must be kept straightened. However, these hypotheses have not been tested and indeed might be difficult to test at all given that modern race walkers train deliberately to achieve knee straightness, and any athletes who would potentially benefit from flexed knees are in danger of disqualification. In race walk research, the risk of disqualification must always be taken into account, both when making suggestions about particular ways of improving performance, and by ensuring that testing carried out is externally valid.

Two patterns of disqualification for bent knees have been described by coaches; first, many athletes who have poor technique or are inexperienced (e.g. junior race walkers) are disqualified early; second, others suffering from fatigue are disqualified when their previously correct technique breaks down (Drake, 2003). These late disqualifications, more common in 50 km competition, are believed by coaches to demonstrate a lack of physical preparation on behalf of the athletes in terms of maintaining correct technique with the onset of fatigue (Reiss et al., 1993), and hence the scientific study of any fatigue effects on knee angles is of particular relevance in establishing the validity of such coaching beliefs.

One effect of the current rule is that athletes must fully extend their knee by the time of initial contact, towards the end of terminal swing (Villa, 1990), rather than after it, and theoretically this might demand considerable activation of the quadriceps femoris muscle group. Coaches hence suggest that poor quadriceps femoris strength can contribute to an inability to achieve correct knee straightness, along with other anatomical factors such as a lack of hamstring flexibility (Fruktov et al., 1984; Drake, 2003). To avoid being unable to straighten the knee, Hedge (2002) recommends from a coaching viewpoint that young athletes should develop mobility about the knee to aid straightening. In this regard, it is believed that repeated sessions of race walk training increase the laxity of the ligaments and the length of the muscles at the rear of the knee joint, and hence lead to easier knee hyperextension during stance (Hopkins, 1985). Coaches Payne & Payne (1981) believe that any knee hyperextension during midstance can in fact benefit the race walker as this abnormal gait movement will theoretically reduce the vertical displacement of the CM in a similar way to knee flexion (Figure 2.13); however, knee hyperextension during stance might have other negative consequences that have not yet been tested. These coaching points are predominantly made based on personal observations or on generic anatomical descriptions, and the effect of an abnormal gait pattern on knee muscle activity is not fully appreciated. Training the correct movements (and muscles) is clearly an important point for coaches, including those of junior athletes, and hence a study of muscle activity patterns using EMG across both senior and junior race walkers will be very useful in identifying more specifically the role the quadriceps femoris plays in knee extension.

Figure 2.13. Knee hyperextension has been suggested to reduce CM vertical displacement as it decreases the knee angle at midstance (Trotman, 2010).

In sprinting and distance running, research has measured the lower limb angles, their alteration and their importance (e.g. Williams et al., 1991), but despite its great significance in race walking, few authors have actually published measured knee angles since the current rule was introduced. One exception was Zhang & Cai's (2000) study of elite Chinese women walkers, where the mean knee angle was 181° (± 2) at initial contact and 186° (± 3) at midstance. Zhang & Cai (2000) also found that this knee angle decreased to a mean of 147° (± 4) at toe-off. However, Zhang & Cai (2000) only reported these data to provide a basic kinematic description and no relationships with other variables were measured, and so it remains unknown what effect these knee angles had on general gait kinetics or kinematics. In terms of any possible fatigue effects, Brisswalter et al. (1998) measured knee angles at midstance in nine 50 km competitors before a three-hour training session (179.1° ± 0.8) and afterwards (179.4° ± 0.3) and found no difference. However, training is not the same as competing (the participants walked at a constant, controlled pace) and analysis in competition might reveal the effects of fatigue when athletes are pushing themselves to their physical limits and are motivated to finish as quickly as possible. While other aspects of knee motion have been studied (e.g. on variability (Neumann et al., 2008; Preatoni et al., 2010)) the lack of data on elite race walkers' stance knee kinematics is of concern when such measurements are invaluable in assessing adherence to the race walking rule, and in appreciating their role in the overall picture of lower limb joint movements. Further research to assess typical knee joint movement patterns across junior and senior men and women in competition is warranted, and additionally in terms of any fatigue effects. These measurements will complement those of lower limb muscle activity to provide insights into the effects of the abnormal motions of the knee, and help understand the coaching requirements for fast, legal race walking. Given that one coaching opinion is that no propulsion occurs during the early- to midstance phases (Summers, 1991), it will certainly be invaluable to assess just how much the straightened knee rule affects the knee muscles' role in forward propulsion, and not just during the early stages when it must be straightened, but also during late stance and swing.

2.7.1.1.3 Knee angle during swing

In gait, the function of the swing phase is to allow the rear foot to clear the ground and be repositioned ahead of the CM ready for initial contact (Levine et al., 2012). The movements of the swing knee are therefore also of importance in elite race walking in reducing the leg's moment of inertia so that less effort is required, and in preparing it for full knee extension at initial contact (Villa, 1990). Actual measured knee swing angles in biomechanical research have varied. For example, Cairns et al. (1986) found maximum knee flexion during swing in 10 non-elite race walkers to be 108° (± 7), more than during running at the same speed (89° ± 11). Knicker & Loch (1990) measured the minimum swing knee angle in five male race walkers as between 87° and 108°, and this did not vary with fatigue within the very small group analysed. However, these two studies were conducted before 1995, and it is possible that the current requirement for a straightened knee by initial contact has affected the angles achieved during swing. More recently, Zhang & Cai (2000) found maximum knee flexion in seven elite women walkers to be 101° (± 6), but as with their other angular measurements, no further analysis was conducted. Of course, it is not simply the knee angle during swing that is of interest to the race walk researcher or coach, rather it is the contribution of the whole swing leg to the gait cycle that is important (e.g. to forward momentum) and the angle at any given instant is just a description of this. Restricting analysis of the knee joint to only measuring its angle during a gait event does not fully explain the role of the joint in the movement and can in fact be of little real value. In addition, the leg muscles that provide propulsion during stance are also active during swing, and this activity might affect their functioning during the stance phase (i.e. the two gait phases are not exclusive but interdependent), but this relationship is not yet understood. In effect, the role and importance of the knee angle during swing has not been established with regard to either kinematic or kinetic performance parameters and further research on elite male and female race walkers is therefore warranted.

2.7.1.2 The hip joint

As the lower limb’s proximal joint, the hip will partially determine how far in front or behind the body the foot is positioned during stance (Erdmann, 2007). In this study, the ‘hip’ refers to the ball-and-socket joint formed by the acetabulum and head of the femur. The ‘pelvis’ is used to describe the six fused bones of the pelvic girdle, which is often referred to as the hips. Inman et al. (1981) found that increased speed in normal walking was usually achieved through greater hip flexion rather than hyperextension, because the range of possible hip motion is much greater for flexion. This is because hip hyperextension is limited by the restraining function of the iliofemoral, pubofemoral and ischiofemoral ligaments (Kapandji, 1987). It would be of interest to determine whether these angular features of normal walking are also evident in the faster, abnormal gait of race walking, especially given the mobility training that would be typical of elite athletes. Coaches of race walkers have in fact suggested that athletes with larger hip flexion angles at contact and larger hip hyperextension angles at toe-off can achieve longer step lengths (McGuire, 1989) and drills have been used to develop these movements (Figures 2.14 and 2.15).

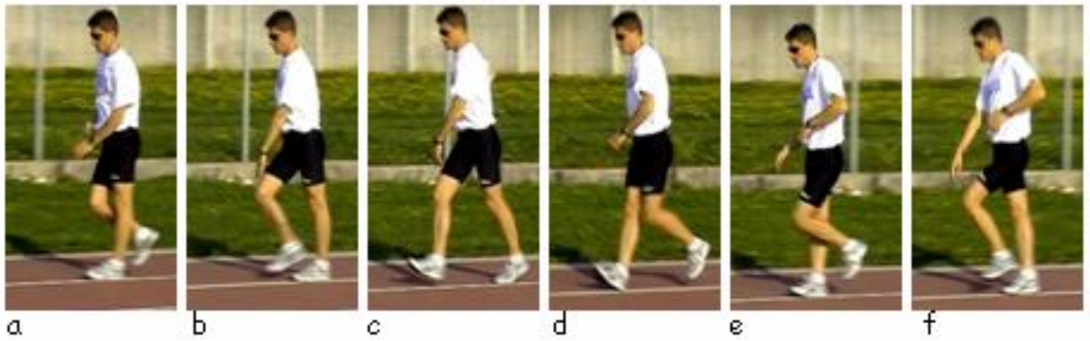


Figure 2.14. Drill used to develop the hip flexion movement (Drake, 2003).

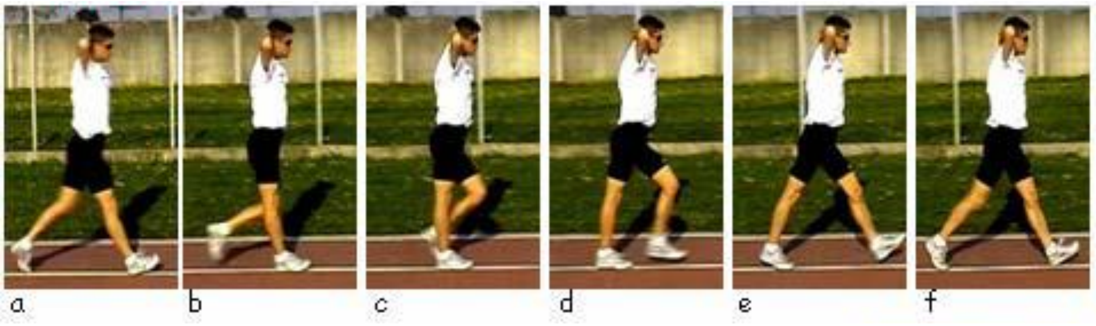


Figure 2.15. Drill used to develop the hip extension movement (Drake, 2003).

While this focus on hip flexion and hyperextension seems logical, there is generally an optimal range of motion for a joint to move through (e.g. in terms of torque production) and larger angles do not always equate with better joint movements. For example, Morgan & Martin (1986) found that race walkers were most economical (with regard to maximum oxygen uptake) at their ‘freely chosen stride length’ compared with either deliberately lengthened or shortened stride lengths, which suggests that forced, exaggerated step lengths should not be encouraged (e.g. through excessive hip flexion at initial contact) although increased step length might be made easier through improved hip mobility (Payne & Payne, 1981).

Unfortunately, very few biomechanical studies have measured hip joint angles at any gait cycle event. In one notable exception, Cairns et al. (1986) measured and compared joint angular data for 10 non-elite race walkers between four different gait modes (normal walking, race walking at training pace, race walking at competitive pace, and running). The participants displayed an earlier reversal into hip extension during swing while race walking compared with normal walking. This finding might be important for race walking coaches as Murray et al. (1983) believe this hip extension pattern is used to gain momentum to pull the body forwards at initial contact and thereby reduce horizontal deceleration. Lafortune et al. (1989) measured hip extension angular velocity at the instant of initial contact for 10 non-elite race walkers. The mean value of 104°/s (± 19) found at race pace increased to 116°/s (± 19) ($p < .05$) when the race walkers increased their speed to the maximum they could manage over 10 m while still adhering to the rules. Similar to Murray et al.'s (1983) opinion, the authors' conclusion is that a reduction in braking is caused by increasing hip extension velocity to reduce foot ahead distance, eventually resulting in increased speed (Lafortune et al., 1989). Ultimately, however, Lafortune et al.'s (1989) conclusions are based on very small changes in foot ahead distance (1 cm), velocity decrease during braking (.002 m/s), and hip angular velocity (12°/s). Such tiny differences could very well be meaningless given measurement errors and typical variations in gait parameters, and hence are not enough to support fully the importance placed on hip extension angular velocity by Lafortune et al. (1989). Nonetheless, the role of the hip joint throughout the gait cycle is a worthwhile avenue of investigation, given not just its obvious role in lower limb movement, but also in improving race walk efficiency. If, as suggested, the hip muscles are able to move the leg during late swing in such a way as to reduce the braking effects of foot placement ahead of the CM then this would be an important aspect for coaches to be made aware of. Further research on elite race walkers across different categories will assist in improving understanding of typical hip joint movements throughout stance and swing, specific contributions made towards efficient race walking gait, and the muscle activity patterns and muscle moments and powers involved in these movements. The value of this final information to coaches is an ability to develop training and conditioning regimens for particular muscles and movements, both for junior athletes whose techniques might be underdeveloped, and for senior athletes competing over the longer distances of 20 km and 50 km.

2.7.1.3 The ankle joint

The ankle is obviously an important joint in all forms of gait. Its orientation can be defined by a line passing between the tips of the medial and lateral malleoli (Czerniecki, 1988), and Cairns et al. (1986) defined the neutral position of the ankle as 110°, so that angles greater than this were indicative of plantarflexion, and angles less than this of dorsiflexion. There has been little coaching advice given regarding the ankle's role in race walking, except for the concept that the heel should strike the ground first (i.e. ankle dorsiflexion at initial contact) followed by a heel-to-toe ‘roll’ (Fruktov et al., 1984; McGuire, 1989; Villa, 1990; Scholich, 1992; McGovern, 2008; Salvage & Seaman, 2011) that culminates in the calf and toe muscles pushing the body forward in late stance (Laird, 1996; Salvage & Seaman, 2011). After toe-off, the ankle has to dorsiflex quickly in order for the foot to clear the ground. If dorsiflexion is not sufficient for ground clearance, because of the speed of the movement required or weakness in the dorsiflexor muscles, the knee must flex instead to raise the foot sufficiently (Laird, 1996). In general, the more flexed the knee, the higher the foot height. From a coaching viewpoint, Villa (1990) and Salvage & Seaman (2011) recommend not raising the foot too high during swing (instead keeping it parallel and close to the ground), so that the foot can return to the ground quicker and avoid any potential visible loss of contact (Figure 2.16). Indeed, Hoga et al. (2009) found that race walk judges were more likely to give red cards to walkers with ‘high’ feet as opposed to those with long flight phases.

Figure 2.16. Race walkers keep their feet low to the ground during swing.

As with the coaching resources, little attention has been paid to the role of the ankle during race walking in the scientific literature. In terms of joint angle measurements, Zhang & Cai’s (2000) observational study measured the ankle angles in seven elite female walkers at initial contact (113 ± 2°) and toe-off (135 ± 4°), but no correlation tests were performed, and their suggestion that this ankle angle at initial contact results in stored energy in the triceps surae is entirely speculative. Prior biomechanical research on race walking shows that ankle dorsiflexion is thought to augment step length by projecting the heel forwards (Murray et al., 1983; Fenton, 1984), and indeed Murray et al. (1983) found more dorsiflexion at initial contact (and during swing) in race walking compared with normal fast walking. In Cairns et al.'s (1986) study comparing four gait modes, the range of ankle dorsiflexion during late swing was greater in the competitive pace condition (27° ± 7) than in normal walking, fast walking or running.

The ankle joint is also considered important in late stance as plantarflexion aids the drive phase of the step (Fenton, 1984; White & Winter, 1985) and the plantarflexion angle at toe-off in race walking was found to be higher than in normal walking (Preatoni et al., 2006). Inverse dynamic analyses of race walking in a single subject case study before the rule change suggest that ankle plantarflexion provides the major energy required in forward propulsion (White & Winter, 1985), rather than any other joint movement. This previous research provides some indication of the role played by the ankle during race walking, but a full appreciation of this distal joint's function is far from being complete and there are still many gaps to fill. For example, it will be worth exploring any possible effects of fatigue on the ankle's joint motion, the relationship between ankle angle and key kinematic and kinetic variables in elite competition, typical muscle activity patterns, and muscle moments and powers in the ankle dorsi- and plantarflexors.

2.7.2 The upper limb joints

One major function of the arm movements during normal walking and running is to counteract moments of the swinging legs around the vertical axis (Hinrichs, 1987; Herr & Popovic, 2008; Pontzer et al., 2009), and this action is considered by several coaches to be particularly important in race walking (Hopkins, 1981; Villa, 1990; Bubanj et al., 2009). Furthermore, Hinrichs et al. (1987) state that in running the arm swing provides a meaningful contribution to lift (and subsequently flight), and while the arms do not provide forward propulsion of the CM, they do minimise changes in horizontal velocity. In normal gait, there is still a debate as to whether the shoulder muscles are primarily responsible for the swinging motion of the arms or whether their movement is predominantly a passive response to the legs' moments (Pontzer et al., 2009). Whilst this has not been studied in race walking, Payne & Payne (1981) suggest that a strong upward swing of the arms evokes extra forces from the ground through the driving leg, hence aiding forward movement of the CM, although no scientific basis was given for this opinion. Similarly, McGuire (1989) proposes that the arms are most important in assisting the walker’s speed, but Burrows & Fitzgerald (1990) recommend that race walkers should be careful about increasing upper body strength (presumably meaning increased muscle mass) as the increased angular momentum about the upper limbs might raise the path of the CM too high. Many race walk coaches recommend that athletes walk with elbow angles of 90° or slightly greater (Hopkins, 1978; Fruktov et al., 1984; Markham, 1989; Laird, 1996) (e.g. Figures 2.17 and 2.18), and Villa (1990, p.68) even went as far as to say that an elbow angle of 90° is “required”. Several reasons have been provided for this opinion; for example, Fruktov et al. (1984) believe a 90° angle helps increase step length and relax the shoulder muscles. In addition, Hopkins (1978) noted this feature in the then-dominant Mexican walkers and believes the right angle at the elbow reduces moment of inertia about the shoulder axis and therefore lowers the energy required to swing the arms at the same high frequency as the legs. Hopkins (1978) was of the opinion that this then leads to a relaxation of the shoulder and thorax muscles that aids movement of the diaphragm (and hence breathing). Few coaches have considered that the elbow angle might change during a single gait cycle; however, Fruktov et al. (1984) do think the elbow angle to be largest in midstance and slightly lower at both initial contact and toe-off.

Figure 2.17. Coaching manuals recommend that the arms cross in front of the body and that the elbow is held at roughly 90° (Markham, 1989).

Figure 2.18. Coaching drill to develop arm action; the athlete is advised to flex the elbow to 90° (Drake, 2003).

As it typical in race walking, very few research studies have supported or refuted these coaching recommendations with reported values for the shoulder and elbow angles. In those that have measured upper limb angles, Polozkov & Papanov (1982) found that Olympic Champion Maurizio Damilano had an elbow angle of 80° at midstance, while Douglass & Garrett (1984) measured the elbow angle in eight international junior men at three different distances; midstance elbow angles decreased from 86° at the first measurement distance (± 13) to 83° (± 9) at the final distance, and initial contact elbow angles decreased from 80° (± 11) to 76° (± 9). Large variations were found both between athletes and within each individual at each measurement distance (Douglass & Garrett, 1984). However, what possible effects their analysis position (on the bend of a 400 m track) had on these angles is unclear. Murray et al. (1983) found a mean elbow angle of 114° at ipsilateral initial contact in two national-standard race walkers, and a smaller mean elbow angle of 92° at midstance (contrary to where Fruktov et al. (1984) had thought the smallest angle would occur). The mean shoulder hyperextension angle at ipsilateral initial contact was 85°, and shoulder flexion at toe-off was 34° (Murray et al., 1983). Unfortunately, these results are only descriptive and the lack of further analysis means these data have not been fully exploited to make them useful to coaches. Future studies need to put angular measurements like these into context (e.g. with regard to performance) so that their importance is ascertained to a greater degree.

There is clearly a considerable range of elbow angles reported in the literature (from 76° to 114° at initial contact) and this is possibly indicative of the large variations between individuals as described by Douglass & Garrett (1984). However, the small amount of previous research was conducted entirely on male race walkers, of whom only the single participant in Polozkov & Papanov's (1982) study was an elite senior athlete (approaching the finish line). Further research on both the elbow and the even less-studied shoulder that analyses the role of these upper limb joints in elite race walking both within and between groups might be informative for race walk coaches, and provide actual scientific measurements to inform technical training. Douglass & Garrett’s (1984) finding that elbow angles varied within individuals over the course of junior 10,000 m races is indicative that there might be a fatigue effect on the upper limb that is worth analysing in the longer races, particularly the 50 km.

2.7.3 Pelvic and shoulder girdle movements

2.7.3.1 Pelvic girdle rotation

The predominantly sagittal plane movements at the hip, knee and ankle described above are not the only important angular movements important in gait, and certainly not in race walking. Pelvic rotation (in the transverse plane) is the way in which the pelvis twists about a vertical axis, moving each hip joint forwards as that hip flexes, and backwards as the hip extends (Levine et al., 2012) (Figure 2.19). Researchers of normal walking believe this means less hip flexion and extension are required as a portion of step length is achieved by the anteroposterior movements of the pelvis instead (Inman et al., 1981). In terms of accepted norms for typical people walking at their natural cadence and step length, pelvic rotation is usually about 4° to 6° to each side (8° to 12° in total) (Inman et al., 1981; Levine et al., 2012), but the value increases markedly with increased speed (Inman et al., 1981).

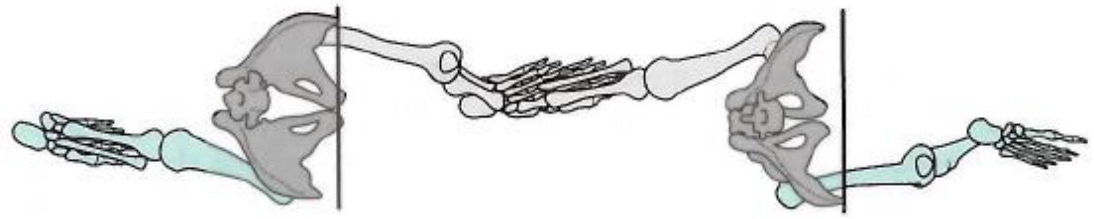


Figure 2.19. In normal gait, the pelvis twists about a vertical axis (Levine et al., 2012).

In race walking, effective control of the pelvic girdle is considered especially important in increasing speed because it is widely believed that pelvic rotation elicits greater step lengths (Trowbridge, 1981; Murray et al., 1983; Knicker & Loch, 1990). Furthermore, race walk coaches Fruktov et al. (1984) suggest that the rotation of the pelvis increases cadence as well as step length, because it allows the recruitment of additional muscle groups during the forward movement of the legs, although they do not specify which additional muscle groups are recruited or how this mechanism works. Only a very few race walking studies have measured this variable despite the importance placed upon it by coaches; Murray et al. (1983) analysed two national-standard athletes and found that total pelvic rotation increased from a mean total of 23° in normal fast walking to 44° in race walking (i.e. 22° to each side). Similarly, Cairns et al. (1986) found that total pelvic rotation in 10 non-elite race walkers increased from 21° (± 8) during normal walking to 36° (± 8) during race walking at competitive speeds. Although these authors seem to be in agreement that pelvic rotation increases with speed, no associations were made between this variable and any others (e.g. step length, cadence) that had been suggested by coaches. Therefore, this is an important aspect of race walking technique that must be analysed in elite performers, particularly considering its supposed role in increasing step length, as this movement could help in achieving greater speeds without risk of visible loss of contact. It might also be a movement whose range deteriorates in longer competitions, and so the analysis of pelvic rotation in terms of the effects of fatigue will be very useful in understanding further its role in elite race walking.

2.7.3.1.1 Stride width

Apart from its role in reducing the requirements of hip flexion and hyperextension (or in race walking, to possibly complement these movements), rotation of the pelvis is also believed by coaches to allow for narrowing of the stride width and placing of the feet closer to the line of progression so that an effective increase in step length is achieved (Hopkins, 1978; Payne & Payne, 1981) (Figure 2.20). The stride width is sometimes referred to as the walking base or base of support (Levine et al., 2012).

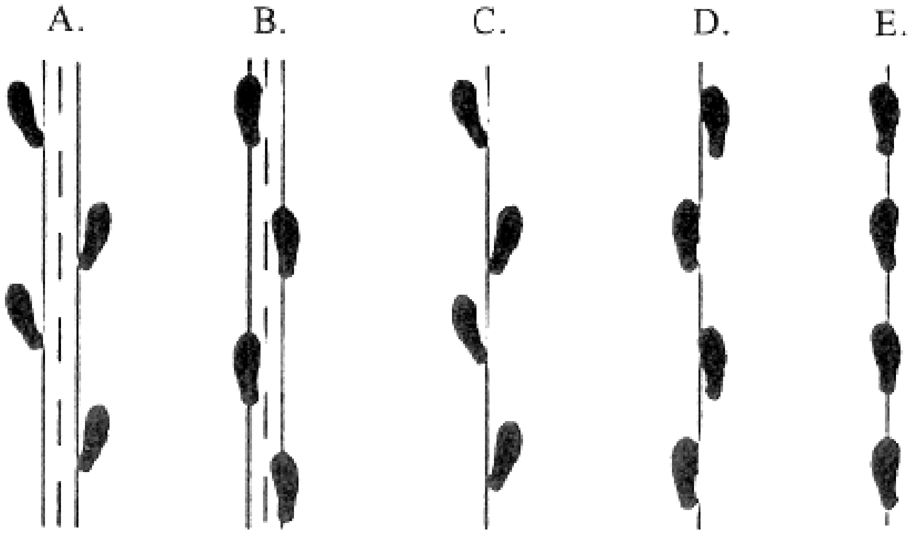


Figure 2.20. Race walkers are advised to have a narrow stride width with the feet pointing forwards (D and E) (Markham, 1989).

There appears to be a strong rationale for minimising stride width, because in normal walking, research shows that an increase in either stride width or stride length results in an increase in metabolic cost (Donelan et al., 2002). By contrast, by keeping the stride width narrow, less lateral movement is needed to maintain balance and therefore a reduction in muscular energy requirements is achieved (Levine et al., 2012). The stride width in normal walking is usually between 5 and 13 cm (Levine et al., 2012), and in the one race walking biomechanics study that measured this variable, it was found to be 6.5 and 9.2 cm in two non-elite male race walkers respectively (Murray et al., 1983). As with other aspects of technique, this seemingly important gait variable has not been measured adequately or assessed for its role in race walking. Practically all current coaching advice and drills adopted (e.g. Figure 2.21) are based on theoretical points of view that need to be supported (or otherwise) by biomechanical measurements on elite male and female race walkers (gender being of specific interest because of differences in pelvic shape and size).

Figure 2.21. A race walking drill used by coaches to develop narrow stride widths (Drake, 2003).

2.7.3.2 Shoulder girdle rotation

Anatomically, each shoulder girdle is comprised of the clavicle and the scapula, and one of the shoulder girdle’s main functions is to increase the range of movement possible at the shoulder joint. However, in this study, the term ‘shoulder girdle’ has been used to refer to the uppermost part of the trunk, in a sense combining both shoulder girdles as a unit, similar to how the two *os coxae* of the pelvis are described as a single pelvic girdle. The use of the term ‘shoulder girdle’ in this manner (visualised as a straight line from right acromion to left acromion) describes upper trunk rotation, whereas the shoulder joint has been simply described as the ‘shoulder’. In race walking, a transverse plane shoulder girdle movement is believed by coaches to counterbalance the pelvic girdle and provide economy of movement

(Hopkins, 1981; Schmolinsky, 1996) (Figure 2.22). A similar motion has been found in other forms of gait, and indeed the trunk rotation that occurs in running has been associated with increased efficiency (Bramble & Lieberman, 2004). Equally, restraint of the balancing movements of the shoulder girdle is believed to lead to an inability to progress in a straight line at higher speeds and to increase energy expenditure (Inman et al., 1981).

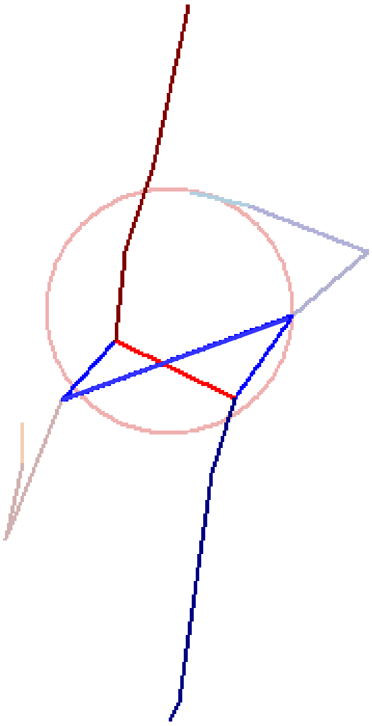


Figure 2.22. A bird's eye view of a stick figure diagram of one of the world's best race walkers (from digitised data). The blue diagonal line represents the shoulder girdle and the red diagonal line represents the pelvic girdle. The distortion angle is visualised as the degree at which the two lines intersect.

In normal walking the shoulder girdle rotates approximately 7° in total (Levine et al., 2012), while Murray et al. (1983) found that total shoulder girdle rotation increased from a mean of 10° in normal fast walking to 20° in race walking, supporting the concept that larger rotations occur in conjunction with higher speeds. However, it is not clear if the increases in shoulder (or pelvic) rotation are a cause of higher walking speeds, or a result of them. Based on biomechanical research on running, Williams & Ziff (1991) warn that if shoulder girdle rotation is increased, an increase in pelvic rotation might also occur, with the possibility that the lower leg and foot will cross over the midline more than usual (as in the race walking coaching point made in Figure 2.23 below). This concurs with the earlier comments on hip joint range of motion (Section 2.7.1.2) that larger angles do not always equate with better movement, and as it is not clear what the optimal ranges of motion at the pelvic and shoulder girdles are, it will be very worthwhile not just measuring these variables in large numbers of elite male and female athletes, but also looking for associations with other key variables.

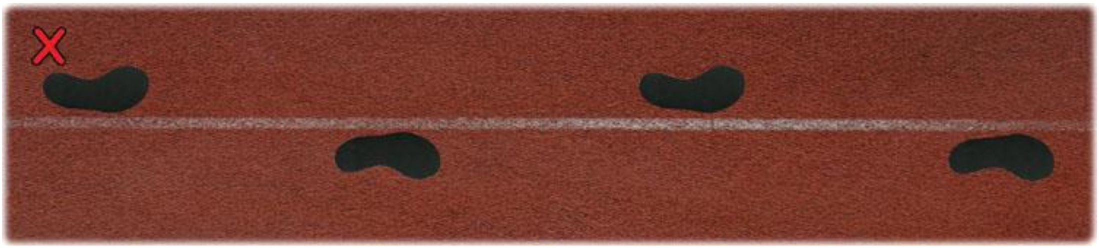


Figure 2.23. Race walkers are warned by coaches not to allow their feet to cross over the mid-line of the walking direction (Salvage & Seaman, 2011).

2.7.3.3 Distortion angle

The motion of the pelvic and shoulder girdles can be expressed by the degree of distortion that occurs between them (Knicker & Loch, 1990) (Figure 2.22). This value is calculated by adding the magnitudes of rotation at both pelvic and shoulder girdles at the same instant (Portus et al., 2004) so that a magnitude of 'torsion' in the trunk is provided; a value of 0° indicates the girdles are in line with one another, as in quiet standing. In general, this particular measurement has not been discussed by coaches, but from a biomechanical research point of view, Knicker & Loch (1990) found the value for distortion angle to be 32°, 36°, and 39° on average for three male walkers. There were, however, large differences between the left and right sides for some athletes (one athlete rotated his trunk approximately 28° to the right and 50° to the left). Although it is quite common for athletes to be not equally flexible or strong on different sides of the body, errors in calculating these rotations were possibly inherent in this 2D, sagittal plane study (Knicker & Loch, 1990), and further measurements assessing the rotational movements of the trunk are warranted to find associations within and between groups to identify the importance of this upper body action.

2.7.3.4 Pelvic obliquity

In gait, pelvic obliquity (in the frontal plane) is the way the pelvis turns about the sagittal axis so that the hip joint of the swing leg is lower than that of the stance leg (Levine et al., 2012). In race walking, this pelvic movement is very frequently exaggerated and is one of the motions giving it its familiar, distinctive 'wiggle'.

Cairns et al. (1986) and Ruhling & Hopkins (1990) suggest that this obliquity movement (combined with pelvic rotation) (Figure 2.24) minimises the vertical displacements of the CM during the stance phase. Its exaggerated appearance, compared with normal walking or running, is believed to be in response to the straightened knee during early stance and midstance (Murray et al., 1983) and it has been put forward that the corresponding movements of the shoulder girdle (Cavagna & Franzetti, 1981), spine (Crosbie et al., 1997) and arms (Fenton, 1984) also contribute to reducing vertical displacement. As a coaching point, Villa (1990) proposes that both pelvic obliquity and rotation have further benefits beyond reduced energy cost as they might help reduce visible loss of contact.

Figure 2.24. Pelvic and shoulder rotation can be seen in the picture on the left, while pelvic obliquity can be seen in the picture on the right (IAAF, 2009).

In terms of actual biomechanical measurements, Cairns et al. (1986) found increased pelvic obliquity in race walking (24 ± 5°) compared with normal walking (18 ± 4°) and running (15 ± 4°). Pelvic obliquity is considered the primary cause of the decrease in vertical displacement of the CM by Cairns et al. (1986), and causes the appearance of alternately formed S-shaped and reverse S-shaped vertebral column curves as weight-bearing shifts from one leg to the other (Figure 2.25)

(Murray et al., 1983). Cairns et al. (1986) believe that the increased medial GRFs recorded during midstance in race walking occur to decelerate pelvic obliquity and to move the pelvis in the opposite direction in preparation for the contralateral stance phase. It would be useful based on this premise to conduct further studies on elite race walkers to see if they have similar GRF patterns and magnitudes to those of non-elite athletes as tested by Cairns et al. (1986) and to go further by assessing what relationships exist with other key variables, such as speed and step length.

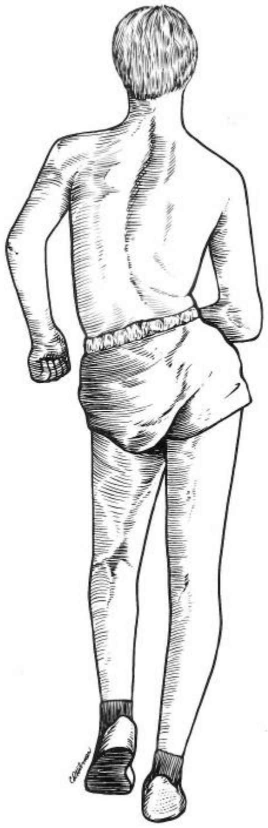


Figure 2.25. A reverse S-shaped vertebral column curve during right leg weight-bearing in race walking (Murray et al., 1983).

2.8 Vertical displacement in normal and race walking

As noted in the previous section, vertical displacement of the CM has been commented on by race walking coaches and researchers and is therefore an aspect worth investigating. In normal walking, it is generally accepted that vertical displacement of the CM increases during the gait cycle with increased walking speed and step length (Inman et al., 1981) and is generally between 4 and 5 cm (Gard et al., 2004). In normal walking, the CM is considered to reach its highest position at midstance, whereas in running the opposite is true (i.e. the CM is at its lowest height in midstance, and is highest during flight) (Lee & Farley, 1998).

Because vertical displacement during gait is considered to require a considerable muscle energetic cost (Neptune et al., 2004), movements that reduce its magnitude and thereby decrease inefficiency have been of interest to gait researchers for some time (e.g. Saunders et al., 1953). The competitive and long-distance nature of race walking means that reducing this inefficiency is of particular interest to athletes and their coaches. While Cairns et al. (1986) suggest that the rule requiring straightened knees in race walking results in an increase in vertical displacement, Murray et al. (1983) in fact found that vertical displacement in two national-standard race walkers decreased from 4.1 cm upwards when walking quickly (but with a normal gait) to 2.8 cm downwards when race walking (Figure 2.26). The CM was also lowest at midstance in race walking, thereby suggesting that the unnatural-looking movements of the pelvis (and other body parts such as the shoulder girdle) were able to prevent the increase in vertical displacement anticipated by Cairns et al. (1986). Murray et al.’s (1983) study was conducted on non-elite race walkers who experienced practically no flight times (< .005 s) and their gait might be considerably different from those in other studies and, more importantly, from those of elite athletes. Further analysis of vertical displacement in male and female race walkers, measured at successive distances over the course of high-standard competition, will help appreciate typical magnitudes of this gait variable, if there is any possible effect of fatigue, and what relationships actually exist with other key variables.

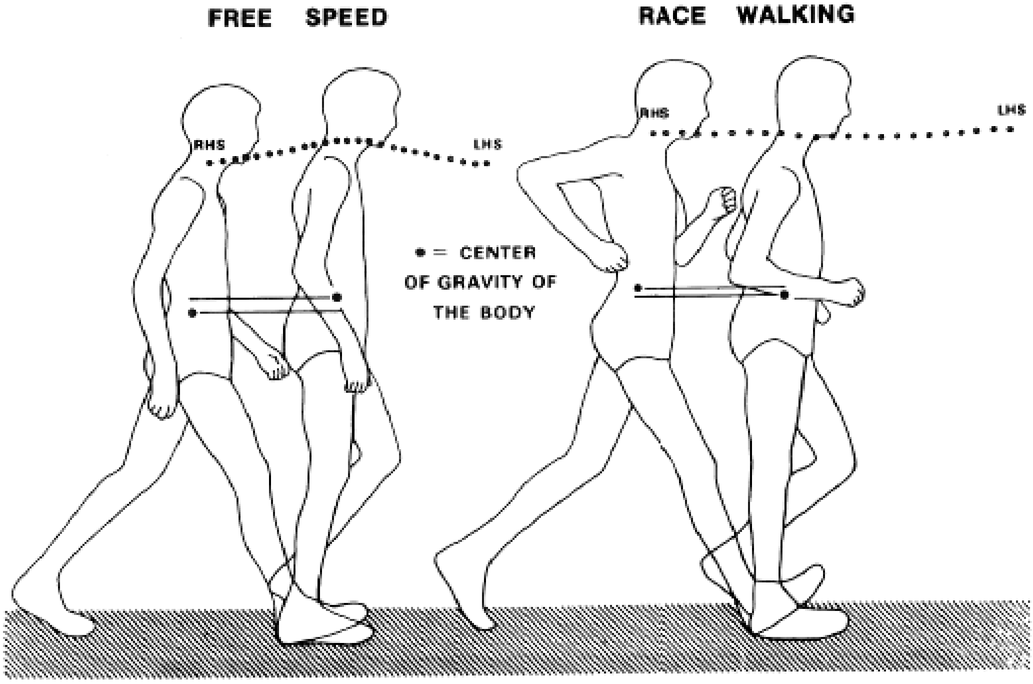


Figure 2.26. Vertical displacement decreased from initial contact to midstance from 4.1 cm during free speed normal walking to –2.8 cm during race walking in the study by Murray et al. (1983).

2.9 Race walking kinetics

2.9.1 GRF patterns in normal walking

Kinetic measurements allow for analyses of gait (i.e. measurement of GRF patterns, directions and magnitudes) that complement kinematic methods and have proven invaluable in describing the biomechanics of normal walking (e.g. Martin & Marsh, 1992), pathological gait (e.g. White et al., 1999) and running (e.g. Novacheck, 1998), not least when they are combined with kinematic data to calculate joint moments, powers and work (Zajac et al., 2002). Race walking is an abnormal form of walking, but to provide a conceptual basis for the later descriptions of race walking GRFs, a typical GRF trace of normal walking is shown and annotated in Figure 2.27, and described below.

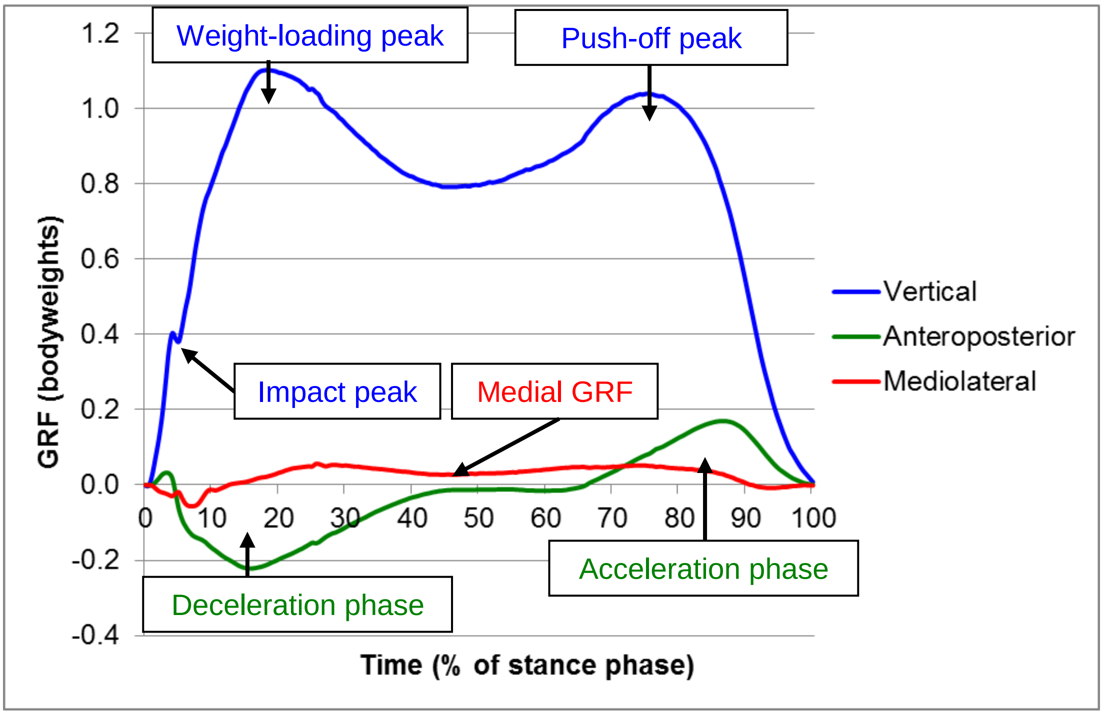


Figure 2.27. A typical GRF trace for normal walking (left foot contact); its three directional components are displayed as separate traces.

Normal walking GRF patterns consist of a vertical component with two smooth peaks, the first corresponding to a weight-loading period after initial contact, and the second corresponding to a push-off phase ending with toe-off (Watkins, 2010). Both of these peaks usually have a magnitude above one bodyweight (BW) while the short period between these peaks during midstance normally drops below 1 BW (Rodgers, 1993). In some cases, a short impact peak occurs within the first 0.05 s after initial contact and before the weight-loading peak (Frederick & Hagy, 1986). The anteroposterior component also comprises of two main peaks; the first occurs during foot ahead and is associated with deceleration of the CM; the second occurs during foot behind and causes acceleration of the CM (Watkins, 2010). The mediolateral component acts medially during the single support phase, and laterally during double support (at the very beginning and very end of the stance phase).

2.9.2 GRF patterns in race walking

Most of the limited biomechanical research on race walking has been concerned with kinematic variables, although there have been a very small number of studies that measured GRF data and are worth describing. Fenton (1984) measured GRFs in seven race walkers, and found that the traces differed between those of four 'nationally-competitive' race walkers and three less-skilled athletes (Figure 2.28).

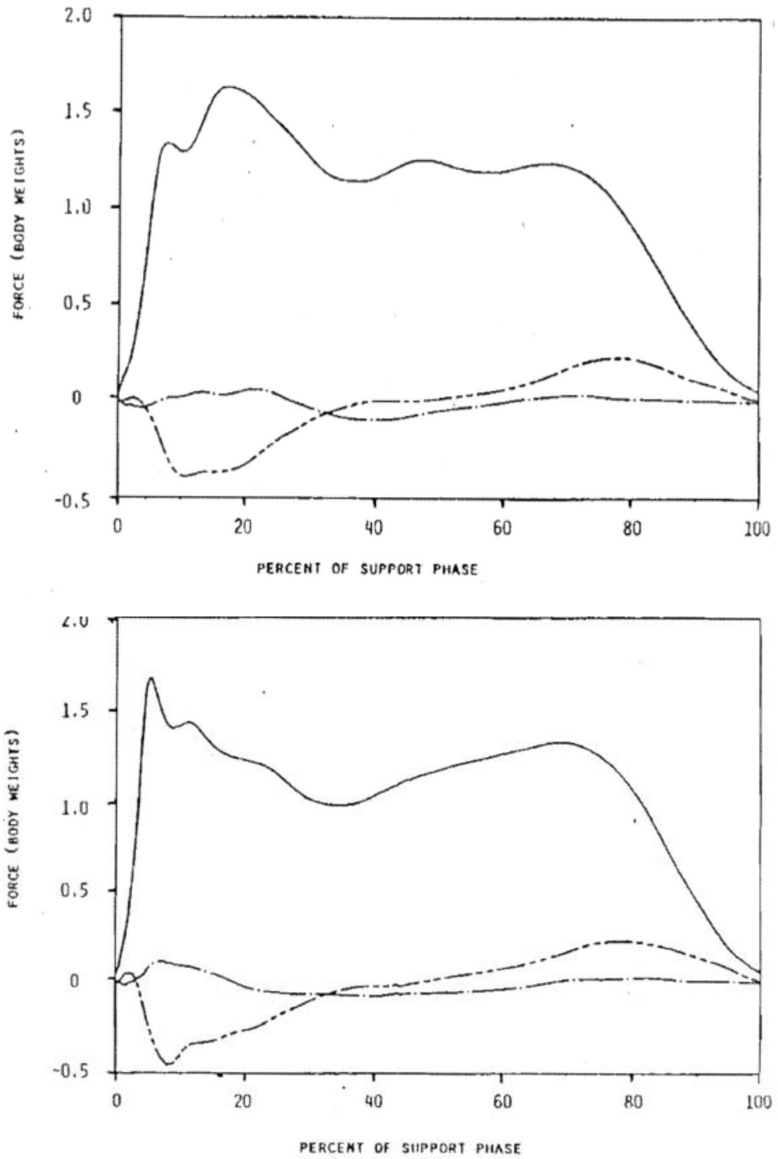


Figure 2.28. Averaged GRF traces for four national-standard race walkers (top diagram) and three race walkers of lesser ability (bottom diagram) (Fenton, 1984).

One of Fenton’s most revealing findings was that in the better walkers the vertical push-off peak was approximately 0.5 BW lower than the peak weight-loading force (unlike in normal walking). Fenton (1984) suggests this phenomenon occurs so that vertical displacement is reduced upon toe-off, and thus the possibility of loss of contact is lessened. In the anteroposterior direction, braking forces lasted for approximately 30 to 40% of stance and Fenton (1984) considers these forces (of approximately 0.5 BW) indicative of overstriding. He suggests that minimising the decelerating impulse should result in less work being necessary (during the propulsive phase) to maintain constant walking speed, but no kinematic data were collected to measure the magnitude of this assumed overstriding. In some cases a small anterior force was found at initial contact that might have helped to reduce deceleration during early stance (Fenton, 1984). Medial forces occurred in the middle third of stance, and were believed to be associated with pelvic obliquity during midstance. In the other study featuring race walking kinetics, Cairns et al. (1986) measured GRFs of the right foot stance phase in 10 non-elite race walkers (Figure 2.29). As with Fenton (1984), the GRF pattern in race walking was similar to normal walking but with greater magnitudes for peak vertical force, while peak medial force was greater than in normal walking and running, and attributed as in the other study to pelvic obliquity (Cairns et al., 1986).

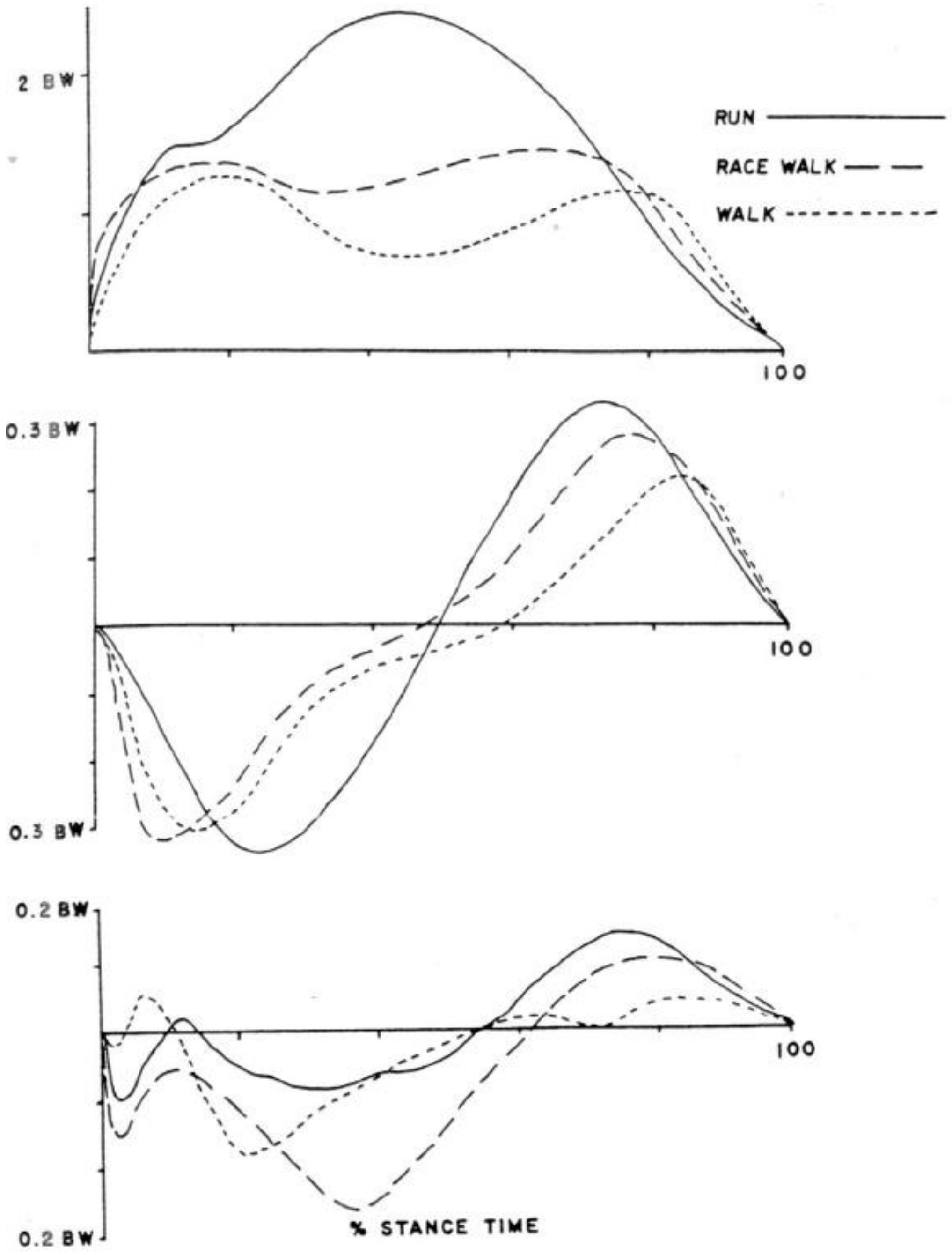


Figure 2.29. From top to bottom: vertical, anteroposterior and mediolateral GRF traces in running, race walking and normal walking (Cairns et al., 1986).

These two studies, by Fenton (1984) and Cairns et al. (1986), represent the main research on GRF traces in race walking and yet provide only basic descriptions of the force trace patterns found. In addition, both were conducted before the rule change in 1995 and only measured GRF traces in non-elite athletes. While there has been more recent analysis on a small sample of four national standard race walkers (Preatoni et al., 2006), it is still the case that potentially valuable and important data have been neglected in the intervening three decades considering their widespread use in normal and pathological gait. All three studies had both male and female participants but there was no indication given as to whether the women's results differed from the men's (although this might have been meaningless in any case as the ratio of men to women in Cairns et al.'s (1986) study was 8:2, and in Fenton's (1984) it was 6:1) and such information might be useful given body shape differences and strength levels. Furthermore, race walking is a learned skill and the GRF profiles of elite race walkers who spend considerable time practising correct technique might differ substantially from those of non-elite walkers.

There are great benefits to be obtained from using force plates in race walking research. For example, contact and flight times can be measured with greater precision (sampling rates are typically between 500 and 1000 Hz); the combination of these data with simultaneously collected kinematic data can be used in the calculation of joint moments, powers and work; and in-depth and revealing associations can be identified (e.g. spatiotemporal variables of race walking such as foot ahead and foot behind distances can be associated with deceleration and acceleration impulses respectively). To understand gait in any depth requires the collection of GRF data to fully appreciate the biomechanics of the movement, and the limitations of the very few studies to date on race walking GRFs mean that this understanding is not currently present in elite race walking. Further research on GRFs is therefore required to identify key kinetic variables and their relationship with key kinematic variables in the modern elite race walking techniques of junior and senior athletes.

2.10 Muscular activity

Typical muscle activity patterns in normal walking and running have been studied in detail by numerous authors (e.g. Inman et al., 1981; Shiavi et al., 1987; Winter, 1996) and have greatly enhanced understanding of these forms of gait. For example, it has been possible using EMG to identify typical muscle recruitment patterns during sprinting (Mero & Komi, 1987) that can help coaches implement effective strength and conditioning regimens. Similar measurements would obviously be of great value and practical use to race walking coaches, because coaches seek not just to develop the endurance abilities of their athletes (Raković et al., 2008a), but also the muscular qualities of economical and correct technique (Hilliard, 1991; La Torre et al., 2008). Despite this, Dunster et al. (1993) found that many female race walkers did not perform any strength training at all, and that no literature documented the muscle characteristics of female race walkers. Comprehensive research that does document these muscle characteristics in both male and female elite race walkers might be useful therefore in providing a strong rationale for strength training and a basis for the choice of exercises adopted. In addition, appreciating the muscle activity of elite race walkers can highlight areas of considerable stress (on particular muscle groups, for instance) so as to improve understanding of race walking injury mechanisms, and thereby help coaches to avoid overloading these muscles.

Coaches have advised that strength training in race walking needs to be orientated towards maintenance of technique and based on the specificity of the movements involved (Scholich, 1992), with the development of all-round strength and endurance considered a necessity (Hadrych & Schroter, 1980). For instance, strong hip flexors are believed by coaches to be important in driving the swing leg forwards after toe-off (Hilliard, 1986; Villa, 1990), and the exercises generally prescribed are those found in general weight and circuit training programmes (e.g. weightlifting, plyometrics, medicine ball activities) (Hopkins, 1978; Bondarenko & Korobov, 1986; Hilliard, 1986; Hilliard, 1991; Scholich, 1992). None of these training programmes have been based on objective analyses of muscle activity during elite race walking (e.g. there is no appreciation of the specific roles of muscles during each gait cycle or what types of muscle contraction occur during different phases) and as a result there is no guidance as to which exercises are most appropriate for race walkers and which might be useless or counterproductive. By contrast, Hilliard (1986, p.24) suggested that the only limit on choosing suitable circuit exercises for race walkers was “one’s imagination”. Historically, the only logic that seems to have been adopted when coaches have prescribed strength development activities is whether or not the muscle contracts concentrically during a particular exercise and whether that muscle also appears to contract during race walking (based on visual observation or anatomical knowledge). As with commonly used race walking drills, current coaching advice on appropriate strength and conditioning is based more on coaches' experiences than on any objective evidence, and hence there is a need for new studies of muscle activity in elite race walkers. This will not only aid experienced, senior walkers, but also junior athletes for whom the current coaching advice is simply based around coaches' perceptions of ideal technique that should be strived for (e.g. McGuire, 1989; Hedge, 2002). While there can be value in coaching based on previous experience (e.g. trying different approaches to see which works best), providing race walk coaches with scientific measurements and interpretation will enable them to use evidence-based practice, and lead to a systematic approach to the training of athletes (English et al., 2012).

Only two studies were found in the literature that measured the EMG patterns of major muscles involved in race walking (Murray et al., 1983; Padulo et al., 2012a) although neither set of EMG results was combined with inverse dynamics to measure muscle moments and periods of energy absorption and generation. Murray et al.'s (1983) study on two male race walkers provided a qualitative description of the actions of important muscle groups; eight lower body muscles (described as gluteus maximus, hip abductors, anterior hip adductors, hamstrings, rectus femoris, vastus lateralis, calf, and pretibial muscles) were analysed in both athletes, and eight upper body muscles (upper trapezius, pectoralis major, teres major, middle deltoid, posterior deltoid, triceps brachii, biceps brachii, obliquus externus abdominis, erector spinae) in just one of the race walkers. They found that all upper body muscles increased in activity from normal fast walking to race walking, similar to what occurred in the lower limb (Figure 2.30).

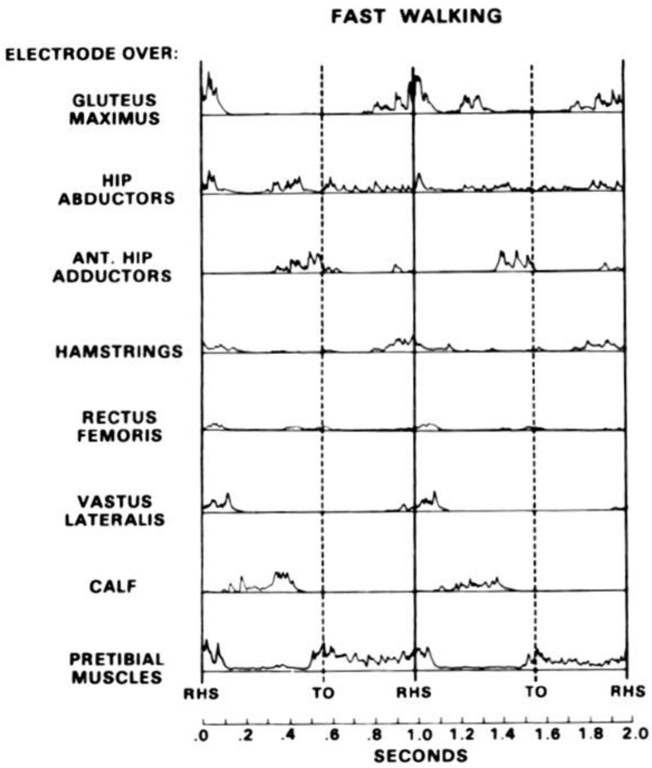


Figure 2.30. Differences in EMG patterns between fast normal walking and race walking (Murray et al., 1983).

As was expected from previous studies on other forms of gait, the gluteus maximus and hamstrings contracted at initial contact to extend the hip while the vastus lateralis acted early in stance to hyperextend the knee. During the swing phase, the anterior hip muscles (e.g. rectus femoris) acted early to accelerate flexion of the hip, while the gluteus maximus and hamstrings acted at approximately midswing to decelerate hip flexion and initiate hip extension. Increased activity was also found in the tibialis anterior throughout swing (Murray et al., 1983). Slightly different results were found by Padulo et al. (2012a) who compared EMG patterns between different slopes and speeds (Figure 2.31); using the 0% gradient to compare with Murray et al.'s (1983) findings, there appears to be less biceps femoris activity at initial contact and more rectus femoris activity during mid- to late stance. It is possible that these differences were a result of the change in rule governing the knee post-1995, although it could also be due to different methodologies (the participants in Murray et al.'s (1983) study walked at their own pace down a runway, whereas in Padulo et al.'s (2012a) study a treadmill was used with the belt moving at a predefined speed), or because of individual differences between the participants themselves (e.g. techniques used, distance typically raced, muscle mass).

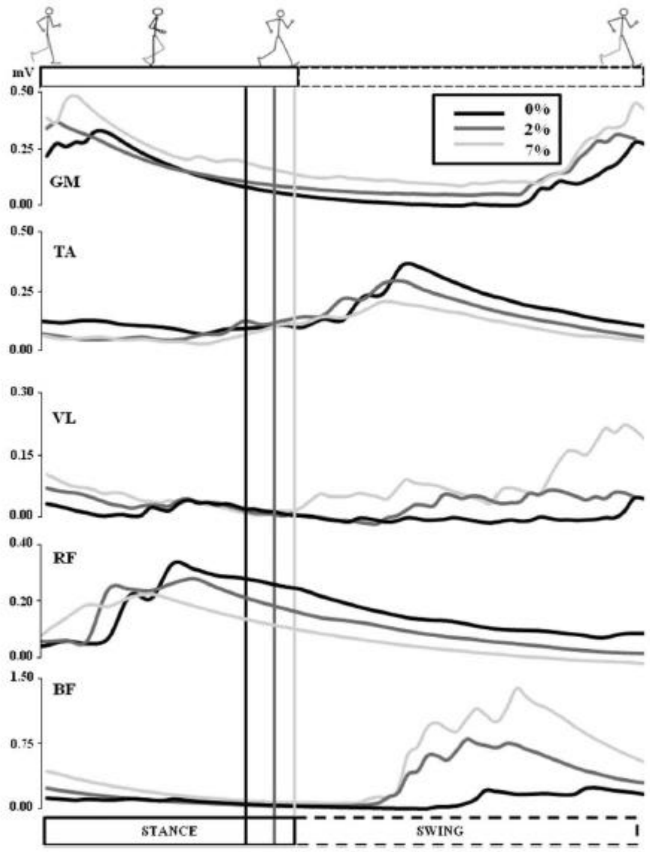


Figure 2.31. EMG recordings of the gastrocnemius (medial head) (GM), tibialis anterior (TA), vastus lateralis (VL), rectus femoris (RF) and biceps femoris (BF) at three different speeds and inclinations (12.5 km/h at 0%; 11.8 km/h at 2%; 10.3 km/h at 7%) (Padulo et al., 2012a).

While some differences in EMG patterns were found between gradients used in Padulo et al.'s (2012a) study, there might be little external validity in analysing muscle patterns at gradients other than 0% as race walk competitions are required to be held on level, smooth surfaces (IAAF, 2010), and race walkers find it difficult to achieve full knee straightness on inclined surfaces (Amano et al., 2008). Padulo et al. (2012a) unfortunately did not state whether their participants were male or female (or if both were included), and taking into account that Murray et al.'s (1983) study was only on male participants it is not clear from prior research if there are muscle activity differences between men and women. In addition, both studies were conducted using national-standard race walkers whose results might not reflect what occurs in elite athletes at race speeds, and no measurements were taken of junior race walkers whose EMG patterns might differ because of less-developed techniques and muscle strength. Furthermore, these two studies did not combine collection of EMG data with that of muscle moments, powers or work, which is crucial for a complete assessment of the role of particular muscle groups as it links the neural drive mechanisms with muscular contractions and production of motion.

2.11 Joint moments, powers and work

The collection and analysis of EMG data can be interesting in its own right, but Zajac et al. (2003) suggest that the causal relationship between EMG patterns and gait kinematics and kinetics has to be ascertained to fully understand how muscles coordinate human gait. The combination of kinetic, kinematic and anthropometric data allows for the calculation of joint moments, powers and work through processes of inverse dynamics (Winter, 1996; 2005). Joint moments (or torques) indicate the amount and direction of rotational force about a joint and are useful because they give information about the relative contributions of different muscle groups during different phases of a movement (Enoka, 2008). For example, joint moment data can inform whether the ankle dorsiflexors or plantarflexors are dominant during a particular gait event, such as heel strike. Mechanical power calculations complement the joint moment data by providing a measure of the rate of work done by muscles crossing a joint (White & Winter, 1985), although work has been less reported, even in elite sprinting (Bezodis et al., 2008). Muscles contracting concentrically generate power whereas those contracting eccentrically absorb it (Vardaxis & Hoshizaki, 1989) and muscles can absorb or generate power at segments other than those to which they are attached (Zajac et al., 2002). Absorbed power in muscles, which can also occur in stretched ligaments, stores elastic energy that can be converted to kinetic energy later with resulting power generation (Levine et al., 2012) via the stretch-shortening cycle mechanism that increases efficiency in locomotion (Belli et al., 2002).

In previous biomechanical research, race walking has been found to be more efficient than normal walking (Cavagna & Franzetti, 1981), but less efficient and with a higher energy cost than running (Marchetti & Cappozzo, 1982; Fougeron et al., 1998). However, actual muscle activity during elite race walking is a very under-researched aspect of this form of gait and is therefore an area worth analysing to ascertain typical joint moment and power magnitudes and patterns, and their relationship with key variables in the hierarchical model such as step length and cadence. As with collecting EMG data in isolation, the inverse dynamics method is suitable for expressing muscle function and joint kinetics in itself but the interpretation is clearer when used simultaneously with EMG measurements (Belli et al., 2001). Studies in this area of race walking research will be of great value to biomechanists and to coaches who want to develop training regimens specific to the actual muscular demands of race walking.

Given the potential benefits of analysing joint moments and powers in race walking, it is unfortunate that very little research has been conducted in this area. Before the rule change in 1995, Cairns et al. (1986) calculated the joint moments (but no power or work data) for eight male and two female non-elite race walkers (Figure 2.32), while White & Winter (1985) calculated the joint moments and powers of one male national-standard race walker (Figures 2.33, 2.34 and 2.35) but did not measure work; both studies analysed the motion of the ankle, knee and hip joints in the sagittal plane, while Cairns et al. (1986) also analysed the hip's frontal plane movements. Cairns et al. (1986) also compared the race walking moments with those in normal walking and running.

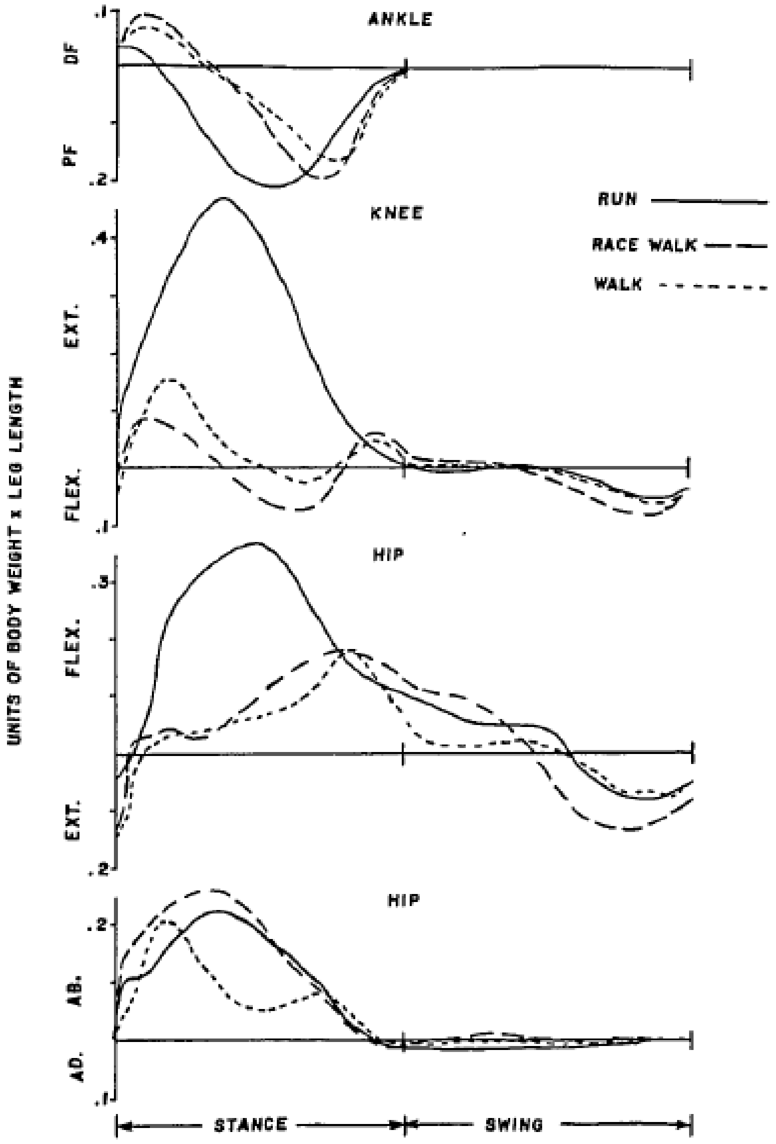


Figure 2.32. Mean joint sagittal moments at the ankle, knee and hip during running, race walking and normal walking. The hip moments in the frontal plane are also shown in the bottom graph (Cairns et al., 1986).

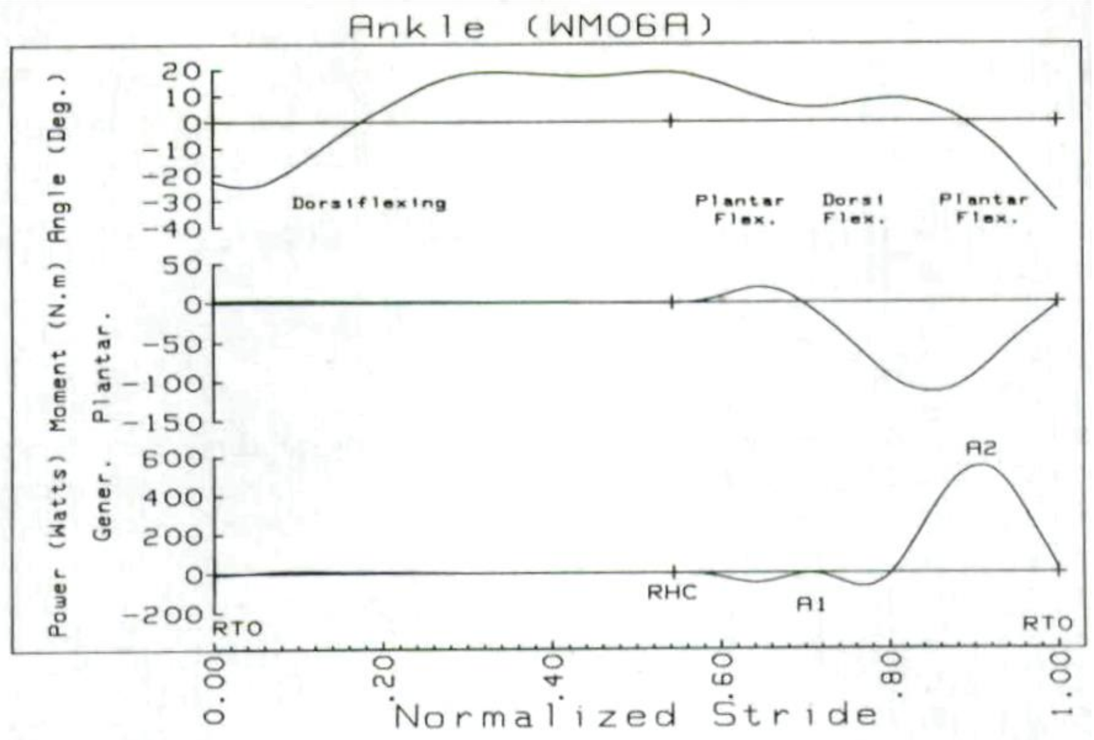


Figure 2.33. Ankle angle, moment and power during a single race walking stride (White & Winter, 1985).

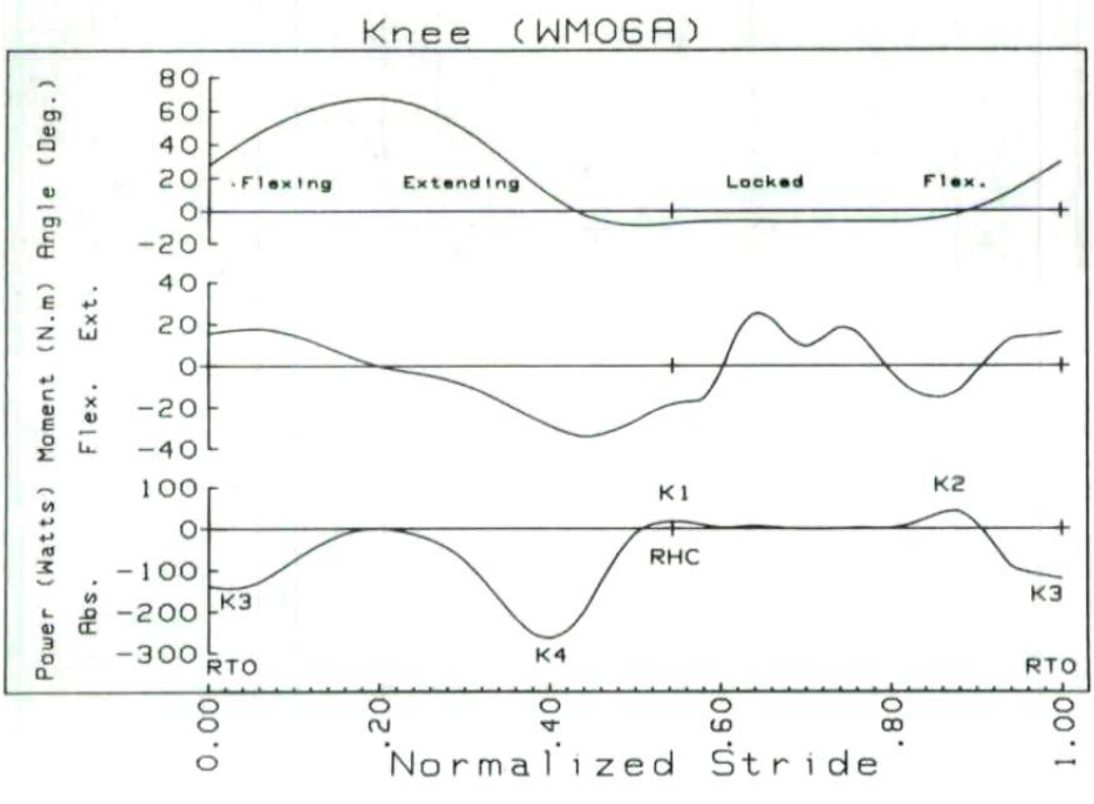


Figure 2.34. Knee angle, moment and power during a single race walking stride (White & Winter, 1985).

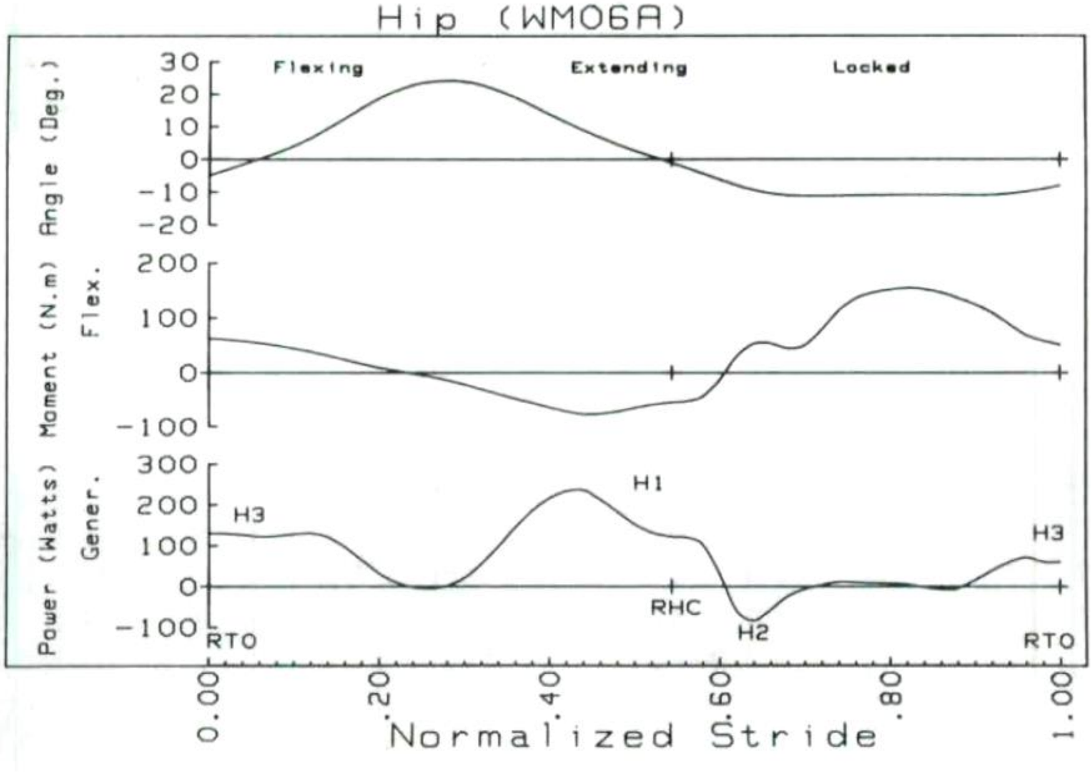


Figure 2.35. Hip angle, moment and power during a single race walking stride (White & Winter, 1985).

The main, original findings of these studies are that the ankle dorsiflexor moment at initial contact is higher in race walking than in running because the ankle has to assume the role of decelerating the downward motion of the body that the knee undertakes in running (Cairns et al., 1986); that a knee flexor moment occurs at initial contact because of a small degree of knee flexion, followed by an extensor moment (White & Winter, 1985; Cairns et al., 1986); and that a brief hip extensor moment at initial contact is followed by a flexor moment that lasts for the remainder of stance and continues up to midswing (White & Winter, 1985; Cairns et al., 1986). Overall, White & Winter (1985) found that the ankle plantarflexors provided the major power in forward propulsion during race walking.

As well as being conducted on small samples of non-elite athletes, the difficulty with applying the findings of the above studies (White & Winter, 1985; Cairns et al. 1986) to modern day race walking is because of the rule change that has occurred since they were undertaken. Both stance and swing joint moments and powers might have changed, and not just those at the knee. With regard to studies conducted since 1995, Hoga et al. (2003) used video footage from one camera (60 Hz) at several 20 km competitions to measure swing moments and powers in 28 elite men. Hoga et al.'s (2003) findings showed that the swing patterns of joint moments were similar to those found by White & Winter (1985) and Cairns et al. (1986), and Hoga et al. (2003) found that the hip moment peak values were correlated with walking speed during both early and late swing; because of this, the authors recommend athletes develop their hip muscle power. However, while the sampling rate of 60 Hz used is sufficient for basic kinematic analysis, it might not be suitable for calculation of internal kinetics, especially given the short duration of each step. Because competitive settings preclude collection of GRF data and therefore the calculation of inverse dynamics during stance, Hoga et al. (2006) used high-speed 2D videography and force plates in a laboratory setting to analyse 12 non-elite race walkers. While many of the joint moments and powers were similar to those of White & Winter (1985) and Cairns et al. (1986), the biggest differences were a hip extensor moment during the early stance phase, and a large knee flexor moment (similar findings were reported by Preatoni et al. (2006) in a sample of four young race walkers. Hoga et al. (2006) attributed these differences to the fact that the athletes in the pre-1995 studies were permitted a flexed knee at initial contact. Another finding of note was that the ankle plantarflexor moment during late stance correlates with walking speed; furthermore, Hoga et al. (2006) recommend that race walkers exert knee extensor and hip flexor moments to maintain walking speed. In another laboratory study, Donà et al. (2009) only reported moments at the knee (with similar results to previous research), and while the knee is of course of particular interest, its contribution to race walking gait needs to be considered in the context of other lower limb joints.

In summary, the patterns of joint internal kinetics in normal walking and running and EMG have been researched extensively (Zajac et al., 2003). To date, similar research on race walking has been sparse although with the increasing popularity of the event such research is now invaluable to elite athletes and their coaches. Because the swing and stance phases are not exclusive gait events but are instead interdependent, analysis of a complete gait cycle is required to assess overall performance. Furthermore, non-elite athletes have been shown to differ from elite athletes with regard to key biomechanical variables and therefore the analysis of non-elite athletes does not adequately describe elite performances (e.g. Leskinen et al., 2009). It is also worth noting that no previous study on race walking has combined the measurement of joint moments and powers with EMG, a technique that increases the validity of the power data by adding a biological perspective to the mechanical analysis. New research on internal kinetics and EMG of elite race walkers that incorporates both swing and stance phases in a single experimental set-up, and includes both men and women at junior and senior levels, is required to fully appreciate this unique form of locomotion. Measurement and analysis of the characteristic patterns of hip, knee and ankle joint movements and their limiting factors is invaluable in appreciating each joint’s role in this abnormal form of gait and in identifying sources of potential performance improvements and injurious stress. The findings of this research can assist coaches and athletes to understand the key biomechanical factors affecting technique and what measures can be taken to improve performance.

2.12 Injuries

Francis et al. (1998) found that the most commonly reported injuries in non-elite race walkers were to the hamstrings and shins (Figure 2.36). Hamstring injuries are also common in competitive running and sports involving fast running because of peak stretch and negative work demands during swing (Chumanov et al., 2011), but potential mechanisms for these injuries in elite race walkers have not been explored scientifically.

Figure 2.36. Shin pain is a common problem for race walkers (photograph courtesy of Bengt Bengtsson).

With regard to the shin muscles, Hreljac et al. (2008) state that the transition from walking to running in normal gait is related to high magnitudes of stress in the dorsiflexor muscles. Prilutsky & Gregor (2001) believe that at the walk-to-run transition speed, individuals prefer to run rather than walk as it requires less activation of the tibialis anterior (as well as the rectus femoris and hamstrings) during the swing phase. The fact that race walkers cannot undertake a walk-to-run transition to reduce the exaggerated activation of the anterior tibial muscles might be a cause of the frequently-reported shin pain (Levin, 1992). It has also been speculated that this shin pain is due to the eccentric contractions experienced as the ankle plantarflexes during pronation in early stance (Sanzén et al., 1986). It is not surprising given the paucity of research in race walking (especially with regard to muscle activation patterns) that the causes of frequent injuries are so poorly understood. The results of studies on muscle activity and muscle moments and powers might consequently be useful in identifying potential reasons for these reported injuries. For example, peak negative work demands at the lower limb joints can be measured using joint powers, and such research has been useful, for example, in identifying the limiting factor of the hamstrings' dual contraction during late swing as a source of injury in sprint running (Wood, 1986). Similar studies of race walking mechanics will be of great benefit to the coach who wants to prevent and manage any injuries associated with the abnormal movements typical of race walking.

2.13 Summary of key points

- Race walkers share similar anthropometric characteristics with other endurance athletes such as distance runners. Reported values for stature generally range between 1.71 m and 1.81 m for men and between 1.60 and 1.70 m for women;
- It is presumed that taller athletes should be able to achieve longer steps than shorter athletes because of leg length, although particularly long legs might be detrimental to achieving high cadences (but less likely to experience visible loss of contact). However, theoretical propositions such as these have not been tested to date;
- Step length is generally restricted by Rule 230.1 as visible loss of contact is not permitted, and so at an individual's maximal step length, cadence might become the determining factor. However, unlike competitive running, there is a distinct lack of understanding of the roles of these two fundamental gait variables that might invalidate current coaching recommendations. In addition, few studies have normalised step length using standing stature (to calculate step length ratio) despite its potential usefulness in providing guidelines to individual athletes;
- Previous research has found that decreases in walking speed during competition have been predominantly due to decreases in step length with little or no difference in cadence, although the total sample size is extremely small and has not analysed the effects of fatigue in elite 20 km and 50 km competition, where profound differences in gait kinematics might be found given the typical decreases in speed found;
- Race walk coaches emphasise that the foot ahead distance should be kept short (suggestions range between 10 and 30 cm) in order to minimise braking impulses. Coaches also suggest that the foot behind distance is important in race walking as it is the period when propulsion occurs, with the caveat that propulsion needs to be forwards rather than upwards. However, these coaching suggestions are based on anecdotal and subjective observations with little research to support them;
- Cadence is the reciprocal of step time, which itself is the sum of contact time and flight time. Flight times are usually very short in race walking (less than 40 ms). Whereas in normal walking the time spent in stance is greater than in swing (because of double support), the ratio of stance:swing in race walkers was found to be as low as 42:58, but in this case a treadmill methodology was

used that might mean similar ratios are not replicated overground, and especially not in competition;

- Although the rule of race walking states that the knee must be straightened from first contact until the 'vertical upright position', the exact knee angle required has not been defined. Most race walkers have hyperextended knees at midstance; whether this provides an advantage or disadvantage to the athletes has been debated but no evidence for either viewpoint currently exists;
- Before 1995, race walkers were not required to straighten the knee at initial contact and this resulted in many older kinematic studies reporting contact knee angles as small as 170°. Caution must therefore be taken when adopting the findings of studies conducted before 1995, as the new rule will have affected joint kinematics and kinetics and removed the external validity of some results;
- Of the other lower limb joints, the hip joint is important as increased flexion at initial contact theoretically allows for greater foot ahead distances. However, previous, albeit limited biomechanical research has found that a reduction in hip flexion occurred because of an extensor moment before initial contact that could be important in maintaining forward momentum. This emphasises that race walking technique requires a balancing of different elements, as increasing one variable (e.g. step length) might lead to an overall decrement in speed because of a negative effect on another (e.g. cadence). These interrelationships need to be established to a much greater degree if coaches are to use the findings of biomechanical research to inform their training practices;
- The ankle joint is also important in race walking; research on non-elite race walkers found that dorsiflexion during swing is greater than in running to allow for ground clearance, and plantarflexion at toe-off is also greater than in running. The ankle joint muscles are a key aspect of race walking gait as they are believed to be key generators of power, and a potential area for injury;
- The arms are believed by coaches to be important in providing balance to the body in compensating the rotational movements of the legs. Despite this, shoulder joint movements have not been measured to any great degree in previous research but the angle of the elbow has been measured, with a range between 76° and 114° in male athletes. No research has yet measured this variable (or most others) in female athletes;
- It is believed that pelvic rotation serves to assist in increasing step length as it allows for positioning of the foot further ahead and behind the CM at initial contact and toe-off respectively, although optimal magnitudes of this movement

have not been assessed, and the differing pelvic sizes and shapes of men and women further emphasise the need to collect data on both sexes and distinguish between them;

- Shoulder girdle rotation acts in opposition to pelvic girdle rotation to counterbalance it. The sum of the magnitudes of pelvic and shoulder girdle rotation at a given instant can be described as the distortion angle. These rotations have been found in research on non-elite athletes to be greater in race walking than in either normal walking or running, but further analyses of their importance (e.g. with the onset of fatigue) have not been conducted;
- In the very few studies conducted on GRF traces in race walking, the most noticeable features are a flatter vertical trace during midstance and late stance than in normal walking, and greater magnitudes of mediolateral forces than in either normal walking or running. However, beyond descriptive analyses no associations have been measured between GRF data and other key race walking variables, so understanding of the effect of specific GRF variables (e.g. impact peak forces) is very limited. Kinetic variables have proven invaluable in assessing normal and pathological gait and their role in complementing kinematic analysis is likewise fundamental to understanding race walking;
- Despite the importance of correct muscular development in race walking, only two studies were found that employed EMG as an objective measure of muscle activity. Of particular note were the high magnitudes of activity of the gluteus maximus and hamstring muscles from late swing until midstance and of the tibialis anterior during swing. Methodological limitations of these studies (e.g. small sample sizes of non-elite athletes, no results for women, and use of a treadmill in one study) mean that there is still a dearth of research on elite race walking, and thus no scientific foundation on which coaches can base their technical training, injury prevention, or strength and conditioning regimens on;
- Movement energetic patterns can also be understood via inverse dynamics, and indeed are vital in supporting the findings of EMG studies in explaining more clearly the role of particular muscle groups. Unfortunately, the results of some early research are no longer completely valid because of the change in rules that has resulted in different lower limb kinematics; more recent research has indeed found differences between those early studies and modern race walking. However, even recent research suffers from not having analysed the race walking stride in full, having few female participants, and no assessment of junior walkers. Perhaps even more crucially, no studies of inverse dynamics

have incorporated EMG analysis to complement their findings and this is an area ready for new analyses of elite race walkers;

- Most of the injuries in race walking (that have been reported in non-elite athletes) were to the hamstrings and shin muscles. Based on findings in other forms of athletic gait, the injuries to the hamstrings might be caused by powerful eccentric contractions during swing, while those to the shin muscles might be due to increased dorsiflexion during swing or the eccentric contraction that occurs at initial contact. Research that measures these potential causes of injury in elite race walkers is therefore warranted.

2.13.1 Limitations of previous literature

The current body of race walking literature is very limited compared with other Olympic athletic events such as sprinting and distance running. Much of what is currently available is based on coaches' personal experiences and theories. There is thus a lack of scientific published research to support these coaching recommendations and comments, and most research conducted has been very limited in terms of participant numbers. For example, studies have been published with only one or two participants whose individual characteristics might limit the application of those results to larger groups, and most of the participants tested have been non-elite race walkers (including some with very slow personal bests) whose limited racing and training experience means they might not have well-developed techniques. Furthermore, quite a few of these past studies have analysed race walkers in laboratory situations where the test speed was faster than the current World Record. There is little value in using such speeds as they would not be replicated (or the associated kinematics / kinetics) in actual competition and as such these studies have limited or no external validity.

Other limitations pertain to the narrow range of participants who took part in these studies. Women have not been tested to any great degree, and when they have, their results are often combined with men's with no rationale provided, and with no recognition of the potential for misleading results. Considering women's race walking has been part of the Olympic Games since 1992, this is particularly disquieting for those involved in coaching female athletes. Race walking is an event also accessible to young athletes as well as their more senior counterparts but little research has focussed on junior athletes. Currently available coaching advice regarding juniors' progression to senior competition has focussed exclusively on developing technique through methods such as drills, and very little evaluation of specific aspects of technique in junior athletes has been conducted.

As mentioned before, much of the current body of literature is based on what was observed or measured in race walkers before 1995, when the new rule was adopted. The mechanics of race walking gait can only have altered considerably with the requirements of the modern rule. Compounding this problem, research to date has not been holistic in its approach to race walking biomechanics. For example, there have been studies on GRF traces with no measurement of spatiotemporal data, and EMG studies with no measurement of internal kinetics (and vice versa in both cases). While it is difficult to combine some or all of these methodologies (e.g. if analysing in competition), a well-blended approach will greatly enhance understanding of the technical intricacies of race walking and lead to a fuller picture of its presently unknown mechanisms.

In summary, the current knowledge and understanding of the biomechanics of elite race walking is incomplete. This is perhaps a major limiting factor of this event, as without mapping scientifically all parameters relevant to this abnormal form of competitive gait, coaching and training will continue to rely solely on anecdotal information. By contrast, decades of rigorous scientific enquiry in sprinting and distance running have led to improved training methods, adapted recovery strategies, and a better understanding of the causes and prevention of injury.

2.13.2 Rationale for the present study

Race walking is an event held as part of the athletics programme up to Olympic standard. There are many coaches and athletes involved in race walking who adopt a variety of training methods and approaches to technical development. The research-based evidence for these methods is sparse, and it appears from the race walking literature that most recommendations are based on coaches' own subjective observations. To improve the scientific basis on which coaches and athletes can base their training regimens, a range of appropriate biomechanical methodologies must be adopted to provide a thorough, holistic analysis of race walking gait. While no study can provide a complete, all-inclusive analysis of a sporting movement, the aim of this study is to measure a large range of key race walking variables (suggested to be important via a hierarchical model and coaching practices), analyse their role in this unique form of competitive gait, assess their relationships with other variables, identify changes that occur over the course of competition, and identify those factors that contribute most to successful race walking. These analyses will be conducted on both men and women, junior and senior athletes, and over the range of distances used in official competition.

2.13.3 Aim of the present study

Because of the profound limitations of previous research in providing a holistic and rounded understanding of elite race walking biomechanics, this study will be the first to measure and identify key variables in determining success in elite race walking. The overall aim of the present study is to provide a comprehensive analysis of the biomechanics of elite race walking by measuring and identifying key variables in determining success, which could contribute to a technical manual for the benefit of the athletics and race walking communities, by reporting and discussing kinematic, ground reaction force, electromyographic and internal kinetic data.

2.13.4 Objectives of the present study

The achievement of this overall aim of the study will be accomplished by achieving the following specific objectives:

- To measure and find relationships between the key kinematic variables in elite race walking in 20 km competition (men and women), 50 km competition (men only) and 10 km competition (junior men and junior women) using 3D videography so that the importance of these variables to performance is evaluated;
- To measure variation in those key kinematic variables at different distances in the 20 km and 50 km competitions, especially so that the effect of fatigue on performance specific to each race distance is better understood;
- To collect data in a laboratory setting in order to analyse joint moments, powers and work, along with EMG activity patterns collected simultaneously, in elite male and female race walkers both at senior and junior standard, to assess the importance of the main kinematic and kinetic variables to elite performance;
- To provide an overall analysis of the key contributors to elite race walking performances, with reference to the needs of athletes and coaches.

CHAPTER 3

METHODS

3.1 Introduction

This chapter outlines the standard procedures that were used in the various different sections of the overall research project. This was divided into studies conducted outdoors at international competitions and a study conducted indoors in a biomechanics laboratory. Where there were specific changes or additions to any individual study, they have been reported in the following chapters.

3.2 Outdoor studies

The low-risk protocols undertaken at each competition had the prior ethical approval of the Leeds Metropolitan University Carnegie Faculty Research Ethics Sub-Committee. Permission to access the course and record the video data at the two European Cup events was obtained from the European Athletic Association (EAA); permission to record at the World Cup was obtained from the IAAF. In total, three outdoor studies were conducted using video data collected at three separate international competitions:

- The 7th European Cup Race Walking, held in Royal Leamington Spa (Great Britain) in May 2007;
- The 23rd World Race Walking Cup, held in Cheboksary (Russia) in May 2008;
- The 8th European Cup Race Walking, held in Metz (France) in May 2009.

To differentiate between the two European Cup competitions, they have been referred to as the 7th European Cup and the 8th European Cup respectively. Video data from the first competition (7th European Cup) and the second competition (23rd World Cup) were used to produce the first two studies, on 20 km athletes and 50 km athletes respectively. The recordings from the 7th European Cup were used to analyse for changes in gait kinematics at different distances of the 20 km and 50 km races, whereas the recordings from the 23rd World Cup were used to analyse a larger number of individuals in each race in order to find associations between key kinematic variables. The recordings from the 8th European Cup were used to find associations between the key kinematic variables in junior athletes.

3.2.1 The World Race Walking Cup

The World Race Walking Cup is a biennial event intended primarily as a team competition between IAAF member nations (Marlow, 1990); however, athletes also compete as individuals. The World Cup is seen as a measure of each competing nation's depth of talent (Vallance, 2007). As nations are allowed up to five entries per senior race, the participating numbers are relatively high compared with the World Championships and Olympic Games. This results in an overall greater depth in talent as strong nations can enter more athletes than in the championship races, and thus the World Cup is a highly regarded competition amongst the leading race walking nations (Lassen, 1990; Huajing & Lizhong, 1991), and was partly responsible for the development of women's international race walking (Frister, 1988). The lack of strict entry standard requirements for the World Cup also allows athletes who would not normally qualify for the World Championship or Olympic races to compete at a global competition. As a result, the World Cup allows for analysis of a greater number of participants from both faster and slower ends of the race. The 2008 World Cup was a particularly strong event as many athletes were attempting to achieve the qualifying time for the Olympic Games later that year, or to achieve selection as one of their nation's three representatives. There were 100 finishers in the men's 20 km race, 81 in the women's 20 km race, and 70 in the men's 50 km race. The overall number of disqualifications in the 23rd World Cup was relatively low compared with previous editions (Maggio, 2008). For this study, 30 athletes were analysed in each race.

The Cheboksary course, built specifically for race walking, was a completely flat 2 km route with fast turns at each end of the racing loop, and long straight stretches. The nature of the course, favourable weather conditions, and a sizeable contingent of world-class race walkers (Figure 3.1) resulted in many athletes recording national records and personal bests. A new World Record was set in the Men's 50 km event, as well as Championship Records in both the men's and women's 20 km events.

Figure 3.1. Opening lap of the men's 20 km race at the 23rd World Race Walking Cup.

The choice of athletes analysed was mostly based on practicality, in that they were the most clearly visible athletes (e.g. unblocked by other athletes), were walking normally (e.g. without sponges in their hands), and were within the boundaries of the reference volume. In total, 34 nations were represented by the athletes analysed in the three World Cup studies. However, European athletes comprised most competitors analysed as they dominate international race walking and particularly the 50 km race (Julin & Jalava, 2011).

3.2.2 The European Cup Race Walking

The European Cup Race Walking is also a biennial event intended primarily as a team competition between EAA member nations with athletes also competing as individuals. The 7th European Cup held in Royal Leamington Spa took place on a 1 km loop. This allowed for filming of each athlete on a greater number of occasions than would have been possible on a more commonly used 2 km loop and made the repeated analysis of athletes easier. There were 53 finishers in the men's 20 km race, 53 in the women's 20 km race, and 36 in the men's 50 km race; 12 athletes were analysed in each race. The 8th European Cup was held in Metz on a 2 km loop. There were 39 finishers in the junior men's 10 km race and 29 in the junior women's 10 km race; 20 athletes were analysed in each race.

3.2.3 Data collection

For each event, the set-up was similar: two stationary 3CCD digital camcorders (DM-XL1, Canon, Tokyo) were placed on one side of the course, approximately 45º and 135º respectively to the plane of motion (Figure 3.2), and positioned so that the right hand side of the walker was always nearest the cameras. Each camera was approximately 8 m from the path of the walkers. The sampling rate was 50 Hz and the shutter speed 1/500 s. The resolution of each camera was 720 x 576 pixels.

Figure 3.2. The two stationary 3CCD digital camcorders cameras were set at an angle to the course.

The section of the course where the camera was placed was chosen because of its straightness at that position and the absence of obstacles in view of the camera. For the World Cup, the reference volume was 5.20 m long, 2.00 m wide and 2.01 m high. For the 7th European Cup, the volume was 5.00 m long, 2.00 m wide and 2.16 m high. For the 8th European Cup, the volume was 5.20 m long, 2.00 m wide and 2.01 m high (Figure 3.3).

Figure 3.3. The reference volume was measured using a metal measuring tape (top photograph) and defined by six reference poles at the 8th European Cup (bottom).

The reference poles were placed so that the volume's 2 m width coincided with the path taken by most walkers. The poles were aligned vertically with the use of a spirit level and plumb bob. The volumes were used later for calibration for 3D Direct Linear Transformation (3D DLT) (Abdel-Aziz & Karara, 1971). At each competition, calibration rods were digitised within the calibration volume and the calculated lengths later compared with their known lengths. In the World Cup, the root mean square (RMS) of the difference was 0.2% of the rod's length in the x-direction (length), 0.5% in the y-direction (height) and 0.6% in the z-direction (width). In the 7th European Cup, the RMS of the difference between the known and calculated values was 0.8% of the rod's length in the x-direction, 1.0% in the y-direction and 0.9% in the z-direction. In the 8th European Cup, the RMS of the difference between the known and calculated values was 0.7% of the rod's length in the x-direction, 1.0% in the y-direction and 0.7% in the z-direction.

3.2.4 Data analysis

The video data were manually digitised to obtain kinematic data using motion analysis software (SIMI Motion version 6.1; SIMI Reality Motion Systems GmbH, Munich). The cameras were not genlocked, so the video footage from each camera was synchronised manually by visual identification: for each athlete right initial contact, right toe-off, left initial contact and left toe-off were identified in the first video sequence. The same four instants were then identified in the second sequence and the digitising start point of each video adjusted in the software so that these critical instants were synchronised. The time error due to differences in the exposure times of each camera had a mean value of 0.005 s. All trials were digitised by a single experienced operator. Each file was first digitised frame by frame and upon completion adjustments were made as necessary using the points over frame method (Bahamonde & Stevens, 2006), where each point (e.g. right knee joint) was tracked through the entire sequence. The magnification tool in SIMI Motion was set at 400% to aid identification of body landmarks. Dropout occurred on the left hand side of the body on some occasions and estimations were made by the operator. Because the hip joint centre markers were used in estimations of seven angles between them, the effect of misidentification of body landmarks on the joint angular data was measured by altering both hip joint centre markers by one pixel laterally for one male and one female participant (from the World Cup data). The difference in angle values between the original and altered files was measured and the RMS of the difference calculated for right and left initial contact and left and right toe-off. The mean RMSD was 0.31° for the male participant and 0.40° for the female participant.

3.2.4.1 Body segment parameter models

Seventeen segment endpoints were digitised for each participant and a fourteen-segment body segment parameter (BSP) model used to obtain data for the CM and particular limb segments. The fourteen segments were the head, trunk, upper arms, forearms, hands, thighs, lower legs and feet. Because the motion analysis software available provided body segment parameter models for de Leva's (1996) and Dempster's (1955) data, it was decided to compare these popular methods to ascertain if differences in important variables occurred. Each BSP model was applied in turn to the digitised data of the 30 men who competed over 50 km and the 30 women who competed over 20 km at the World Cup. The locations of the CM, upper arm, forearm, thigh, lower leg and foot were calculated. Dempster's model was used to analyse both men and women; however, there are separate de Leva models for men and women and so the male BSP model was applied to the 50 km men, and the female model to the 20 km women. Variables measured included stride velocity and the horizontal and vertical coordinates, velocities and accelerations for each segment. These variables were calculated at four separate events during the race walking cycle: initial contact, toe-off, midstance, and midswing.

Certain differences between BSP models were found for height, velocity and acceleration for the CM, upper arm, thigh, and foot (the differences for the thigh were only found in the women's data). No differences were found for the forearm or lower leg. The horizontal velocity of the CM was not found to be different between models in either men or women at any gait event, or as an average over the entire stride. The mean paths of the height of the CM, upper arm and thigh during one full stride are shown in Figure 3.4 (men) and Figure 3.5 (women). The CM height was found to be about 3 cm lower using the de Leva model compared with Dempster for both men and women at all four measurement events ($p < 0.001$), but no other CM variables were found to differ (Hanley & Bissas, 2012).

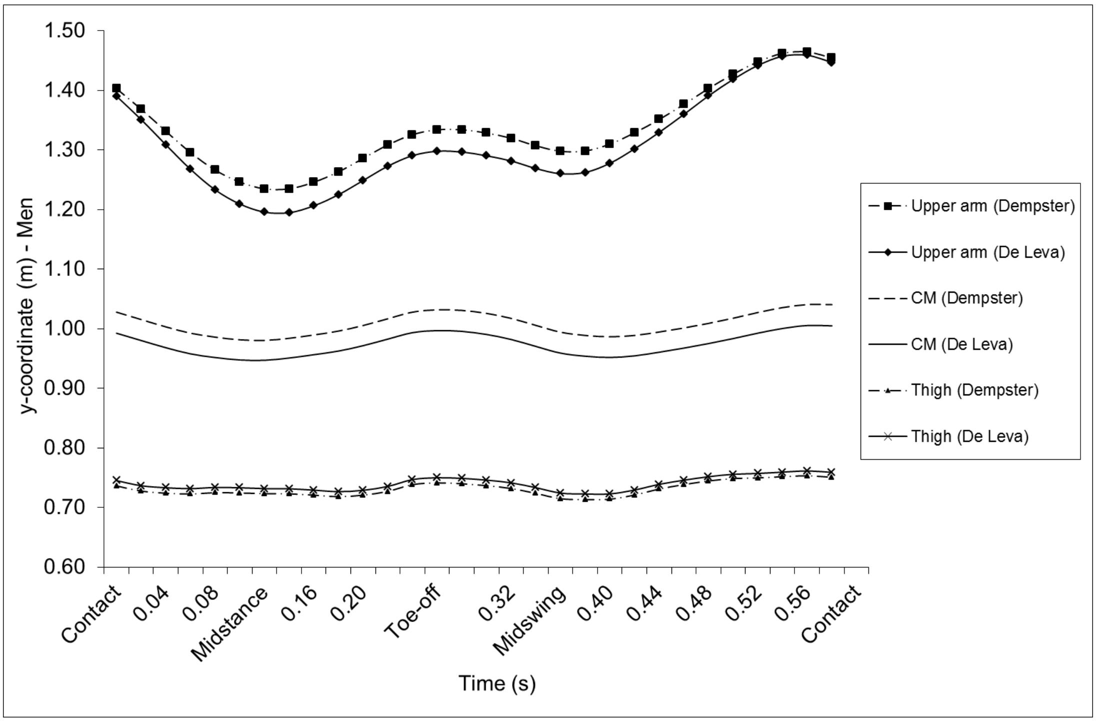


Figure 3.4. Mean paths of the height of the CM, upper arm and thigh in men, calculated using both de Leva and Dempster BSP models (Hanley & Bissas, 2012).

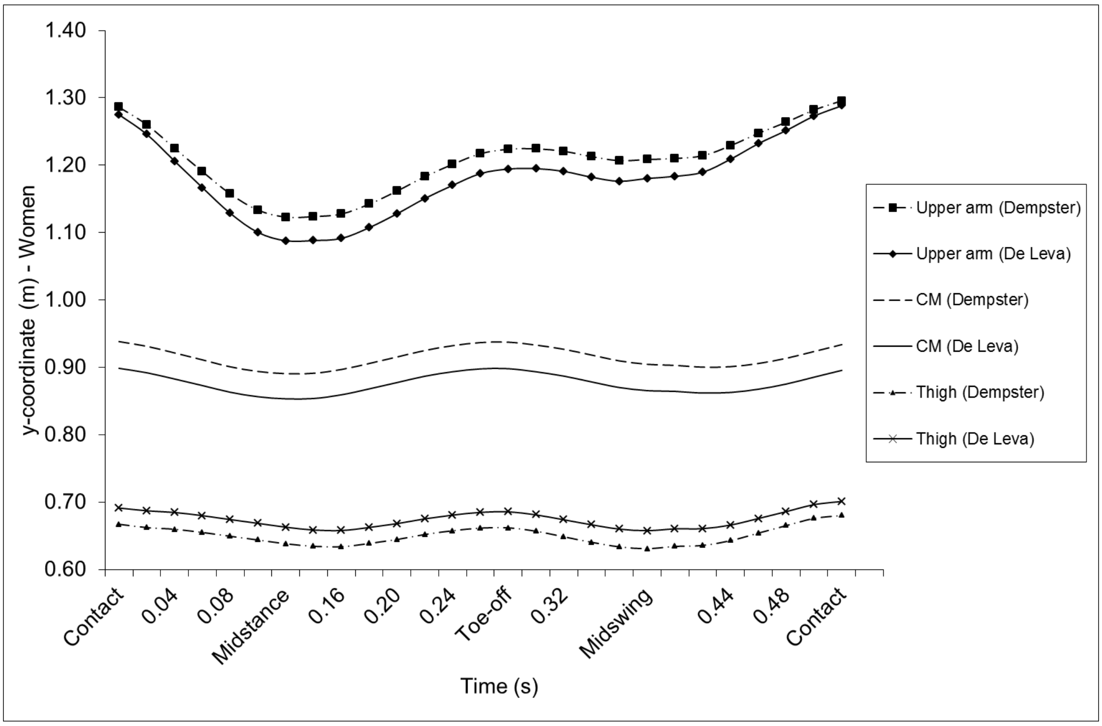


Figure 3.5. Mean paths of the height of the CM, upper arm and thigh in women, calculated using both de Leva and Dempster BSP models (Hanley & Bissas, 2012).

The de Leva model estimated the centre of mass of the thigh to be between 2 and 3 cm higher in women than the Dempster model at each measurement event (p = 0.002), and horizontal acceleration of the thigh at toe-off in women was also found to differ between models (Dempster: 12.13 ± 2.46 m/s^2; de Leva: 10.78 ± 2.37 m/s^2) (p = 0.035). With regard to the upper arm, there was no difference in the height of its centre of mass at contact for either men or women, but lower values for the de Leva model of approximately 3 cm did occur at midstance (men: p = 0.008; women: p = 0.004), toe-off (men: p = 0.008; women: p = 0.009) and midswing (men: p = 0.029; women: p = 0.016). There was no difference in the height of the centre of mass of the foot at contact between models for either men or women. However, the height of the centre of mass of the foot was different between models for women at midstance (p < 0.001), toe-off (men and women: p < 0.001), and midswing (men: p = 0.032; women p = 0.001).

Applying the Dempster model to the women's group led very noticeably to a discrepancy in the location of the thigh centre of mass, with the de Leva model placing it between 2 and 3 cm higher. This is possibly a result of the differing distribution of body fat and shape of the pelvic girdle in men and women and obviously needs to be taken into account when analysing female participants. The only difference found for CM velocity or acceleration in either horizontal or vertical directions was for horizontal acceleration at toe-off. The presence of only one difference for velocity and acceleration means that the choice of BSP model may not affect kinematic findings of race walking adversely. However, when calculating local moment of inertia values (Study 4), the difference in thigh centre of mass location between models might have a notable effect.

Apart from differences in upper arm height, the models also gave different values for the key variables of velocity and acceleration at various times of the gait cycle. The most important variable in an applied analysis of race walk competitors, mean velocity, does not differ between models. The overall effects of the differences between models, such as those of velocity and acceleration, are relatively small. Men and women have different body shapes and this difference can affect the validity of using a model based on male participants on women, and vice versa. Hence, it made sense to apply de Leva's male and female models to men and women respectively in this study.

3.2.4.2 Filtering and reliability analysis

Two separate approaches were taken for removing noise (Giakas & Baltzopoulos, 1997a; 1997b):

- a cross-validated quintic spline was used to smooth the raw data before coordinate calculations (e.g. CM position);
- a recursive second-order, low-pass Butterworth digital filter (zero phase-lag) was employed to filter the same raw data and then obtain first and second derivatives. The cut-off frequencies were selected based on residual analysis and values for the variables included in the kinematic studies (1 – 3) ranged from 4.6 – 5.9 Hz (Winter, 2005).

In order to ensure reliability of the digitising process, repeated digitising (two trials) of one race walking sequence at the same sampling frequency was performed with an intervening period of 48 hours. Three statistical methods for assessing reliability were used: 95% limits of agreement (LOA), coefficient of variation (CV) and intraclass correlation coefficient (ICC). The data for each tested variable were assessed for heteroscedasticity by plotting the standard deviations against the individual means of the two trials. If the data exhibited heteroscedasticity, a logarithmic transformation of the data ($\log_e$) was performed before the calculation of absolute reliability measures (Bland & Altman, 1986). Therefore, depending on the presence of heteroscedasticity, the LOA and CV values were expressed in either original or ratio scale (Atkinson & Nevill, 1998). The results that relate to the most important biomechanical variables considered in the competition studies are shown in Table 3.1; they showed minimal systematic and random errors, and therefore confirmed the high reliability of the digitising process with regard to the overall group of athletes. A CV has not been calculated for variables that were not bound by zero (Atkinson & Nevill, 1998).

Table 3.1. Reliability of race walking variables in the competition studies.

	LOA (Bias ± Random Error)	CV (%)	ICC (3,1)
CM x-coordinate (m)	0.001 ± 0.003	± 0.04	1.00
CM y-coordinate (m)	0.001 ± 0.002	± 0.08	1.00
CM x-velocity (m/s)	1.00 ×/÷ 1.01	×/÷ 1.55	1.00
CM y-velocity (m/s)	–0.01 ± 0.02		1.00
Right foot x-coordinate (ratio)	1.00 ×/÷ 1.00	×/÷ 1.09	1.00
Left foot x-coordinate (m)	0.001 ± 0.006	± 0.08	1.00
Right hip angle (°)	1.00 ×/÷ 1.01	×/÷ 1.04	1.00
Left hip angle (°)	–0.4 ± 0.7	± 0.2	1.00
Right knee angle (°)	–0.5 ± 1.0	± 0.2	1.00
Left knee angle (°)	1.00 ×/÷ 1.01	×/÷ 1.05	1.00
Right ankle angle (°)	1.00 ×/÷ 1.01	×/÷ 1.07	1.00
Left ankle angle (°)	1.01 ×/÷ 1.02	×/÷ 1.12	0.98
Right shoulder angle (°)	0.0 ± 1.1	± 1.2	1.00
Left shoulder angle (°)	0.1 ± 0.9	± 0.7	1.00
Right elbow angle (°)	1.00 ×/÷ 1.02	×/÷ 1.14	0.95
Left elbow angle (°)	0.2 ± 1.4	± 0.5	0.98
Pelvic girdle angle (°)	–0.2 ± 1.5		1.00
Shoulder girdle angle (°)	–0.1 ± 1.2		1.00

3.2.4.3 Definitions of measured variables

Walking speed was determined as the mean horizontal speed during one complete gait cycle. Step length has been defined as the distance between successive foot contacts from a specific instant of the gait cycle on one foot to the equivalent instant on the other foot. Step length has also been expressed as a percentage of the participants' statures, and referred to as the step length ratio. Cadence was calculated by dividing horizontal speed by step length (Mero & Komi, 1994) and the proportion of time spent in stance compared with swing was reported as the stance:swing ratio. The distance the CM travelled during flight was measured from the instant of toe-off to the instant of initial contact and called flight distance in this study (Hunter et al., 2004). The distance the foot centre of mass moved horizontally from initial contact to toe-off has been referred to as foot movement. 'Foot ahead' was used to describe the distance from the centre of mass of the landing foot to the body's overall CM. Similarly, 'foot behind' was the distance from the centre of mass of the toe-off foot to the body's overall CM. Both of these distances have also been expressed as a percentage of the participants' statures and referred to as foot ahead ratio and foot behind ratio respectively. The change in horizontal velocity of the CM was measured during stance time in two sections: when the foot was ahead of the CM from initial contact to midstance (decrease in velocity), and when the foot was behind the CM from midstance to toe-off (increase in velocity). Vertical displacement was calculated as the difference in CM height between its lowest and highest positions (which occurred in all cases after toe-off) during each step; a method preferable to using any single specific landmark such as the head (Gard et al., 2004).

With regard to angular kinematics, the knee angle was calculated as the sagittal plane angle between the thigh and leg segments and was considered to be 180° in the anatomical standing position. The hip angle was defined as the sagittal plane angle between the trunk and thigh segments and was also considered to be 180° in the anatomical standing position. The ankle angle was calculated in a clockwise direction using the lower leg and foot segments and considered to be 110° in the anatomical standing position (Cairns et al., 1986). The shoulder angle was calculated as the sagittal plane angle between the trunk and upper arm and considered to be 0° in the anatomical standing position. The elbow angle was calculated as the angle between the upper arm and forearm and considered to be 180° in the anatomical standing position. Where appropriate, the results for each side of the body were averaged for the purposes of this study. The rotation values of the pelvic and shoulder girdles (transverse plane) were calculated using the left and right hip joint coordinates and the left and right shoulder joint coordinates respectively. The distortion angle was defined as the maximum amount of torsion in the trunk caused by the pelvic and shoulder girdle counter-rotations at a given instant (Knicker & Loch, 1990; Portus et al., 2004).

Joint angular data have been presented in this study at specific events of the gait cycle. These specific events are initial contact, midstance and toe-off (Figure 3.6). Definitions of these specific events are as follows:

- Initial contact: the first visible instant during stance where the athlete's foot clearly contacted the ground;
- Midstance: the instant during stance where the athlete's foot centre of mass was directly below the CM, used to determine the 'vertical upright position' (IAAF Rule 230.1);
- Toe-off: the last visible instant during stance before the foot left the ground.

These events were chosen as they are of particular interest to athletes and coaches of race walking. Initial contact and midstance are especially important as the athlete must achieve and maintain a straightened knee at, and between, these instants of the gait cycle. Toe-off has been chosen as it is the body's last contact instant before a possible flight phase.

Figure 3.6. Visual appearance of initial contact, midstance and toe-off (left to right) in elite race walkers.

3.2.5 Statistical analysis

All statistical analyses were conducted using SPSS Statistics 19, Release Version 19.0.0 (IBM SPSS, Inc., 2010, Chicago, IL). Descriptive statistics such as means and standard deviations have been used to show group results. Pearson's product moment correlation coefficient was used to find associations in each of the World Cup samples of 30 men and women, and in each of the 8th European Cup samples of 20 junior men and junior women; a confidence level of 5% was set. Independent *t*-tests were also conducted to compare values between the World Cup men and women samples, and between the 8th European Cup junior men and women samples, with adjustments made if Levene's test for equality of variances was less than 0.05; 95% confidence intervals (95% CI) were also calculated (Field, 2009). Effect sizes (ES) for differences between groups were calculated using Cohen's *d* (Cohen, 1988) and considered to be either trivial (ES: ≤ 0.20), small (0.21 – 0.60), moderate (0.61 – 1.20), large (1.21 – 2.00), or very large (2.01 – 4.00) (Hopkins et al., 2009). On the occasions where Cohen's *d* was calculated, only those instances where the effect sizes were moderate, large, or very large have been indicated. Repeated measures ANOVA was conducted on the 7th European Cup variation data recorded at four distances with repeated contrast tests conducted to identify changes between successive measurement distances (Field, 2009; Kinnear & Gray, 2010). An alpha level of 5% was set for these tests with Greenhouse-Geisser correction used if Mauchly's test for sphericity was violated. Effect sizes were reported using eta-squared (η^2) (Kinnear & Gray, 2010). Results of individual walkers (spread out with regard to finishing positions) have also been reported for each competition to provide more information about the importance of particular kinematic variables. In order to assess if changes occurred in associations between key performance variables with distance walked in the men's 50 km race, Pearson's product moment correlation coefficients were carried out at each measurement distance during the 7th European Cup, and coefficients of determination (R^2) calculated as a measure of variability shared by selected variables (Field, 2009).

3.3 Laboratory study

In addition to the studies carried out on performances in competition, a laboratory-based study was undertaken. The purpose of this study was to measure those variables not accessible because of competitive settings (e.g. GRF and EMG recordings) to complement the kinematic studies, and provide novel findings to explain key performance variables in elite race walking. To achieve this, the study measured the muscle moments, joint powers and work values at the hip, knee and ankle joints, as well as the EMG signals of seven muscles of the lower limb. Kinematic and GRF variables were also measured to help explain the interrelationships between muscle activity and movement patterns. To gain a greater understanding of the importance of these variables than has been achieved before, testing was carried out on elite male (N = 10) and female athletes (N = 10), both at junior and senior standard, and included male athletes who competed at a high standard over 20 km and / or 50 km.

3.3.1 Data collection

The protocols undertaken were risk-assessed and had the prior ethical approval of the Leeds Metropolitan University Carnegie Faculty Research Ethics Sub-Committee. The participants were provided with Participant Information Sheets and each gave written informed consent. Before testing, the athletes (described below in Section 8.2.1) were given time to warm up and prepare, with practice trials taken to become accustomed to the laboratory setting and the EMG equipment. For testing, each athlete walked along an indoor running track at a speed equivalent to their season's best race (10 km for juniors, 20 km or 50 km for seniors dependent on specialism). Neither step length nor cadence was controlled to avoid prohibiting the evaluation of representative gait kinematics and kinetics (Martin & Marsh, 1992). The athletes had a 20 m approach along the running track to the force plates and continued walking for a further 20 m after the force plates. Athletes completed at least 10 trials each (Bennell et al., 1999) and the three closest to the target time were analysed provided there was no conscious stride adjustment when contacting the force plates (Frederick & Hagy, 1986). There were no differences between the test speeds of the senior men and junior men (p = .988, 95% CI = –.600 to .592), or between the senior women and junior women (p = .431, 95% CI = –.853 to 1.81).

3.3.1.1 GRF data collection

Two force plates (9287BA, Kistler Instruments Ltd, Winterthur), 0.90 m long and 0.60 m wide (natural frequency ≈ 750 Hz (x-, y-), ≈ 520 Hz (z-); linearity < ± 0.5% full scale output (FSO); cross talk < ± 1.5%; hysteresis < 0.5% FSO), were placed in a customised housing in the centre of the track and separated by a wooden blanking plate 0.45 m long and 0.60 m wide (Figure 3.7). The custom-made pit that housed the force plates was constructed to allow the plates to be moved closer (e.g. if a particular athlete was very short). Before testing, one force plate was used to weigh the participant. Both foot contact phases were recorded at 1000 Hz. The force plates (and blanking plates) were covered with a synthetic athletic surface so that the force plate area was flush with the rest of the runway to preserve ecological validity (Bezodis et al., 2008), while still being separate from the surrounding surface.

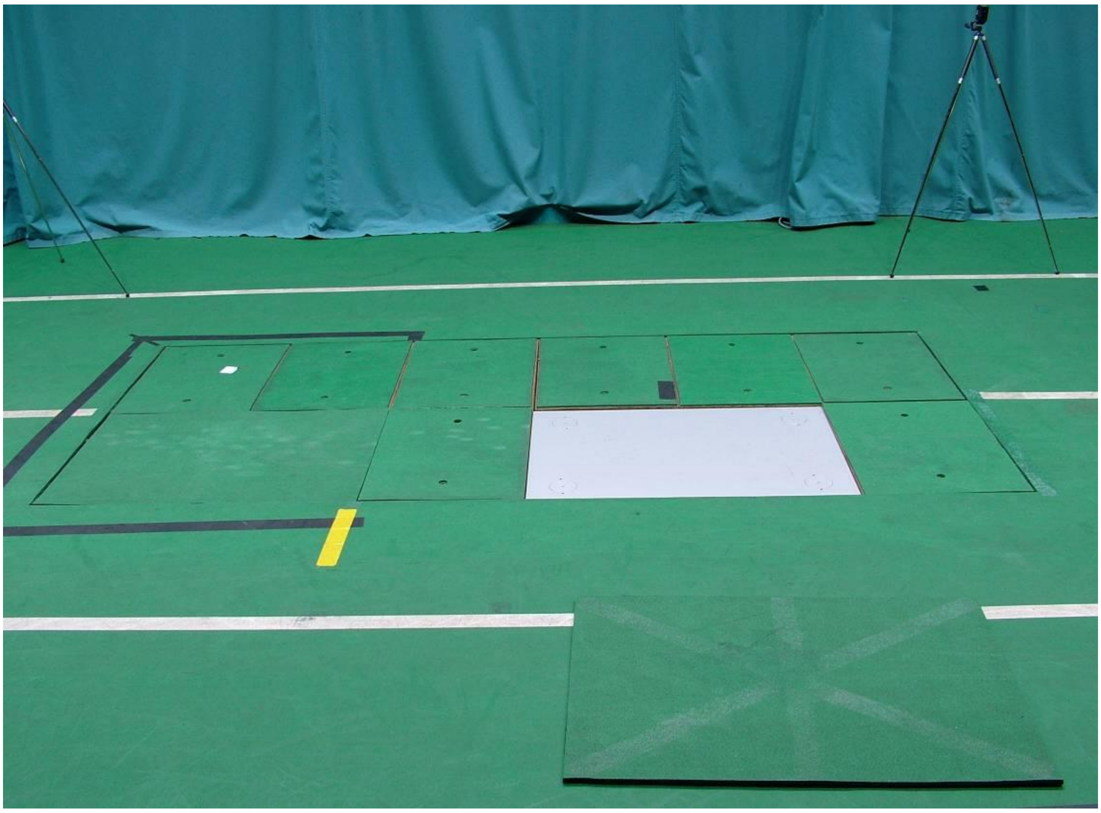


Figure 3.7. Two force plates (90 cm x 60 cm) were used to record the GRFs of both feet. One of the surface mats has been removed in this figure.

Timing gates with photocells (IRD-T175, Brower Timing Systems, Salt Lake City, UT) were placed 4 m apart around the force plates to ensure the correct walking speed was attained (trials were accepted if they were within 3% of the target time). The timing gates were placed at approximately waist height on tripods (Figure 3.8). The speed used in gait analyses is typically measured over a short distance between 3 and 5 m (e.g. DeVita & Bates, 1988; Herzog et al., 1989; Martin et al., 1993; Freychat et al., 1996; Stergiou et al., 1999) to allow for the timing of the actual analysed strides.

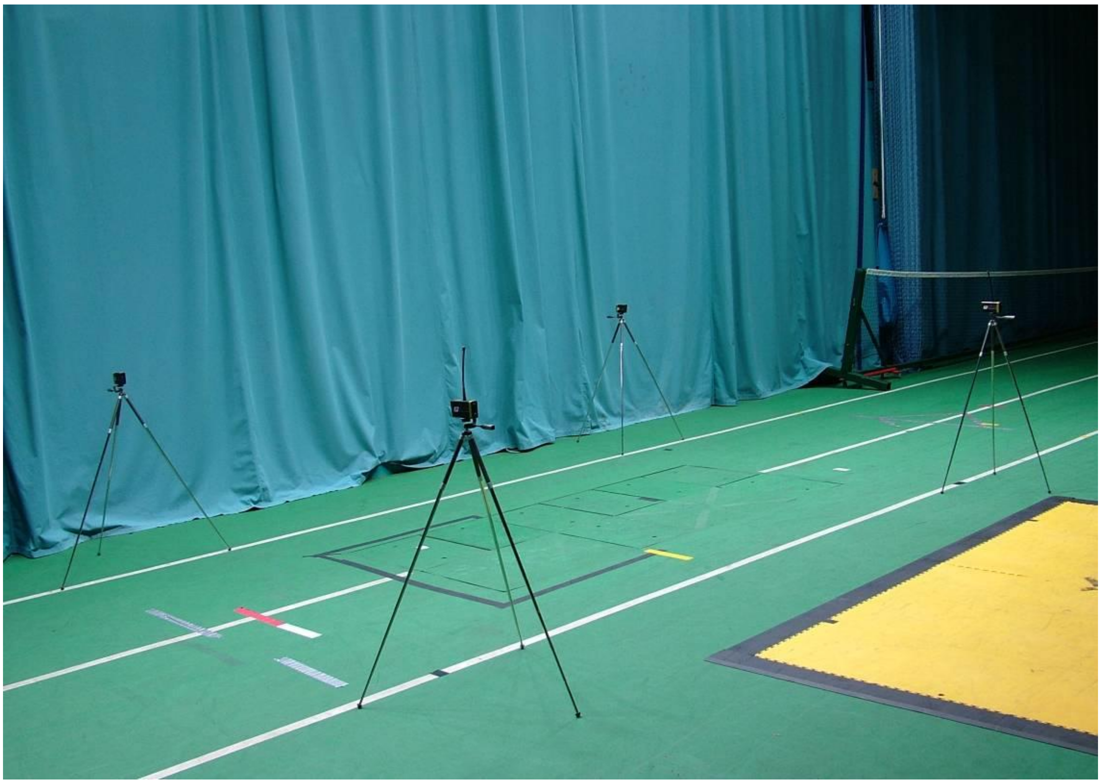


Figure 3.8. The testing area with timing gates positioned 4 m apart.

3.3.1.2 High-speed video data collection

In order to measure important race walking kinematic variables based on the hierarchical model (e.g. speed and step length) (Figure 2.3) and the sagittal plane movements of the hip, knee and ankle, two-dimensional video data were collected at 100 Hz using a high-speed camera (MotionPro, RedLake, San Diego, CA). The shutter speed was 1/500 s, the *f*-stop was set at 2.0, and there was no gain. The camera was placed approximately 12 m from and perpendicular to the line of walking. A 28 mm lens was used and its centre was 1.10 m above the track's surface (Figure 3.9).

Figure 3.9. The high-speed camera set-up for 2D recording.

The resolution of the camera was 1280 x 1024 pixels. Extra illumination was provided by 104 kW of overhead floodlighting (26 lights providing 4 kW each). Four 3 m high reference poles were placed in the centre of the camera's field of view in the centre of the running track in the sagittal plane (Figure 3.10). The reference poles provided a total of twelve reference points (up to a height of 2 m) that were later used for calibration. 2D analysis was conducted because of the availability of only one high-speed camera at the time (which helped with expediency). In any case, Alkjaer et al. (2001) found that using a 2D model of joint moments was appropriate for human gait analysis and, similarly, Metzler et al. (2001) found that a 3D analysis of total body energy during a running gait stance phase did not conclusively provide more accurate information than a 2D analysis. Naturally, only the measurement of sagittal plane movements was included in this 2D study and the measurement of movements in other planes (e.g. pelvic rotation, pelvic obliquity) has been excluded.

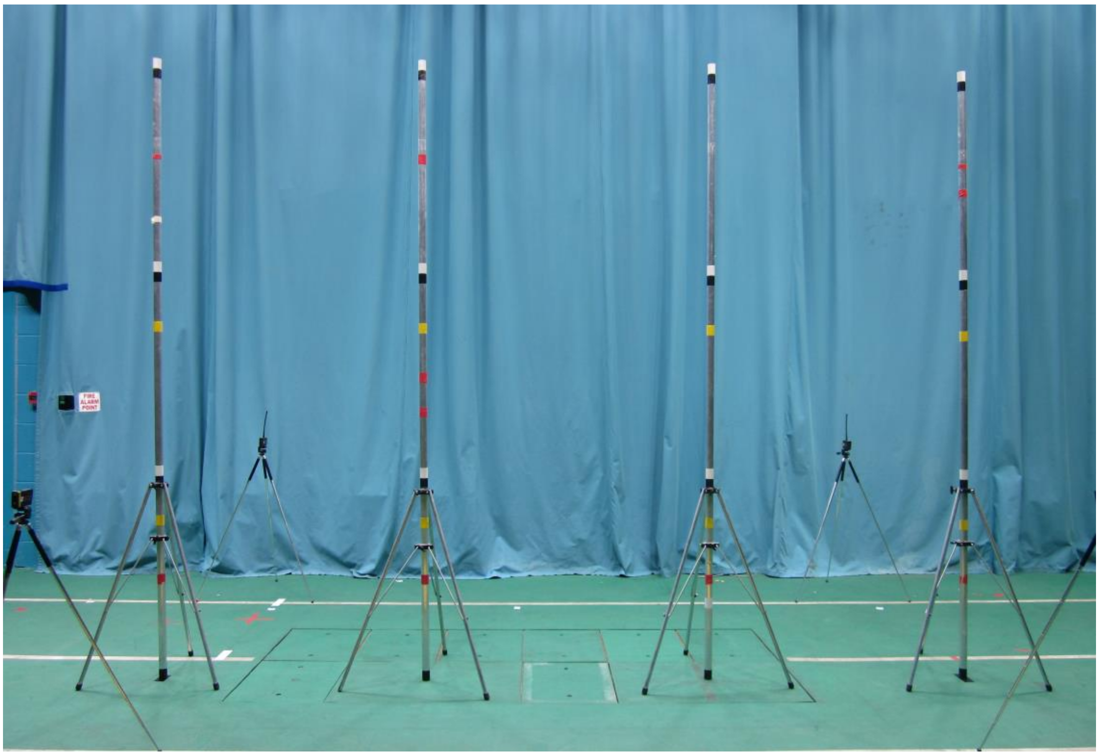


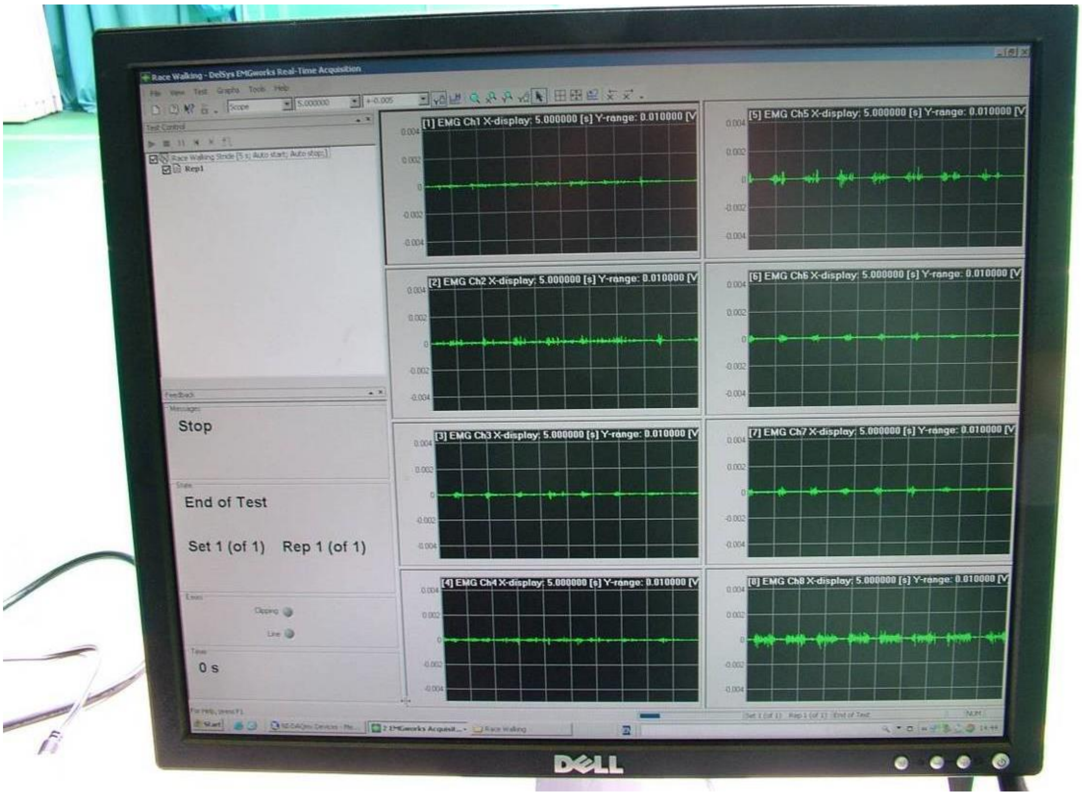
Figure 3.10. Four reference poles were placed in the centre of the camera’s field of view in the centre of the running track before and after data collection.

3.3.1.3 EMG data collection

Surface EMG signals were recorded from seven lower limb muscles of the right leg: gluteus maximus (GM), biceps femoris (BF), rectus femoris (RF), vastus lateralis (VL), gastrocnemius (lateral head) (GL), soleus (SO) and tibialis anterior (TA). These muscles were chosen based on their prime mover roles (as agonists and antagonists) for the sagittal plane movements of the lower limb, and because of the ease of palpation. Skin preparation included shaving to remove any hair and cleansing of the surface with alcohol swabs (Okamoto et al., 1987). The single differential electrodes (DE Series Surface EMG Sensors; DelSys, Inc., Boston, MA) consisted of two silver bars 10 mm long, 1 mm wide, and 10 mm apart set in a rectangular polycarbonate casing 41 mm long, 22 mm wide and 5 mm deep. The reference electrode was placed over the fourth lumbar vertebra. After identifying the appropriate attachment sites by palpating the contracted muscle, each electrode was placed over the muscle belly, aligned parallel to the underlying muscle fibre direction (Clarys & Cabri, 1993). A telemetry unit (Myomonitor IV; DelSys, Inc., Boston, MA), carried in a custom pack worn around the athlete’s waist, was used to collect the data at 1000 Hz (Figure 3.11).

Figure 3.11. The telemetry unit was carried around the athlete’s waist.

The Common Mode Rejection Ratio (CMRR) was 92 dB, the gain 1000 V/V, and the input impedance greater than 100 GΩ. The data were filtered with a bandpass filter (20 – 450 Hz). To ensure reduced cable movement artefact, wires connecting the electrodes to the unit were kept in place with tubular elastic net bandages (Colorline Surgifit; Fra Production, Cisterna d’Asti). EMG data were collected for 5 s and collection was begun using the EMG acquisition software (EMGworks 3.6, DelSys, Inc., Boston, MA) (Figure 3.12). The EMG data collection software triggered both the force plate software (Bioware version 3.20; Kistler, Winterthur, Switzerland) and the camera system (MiDAS version 2.1.8.1 R, Redlake, San Diego, CA) via a Trigger Output Module (Wireless) (National Instruments, Austin) and a Kistler connection box (Kistler, Winterthur). The delay between activation of the EMG software and triggering of the other systems was 5 ms.



Stop

End of Test

Set 1 (of 1) Rep 1 (of 1)

0 s

Figure 3.12. EMG data were collected using the acquisition software via telemetry.

3.3.2 Data analysis

3.3.2.1 GRF data analysis

The GRF data were smoothed using a recursive second-order, low-pass Butterworth filter (zero phase-lag). The optimal cut-off frequency was calculated during a pilot test (three trials) using residual analysis (Winter, 2005), with a range of frequencies between 30 and 80 Hz used based on previous studies (e.g. Ferber et al., 2003; Hunter et al., 2005; Riley et al., 2008). 30 Hz was chosen as the minimum value because the heel strike transient has a frequency approximating this value (Whittle, 1999). The results showed an optimal cut-off frequency ranging from 47 – 52 Hz in all three force directions, so it was decided to use 50 Hz as the cut-off frequency for all trials. For the first pilot study trace, the RMS of the difference between raw and filtered data was 5 N in the vertical direction, 3 N in the anteroposterior direction, and 2 N in the mediolateral direction (Figure 3.13).

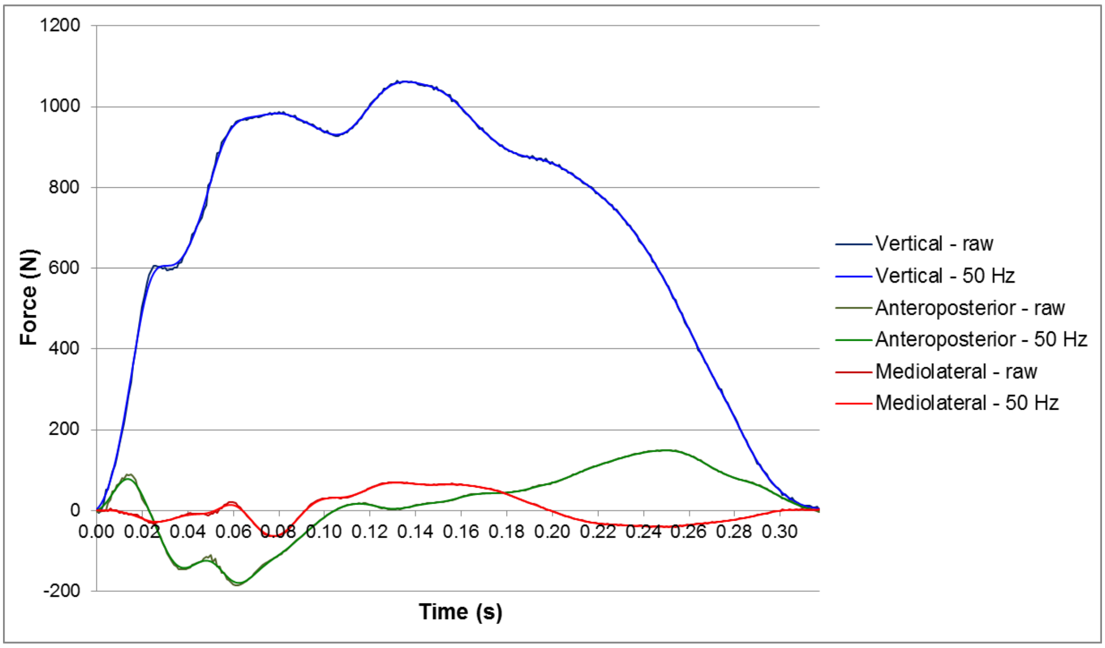


Figure 3.13. Overlay of raw and low-pass filtered (50 Hz) race walking GRF traces.

The three components of the GRF data (vertical, anteroposterior and mediolateral) were analysed during the right foot contact phase (1000 Hz) (Figure 3.14). Contact time was considered to begin when the vertical force trace exceeded 5 N and to end when it decreased below 5 N again; flight time was calculated as the time between successive steps. To allow for comparison between athletes and groups, all GRF data were normalised as bodyweights (BW); additionally, temporal data have been reported as normalised data using percentage of stance time.

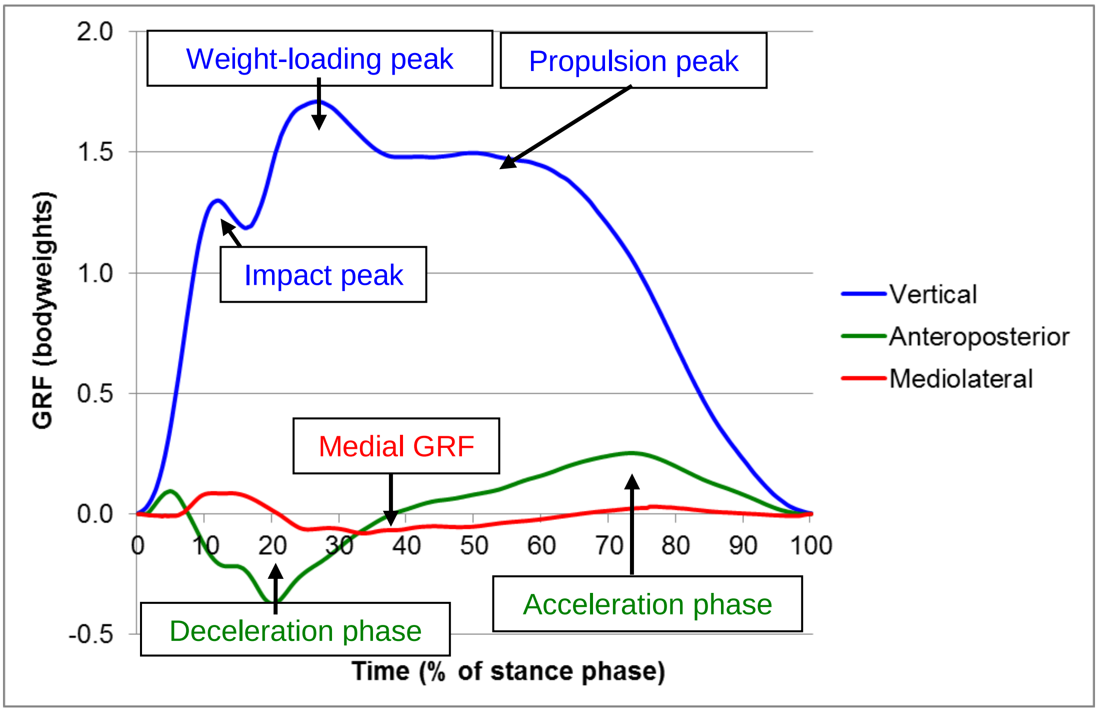


Figure 3.14. A typical race walk GRF trace showing the three components separately (right foot contact).

In addition to the stride width, which was measured using the COP readings from the force plates, the following vertical GRF variables were calculated using the GRF data (Levine et al., 2012):

- impact peak force – the greatest magnitude of the impact peak. This was identified visually as a distinct peak occurring normally within the first 30 ms of contact;
- loading peak force – the greatest magnitude of the next peak in the vertical GRF trace, typically occurring between 50 and 70 ms after initial contact;
- midstance force – measured at the instant where the anteroposterior force trace crossed zero (from the deceleration phase to the acceleration phase);
- push-off peak force – identified as the maximum vertical force after midstance.

The two shear GRF traces were analysed in a similar fashion. The anteroposterior GRF variables chosen for analysis were (Figure 3.15):

- the maximum magnitudes of the deceleration and acceleration forces;
- the duration of the deceleration and acceleration phases;

- the resulting change in velocity values – from the calculation of both negative and positive impulses (calculated by finding the area under the negative and positive curves respectively);
- the ‘spike’ impulse – calculated in those traces showing an initial anteroposterior ‘spike’ peak at initial contact;
- the ‘braking-to-propulsion’ percentage – the ratio of stance time spent in the braking phase to the time spent in propulsion.

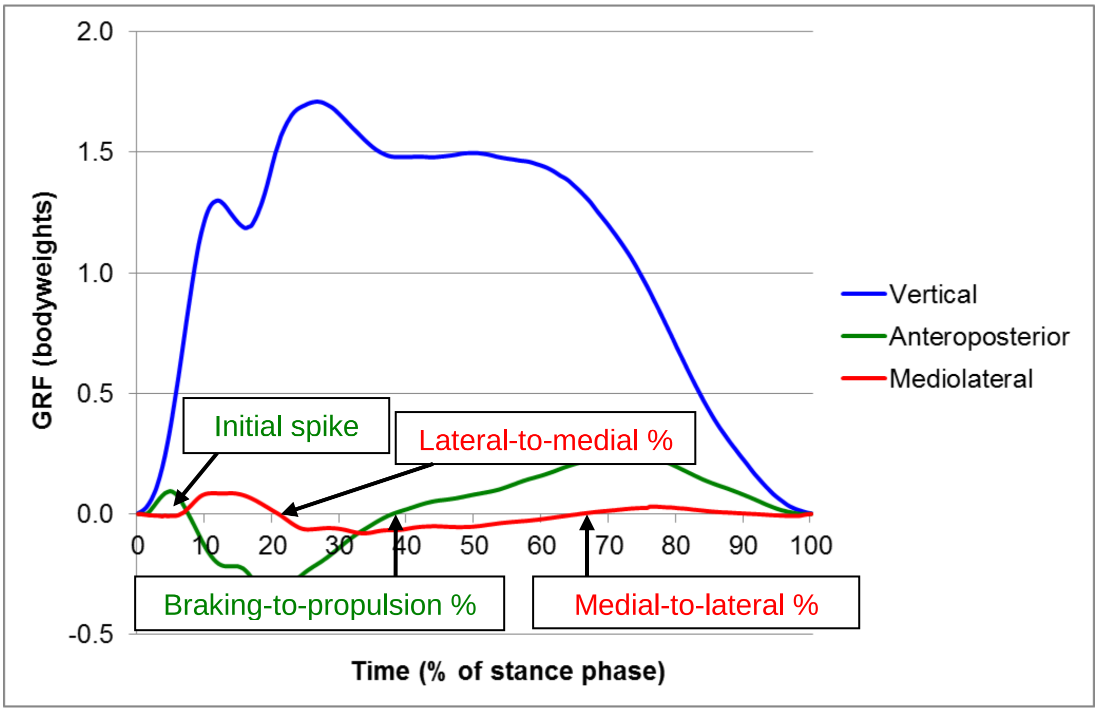


Figure 3.15. A typical race walk GRF trace with specific anteroposterior and mediolateral events identified (right foot contact).

In the mediolateral direction, the variables chosen were:

- the magnitude of the maximum lateral force (during late stance);
- the magnitude of the maximum medial force (during midstance). However, early stance values have not been reported as no consistent pattern emerged during this phase;
- The instants during contact where the predominant lateral force became medial (‘lateral-to-medial’ percentage) and then reversed back (‘medial-to-lateral’ percentage) were also measured (Figure 3.15).

3.3.2.2 High-speed video data analysis

The video files were manually digitised by a single experienced operator to obtain kinematic data using motion analysis software (SIMI Motion version 6.1; SIMI Reality Motion Systems GmbH, Munich). Digitising was started at least 10 frames before the beginning of the stride and completed at least 10 frames after to provide padding during filtering (Smith, 1989). Each video was first digitised frame by frame and upon completion adjustments were made as necessary using the points over frame method (Bahamonde & Stevens, 2006). The magnification tool in SIMI Motion was set at 400% to aid identification of body landmarks. De Leva's (1996) body segment parameter models for men and women were used to obtain data for the CM, right thigh, right lower leg, and right foot. Two separate approaches were taken for removing noise (Giakas & Baltzopoulos, 1997a; 1997b):

- a cross-validated quintic spline was used to smooth the raw data before coordinate calculations (e.g. CM position);
- a recursive second-order, low-pass Butterworth digital filter (zero phase-lag) was employed to filter the same raw data and then obtain first and second derivatives. The cut-off frequencies were calculated using residual analysis (Winter, 2005) and ranged from 7.0 – 11.6 Hz.

As in the competition studies, the effect of misidentification of body landmarks on the joint angular data was measured by altering the right knee joint centre marker by one pixel anteriorly for one female participant. The knee joint centre marker was used in estimations of five angles (hip, knee, ankle, thigh and leg). The difference (RMS) between the original and altered files for one complete stride was 0.23°.

In order to ensure reliability of the digitising process, repeated digitising (two trials) of one race walking sequence at the same sampling frequency was performed with an intervening period of 48 hours. The same three statistical methods for assessing reliability were used: 95% limits of agreement (LOA), coefficient of variation (CV) and intraclass correlation coefficient (ICC). The data for each tested variable were assessed for heteroscedasticity by plotting the standard deviations against the individual means of the two trials. If the data exhibited heteroscedasticity, a logarithmic transformation of the data ($\log_e$) was performed before the calculation of absolute reliability measures (Bland & Altman, 1986). Therefore, depending on the presence of heteroscedasticity, the LOA and CV values were expressed in either original or ratio scale (Atkinson & Nevill, 1998). The results of the most important biomechanical variables are shown in Table 3.2, and show minimal systematic and random errors, therefore confirming the high reliability of the digitising process with regard to the overall group of athletes. A CV has not been calculated for variables that were not bound by zero (Atkinson & Nevill, 1998).

Table 3.2. Reliability of race walking variables in the laboratory study.

	LOA (Bias ± Random Error)	CV (%)	ICC (3,1)
CM x-coordinate (m)	–0.001 ± 0.004	± 0.05	1.00
CM y-coordinate (m)	0.003 ± 0.005	± 0.24	0.96
CM x-velocity (m/s)	–0.01 ± 0.08	± 0.72	0.98
CM y-velocity (m/s)	–0.01 ± 0.07		0.99
Right foot x-coordinate (m)	0.000 ± 0.002	± 0.03	1.00
Left foot x-coordinate (m)	–0.001 ± 0.006	± 0.07	1.00
Hip angle (°)	1.00 ×/÷ 1.01	×/÷ 1.04	1.00
Knee angle (°)	–0.3 ± 1.2	± 0.24	1.00
Ankle angle (°)	–0.3 ± 1.8	± 0.22	1.00
Hip angular velocity (rad/s)	0.03 ± 0.44		1.00
Knee angular velocity (rad/s)	0.01 ± 0.47		1.00
Ankle angular velocity (rad/s)	0.01 ± 0.62		1.00
Thigh x-acceleration (m/s^2)	–0.01 ± 1.38		1.00
Thigh y-acceleration (m/s^2)	0.05 ± 1.46		0.99
Leg x-acceleration (m/s^2)	–0.02 ± 1.01		1.00
Leg y-acceleration (m/s^2)	–0.01 ± 1.04		1.00
Foot x-acceleration (m/s^2)	0.12 ± 2.71		1.00
Foot y-acceleration (m/s^2)	–0.07 ± 1.23		1.00
Thigh angular acceleration (rad/s^2)	0.07 ± 7.83		0.99
Leg angular acceleration (rad/s^2)	–0.42 ± 9.15		1.00
Foot angular acceleration (rad/s^2)	–0.18 ± 13.56		1.00

3.3.2.3 Calculation of muscle moments, powers and work

The filtered force data were matched with the kinematic data and extracted at 100 Hz (Bezodis et al., 2008). The kinetic data included anteroposterior and vertical GRFs and centre of pressure (COP) data; the kinematic data included linear and angular velocities and accelerations of body segments and joints. These data were used to calculate net joint moments using a link segment rigid body model (Figure 3.16) (Winter, 2005).

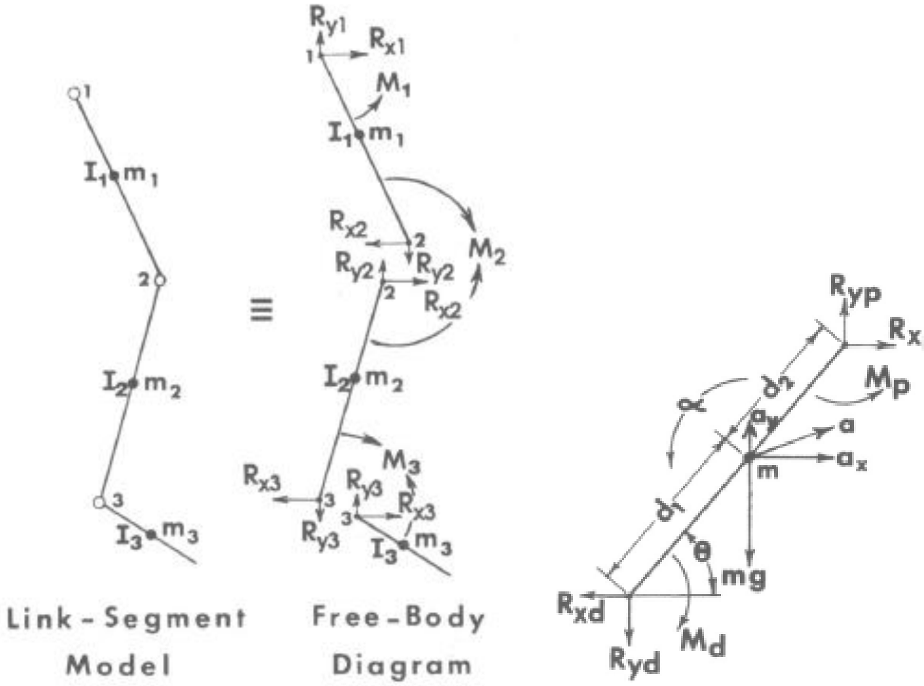


Figure 3.16. Diagrams of rigid link segment models used to calculate muscle moments and powers (left to right): Link segment model of the lower limb, free body diagram of the lower limb, and free body diagram of a single segment with all inputted variables included (Winter, 2005).

The process involved calculating joint reaction forces at each lower limb joint of interest (hip, knee and ankle) using the GRFs recorded by the force plate, the linear (x-, y-) accelerations of the relevant segment (thigh, leg and foot), and its estimated mass (from data provided by de Leva (1996)). These joint reaction forces were then further used with COP values (as appropriate), segment centre of mass x- and y-positions, angular acceleration data of each segment, and estimated moment of inertia values (using the already estimated masses and radius of gyration data provided by Winter (2005)) to calculate net joint moments. Power was calculated by multiplying each moment by the joint’s angular velocity (Winter, 2005). Extensor moments at the hip, knee and ankle (dorsiflexor (Bartlett, 2007)) have been presented as positive values, and flexor moments as negative. Positive power indicated that mechanical energy was being generated, while negative power indicated energy absorption (White & Winter, 1985; Winter, 2005). The amount of work done at each joint was calculated as the time integral of the power curve using the trapezoidal rule (Kibele, 1998; Bezodis et al., 2014). The total amount of work performed at each joint during specific phases as identified from the moment and power curves (flexion or extension, and either energy generating or absorbing) was calculated to show the contribution of different muscle groups (e.g. hip extensors). Muscle moments and work were normalised using both body mass and standing height; powers were normalised using body mass only (Hoga et al., 2006). Because the mean swing duration was found to be 54.1% of total stride time, each athlete's swing data were interpolated to 55 points and their stance data to 46 points (for a total of 101 points) using a cubic spline (van der Falk, 2010) to normalise both periods of the gait cycle and for calculation of group means and standard deviations.

3.3.2.4 EMG data analysis

The raw EMG signals were processed in the data analysis software (EMGworks 3.6, DelSys, Inc., Boston, MA) using average rectified EMG (AREMG) (Bartlett, 2007), with a time window of 50 ms and an overlap of 25 ms. As with the internal kinetic data, these data were also interpolated to 101 points using a cubic spline.

3.3.3 Statistical analysis

All statistical analyses were conducted using SPSS Statistics 19, Release Version 19.0.0 (IBM SPSS, Inc., 2010, Chicago, IL). Descriptive statistics such as means and standard deviations have been used to show group results. Pearson's product moment correlation coefficient was used to find associations between and within key kinematic and kinetic variables. Independent *t*-tests were conducted to compare values between men and women (and on some occasions between junior and senior athletes), with adjustments made if Levene's test for equality of variances was less than 0.05; 95% confidence intervals (95% CI) were also calculated (Field, 2009). Comparisons between the four subgroups (as identified later in Table 8.1) were carried out using one-way ANOVA with post-hoc Tukey tests conducted. One-way ANOVA was also used to compare vertical force peak magnitudes with post-hoc Tukey tests conducted. The EMG traces were visually compared between subgroups by first expressing each athlete's individual traces (e.g. of gluteus maximus) as a percentage of the highest magnitude found during that trace, and then averaging across all athletes within that subgroup. An alpha level of 5% was set for all tests. Effect sizes (ES) for differences between groups were calculated using Cohen's *d* (Cohen, 1988) and considered to be either trivial (ES: ≤ 0.20), small (0.21 – 0.60), moderate (0.61 – 1.20), large (1.21 – 2.00), or very large (2.01 – 4.00) (Hopkins et al., 2009). On the occasions where Cohen's *d* was calculated, only those instances where the effect sizes were moderate, large, or very large have been indicated.

CHAPTER 4

STUDY 1: 20 KM COMPETITIONS

4.1 Introduction

A number of research studies have analysed race walking but few, if any, have fully evaluated the techniques of the world's very best walkers. Additionally, previous research tended to test very small numbers of only male participants. Research on the kinematics of both male and female race walkers is therefore crucial in identifying the most important variables for the benefit of biomechanists, athletes and coaches. Furthermore, the best means by which the kinematics of elite athletes are analysed is in competition, as the analysis of athletes in such situations optimises external validity (Atkinson & Nevill, 2001).

Previous research has found kinematic differences between men and women in other athletics events, such as distance running. Atwater (1990) reported that women had greater cadences and shorter steps than men at comparable running speeds, while Schache et al. (2003) found gender differences in the angular motion of the lumbo-pelvic-hip complex during running, and advised future researchers to be cautious about averaging such data across male and female participants. In some instances in race walking research (e.g. Morgan & Martin, 1986; Cairns et al., 1986; Lafortune et al., 1989), both men and women have been tested but their results were combined and gender differences not taken into account. It is therefore important to ascertain if and where there are kinematic differences in men's and women's elite race walking. Knowledge of the differences between how men and women walk, and why these differences occur, can aid athletes of both sexes in developing their techniques. It is also important to measure kinematic variables over the course of a race to identify what variations occur and how they affect performance. Apart from fatigue, changes over the course of the race in walking kinematics could be due to race tactics, risk of disqualification, or pain. In this study, the term 'variation' has been employed to describe these changes.

The first objective of this part of the study was to measure and identify key kinematic variables in determining success in elite men's and women's 20 km race walking, based on the hierarchical model of race walking (Figure 2.3) and using data from a World Cup event. Comparisons between men and women were conducted, as well as associations between the key variables identified as important within each group. The second objective was to measure variation in those variables at different distances in a European Cup event, in order to ascertain possible effects of changes in pace (e.g. because of fatigue or tactical increases in pace).

4.2 Methods

4.2.1 Participants

Video data were collected at two separate events. The men's and women's 20 km races were recorded at the 23rd IAAF World Race Walking Cup. The competitors were filmed as they passed 14.2 km (before this distance the athletes walked in packs for tactical reasons). Participants' heights, masses and dates of birth were obtained from the IAAF (2011b). Thirty men (age 27 ± 5 yr, height 1.78 ± 0.06 m, mass 65 ± 5 kg) and 30 women (age 31 ± 5 yr, height 1.64 ± 0.05 m, mass 51 ± 4 kg) were analysed in each race; this part of the study was intended to find associations between key variables and to compare men and women. The men were taller ($p < .001$, 95% CI = .113 to .171, ES = 2.54) and heavier ($p < .001$, 95% CI = 11.36 to 16.18, ES = 3.09) than the women. The analysed competitors included the men's 2004 Olympic champion, the women's 2004 and 2008 Olympic champions, the men's 50 km 2013 World Champion, and 10 other athletes who have won medals at the Olympic Games or World Championships (IAAF, 2011b). From the judging records of the analysed athletes over the course of the entire race, one male walker received two red cards for loss of contact and seven others received one red card each for the same offence. Four men received one red card each for not straightening their knees correctly. Of the analysed women, three athletes received two red cards for loss of contact, and three others received one red card each. With regard to not straightening the knees correctly, one woman received two red cards and three others one red card each. These low percentages of red cards received are indicative of correct, legal race walking techniques and show the validity of analysing these individuals.

The men's and women's 20 km races were also recorded at the 7th European Cup Race Walking. The athletes in each race were analysed on four occasions: at 4.5 km, 8.5 km, 13.5 km, and 18.5 km. Twelve men (age 25 ± 4 yr, height 1.80 ± 0.06 m, mass 67 ± 5 kg) and 12 women (age 25 ± 5 yr, height 1.65 ± 0.07 m, mass 52 ± 6 kg) were analysed; this part of the study was to provide an indication of variation in kinematic measurements over the course of the race. These athletes were chosen as they were the only competitors who could be clearly seen at all four recording distances. Of the 12 men analysed, one received a single red card for loss of contact and two received one red card each for not straightening the knee correctly. Of the 12 women analysed, only one received a red card (for loss of contact), and as with the World Cup athletes, these few red cards show the correct, legal techniques adopted. A summary of the race performances from both events is presented in Table 4.1, and the current World Record for each event is also presented. No athletes from either competition who did not finish or were disqualified have been included in the study. With regard to comparisons between competitions (i.e. between the 7th European Cup and 23rd World Cup), no differences were found for men or women for finishing times, height, or mass.

Table 4.1. Race performances (mean ± *s*) in the men's and women's 20 km competitions.

	Time (h:min:s)	Time (h:min:s)
World Cup	**Men (N=30)**	**Women (N=30)**
Mean finishing time	1:23:28 (± 3:54)	1:34:18 (± 5:58)
Range	1:18:34 – 1:32:51	1:25:42 – 1:51:12
European Cup	**Men (N=12)**	**Women (N=12)**
Mean finishing time	1:24:43 (± 3:08)	1:35:05 (± 3:54)
Range	1:18:58 – 1:30:59	1:28:13 – 1:42:09
World Record	1:17:16	1:25:02

4.3 Results

4.3.1 World Cup data

4.3.1.1 Speed, step length and cadence

The values for speed, step length and cadence for the 60 World Cup participants are shown in Table 4.2, and correlations between these and other key race walking variables for men and women are shown in Tables 4.3 and 4.4 respectively. With regard to the components of step length, in the men's group foot ahead comprised 30% of total step length, foot behind 40%, flight distance 16%, and foot movement 14%; in the women's group the respective ratios were 31%, 40%, 12% and 16%.

Table 4.2. Mean (± *s*) and between-subjects effects of key race walking variables. Differences were significant at $p < 0.05$ (bold). Effect sizes were based on Cohen's *d* and indicated when very large (‡), large (†), or moderate (*).

	Men	Women	*p*	95% CI
Speed (km/h)	14.52 (± .86)	12.73 (± .98)	**< .001**	**1.32 to 2.72†**
Step length (m)	1.21 (± .07)	1.06 (± .06)	**< .001**	**.119 to .183‡**
Step length ratio (%)	68.0 (± 3.7)	64.7 (± 4.2)	**.002**	**1.24 to 5.31***
Cadence (Hz)	3.34 (± .12)	3.34 (± .17)	.929	–.078 to .071
Contact time (s)	0.27 (± .02)	0.28 (± .02)	.081	–.020 to .001
Flight time (s)	0.03 (± .01)	0.02 (± .01)	**.037**	**.000 to .013**
Contact time (%)	91.3 (± 4.4)	93.6 (± 3.7)	**.036**	**–4.39 to –.16**
Foot ahead (m)	0.37 (± .02)	0.33 (± .02)	**< .001**	**.026 to .049†**
Foot ahead ratio (%)	20.6 (± 1.1)	20.3 (± 1.5)	.348	–.350 to .981
Foot behind (m)	0.48 (± .02)	0.43 (± .02)	**< .001**	**.044 to .067‡**
Foot behind ratio (%)	27.1 (± 0.9)	26.2 (± 1.8)	**.024**	**.127 to 1.60***
Flight distance (m)	0.19 (± .06)	0.13 (± .05)	**< .001**	**.032 to .089***
Foot movement (m)	0.17 (± .02)	0.17 (± .01)	.335	–.004 to .012

Table 4.3. Correlation analysis of key race walking variables across the World Cup men’s sample. Correlations were significant at p < 0.05 (bold).

	Step length	Step length ratio	Cadence	Contact time	Flight distance	Foot ahead (m)	Foot behind (m)
Stature	r = .36 p = .054		**r = –.64** **p < .001**	**r = .44** **p = .017**	r = –.10 p = .607	**r = .50** **p = .005**	**r = .68** **p < .001**
Speed	**r = .80** **p < .001**	**r = .87** **p < .001**	**r = .42** **p = .020**	**r = –.78** **p < .001**	**r = .79** **p < .001**	r = .09 p = .695	r = .04 p = .834
Step length		**r = .81** **p < .001**	r = –.20 p = .280	**r = –.38** **p = .037**	**r = .74** **p < .001**	**r = .42** **p = .021**	**r = .40** **p = .028**
Step length ratio			r = .18 p = .339	**r = –.68** **p < .001**	**r = .83** **p < .001**	r = .11 p = .581	r = –.02 p = .940
Cadence				**r = –.69** **p < .001**	r = .18 p = .334	**r = –.49** **p = .006**	**r = –.55** **p = .002**
Contact time					**r = –.73** **p < .001**	r = .23 p = .225	**r = .39** **p = .032**
Flight distance						r = –.04 p = .833	r = –.18 p = .341
Foot ahead (m)							**r = .52** **p = .003**

Table 4.4. Correlation analysis of key race walking variables across the World Cup women's sample. Correlations were significant at $p < 0.05$ (bold).

	Step length	Step length ratio	Cadence	Contact time	Flight distance	Foot ahead (m)	Foot behind (m)
Stature	$r = -.01$ $p = .965$		$r = -.33$ $p = .073$	$r = .11$ $p = .557$	$r = .06$ $p = .759$	$r = .10$ $p = .614$	$r = -.25$ $p = .176$
Speed	**$r = .76$** **$p < .001$**	**$r = .77$** **$p < .001$**	**$r = .71$** **$p < .001$**	**$r = -.79$** **$p < .001$**	**$r = .77$** **$p < .001$**	$r = -.09$ $p = .642$	**$r = .51$** **$p = .004$**
Step length		**$r = .86$** **$p < .001$**	$r = .08$ $p = .663$	$r = -.34$ $p = .068$	**$r = .79$** **$p < .001$**	$r = .20$ $p = .300$	**$r = .64$** **$p < .001$**
Step length ratio			$r = .25$ $p = .189$	$r = -.35$ $p = .059$	**$r = .61$** **$p < .001$**	$r = .11$ $p = .557$	**$r = .68$** **$p < .001$**
Cadence				**$r = -.84$** **$p < .001$**	$r = .33$ $p = .079$	$r = -.34$ $p = .067$	$r = .09$ $p = .633$
Contact time					**$r = -.62$** **$p < .001$**	**$r = .38$** **$p = .039$**	$r = -.02$ $p = .928$
Flight distance						$r = -.25$ $p = .189$	$r = .26$ $p = .164$
Foot ahead (m)							$r = .24$ $p = .211$

In Figure 4.1 below, it can be seen that most of the fastest walkers were men with step lengths greater than 1.20 m. When step length was normalised for stature (Figure 4.2), the fastest athletes had step length ratios of 70% or more.

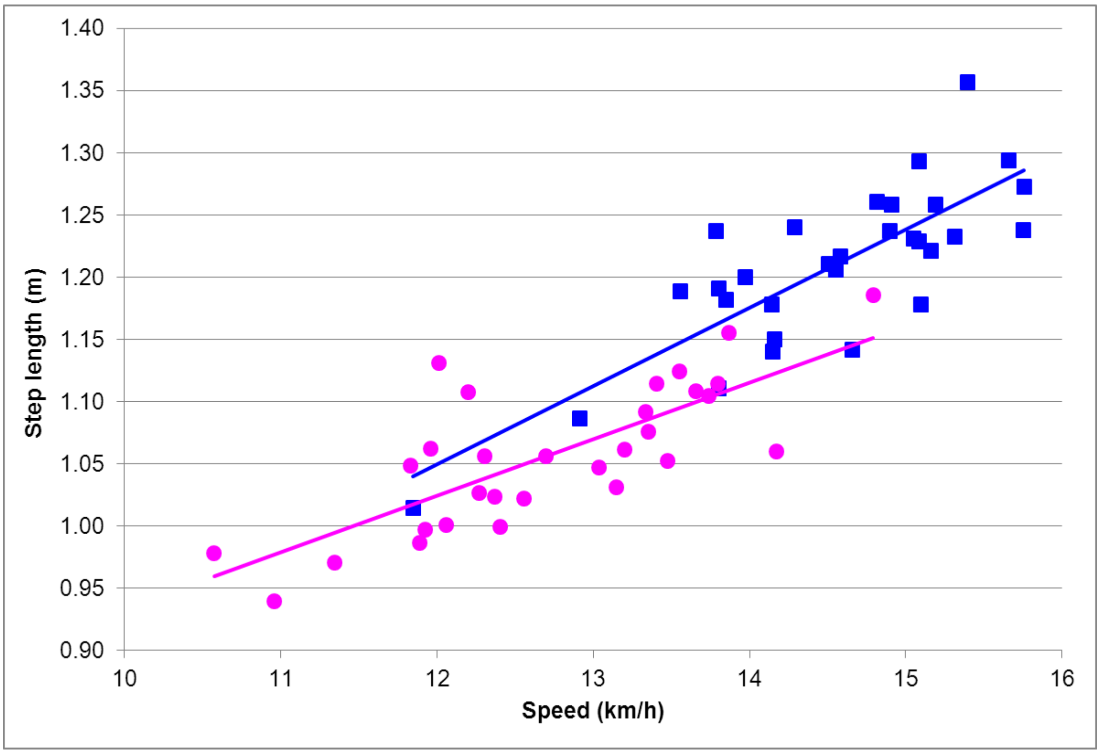


Figure 4.1. Step length was correlated with speed in both men (blue squares; *r* = .80) and women (pink circles; *r* = .76).

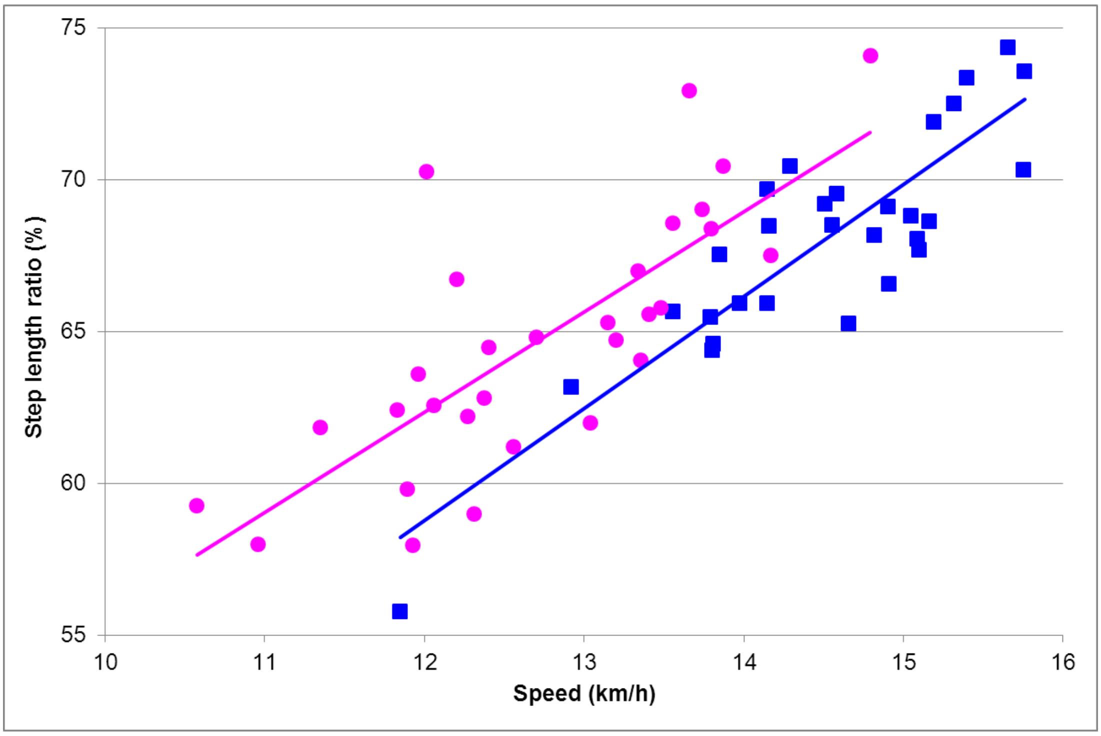


Figure 4.2. Step length ratio was correlated with speed in both men (blue squares; *r* = .87) and women (pink circles; *r* = .77).

4.3.1.2 Relative position of the foot at initial contact and toe-off

The position of the support foot relative to the CM is shown in Table 4.2. Both foot ahead and foot behind distances were positively correlated with height in men (foot ahead: *r* = .50, *p* = .005; foot behind: *r* = .68, *p* < .001) and as a result they have also been reported as ratios (neither flight distance nor foot movement was correlated with height). Foot ahead ratio was not correlated with speed in either group, and while foot behind ratio was also not correlated with speed in the men's group, it was associated with speed in the women's group (*r* = .51, *p* = .004). Within the men's group, the foot ahead absolute value was positively correlated with step length and negatively correlated with cadence. However, there were no correlations between foot ahead distances and step length and cadence when expressed as foot ahead ratio (Figure 4.3). In the women's group, neither step length nor cadence was correlated with foot ahead when expressed either as an absolute value, or as a ratio (Figures 4.4).

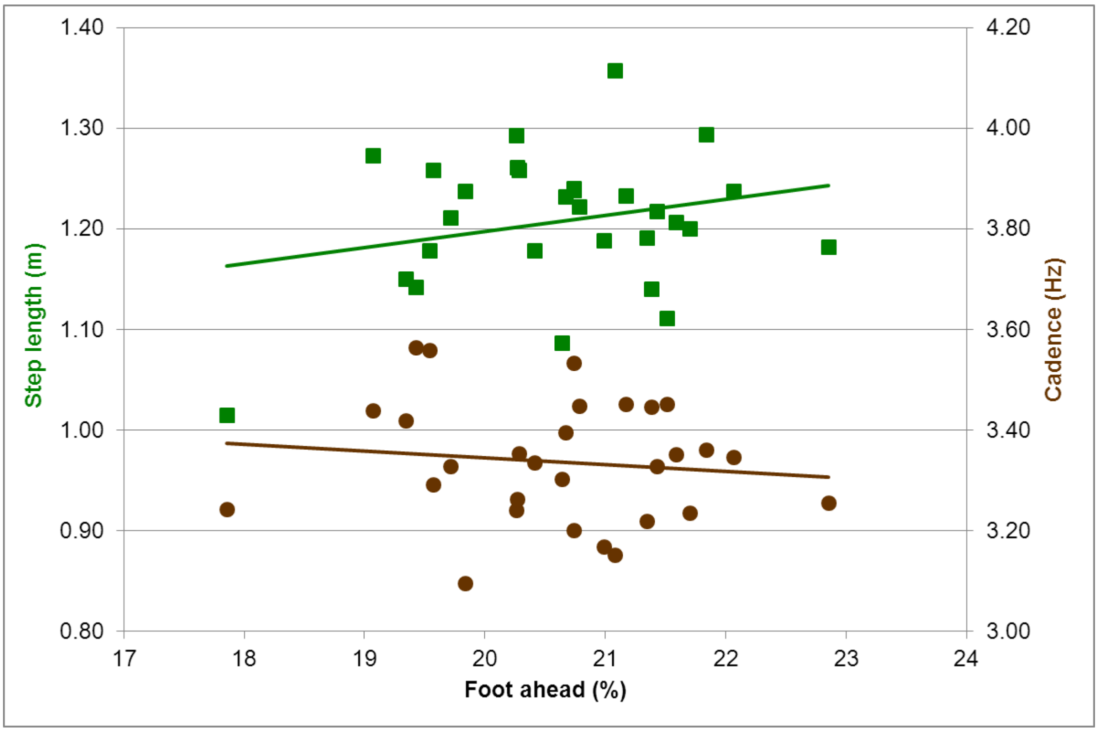


Figure 4.3. Foot ahead ratio was not correlated with either step length (green squares) or cadence (brown circles) in men.

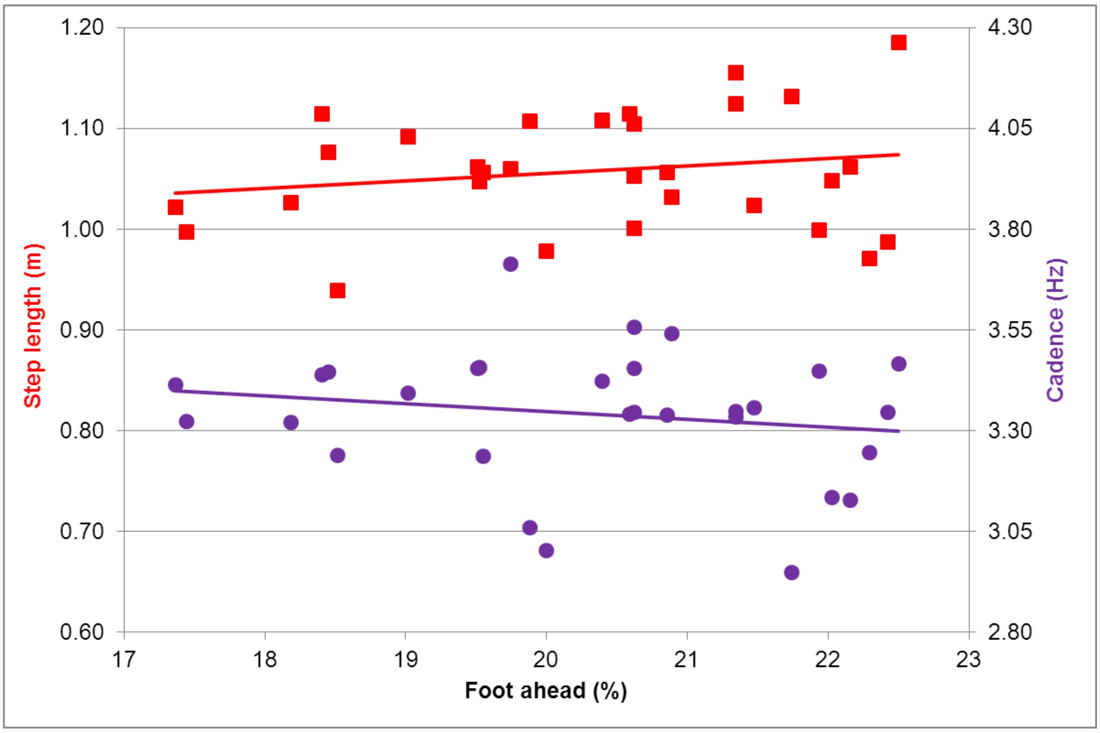


Figure 4.4. Foot ahead ratio was not correlated with either step length (red squares) or cadence (purple circles) in women.

The mean decrease in velocity during foot ahead in the men's group was –0.13 m/s (± .05) and the mean increase in velocity during foot behind was 0.15 m/s (± .05). However, there was no correlation between decrease in velocity and foot ahead distance (*r* = .17, *p* = .619) nor was there any correlation between increase in velocity and foot behind distance (*r* = .10, *p* = .368). In the women's group, the mean decrease in velocity during foot ahead was –0.12 m/s (± .05) and the mean increase in velocity during foot behind was 0.14 m/s (± .06). The distance of the foot ahead was correlated with decrease in velocity in the women's group (*r* = .52, *p* = .003) although foot behind distance did not correlate with the increase in velocity during this phase (*r* = .23, *p* = .217).

4.3.1.3 Contact time and flight time

Table 4.2 also shows the key components of step time, i.e. contact time and flight time. As expected, the duration of flight time was correlated with the flight distance (men: *r* = .85, *p* < .001; women: *r* = .67, *p* < .001). The amount of contact time as a percentage of overall step time is presented as contact time (%). In addition to the correlations shown in Tables 4.3 and 4.4, it was found that the lower the contact time (%), the faster the athlete (men: *r* = –.71, *p* < .001; women: *r* = –.56, *p* = .001).

4.3.1.4 Stance:swing ratio

The mean stance:swing ratio was 45:55 (± 2) for men and 47:53 (± 2) for women, and these were found to be different ($p = .001$, 95% CI = –2.92 to –.811, ES = 1.00). In both groups, lower stance proportions were correlated with higher speeds (men: $r = –.81$, $p < .001$; women: $r = –.62$, $p < .001$), longer steps (men: $r = –.62$, $p < .001$; women: $r = –.60$, $p < .001$), and longer flight distances (men: $r = –.87$, $p < .001$; women: $r = –.83$, $p < .001$).

4.3.1.5 Vertical displacement

The mean vertical displacement of the CM for men was 51 mm (± 5), which was higher than that found for women (44 ± 5 mm) ($p = .003$, 95% CI = .002 to .008, ES = 1.40). The vertical displacement of the CM was positively correlated with step length in the men's group only ($r = .64$, $p < .001$) and negatively correlated with cadence in both groups (men: $r = –.41$, $p = .026$; women: $r = –.52$, $p = .004$). Vertical displacement was also correlated with flight distance in men ($r = .54$, $p = .002$).

4.3.1.6 Pelvic and shoulder girdle rotation

The transverse plane rotation values of the pelvis and shoulder girdles are shown in Table 4.5, while correlations with key performance variables are shown in Tables 4.7 and 4.8. In addition to these, pelvic rotation was positively correlated with overall stature in men ($r = .42$, $p = .024$,) but not in women ($r = –.32$, $p = .084$). Similarly, shoulder girdle rotation was negatively correlated with mass in men ($r = –.37$, $p = .049$) but not in women ($r = –.34$, $p = .063$).

Table 4.5. Mean (± *s*) and between-subjects effects of rotation angles. Differences were significant at $p < 0.05$ (bold). Effect sizes were based on Cohen's *d* and indicated when very large (‡), large (†), or moderate (*).

	Men	Women	*p*	95% CI
Pelvic rotation (°)	18 (± 3)	14 (± 4)	**< .001**	**2.08 to 5.89***
Shoulder rotation (°)	16 (± 2)	19 (± 2)	**< .001**	**–5.08 to –2.65†**
Distortion angle (°)	32 (± 3)	32 (± 4)	.701	–1.42 to 2.06

4.3.1.7 Knee joint angles

Table 4.6 shows the mean knee angles at initial contact, midstance and toe-off, with correlations between key performance variables and the knee angle at contact and during swing shown in Tables 4.7 and 4.8. The range of knee values for men at initial contact was between 177° and 184°; for women it was between 174° and 183°. Overall, the men had hyperextended knees for 72% (± 12) of contact time and women 76% (± 11) (*p* = .169, 95% CI = –10.1 to 1.8, ES = 0.36). Amongst the women competitors, the knee angle at contact was negatively correlated with contact time as a percentage of step time (*r* = –.48, *p* = .007). In addition, the women's knee toe-off angle was also correlated with flight distance (*r* = .41, *p* = .025). The minimum knee angle (maximum knee flexion) during swing was 103° (± 4) for the men, which was different from the value for women (100° ± 4) (*p* = .015, 95% CI = .561 to 5.07, ES = 0.75).

4.3.1.8 Hip and ankle joint angles

In Table 4.6, the values for the hip angle represent means of 13° and 11° hip flexion at contact for men and women respectively, and 11° and 10° hyperextension at toe-off. Correlations between hip contact angle, hip toe-off angle and ankle contact angle with other key variables are shown in Tables 4.7 and 4.8. In addition to these, in the men's group the ankle midstance values correlated with flight distance (*r* = .53, *p* = .003), and the hip toe-off angle was correlated with step length ratio (*r* = .46, *p* = .010) and flight time (*r* = .39, *p* = .035), while in the women's group, knee contact angle was correlated with step length ratio (*r* = .38, *p* = .038).

Table 4.6. Mean (± *s*) and between-subjects effects of leg and arm joint angles. Differences were significant at $p < 0.05$ (bold). Effect sizes were based on Cohen's *d* and indicated when very large (‡), large (†), or moderate (*).

	Men	Women	*p*	95% CI
Knee angle (°)				
Initial contact	180 (± 2)	179 (± 2)	.143	–.290 to 2.06
Midstance	189 (± 4)	190 (± 3)	.050	–3.53 to .003
Toe-off	156 (± 5)	158 (± 4)	.081	–4.34 to .405
Hip angle (°)				
Initial contact	167 (± 3)	169 (± 3)	.076	–3.13 to .160
Midstance	187 (± 2)	190 (± 3)	**< .001**	**–4.66 to –1.87***
Toe-off	189 (± 3)	190 (± 3)	.159	–2.27 to .437
Ankle angle (°)				
Initial contact	101 (± 3)	104 (± 3)	**.001**	**–4.27 to –1.16***
Midstance	109 (± 2)	110 (± 3)	**.032**	**–2.33 to –.107**
Toe-off	125 (± 4)	129 (± 4)	**< .001**	**–6.25 to –1.99***
Shoulder angle (°)				
Initial contact	–64 (± 7)	–70 (± 7)	**.001**	**–9.73 to –2.71***
Midstance	–21 (± 4)	–23 (± 5)	.076	–4.40 to .236
Toe-off	37 (± 5)	40 (± 6)	**.031**	**–5.81 to –.255**
Elbow angle (°)				
Initial contact	79 (± 9)	72 (± 10)	**.010**	**1.63 to 11.37***
Midstance	82 (± 7)	76 (± 7)	**.003**	**1.97 to 9.27***
Toe-off	65 (± 7)	66 (± 6)	.585	–4.34 to 2.47

Table 4.7. Correlation analysis of key angular variables across the World Cup sample for 20 km men. Correlations were significant at $p < 0.05$ (shown in bold).

	Speed	Step length (m)	Cadence	Contact time	Flight distance	Foot ahead (m)	Foot behind (m)
Knee (contact)	**r = .39** **p = .033**	**r = .40** **p = .027**	r = .03 p = .866	r = –.29 p = .119	**r = .43** **p = .019**	r = –.10 p = .585	r = –.14 p = .475
Hip (contact)	r = .15 p = .416	r = .29 p = .115	r = –.19 p = .303	r = –.16 p = .409	r = .34 p = .069	r = .03 p = .864	r = –.11 p = .577
Ankle (contact)	r = .03 p = .873	r = –.02 p = .927	r = .07 p = .699	r = –.22 p = .238	r = .18 p = .331	r = –.14 p = .456	r = –.10 p = .602
Shoulder (midstance)	r = –.24 p = .196	r = –.29 p = .121	r = .05 p = .786	r = .22 p = .254	r = –.27 p = .149	r = –.05 p = .812	r = –.08 p = .686
Hip (toe-off)	**r = .45** **p = .013**	r = .34 p = .064	r = .22 p = .246	**r = –.43** **p = .017**	r = .36 p = .054	r = .11 p = .553	r = –.20 p = .293
Knee (swing)	**r = .36** **p = .049**	r = –.20 p = .290	r = –.29 p = .121	r = .34 p = .070	r = –.13 p = .481	r = .01 p = .975	r = .00 p = .995
Pelvic rotation	r = .05 p = .798	r = .22 p = .241	r = –.25 p = .181	r = .11 p = .575	r = .04 p = .834	r = .27 p = .153	r = .36 p = .050
Shoulder rotation	r = –.01 p = .975	r = –.06 p = .759	r = .08 p = .666	r = –.20 p = .287	r = .17 p = .383	r = .02 p = .910	r = –.12 p = .526
Distortion angle	r =.04 p = .852	r = .18 p = .343	r = –.21 p = .268	r = .07 p = .729	r = .19 p = .328	r = .33 p = .975	r = .24 p = .995

Table 4.8. Correlation analysis of key angular variables across the World Cup sample for 20 km women. Correlations were significant at $p < 0.05$ (shown in bold).

	Speed	Step length (m)	Cadence	Contact time	Flight distance	Foot ahead (m)	Foot behind (m)
Knee (contact)	**$r = .37$** **$p = .042$**	$r = .32$ $p = .087$	$r = .21$ $p = .262$	$r = -.34$ $p = .062$	**$r = .46$** **$p = .010$**	$r = -.12$ $p = .521$	$r = .11$ $p = .562$
Hip (contact)	$r = -.08$ $p = .666$	$r = .05$ $p = .815$	$r = -.17$ $p = .357$	$r = -.12$ $p = .527$	$r = .35$ $p = .055$	$r = -.15$ $p = .420$	**$r = -.53$** **$p = .003$**
Ankle (contact)	$r = .13$ $p = .488$	$r = .16$ $p = .407$	$r = .00$ $p = .997$	$r = -.03$ $p = .866$	$r = -.06$ $p = .740$	$r = -.15$ $p = .420$	$r = .23$ $p = .224$
Shoulder (midstance)	**$r = -.45$** **$p = .013$**	$r = -.23$ $p = .230$	**$r = -.45$** **$p = .013$**	**$r = .41$** **$p = .023$**	$r = -.34$ $p = .063$	$r = .16$ $p = .404$	$r = -.13$ $p = .512$
Hip (toe-off)	$r = .20$ $p = .284$	**$r = .44$** **$p = .015$**	$r = -.17$ $p = .381$	$r = -.11$ $p = .581$	**$r = .38$** **$p = .040$**	$r = .07$ $p = .706$	$r = .06$ $p = .743$
Knee (swing)	$r = .25$ $p = .183$	$r = .23$ $p = .216$	$r = .11$ $p = .554$	$r = .13$ $p = .502$	$r = .27$ $p = .151$	$r = -.16$ $p = .392$	$r = .11$ $p = .553$
Pelvic rotation	$r = -.06$ $p = .769$	$r = .24$ $p = .194$	$r = -.33$ $p = .075$	$r = .23$ $p = .226$	$r = -.01$ $p = .949$	$r = .23$ $p = .217$	$r = .26$ $p = .170$
Shoulder rotation	$r = .34$ $p = .063$	$r = .23$ $p = .218$	$r = .29$ $p = .127$	**$r = -.36$** **$p = .049$**	$r = .27$ $p = .143$	$r = -.02$ $p = .901$	$r = .20$ $p = .302$
Distortion angle	$r =.08$ $p = .671$	$r = .08$ $p = .667$	$r = -.18$ $p = .343$	$r = .05$ $p = .782$	$r = .06$ $p = .747$	$r = .21$ $p = .278$	$r = .32$ $p = .088$

4.3.1.9 Shoulder and elbow joint angles

Table 4.6 also shows the values for the angles of the shoulder and elbow, with selected correlations shown in Tables 4.7 and 4.8. Twenty-three of the men and 25 of the women had their largest recorded elbow angle at midstance, while all 30 men and 26 of the women had their smallest elbow angle at toe-off. An association was found amongst the women between shoulder contact angle and flight distance (*r* = –.41, *p* = .024), while the shoulder toe-off angle was correlated with foot behind ratio (*r* = .37, *p* = .047). Furthermore, in the women's sample, elbow midstance and toe-off angles were correlated with stature (*r* = –.43, *p* = .019 and *r* = –.34, *p* = .042 respectively), while all three elbow angles (initial contact, midstance and toe-off) were correlated with foot ahead ratio (*r* = .41, *p* = .023; *r* = .39, *p* = .035; and *r* = .47, *p* = .008 respectively). Also, in the women's sample, elbow contact angle was correlated with step length ratio (*r* = .38, *p* = .038) and elbow toe-off angle was negatively correlated with cadence (*r* = –.48, *p* = .007). By contrast, there were very few correlations found for either the shoulder or elbow angles in the men's group: the shoulder angle at initial contact correlated with ipsilateral hip contact angle (*r* = .42, *p* = .022), the midstance elbow angle correlated with foot ahead (*r* = –.49, *p* = .006) and foot ahead ratio (*r* = –.39, *p* = .039).

4.3.1.10 Analysis of individual athletes

A selection of five athletes was chosen from both the men's 20 km race and the women's 20 km race, and their results for particular variables compared in Tables 4.9 and 4.10 respectively. All men apart from the athlete who finished 78th, and all women apart from the athlete who finished 68th, have competed at the Olympic Games (IAAF, 2011b).

Table 4.9. Sample of individuals' results from the men's 20 km (World Cup).

Finishing position	3	15	40	58	78
Stature (m)	1.76	1.75	1.82	1.81	1.82
Speed (km/h)	15.75	15.19	13.98	13.56	11.85
Step length (m)	1.24	1.26	1.20	1.19	1.02
Step length ratio (%)	70.3	71.9	65.9	65.7	55.8
Cadence (Hz)	3.53	3.35	3.24	3.17	3.24
Foot ahead (m)	0.37	0.36	0.40	0.38	0.33
Foot ahead ratio (%)	20.7	20.3	21.7	21.0	17.9
Foot behind (m)	0.47	0.48	0.50	0.48	0.49
Foot behind ratio (%)	26.4	27.4	27.2	26.5	26.9
Flight distance (m)	0.27	0.26	0.16	0.15	0.06
Foot movement (m)	0.15	0.16	0.17	0.18	0.15
Pelvic rotation (°)	16	16	13	20	16
Shoulder rotation (°)	17	17	20	13	17
Knee at contact (°)	179	181	182	178	178
Knee at midstance (°)	186	187	187	186	186

Table 4.10. Sample of individuals' results from the women's 20 km (World Cup).

Finishing position	1	17	37	57	68
Stature (m)	1.60	1.63	1.60	1.57	1.65
Speed (km/h)	14.79	13.34	12.06	11.35	10.58
Step length (m)	1.19	1.09	1.00	0.97	0.98
Step length ratio (%)	74.1	67.0	62.6	61.8	59.3
Cadence (Hz)	3.47	3.39	3.35	3.25	3.00
Foot ahead (m)	0.36	0.31	0.33	0.35	0.33
Foot ahead ratio (%)	22.5	19.0	20.6	22.3	20.0
Foot behind (m)	0.46	0.43	0.39	0.45	0.38
Foot behind ratio (%)	28.8	26.4	24.4	28.7	23.0
Flight distance (m)	0.23	0.15	0.11	0.00	0.07
Foot movement (m)	0.16	0.18	0.16	0.16	0.18
Pelvic rotation (°)	15	10	16	18	13
Shoulder rotation (°)	26	19	16	21	16
Knee at contact (°)	183	177	181	179	178
Knee at midstance (°)	191	187	193	190	191

4.3.2 European Cup variation data

4.3.2.1 Speed, step length and cadence

Table 4.11 shows the variations in speed, step length and cadence for all athletes analysed at the European Cup, as well as the percentage decrease with regard to the previous measurement. Within the men's group, the values for speed decreased during the course of the race; at 18.5 km they were 4.2% slower than at 4.5 km; step length was 2.4% shorter and cadence 1.5% lower. Decreases in speed were also found in the women's group; their mean walking speed at 18.5 km was 6.8% slower than at 4.5 km, while step length was 4.5% shorter and cadence 2.3% lower. There were no changes found for the mean foot ahead or foot behind distances, but there were for flight distance (Table 4.12). In addition, the men's foot movement distance increased from 0.16 m (± .01) to 0.18 m (± .02) between 13.5 and 18.5 km (p = .002). There were no changes found for foot movement distance in the women's group.

Table 4.11. Mean (± *s*) and within-subjects effects of key race walking variables. Differences (overall and repeated contrasts) were significant at $p < 0.05$ (bold).

	Men	Women
Speed (km/h)		
4.5 km	**15.12 (± .53)**	13.55 (± 1.21)
8.5 km	**14.73 (± .63)**	13.20 (± .72)
13.5 km	14.66 (± .79)	**13.08 (± .77)**
18.5 km	14.48 (± .95)	**12.63 (± 1.03)**
Difference (%)	***–2.6****, –0.5, –1.2*	*–2.6, –1.0,* ***–3.4***
ANOVA	**$F_{3,33}$ = 5.05, p = .005, η^2 = .32**	**$F_{3,33}$ = 5.02, p = .006, η^2 = .31**
Step length (m)		
4.5 km	**1.27 (± .02)**	1.10 (± .08)
8.5 km	**1.24 (± .04)**	1.07 (± .05)
13.5 km	1.24 (± .03)	1.07 (± .05)
18.5 km	1.24 (± .04)	1.05 (± .07)
Difference (%)	***–2.4****, 0.0, 0.0*	*–2.7, 0.0, –1.9*
ANOVA	**$F_{3,33}$ = 4.51, p = .009, η^2 = .29**	$F_{1.76,19.34}$ = 2.35, p = .127, η^2 = .18
Cadence (Hz)		
4.5 km	3.30 (± .11)	3.42 (± .11)
8.5 km	3.29 (± .11)	3.41 (± .13)
13.5 km	**3.29 (± .15)**	**3.41 (± .13)**
18.5 km	**3.25 (± .18)**	**3.34 (± .17)**
Difference (%)	*–0.3, 0.0,* ***–1.2***	*–0.3, 0.0,* ***–2.1***
ANOVA	$F_{1.73,19.02}$ = 2.80, p = .092, η^2 = .20	**$F_{3,33}$ = 6.98, p = .001, η^2 = .39**

Table 4.12. Mean (± *s*) and within-subjects effects of step distances. Differences (overall and repeated contrasts) were significant at $p < 0.05$ (bold).

	Men	Women
Foot ahead (m)		
4.5 km	0.38 (± .03)	0.34 (± .03)
8.5 km	0.39 (± .03)	0.33 (± .04)
13.5 km	0.39 (± .03)	0.33 (± .03)
18.5 km	0.38 (± .04)	0.32 (± .03)
Difference (%)	*2.9, –0.6, –3.1*	*–4.1, 0.1, –2.2*
ANOVA	$F_{3,33}$ = 1.74, p = .178, η^2 = .14	$F_{3,33}$ = 1.60, p = .209, η^2 = .13
Foot behind (m)		
4.5 km	0.49 (± .02)	0.44 (± .03)
8.5 km	0.49 (± .03)	0.44 (± .03)
13.5 km	0.49 (± .03)	0.44 (± .03)
18.5 km	0.50 (± .02)	0.43 (± .02)
Difference (%)	*0.7, 0.2, 2.0*	*1.9, –0.9, –1.7*
ANOVA	$F_{3,33}$ = 1.52, p = .227, η^2 = .12	$F_{3,33}$ = 1.56, p = .217, η^2 = .13
Flight distance (m)		
4.5 km	**0.22 (± .06)**	**0.16 (± .06)**
8.5 km	**0.19 (± .07)**	**0.14 (± .05)**
13.5 km	0.19 (± .06)	0.14 (± .04)
18.5 km	0.17 (± .07)	0.13 (± .06)
Difference (%)	***–12.9****, –1.3, –9.3*	***–16.3****, 0.0, –4.9*
ANOVA	**$F_{3,33}$ = 6.09, p = .002, η^2 = .36**	$F_{3,33}$ = 2.67, p = .062, η^2 = .20

Changes in velocity occurring during the deceleration and acceleration phases of each step are shown in Table 4.13; the decreases in velocity refer to changes in velocity measured during the foot ahead phase between initial contact and midstance, while increases in velocity were measured during the foot behind phase between midstance and toe-off.

Table 4.13. Mean (± *s*) and within-subjects effects of velocity changes per step. Differences (overall and repeated contrasts) were significant at $p < 0.05$ (bold).

	Men	Women
Decrease in velocity (m/s)		
4.5 km	–0.15 (± .04)	–0.08 (± .05)
8.5 km	–0.15 (± .05)	–0.10 (± .04)
13.5 km	–0.14 (± .06)	–0.10 (± .05)
18.5 km	–0.14 (± .05)	–0.09 (± .06)
Difference (%)	*0.5, –5.6, 1.2*	*7.1, –0.8, –4.9*
ANOVA	$F_{3,33} = 0.38$, $p = .770$, $\eta^2 = .03$	$F_{3,33} = 0.78$, $p = .515$, $\eta^2 = .07$
Increase in velocity (m/s)		
4.5 km	0.16 (± .04)	0.08 (± .06)
8.5 km	**0.17 (± .06)**	0.12 (± .04)
13.5 km	**0.14 (± .05)**	0.11 (± .06)
18.5 km	0.13 (± .05)	0.09 (± .06)
Difference (%)	*2.6, **–10.7**, –3.2*	*14.9, –2.9, –6.4*
ANOVA	**$F_{3,33} = 3.16$, $p = .037$, $\eta^2 = .22$**	$F_{3,33} = 1.75$, $p = .176$, $\eta^2 = .14$

4.3.2.2 Contact time and flight time

There were no differences for any temporal variable in the men's group: mean contact time was 0.27 s at 4.5 km (± .02) and 13.5 km (± .03), and 0.28 s at 8.5 km (± .02) and 18.5 km (± .03); mean flight time was 0.03 s at all four measurement distances (± .01 at 4.5 and 8.5 km; ± .02 at 13.5 and 18.5 km); and stance:swing ratio was 45:55 at all four distances (± 2 at 4.5 and 8.5 km; ± 3 at 13.5 and 18.5 km). However, in the women's group contact time did increase, from 0.27 s (± .03) at 4.5 km to 0.29 s (± .03) at 18.5 km ($F_{3,33}$ = 8.33, p < .001, η^2 = .43) and flight time decreased at the same distances from 0.03 s (± .02) to 0.02 s (± .01) ($F_{3,33}$ = 4.00, p = .016, η^2 = .27). The proportion of time spent in stance also increased from 45% (± 3) at 4.5 km to 47% (± 2) at 18.5 km ($F_{3,33}$ = 7.86, p < .001, η^2 = .42).

4.3.2.3 Pelvic and shoulder girdle rotation

Table 4.14 shows the variations in pelvic girdle rotation, shoulder girdle rotation and distortion angle for all athletes analysed. Changes with distance walked were only found in the men's sample.

Table 4.14. Mean (± *s*) and within-subjects effects of rotation angles. Differences (overall and repeated contrasts) were significant at $p < 0.05$ (bold).

	Men	Women
Pelvic rotation (°)		
4.5 km	**18 (± 3)**	14 (± 2)
8.5 km	**21 (± 3)**	14 (± 3)
13.5 km	22 (± 3)	14 (± 2)
18.5 km	22 (± 2)	15 (± 3)
Difference (%)	***16**, 6, –3*	*0, 2, 4*
ANOVA	$\boldsymbol{F_{3,33} = 6.19, p = .002, \eta^2 = .36}$	$F_{3,33} = 0.47$, $p = .704$, $\eta^2 = .04$
Shoulder rotation (°)		
4.5 km	16 (± 2)	22 (± 3)
8.5 km	16 (± 2)	23 (± 4)
13.5 km	16 (± 2)	22 (± 4)
18.5 km	16 (± 3)	22 (± 4)
Difference (%)	*3, 3, –3*	*3, –5, 0*
ANOVA	$F_{3,33} = 0.77$, $p = .521$, $\eta^2 = .07$	$F_{1.76,19.34} = 0.70$, $p = .561$, $\eta^2 = .06$
Distortion angle (°)		
4.5 km	33 (± 4)	35 (± 3)
8.5 km	**35 (± 3)**	36 (± 4)
13.5 km	**37 (±5)**	35 (± 4)
18.5 km	36 (± 4)	36 (± 4)
Difference (%)	*7, **6**, –2*	*2, –2, 2*
ANOVA	$\boldsymbol{F_{3,33} = 5.16, p = .005, \eta^2 = .32}$	$F_{3,33} = 0.37$, $p = .779$, $\eta^2 = .03$

4.3.2.4 Knee, hip and ankle joint angles

There were no differences in knee contact angle for either men or women with distance walked. The women's initial contact angle was 180° at every measurement distance (± 2 at all distances except at 18.5 km (± 3)) ($F_{3,33}$ = 0.42, p = .988, η^2 = .004), whereas for the men it was 179° at every distance (± 3 at 4.5 and 8.5 km, and ± 2 at 18.5 km) except 13.5 km (180 ± 3°) ($F_{3,33}$ = 0.20, p = .898, η^2 = .02). There were also no differences for the knee at midstance, toe-off or midswing for either group. The hip angle at initial contact and toe-off altered little, with no differences in either men or women. There was a small increase in the ankle contact angle in the men's group (meaning less dorsiflexion), from 101° (± 3) at 4.5 km to 103° (± 3) at 8.5 km with another small increase to 104° (± 3) at 13.5 and 18.5 km ($F_{1.99,21.89}$ = 5.63, p = .011, η^2 = .34); no similar differences were found in women. Ankle plantarflexion at toe-off increased from 126° (± 4) at 4.5 km to 130° (± 4) at 8.5 km in women (p = .009), and from 125° (± 3) at 13.5 km to 127° (± 3) at 18.5 km (p = .026) in men.

4.3.2.5 Shoulder and elbow joint angles

The data showed that no changes occurred within the men's group for either shoulder or elbow angles. The women also had no differences between shoulder angles at each distance, but they did experience changes for the elbow angle. At midstance, there was a decrease from 83° (± 7) at 4.5 km to 77° (± 5) at 18.5 km ($F_{3,33}$ = 10.04, p < .001, η^2 = .48) and at toe-off the elbow angle decreased from 69° (± 8) at 4.5 km to 64° (± 3) at 18.5 km ($F_{1.85,20.34}$ = 5.39, p = .015, η^2 = .33).

4.3.2.6 Analysis of individual athletes

To complement the overall findings on both men and women competing over 20 km, individual athletes' results have been presented in Tables 4.15, 4.16, 4.17 and 4.18 below. All four men and the two highest-finishing women have competed at either the Olympic Games or World Championships in Athletics (IAAF, 2011b).

Table 4.15. Sample of individuals' results from the men's 20 km (7th European Cup).

Posn.	Distance (km)	Speed (km/h)	Step length (m)	Step length ratio (%)	Cadence (Hz)
1	4.5	15.73	1.29	69.6	3.39
	8.5	16.05	1.32	71.1	3.39
	13.5	15.97	1.30	70.1	3.42
	18.5	15.56	1.29	69.9	3.34
15	4.5	15.57	1.27	69.9	3.40
	8.5	15.07	1.22	67.0	3.43
	13.5	15.06	1.22	67.0	3.43
	18.5	14.83	1.21	66.6	3.40
34	4.5	15.30	1.30	74.5	3.26
	8.5	14.72	1.24	71.0	3.29
	13.5	14.67	1.24	70.9	3.28
	18.5	13.98	1.22	69.7	3.18
43	4.5	14.20	1.23	68.9	3.22
	8.5	14.64	1.25	70.1	3.26
	13.5	13.89	1.24	69.5	3.12
	18.5	13.62	1.24	69.9	3.04

Table 4.16. Extended sample of individuals' results from the men's 20 km (7th European Cup).

Posn.	Distance (km)	Foot ahead (m)	Foot behind (m)	Flight distance (m)	Pelvic rotation (°)	Shoulder rotation (°)
1	4.5	0.37	0.50	0.26	17	18
	8.5	0.35	0.52	0.27	22	14
	13.5	0.40	0.50	0.26	20	16
	18.5	0.43	0.51	0.18	23	16
15	4.5	0.41	0.49	0.17	17	19
	8.5	0.44	0.50	0.16	18	19
	13.5	0.40	0.49	0.17	23	18
	18.5	0.38	0.51	0.16	20	18
34	4.5	0.38	0.51	0.26	19	18
	8.5	0.39	0.48	0.25	23	17
	13.5	0.38	0.51	0.21	24	19
	18.5	0.37	0.49	0.16	21	17
43	4.5	0.40	0.49	0.16	21	16
	8.5	0.43	0.49	0.17	22	15
	13.5	0.43	0.48	0.15	22	15
	18.5	0.42	0.50	0.15	22	14

Table 4.17. Sample of individuals' results from the women's 20 km (7th European Cup).

Posn.	Distance (km)	Speed (km/h)	Step length (m)	Step length ratio (%)	Cadence (Hz)
2	4.5	13.74	1.08	67.3	3.55
	8.5	14.29	1.10	68.5	3.62
	13.5	14.89	1.14	71.4	3.62
	18.5	14.10	1.07	67.0	3.65
15	4.5	13.53	1.15	66.7	3.27
	8.5	13.63	1.18	68.4	3.22
	13.5	13.39	1.14	66.0	3.28
	18.5	13.24	1.17	68.3	3.13
31	4.5	13.35	1.07	63.5	3.46
	8.5	13.15	1.09	64.5	3.35
	13.5	12.87	1.06	62.8	3.37
	18.5	12.81	1.04	61.7	3.41
40	4.5	12.98	1.03	66.2	3.49
	8.5	12.53	0.99	63.3	3.53
	13.5	12.14	0.96	61.2	3.53
	18.5	11.83	0.96	61.6	3.42

Table 4.18. Extended sample of individuals' results from the women's 20 km (7th European Cup).

Posn.	Distance (km)	Foot ahead (m)	Foot behind (m)	Flight distance (m)	Pelvic rotation (°)	Shoulder rotation (°)
2	4.5	0.31	0.45	0.16	16	20
	8.5	0.30	0.46	0.16	13	29
	13.5	0.37	0.45	0.17	15	28
	18.5	0.35	0.44	0.15	11	26
15	4.5	0.37	0.46	0.15	14	18
	8.5	0.35	0.48	0.16	20	16
	13.5	0.34	0.47	0.15	15	17
	18.5	0.34	0.46	0.18	19	19
31	4.5	0.33	0.43	0.15	11	25
	8.5	0.33	0.45	0.15	14	27
	13.5	0.32	0.44	0.15	12	27
	18.5	0.31	0.43	0.14	9	24
40	4.5	0.31	0.38	0.20	15	20
	8.5	0.30	0.39	0.14	10	20
	13.5	0.30	0.38	0.13	14	14
	18.5	0.25	0.41	0.14	14	15

4.4 Discussion

4.4.1 Predictors of faster race walking

It was clear from the associations found within groups, as well as the differences between genders, the changes due to fatigue, and the individual analyses, that the two main determinants of race walking speed are step length and cadence. This was unsurprising given the theoretical knowledge and previous research on other forms of gait that were used to create the hierarchical model of race walking (Figure 2.3). The fastest athletes tended to have both the longest steps (with step length ratios of approximately 70% or more) and the highest step frequencies (of approximately 3.34 Hz, or about 200 steps per minute), and therefore coaches should note that athletes cannot rely on one of these components alone, especially given the decreases to both caused by fatigue. The importance of having a high cadence was further emphasised by the values achieved by the best athletes analysed in both the men's (bronze medallist) and women's (gold medallist) races, whose cadences were 3.53 Hz and 3.47 Hz respectively.

On the whole, elite male race walkers were faster than their female counterparts because of greater absolute step lengths, which were partially due to their greater overall statures, rather than differences in cadence. However, men seemed to rely more on step length for achieving fast speeds (r = .80) than on cadence (r = 0.42), in comparison with women, whose reliance was more balanced (step length: r = .76; cadence: r = .71), although the fatigue data showed that the women only suffered decreases in cadence and not also in step length as men did. In addition, the proportion of step time each group spent in contact and flight was important with regard to walking speed. On average, men spent 2.3% less time in contact (and therefore 2.3% more time in flight) than women. Men also spent less time with each leg in stance compared with swing, which was found to be associated with longer steps (r = –.62) because of longer flight distances, and greater speeds (r = –.81). Flight times occurred in practically all competitors, with longer flight times associated with higher walking speeds and longer steps. Longer flight times, and more importantly the resulting longer flight distances, were therefore also a reason for men's overall greater step lengths. Indeed, it was clear from both the overall and individual analyses that elite race walkers relied on relatively long flight times for a large component of step length, and without these flight periods the athletes would have been considerably slower. Aside from the increased risk of disqualification because of visible loss of contact, race walkers should note that the CM was at its highest position during flight, and unnecessary vertical displacement should be minimised as it was associated with decreased cadence in both men and women, and can result in an inefficient motion path (Murray et al., 1983).

To reduce step time and therefore increase cadence, athletes can either reduce flight time, which is already relatively brief, or shorten contact time. Balancing the need for a shorter contact time with that of increasing step length is one of the inherent difficulties of race walking. During contact, the body was required to move over a stance leg that began contact approximately 20% of stature in front of the CM and ended approximately 27% behind it. An athlete who wishes to lengthen their steps while avoiding increasing flight time too much must increase either foot ahead or foot behind distances. The problem with this is that it has been suggested that if the swing foot lands too far in front of the body, the braking effect will decrease forward velocity considerably (Lafortune et al., 1989). Indeed, longer foot ahead distances were associated with greater decreases in horizontal velocity (r = .52) and longer contact times (r = .38) in the women's group, and therefore female walkers in particular should take care to ensure they are not overstriding. An interesting counterpoint was the winner of the women's race whose foot ahead (22.5%) and foot behind ratios (28.8%) were well above the average for both men and women (providing her with a considerable step length of 1.19 m and step length ratio of 74%), but where she was still able to achieve a high cadence of 3.47 Hz. Being able to overcome apparent disadvantages such as increased foot ahead distance in this way might be an indication of superior performances and highlight the features of the world's very best athletes (in this case, a three-time World Champion and 2008 Olympic Champion). The absence of the associations between foot ahead distance and decrease in velocity and contact time in the men's group suggests that the positioning of their feet at initial contact was better suited to maintaining forward momentum. This might be related to their ability to compensate for the position of the foot because of more muscular physiques. Optimising the length of the foot behind distance is also crucial as this factor was associated with step length.

The unique rule of race walking that requires the knee to be straightened results in a gait that is quite distinct from normal walking or running. The data from both competitions showed that men and women had, on average, full or nearly full extension of the knee (180°) at initial contact. The knee then hyperextended by approximately 10° in both male and female athletes and continued for most of the stance phase. Although such magnitudes and durations of hyperextension are unnecessary with regard to legal walking, they were probably inevitable considering the deliberate attempts by athletes to maintain knee straightness. Apart from its obvious role in adhering to the rule, the knee angle during stance did not appear to be a critical factor contributing to walking speed. However, because of its unique movement pattern (and hence the inability to generalise from other forms of gait), more in-depth analysis of the knee's role in race walking is required beyond these kinematic analyses so that the effects on muscle activity throughout the lower limb are better understood.

With regard to the ankle joint, it has been suggested that greater dorsiflexion at contact increases step length by placing the heel further forwards (Murray et al., 1983) with a resulting increase in speed. However, while the faster group of men had more ankle dorsiflexion at contact than women, there was no association with any of the main performance variables. This might be because the range of values across all athletes was quite small, in turn because this is a well-coached feature of race walking technique (e.g. Salvage & Seaman, 2011). With regard to gender comparisons, there were several differences found for the angles of the ankle, hip, shoulder and elbow. In addition, while greater hip hyperextension at toe-off was associated with longer steps in women, its importance was more evident in men where it was correlated with speed, step length ratio, contact time and flight time. These dissimilarities might be due to the differences in emphasis on step length and cadence as mentioned above, and highlights further that men and women do not have identical race walking kinematics and coaching practices should take this into account.

Pelvic rotation is exaggerated in race walking compared with normal walking. A principal aim of the relatively large amounts of pelvic rotation is to place the feet along a straight line to assist in increasing step length (Murray et al., 1983; Knicker & Loch, 1990). However, the results of this study showed that there were no correlations between pelvic rotation and either step length or speed in either men or women. The analyses of individual athletes likewise showed that there was no clear trend to demonstrate that greater pelvic or shoulder girdle rotations were either an advantage or a disadvantage (e.g. the fastest and slowest individual men analysed had identical magnitudes for both pelvic and shoulder rotations), and therefore optimum rotation magnitudes are individual to each athlete. Men had more pelvic rotation than women, and this might have been due to their greater statures (larger athletes being required to rotate their pelvises through a wider arc to achieve straight line walking) or greater strength levels. The amount of shoulder girdle rotation counterbalancing pelvic rotation might also be related to individual body size. Men's larger upper bodies could possibly require less shoulder girdle rotation than women's because of greater moments of inertia, as increased mass was associated with less rotation, but all athletes need to ensure that these rotations are optimised and controlled to reduce the effects of inefficient walking.

The motion of the arms is also important in the maintenance of optimal walking technique. Unnecessary side-to-side and vertical movements of the arms increase the mediolateral and vertical displacements of the CM. Whereas the standard deviations for the lower limb and rotation angles ranged from 2° to 5°, there was a much greater degree of variation (between 4° and 10°) in the shoulder and elbow joint angles. There were a number of associations found between upper limb angles and key variables, although most of these differed between men and women, and it was difficult to identify clearly the importance of particular joint angles. However, the upper limbs do function in gait to balance the movements of the lower limbs (Pontzer et al., 2009) and athletes are therefore advised not to neglect the upper body when developing race walk technique.

4.4.2 Kinematic variations during 20 km race walking

The decrease in mean speed in the variation study (7th European Cup) as the races progressed was initially caused by a decrease in mean step length and later by a decrease in mean cadence. The results of the individual analyses also suggested that changes in step length were more critical to early variations in speed than changes in cadence. For example, the winner of the men's race increased velocity by 0.32 km/h between 4.5 and 8.5 km by increasing step length by 3 cm (cadences were identical), while the men in 15th and 34th positions suffered decreases of 0.50 km/h or more between these two distances because of reductions in step length (5 cm and 6 cm respectively), and despite increases in cadence of 0.03 Hz. While some athletes suffered reductions in both step length and cadence later in the race, there were large decreases in velocity between 13.5 and 18.5 km for the male athlete finishing 43rd and the female athletes finishing 15th and 40th that were not caused by decreased step length, but reduced cadence.

The decrease in women's speed as the European Cup race progressed coincided with an increase in contact time and a decrease in flight time, again highlighting the higher importance of cadence to female race walkers as shown by the predictors of faster walking. Similar findings were not apparent in the men's race; however, changes in flight distance did occur for both groups between 4.5 and 8.5 km that were roughly equal to the reductions in step length and might therefore have been the cause of shorter steps. This view is supported by the fact that the two other main contributors to step length, foot ahead and foot behind, did not change over the course of competition. In addition, with only one exception, all individual athletes analysed had their longest flight distance when they were walking at their fastest speed, and their shortest flight distance at their slowest speeds. As noted earlier, flight distance accounts for a considerable proportion of step length and the results of the variation study further emphasised its importance in modern elite race walking. With regard to the two main components of step length, the individual analyses showed that whereas foot behind distances were relatively consistent (its range was never more than 3 cm in any individual), there was considerable variation within participants for foot ahead distance. For example, the winner of the men’s race had foot ahead distances that ranged from 0.35 to 0.43 m, while the winner of the women’s race had a range from 0.30 to 0.37 m. Interestingly, the winner of the men’s race was slowest when his foot ahead was at its longest value, while the winner of the women’s race was fastest when her foot ahead was at its longest. The results of the athletes highlighted in Tables 4.15 to 4.18 show that for an individual to achieve their optimum foot ahead length is not a matter of maximising or minimising distance but instead of placing the foot in the best position to balance step length and cadence. Coaches should note that there was considerable individual variation in this key mechanical variable over the course of the race and achieving the optimum foot ahead (or foot behind) distance could require muscular endurance training that maintains this optimum length throughout the competition despite fatigue.

Deceleration during gait occurs because the magnitude of impulse experienced during braking in early stance is greater than that experienced during propulsion in late stance. Reductions in walking speed therefore occur in competition because of the gradual accumulation of net negative impulses over the course of the race. These might occur because of increases in braking forces or decreases in propulsive forces, or because of changes in their respective durations. The results from the men’s 20 km race showed that there was a reduction of 0.03 m/s for increase in velocity (and hence impulse) during the foot behind phase between 8.5 and 13.5 km, and this might be symptomatic of a decrease in propulsion forces due to muscular fatigue. It is important for coaches to note that it is the ability to maintain propulsive impulse (and minimise negative impulse during foot ahead) that enables an athlete to avoid slowing during competition. The exact (muscular) mechanisms that are involved in maintaining this impulse cannot be measured in competition and the study of muscle activity during elite race walking will be very informative in this regard.

With regard to angular data, the mean knee angles at initial contact and midstance at each of the four measurement distances showed no reduction in knee extension angles during stance with distance walked. This was similar to the findings in previous research on the effects of fatigue in non-elite athletes (Knicker & Loch, 1990) and showed that this key element of race walking is unsurprisingly also a well-trained feature in elite athletes. The mean increase in pelvic rotation for men from 4.5 km onwards corresponded to a decrease in step length, and its increase was also noticeable in the individual analyses. This strategy of increasing pelvic rotation was possibly undertaken to try to prevent any further decreases in step length that would have been detrimental to performance, but ultimately any success was limited (larger pelvic rotation angles did not lead to greater step lengths) and flight distance is a much more important variable in attaining and maintaining long steps. This is not to say that pelvic rotation is unimportant, and it appeared that men required about 20° of pelvic rotation for optimum performance, whereas women required a smaller amount (approximately 15°). The only other changes of note were the reductions in elbow angle that occurred in the women’s group. These reductions in elbow angle brought the arm segments closer together and the resulting decrease in the moment of inertia might have made shoulder flexion and extension easier, but might also have been detrimental to overall upper body movement. The motions of the arm and its joint angles might therefore require individualised adjustments during the race rather than as set ‘standard’ positions as recommended by coaches (e.g. Markham, 1989).

4.5 Conclusion

The aim of this study was to provide a comprehensive analysis of the key mechanical variables in men's and women's 20 km race walking. Correct race walking technique, where the athlete walks at a high speed while adhering to the rules, requires the balancing of the principal components of step length and cadence, relatively powerful muscles with high muscular endurance, and exact timing of limb movements. To summarise, the most important key findings of this study are:

- The fastest athletes, whether male or female, tended to have both the longest steps (step length ratios of about 70%) and the highest step frequencies (about 200 steps per minute);
- Men relied more on step length for their fast speeds than on cadence, in comparison with women, whose reliance on cadence was very close to that of step length. Women only suffered decreases in cadence in the fatigue study and this further highlighted the greater importance of this variable to elite female race walkers;
- These elite race walkers relied heavily on long flight times in achieving their long step lengths, and without these flight periods would have been considerably slower. In addition, the decrease in flight distance over the course of the race was a primary cause of reduced step length, and the results from both parts of this study therefore highlight its key role in the high race walking speeds attained;
- Achieving optimum foot ahead length is not about maximising or minimising distance but instead is achieved by placing the foot in the best position to balance step length and cadence. Although it might have been expected that greater foot ahead distances would lead to greater decreases in velocity and longer flight times, the absence of any such associations in the men's group suggests that they were able to compensate for this potentially negative foot position through their muscular physiques;
- By contrast, in the women's group, longer foot ahead distances were associated with greater decreases in horizontal velocity and longer contact times, and female walkers should take care to ensure they are not overstriding. Nonetheless, the fact that the fastest woman was able to achieve long foot ahead distances and a high cadence means that women can achieve similar foot ahead ratios to men provided they have the appropriate ability and training;

- The requirement for a straightened knee at initial contact and during early stance did not negatively affect walking speed. Furthermore, knee extension did not change with distance walked in the variation study, and overall the results showed the ubiquity of this characteristic of elite race walkers;
- With regard to changes caused by fatigue, the decreases in mean speed during the men's race were predominantly caused by changes in step length first and then cadence, whereas in the women's race they were caused by changes in cadence;
- A strategy of increasing pelvic rotation appeared to be undertaken by the men's group to try to prevent further decreases in step length, but the success of this approach was limited because of a lack of association between pelvic rotation and step length in this homogenous group of elite athletes.

CHAPTER 5

STUDY 2: 50 KM COMPETITIONS

5.1 Introduction

The 50 km walk is the longest race in the athletics programme at the Olympic Games and all other major championships, where just completing the race is affected by an individual's ability to tolerate pain and fatigue. For example, the percentage of competitors failing to finish at the six World Championships from 2001 to 2011 ranged from 34 to 51%. Disqualifications accounted for 54% of these non-finishers (IAAF, 2011a) and this might have been due to a negative effect of fatigue on the ability to maintain legal technique (Drake, 2003). Correct pace judgement in 50 km competitions is considered crucial to avoid large decreases in speed towards the end (Hopkins, 1990), although even world-class athletes experience a reduction in walking speeds in the latter stages (Hanley, 2013a). Race walking speed can decrease during a 50 km race because of physiological factors such as reduced aerobic power (Arcelli, 1996) and might be manifested in kinematic changes.

To date, the kinematic characteristics of the world's elite 50 km race walkers have not been analysed. While it is likely that many similarities exist between 20 km and 50 km race walking techniques (many men compete in both events), it is possible that the different physiological demands of the event lead to differences in kinematics. New research on these athletes in competition is therefore essential to understand the technical demands of the event. In particular, kinematic differences might be most obvious in the latter stages of competition when tiredness is more likely, but unfortunately no previous research has focussed on the possible effects of fatigue on 50 km race walking kinematics. It is therefore important to measure the kinematic changes that occur during a 50 km race as these can provide a greater indication of the influence of key variables. Because of the longer duration of the 50 km race, more emphasis has been placed on the variations in key mechanical variables and their importance to elite race walking. The objectives of this study were to identify and measure key kinematic variables in determining success in elite men's 50 km race walking (using data from a World Cup event), and to measure variation in those variables at different distances (in a European Cup event).

5.2 Methods

5.2.1 Participants

Video data were collected at two separate events. For the first part of the study, the men's 50 km race was recorded at the 23rd IAAF World Race Walking Cup. The competitors were filmed as they passed 28.2 km. Participants' heights, masses and dates of birth were obtained from the IAAF (2011b). Thirty competitors (age 30 ± 6 yr, height 1.78 ± 0.07 m, mass 66 ± 5 kg) were analysed; this part of the study intended to find associations between key variables. The analysed competitors included the 2008 and 2012 Olympic champions, the 1993, 2005 and 2009 World Champions, and the current World Record holder (achieved at this competition) (IAAF, 2011b). From the judging records of the analysed athletes over the course of the entire race, four competitors received one red card for loss of contact, two men received two red cards each for not straightening their knee correctly, while five others received one red card each for the same offence.

The men's 50 km race was also recorded at the 7th European Cup Race Walking. The athletes were analysed on four occasions: at 18.5 km, 28.5 km, 38.5 km, and 48.5 km. Twelve competitors (age 28 ± 6 yr, height 1.81 ± 0.07 m, mass 67 ± 4 kg) were analysed; this part of the study was to provide an indication of variation in kinematic measurements over the course of the race. The relative importance of variables at different stages of the event has also been measured. The analysed competitors included three athletes who had won medals at either the Olympic Games or World Championships (IAAF, 2011b). The 12 athletes were chosen as they were the only competitors who could be seen clearly at all four recording distances. Of those analysed, two received one red card for loss of contact each and one received one red card for not straightening the knee correctly. A summary of the race performances from both events is presented in Table 5.1, and the World Record is also presented. No athletes from either competition who did not finish or were disqualified have been included in the study. With regard to comparisons between the World Cup and European Cup competitions, no differences were found for participants' finishing times, heights, or masses.

Table 5.1. Race performances (mean ± *s*) in the men's 50 km competitions.

	Time (h:min:s)	Time (h:min:s)
	World Cup (N=30)	**European Cup (N=12)**
Mean finishing time	3:57:35 (± 11:59)	3:52:33 (± 7:18)
Range	3:34:14 – 4:25:26	3:40:57 – 4:03:42
World Record	3:34:14	

5.3 Results

5.3.1 World Cup data

5.3.1.1 Speed, step length and cadence

The values for speed, step length and cadence for the World Cup participants are shown in Table 5.2, and correlations between these and other key variables are shown in Table 5.3. Step length ratio ranged from 60 to 71%, with a mean of 65.3 ± 2.8%. Contact time and flight time values are also shown in Table 5.2. Contact time accounted for 94.0 ± 3.0% of total step time; in total 26 of the 30 athletes had some loss of contact. Flight time was correlated with both speed ($r = .57$, $p = .001$) and step length ratio ($r = .66$, $p < .001$).

Table 5.2. Mean (± *s*) values for speed, step length, cadence and temporal values.

Speed (km/h)	Step length (m)	Cadence (Hz)	Contact time (s)	Flight time (s)
13.15 (± .75)	1.16 (± .06)	3.16 (± .16)	0.30 (± .03)	0.02 (± .01)

Table 5.3. Correlation analysis of key race walking variables across the World Cup sample. Correlations were significant at $p < 0.05$ (shown in bold).

	Step length	Step length ratio	Cadence	Contact time	Flight distance	Foot ahead (m)	Foot behind (m)
Stature	**r = .55** **p = .003**		**r = –.61** **p = .001**	**r = .48** **p = .011**	r = –.17 p = .393	**r = .64** **p < .001**	**r = .52** **p = .006**
Speed	**r = .54** **p = .002**	**r = .69** **p < .001**	**r = .58** **p = .001**	**r = –.70** **p < .001**	**r = .77** **p < .001**	r = –.17 p = .362	r = .08 p = .684
Step length		**r = .66** **p < .001**	**r = –.37** **p = .042**	r = .07 p = .705	**r = .45** **p = .013**	**r = .45** **p = .013**	**r = .69** **p < .001**
Step length ratio			r = .12 p = .540	r = –.36 p = .065	**r = .68** **p < .001**	r = –.13 p = .528	r = .29 p = .143
Cadence				**r = –.84** **p < .001**	**r = .42** **p = .020**	**r = –.62** **p < .001**	**r = –.60** **p < .001**
Contact time					**r = –.75** **p < .001**	**r = .69** **p < .001**	**r = .57** **p = .001**
Flight distance						**r = –.42** **p = .021**	r = –.23 p = .219
Foot ahead (m)							**r = .69** **p < .001**

Speed was positively correlated with step length when expressed as its absolute value (Figure 5.1) and as step length ratio. Cadence was positively correlated with speed (Figure 5.1) and negatively correlated with step length as an absolute value (but not as step length ratio).

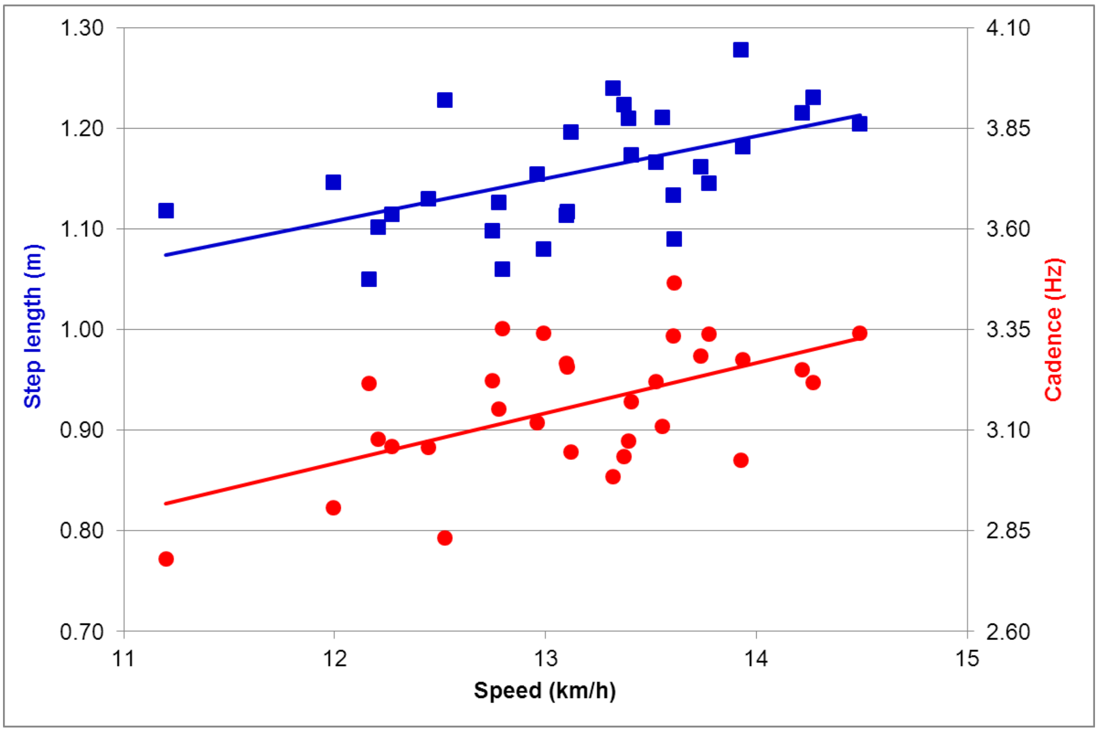


Figure 5.1. Speed was positively correlated with step length (blue squares, *r* = .54) and cadence (red circles, *r* = .58).

5.3.1.2 Foot positioning, foot movement and flight distance

In Table 5.4, the position of the support foot relative to the CM at initial contact (foot ahead) and toe-off (foot behind) is shown, as well as mean flight distance and foot movement. When expressed as a percentage of stature, foot ahead was 21.3% (± 0.9) of height, and foot behind was 26.9% (± 1.5). With regard to the components of step length, foot ahead comprised 33% of total step length, foot behind 41%, flight distance 13%, and foot movement 13%.

Table 5.4. Mean (± *s*) values for foot ahead and foot behind distances.

Foot ahead (m)	Foot behind (m)	Flight distance (m)	Foot movement (m)
0.38 ± (.02)	0.48 ± (.03)	0.15 ± (.05)	0.15 ± (.01)

Correlations between these variables and other key kinematic variables are shown in Table 5.3. In addition, speed was not correlated with either foot ahead ratio (*r* = –.30, *p* = .136) or foot behind ratio (*r* = .13, *p* = .498). Both foot ahead and foot behind distances were positively correlated with step length, and negatively correlated with cadence (Figure 5.2). However, step length and cadence were not correlated with foot ahead when expressed as a ratio (*r* = –.001, *p* = .996 and *r* = –.33, *p* = .095 respectively). Foot behind ratio was correlated with step length (*r* = .40, *p* = .041) and step length ratio (*r* = .53, *p* = .005) but not with cadence (*r* = –.26, *p* = .187). Flight distance was not correlated with height, unlike both foot ahead and foot behind (Table 5.3) and foot movement distance (*r* = .51, *p* = .005). Finally, foot movement distance was negatively correlated with cadence (*r* = –.42, *p* = .003).

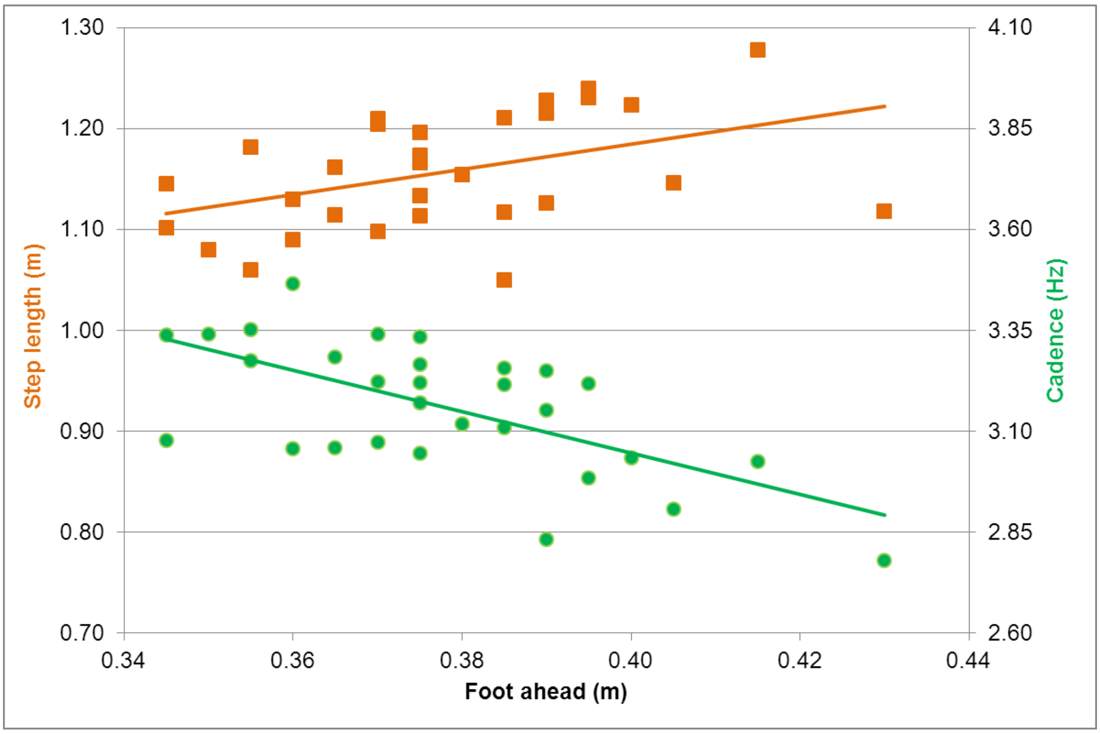


Figure 5.2. Foot ahead was positively correlated with step length (orange squares, *r* = .45) and negatively correlated with cadence (green circles, *r* = –.62).

5.3.1.3 Changes in velocity during foot ahead and foot behind

The mean decrease in velocity during foot ahead was –0.13 m/s (± .04), and the mean increase in velocity during foot behind was 0.14 m/s (± .05). There was no correlation between decrease in velocity and foot ahead distance (*r* = .36, *p* = .053), although there was a correlation between increase in velocity and foot behind distance (*r* = .37, *p* = .042). The increase in velocity was also positively correlated with pelvic rotation (*r* = .38, *p* = .040).

5.3.1.4 Stance:swing ratio

The mean stance:swing ratio was 47:53 (± 2). Lower stance proportions were found in athletes with higher speeds (*r* = –.57, *p* = .001), higher step length ratios (*r* = –.48, *p* = .011), longer flight distances (*r* = –.88, *p* < .001), and shorter foot ahead distances (absolute: *r* = .50, *p* = .005; ratio: *r* = .61, *p* = .001).

5.3.1.5 Vertical displacement

The mean vertical displacement of the CM was 49 mm (± 5). The vertical displacement of the CM was negatively correlated with cadence (*r* = –.41, *p* = .026).

5.3.1.6 Knee, hip and ankle joint angles

The lower limb joint angles are shown in Table 5.5, and relevant correlations between these and other key variables are shown in Table 5.7. Knee angle values at initial contact ranged from 175° to 186°, and between 181° and 198° at midstance (hyperextension lasted 72% (± 11) of stance time). The midstance angle at the hip was 190° (± 3), and 109° (± 4) at the ankle. The knee contact angle was positively correlated with flight time (r = .48, p = .007) and negatively correlated with contact time. During swing, maximum knee flexion was 106° (± 4). This was negatively correlated with speed (r = –.38, p = .036), flight distance (r = –.42, p = .022) and flight time (r = –.46, p = .010), and positively correlated with contact time (r = .37, p = .042). In Table 5.5, the hip angle figures of 170° and 190° represent means of 10° flexion at contact and 10° hyperextension at toe-off respectively. Hip and ankle toe-off angles were both correlated with foot movement distance (r = –.50, p = .005 and r = .42, p = .020 respectively).

Table 5.5. Mean (± *s*) values for lower limb joint angles (knee, hip and ankle).

Knee angles (°)			Hip angles (°)		Ankle angles (°)	
Contact	Midstance	Toe-off	Contact	Toe-off	Contact	Toe-off
181 (± 3)	190 (± 4)	154 (± 4)	170 (± 4)	190 (± 2)	103 (± 3)	126 (± 4)

5.3.1.7 Shoulder and elbow joint angles

Table 5.6 shows the shoulder and elbow angle values; important correlations are shown in Table 5.7. The shoulder's total range of motion from initial contact to toe-off was 108°. Twenty-four of the men had their largest recorded elbow angle at midstance, while 29 of the men had their smallest elbow angle at toe-off. The midstance angles for the shoulder and elbow were –24° (± 4) and 83° (± 7) respectively (the minus sign indicates hyperextension). There were no correlations found between the elbow at midstance and any other variables, but the shoulder angle at midstance was positively correlated with foot behind ratio ($r = .53$, $p = .004$) and negatively correlated with vertical displacement ($r = –.42$, $p = .020$). In addition to the correlations shown in Table 5.7, the elbow angle at toe-off was also correlated with stature ($r = .46$, $p = .015$).

Table 5.6. Mean (± *s*) values for shoulder and elbow joint angles and rotation values of the pelvic and shoulder girdles.

Shoulder angles (°)		Elbow angles (°)		Girdle rotation angles (°)	
Contact	Toe-off	Contact	Toe-off	Pelvis	Shoulders
–72 (± 7)	36 (± 4)	80 (± 8)	67 (± 6)	19 (± 4)	16 (± 2)

5.3.1.8 Pelvic and shoulder girdle rotation

Table 5.6 also shows the pelvic and shoulder girdle rotation values, and important correlations are shown in Table 5.7. The mean distortion angle was 34° (± 3) and as well as being correlated with foot behind absolute distance, it was also correlated with foot behind distance as a ratio ($r = .39$, $p = .047$).

Table 5.7. Correlation analysis of key angular variables across the World Cup sample. Correlations were significant at $p < 0.05$ (shown in bold).

	Speed	Step length (m)	Cadence	Contact time	Flight distance	Foot ahead (m)	Foot behind (m)
Knee (contact)	r = .28 p = .142	r = .11 p = .555	r = .19 p = .304	**r = –.52** **p = .003**	**r = .55** **p = .002**	r = –.36 p = .053	**r = –.44** **p = .014**
Hip (contact)	r = .23 p = .227	r = –.20 p = .300	**r = .46** **p = .011**	**r = –.52** **p = .001**	**r = .53** **p = .003**	**r = –.59** **p = .001**	**r = .62** **p < .001**
Ankle (contact)	r = .05 p = .811	r = –.08 p = .692	r = .11 p = .555	r = –.30 p = .114	r = .25 p = .184	**r = –.39** **p = .035**	r = .29 p = .116
Shoulder (contact)	**r = –.50** **p = .005**	r = –.18 p = .349	**r = –.38** **p = .037**	**r = .45** **p = .012**	**r = –.43** **p = .018**	r = .24 p = .196	r = .12 p = .519
Elbow (toe-off)	r = –.08 p = .691	r = .30 p = .103	**r = –.38** **p = .039**	**r = .40** **p = .030**	r = –.29 p = .121	**r = .57** **p = .001**	**r = .47** **p = .009**
Pelvic rotation	r = –.26 p = .173	r = .33 p = .076	**r = –.61** **p = .001**	**r = .58** **p = .001**	r = –.19 p = .314	r = .34 p = .065	**r = .51** **p = .004**
Shoulder rotation	r = .32 p = .086	r = .25 p = .192	r = .11 p = .550	r = –.24 p = .199	r = .27 p = .153	r = .04 p = .821	r = .00 p = .988
Distortion angle	r = –.11 p = .581	r = .34 p = .066	**r = –.45** **p = .013**	**r = .45** **p = .013**	r = –.09 p = .631	r = .28 p = .137	**r = .44** **p = .014**

5.3.1.9 Individual analysis of athletes

Table 5.8 shows the results for key performance variables of five individual athletes who competed over 50 km at the World Cup event. The winner's performance is the current World Record for the event, while the athlete who finished 14th was a former World Champion, and all three others have competed at the Olympic Games (IAAF, 2011b).

Table 5.8. Sample of individuals' results from the men's 50 km (World Cup).

Finishing position	1	14	31	46	59
Stature (m)	1.74	1.71	1.72	1.74	1.79
Speed (km/h)	14.49	13.61	12.75	12.16	11.20
Step length (m)	1.20	1.13	1.10	1.05	1.12
Step length ratio (%)	69.2	66.3	63.9	60.4	62.5
Cadence (Hz)	3.34	3.33	3.22	3.22	2.78
Foot ahead (m)	0.37	0.38	0.37	0.39	0.43
Foot ahead ratio (%)	21.3	21.9	21.5	22.1	24.0
Foot behind (m)	0.51	0.48	0.43	0.45	0.54
Foot behind ratio (%)	29.3	28.1	25.0	25.6	29.9
Flight distance (m)	0.17	0.16	0.18	0.07	0.00
Foot movement (m)	0.15	0.13	0.13	0.15	0.15
Pelvic rotation (°)	18	15	16	19	26
Shoulder rotation (°)	17	17	13	12	12
Knee at contact (°)	179	179	184	180	175
Knee at midstance (°)	187	181	190	187	183

5.3.2 European Cup variation data

5.3.2.1 Speed, step length and cadence

Table 5.9 shows the variations in speed, step length and cadence for the 12 athletes analysed at the European Cup, as well as the percentage decrease for each of these variables with regard to the previous measurement. Both speed and step length decreased from 38.5 to 48.5 km (p = .011 and p = .014 respectively) with no other changes. The mean walking speed at 48.5 km was 4.8% slower than at 18.5 km, with step length 4% shorter and cadence 0.6% lower.

Table 5.9. Mean (± *s*) values for variation in speed, step length, and cadence. Differences (overall and repeated contrasts) were significant at $p < 0.05$ (bold).

	Speed (km/h)	Step length (m)	Cadence (Hz)
18.5 km	14.11 (± .61)	1.25 (± .05)	3.14 (± .08)
28.5 km	14.15 (± .60)	1.24 (± .04)	3.16 (± .09)
38.5 km	**13.98 (± .76)**	**1.23 (± .05)**	3.16 (± .11)
48.5 km	**13.43 (± .71)**	**1.20 (± .05)**	3.12 (± .13)
Difference (%)	*0.3, –1.2,* ***–3.9***	*–0.8, –0.8,* ***–2.4***	*0.6, 0.0, –1.3*
ANOVA	$\boldsymbol{F_{1.71,18.76} = 9.35}$ $\boldsymbol{p = .002}$ $\boldsymbol{\eta^2 = .46}$	$\boldsymbol{F_{3,33} = 10.88}$ $\boldsymbol{p < .001}$ $\boldsymbol{\eta^2 = .50}$	$F_{3,33} = 1.91$ $p = .147$ $\eta^2 = .15$

5.3.2.2 Temporal variables and foot positioning

Table 5.10 shows the results for foot ahead, foot behind and flight distance. There were no changes for either foot ahead or foot behind, although flight distance decreased between 38.5 and 48.5 km (p = .037). Flight time was 0.02 ± .01 s at the first three measurement distances, and decreased from 38.5 to 48.5 km where it was 0.01 ± .01 s (p = .039); this is reflected in the decreases in flight distance as shown in Table 5.10. No changes were found for contact time (0.31 ± .02 s at all distances except 28.5 km, where it was 0.30 ± .02 s), or for stance:swing ratio, which was 47:53 (± 2) at 18.5 and 28.5 km, and 48:52 (± 2) at 38.5 and 48.5 km. In addition, there were no changes for decreases in velocity during foot ahead, or for increases in velocity during foot behind.

Table 5.10. Mean (± *s*) values for variation in foot ahead, foot behind and flight distance. Differences (overall and repeated contrasts) were significant at $p < 0.05$ (bold).

	Foot ahead (m)	Foot behind (m)	Flight distance (m)
18.5 km	0.38 (± .04)	0.55 (± .03)	0.15 (± .06)
28.5 km	0.37 (± .03)	0.55 (± .03)	0.15 (± .04)
38.5 km	0.37 (± .03)	0.54 (± .03)	**0.14 (± .05)**
48.5 km	0.38 (± .03)	0.54 (± .03)	**0.11 (± .05)**
Difference (%)	*–0.3, –0.3, 3.8*	*–0.5, –0.8, –0.9*	*3.4, –7.7,* ***–19.8***
ANOVA	$F_{1.79,19.69} = 0.11$ $p = .872$ $\eta^2 = .01$	$F_{3,33} = 1.74$ $p = .178$ $\eta^2 = .14$	$\mathbf{F_{1.98,21.73} = 3.49}$ $\mathbf{p = .049}$ $\mathbf{\eta^2 = .24}$

5.3.2.3 Angular data – lower limb

Table 5.11 shows variation data for the knee angle at three gait events. The only change was that knee contact angle decreased between 38.5 and 48.5 km; the range of knee angles at the final measurement distance was between 176° and 183°, and in total eight men had knee angles below 180° at this distance. By contrast, only one had a knee angle below 180° at midstance (178°). There was a small change in the ankle toe-off angle (less plantarflexion), from 127° (± 3) at 38.5 km to 124° (± 5) at 48.5 km (p = .043). However, there were no other changes for any lower limb joint angle at any gait event.

Table 5.11. Mean (± *s*) values for variation in knee angles. Differences (overall and repeated contrasts) were significant at p < 0.05 (bold).

	Knee (contact) (°)	Knee (midstance) (°)	Knee (swing) (°)
18.5 km	179 (± 2)	185 (± 5)	101 (± 3)
28.5 km	179 (± 2)	185 (± 5)	101 (± 4)
38.5 km	**180 (± 2)**	186 (± 4)	101 (± 4)
48.5 km	**178 (± 2)**	185 (± 5)	102 (± 4)
Difference (%)	*0.1, 0.6,* ***–0.9***	*0.1, 0.6, –0.3*	*0.0, –0.6, 0.9*
ANOVA	$F_{3,33}$ = 2.45 p = .081 η^2 = .18	$F_{3,33}$ = 1.51 p = .230 η^2 = .12	$F_{3,33}$ = 0.34 p = .799 η^2 = .03

5.3.2.4 Angular data – upper limb

Table 5.12 shows variation data for upper limb joints at different gait events. These variables were the only ones that changed between measurement distances when measured using repeated contrasts. However, there was an overall effect found for elbow angle at initial contact, which decreased from 81° (± 12) at 18.5 km to 76° (± 9) at 48.5 km ($F_{3,33} = 3.76$, $p = 0.020$, $\eta^2 = 0.26$).

Table 5.12. Mean (± *s*) values for variation in upper limb angles. Differences (overall and repeated contrasts) were significant at $p < 0.05$ (bold).

	Elbow (midstance) (°)	Shoulder (midstance) (°)	Shoulder (toe-off) (°)
18.5 km	86 (± 11)	30 (± 5)	**40 (± 5)**
28.5 km	87 (± 13)	29 (± 6)	**39 (± 6)**
38.5 km	**86 (± 11)**	**28 (± 5)**	39 (± 5)
48.5 km	**83 (± 9)**	**26 (± 5)**	39 (± 4)
Difference (%)	*1.4, –1.4,* ***–3.0***	*–5.1, –0.9,* ***–7.4***	***–3.7****, 0.4, –1.5*
ANOVA	$F_{1.67,18.34} = 3.46$ $p = .060$ $\eta^2 = .24$	**$F_{3,33} = 3.15$** **$p = .038$** **$\eta^2 = .22$**	$F_{3,33} = 2.82$ $p = .054$ $\eta^2 = .20$

5.3.2.5 Angular data – upper body rotation

Table 5.13 shows the values for pelvic girdle and shoulder rotation, as well as distortion angle, at each of the four measurement distances.

Table 5.13. Mean (± *s*) values for variation in pelvic and shoulder girdle rotation and distortion angle. Differences (overall and repeated contrasts) were significant at $p < 0.05$ (bold).

	Pelvic rotation (°)	Shoulder rotation (°)	Distortion angle (°)
18.5 km	**21 (± 3)**	18 (± 3)	**38 (± 3)**
28.5 km	**19 (± 2)**	19 (± 3)	**36 (± 2)**
38.5 km	18 (± 3)	18 (± 3)	**36 (± 2)**
48.5 km	17 (± 3)	18 (± 3)	**34 (± 3)**
Difference (%)	***–10***, *–2, –5*	*1, –4, –2*	***–4***, *–2,* ***–5***
ANOVA	**$F_{3,33}$ = 5.75** **p = .003** **η^2 = .34**	$F_{3,33}$ = 1.86 p = .156 η^2 = .15	**$F_{1.79,19.69}$ = 8.00** **p = .004** **η^2 = .42**

5.3.2.6 Analysis of individual athletes

To complement the overall findings on men competing over 50 km, individual athletes' results for key mechanical variables have been presented in Tables 5.14 and 5.15 below. All four athletes have competed at either the Olympic Games or World Championships in Athletics (IAAF, 2011b).

Table 5.14. Sample of individuals' results from the men's 50 km (7th European Cup).

Posn.	Distance (km)	Speed (km/h)	Step length (m)	Step length ratio (%)	Cadence (Hz)
1	18.5	15.00	1.31	77.2	3.18
	28.5	14.86	1.27	74.9	3.24
	38.5	15.33	1.30	76.2	3.28
	48.5	14.99	1.27	74.6	3.28
10	18.5	14.52	1.26	70.0	3.20
	28.5	14.61	1.26	70.0	3.22
	38.5	13.87	1.20	66.8	3.20
	48.5	13.36	1.19	66.0	3.13
17	18.5	14.22	1.31	68.7	3.01
	28.5	13.93	1.29	67.3	3.01
	38.5	13.91	1.30	67.9	2.98
	48.5	13.15	1.25	65.7	2.91
26	18.5	13.40	1.20	66.6	3.11
	28.5	13.35	1.20	66.6	3.09
	38.5	13.43	1.20	66.5	3.12
	48.5	12.62	1.16	64.2	3.03

Table 5.15. Extended sample of individuals' results from the men's 50 km (7th European Cup).

Posn.	Distance (km)	Foot ahead (m)	Foot behind (m)	Flight distance (m)	Pelvic rotation (°)	Shoulder rotation (°)
1	18.5	0.32	0.55	0.26	21	13
	28.5	0.39	0.54	0.17	19	14
	38.5	0.32	0.56	0.25	22	13
	48.5	0.31	0.54	0.24	19	14
10	18.5	0.37	0.59	0.16	21	21
	28.5	0.38	0.57	0.16	17	22
	38.5	0.37	0.55	0.11	18	20
	48.5	0.36	0.54	0.11	14	18
17	18.5	0.41	0.56	0.16	21	20
	28.5	0.41	0.56	0.16	22	19
	38.5	0.39	0.58	0.15	20	19
	48.5	0.40	0.58	0.11	22	17
26	18.5	0.37	0.51	0.15	21	17
	28.5	0.36	0.53	0.12	19	19
	38.5	0.36	0.51	0.15	17	19
	48.5	0.35	0.52	0.11	19	19

5.3.2.7 Correlation changes with distance walked

Associations found between key performance variables at each distance of measurement during the 7th European Cup are shown below in Figures 5.3 to 5.7. Where appropriate, a dashed horizontal line shows the critical value of the correlation coefficient ($r = 0.576$) required for significance at the 5% level (Thomas & Nelson, 1996) (this has been shown for both positive and negative correlations). The variables chosen for analysis were those considered most important based on the hierarchical model of race walking and the results found for correlations in the World Cup race. The correlations between speed and step length and cadence at each measurement distance in the 50 km race are shown in Figure 5.3. The coefficients of determination (R^2) for step length and speed decreased from 0.66 at 18.5 km to 0.58 at 28.5 km, 0.54 at 38.5 km, and 0.39 at 48.5 km. By contrast, the values for cadence and speed increased from 0.18 at 18.5 km to 0.36 at 28.5 km, and 0.49 at both 38.5 km and 48.5 km.

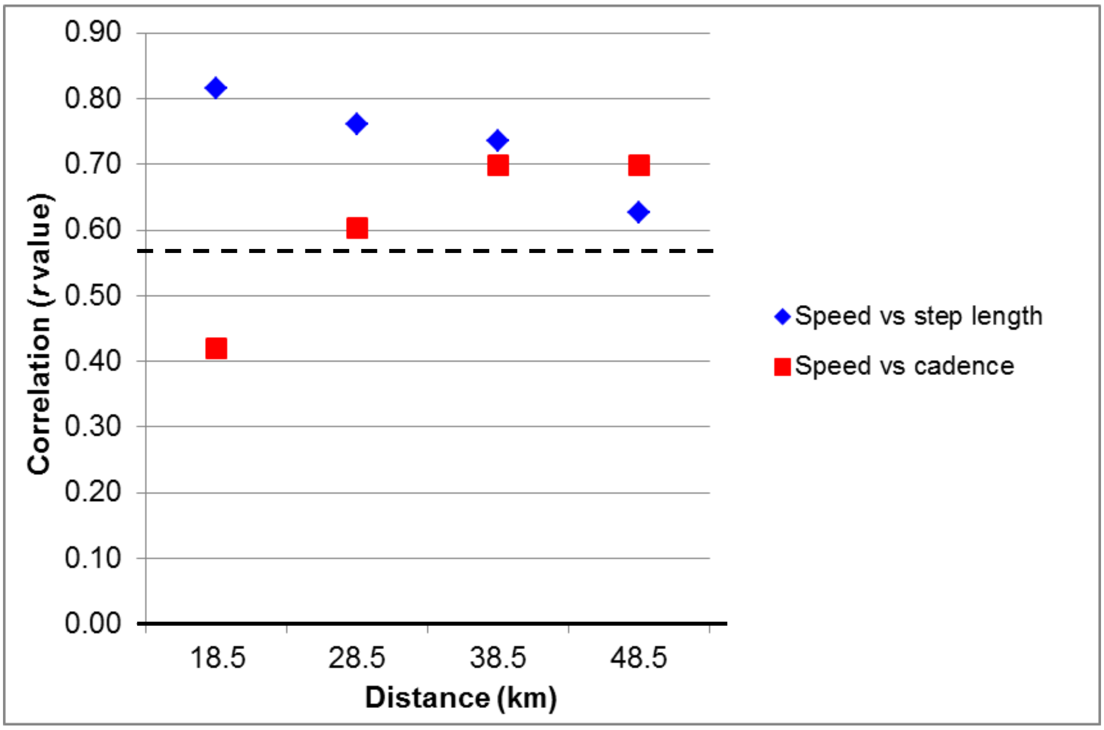


Figure 5.3. Correlations (*r*) between speed and step length and cadence in the men's 50 km event at each measurement distance.

Figure 5.4 shows the correlations between speed and contact time and flight time. The coefficients of determination for contact time were quite consistent at all four measurement distances (0.54, 0.66, 0.56 and 0.50 respectively) but those found for flight time decreased with distance walked (0.40, 0.32, 0.26 and 0.06 respectively).

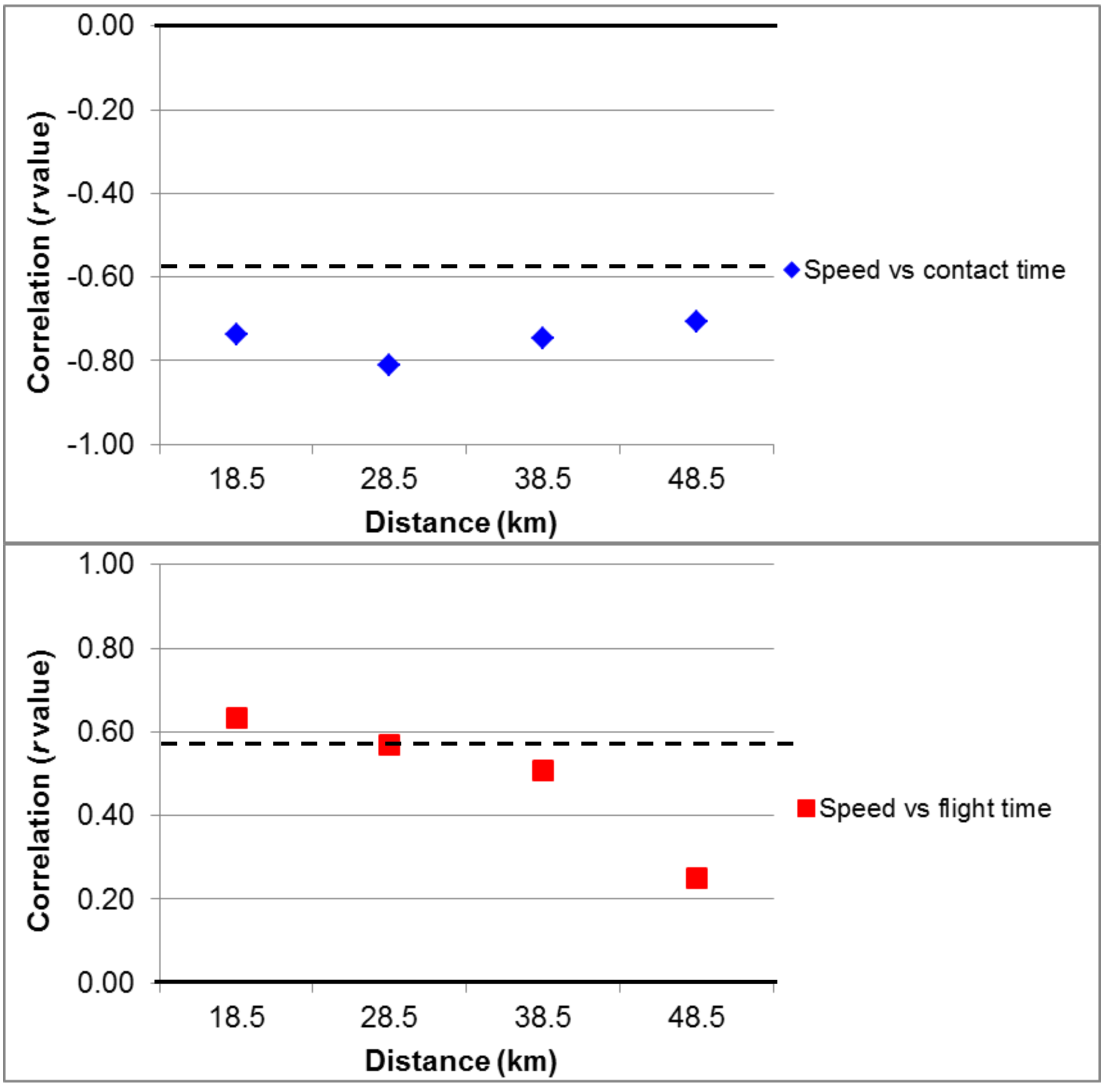


Figure 5.4. Correlations (*r*) between speed and contact time and flight time in the men's 50 km event at each measurement distance.

The three main components of step length (foot ahead, foot behind and flight distance) have been correlated with speed (Figure 5.5), step length (Figure 5.6) and cadence (Figure 5.7). With regard to speed, R^2 values varied at the four measurement distances for foot ahead (0.39, 0.01, 0.16, and 0.06) and foot behind (0.37, 0.18, 0.40 and 0.14), while the flight distance values were higher at every distance (0.67, 0.46, 0.42, and 0.31). The R^2 values for step length versus foot ahead were very low (0.15, 0.04, 0.00 and 0.01) but were higher for both foot behind (0.56, 0.75, 0.75 and 0.56) and flight distance (0.36, 0.26, 0.21 and 0.20). The R^2 values for cadence versus these three distances were generally lower than those for step length; for foot ahead they were 0.23, 0.17, 0.26, and 0.03 respectively, while for foot behind they were 0.02, 0.16, 0.00 and 0.03 respectively, and for flight distance they were 0.20, 0.18, 0.22 and 0.08 respectively.

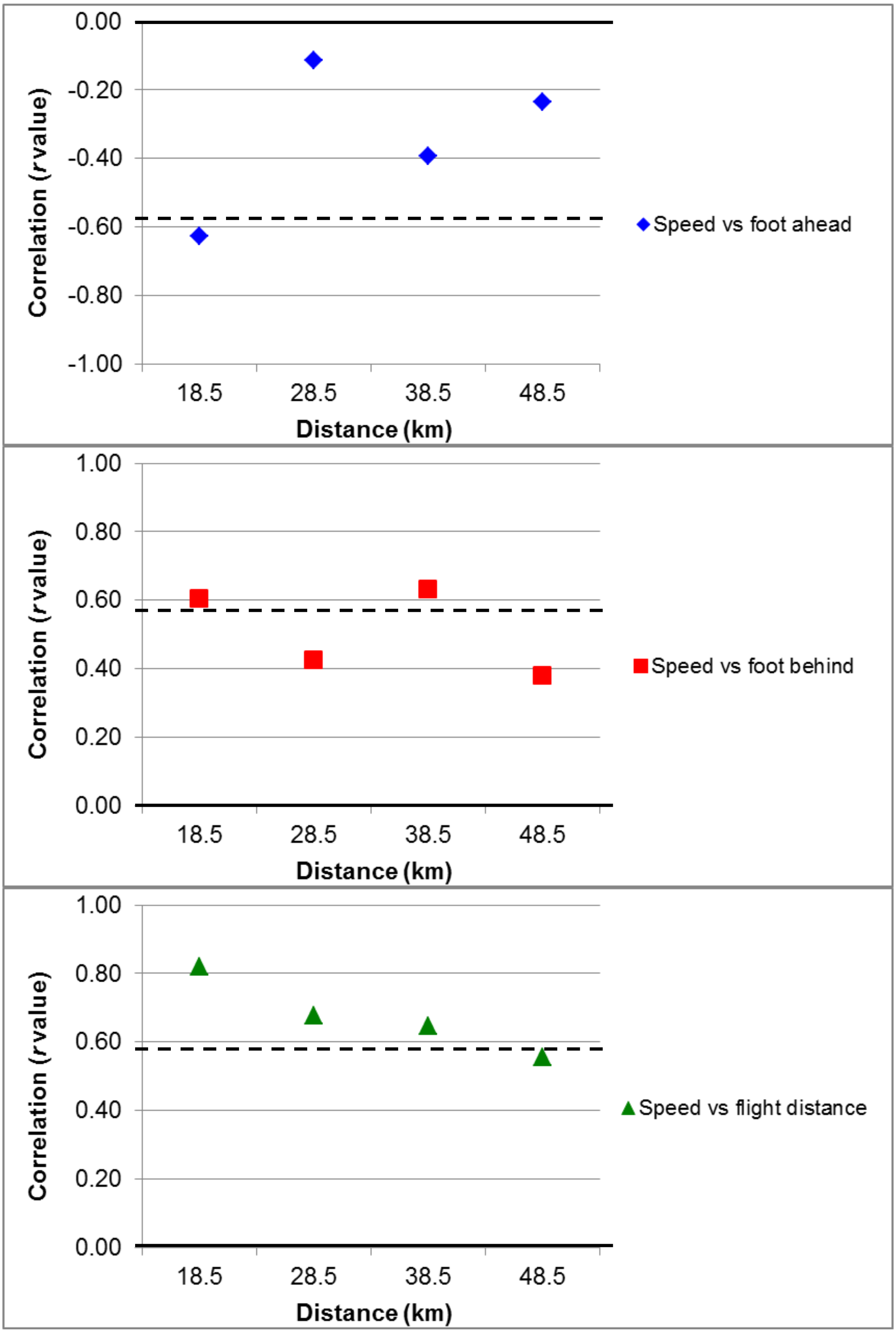


Figure 5.5. Correlations (*r*) between speed and step length components in the men's 50 km event at each measurement distance.

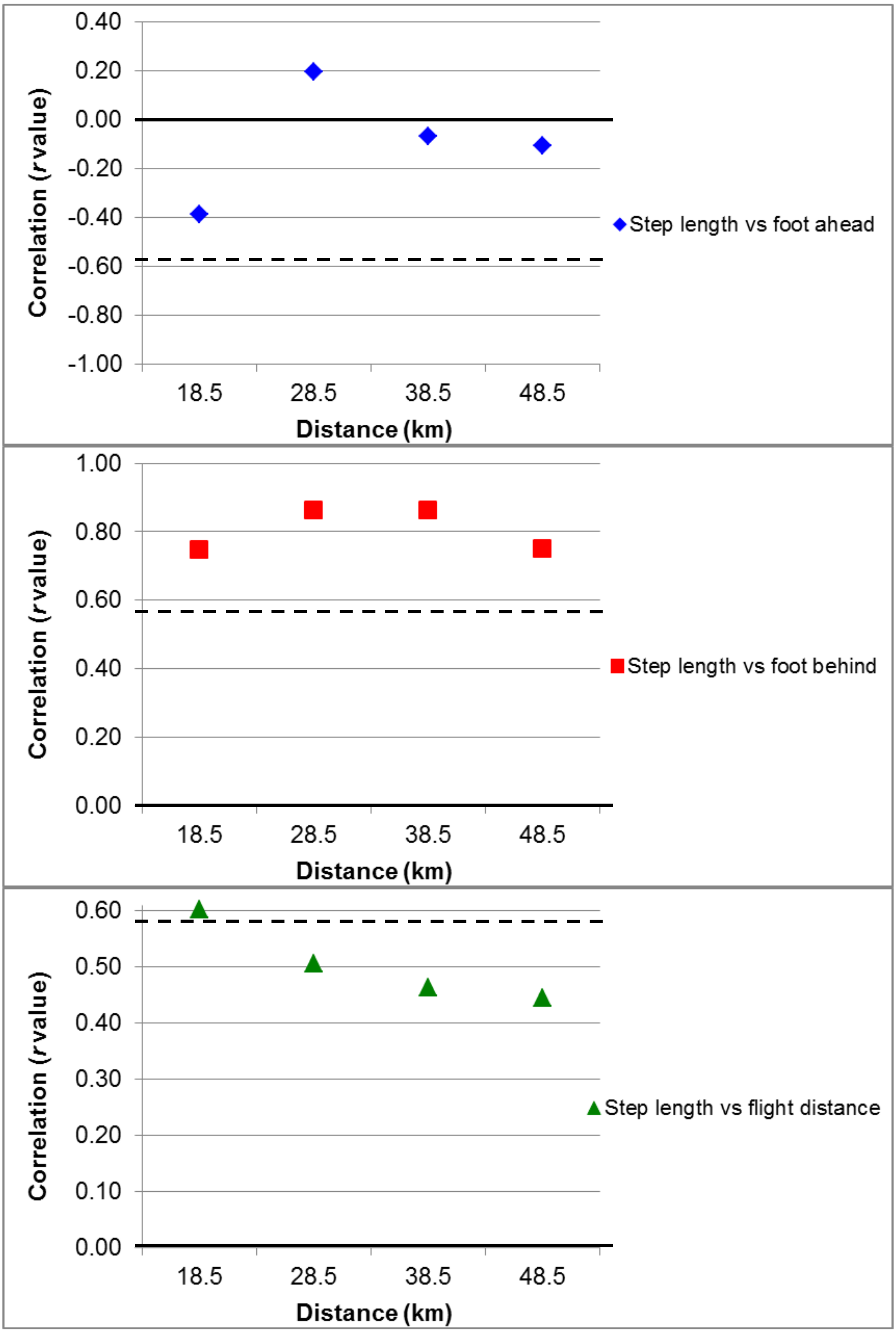


Figure 5.6. Correlations (*r*) between step length and step length components in the men's 50 km event at each measurement distance.

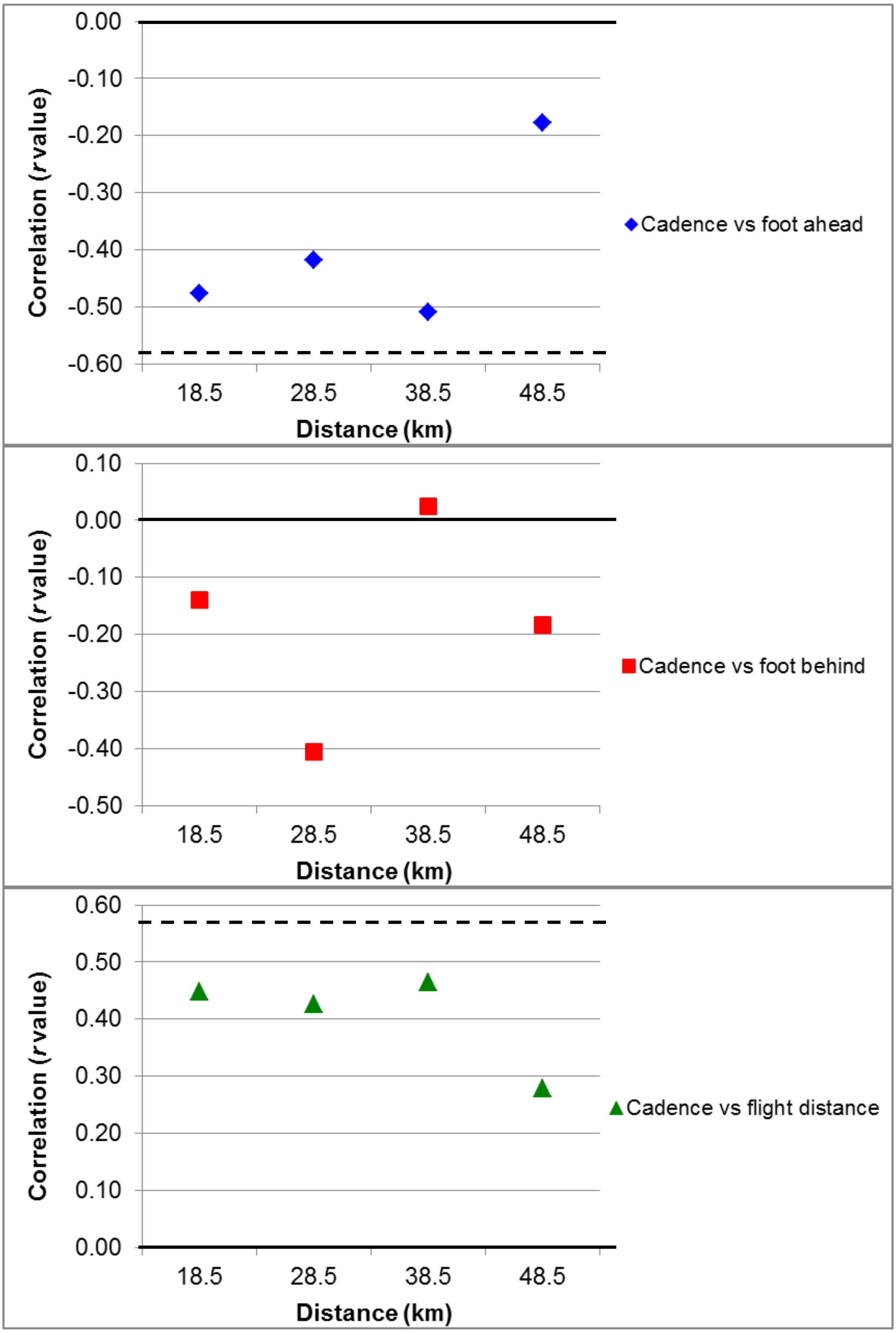


Figure 5.7. Correlations (*r*) between cadence and step length components in the men's 50 km event at each measurement distance.

5.4 Discussion

5.4.1 Predictors of faster race walking

The first objective of this study was to identify key kinematic variables in determining success in elite men's 50 km race walking; comparisons with 20 km race walking were also important and are dealt with in Chapter 7 (Summary of Competition Studies). The results showed that both step length and cadence were correlated with race walking speed. Because step length was negatively correlated with cadence, it could appear that too great a step length might have a negative effect on speed, and this in turn would suggest that taller athletes with naturally longer steps would be at a disadvantage compared with shorter athletes. However, this might not necessarily be the case as the negative correlation between step length and cadence was not present when step length was normalised as step length ratio. A key element of race walking is therefore optimising step length, which can be achieved through the avoidance of either under- or overstriding. This appeared evident as longer foot ahead and foot behind distances were also associated with decreased cadence when expressed as absolute measurements. But as with step length, neither of these variables was correlated with cadence in these athletes when expressed as ratios. With a mean speed of 14.17 km/h, the fastest five athletes had step length ratios between 66 and 71%, foot ahead ratios between 21 and 22%, and foot behind ratios between 26 and 29% (the winner of the race was a good example of these values as shown in Table 5.8). By contrast, the individual analysis data showed that the slowest athlete measured had a step length ratio of only 62.5%, but large foot ahead (24.0%) and foot behind ratios (29.9%) that might have been partly responsible for his low cadence (2.78 Hz). Athletes should be mindful of developing technique with these ratios in mind to minimise any negative effects on cadence, and consequently race walking speed.

Cadence is determined by step time, itself comprised of contact time and flight time. Contact time was negatively correlated with speed and it is therefore important for race walkers to reduce its duration so that the stance:swing ratio is reduced, although this also requires an increase in flight time. Longer flight times were positively correlated with speed because of their association with longer flight distances and hence longer step length ratios. Flight distance was an important contributor to overall step length (mean of 13%), and the results of the individual analyses showed that for the athlete in 59th position, who had no flight distance, to have a step length just 2 cm shorter than the athlete in 14th (flight distance of 16 cm) required a foot ahead distance 5 cm longer, a foot behind distance 6 cm longer, and a foot movement distance 2 cm longer. All of these longer distances contributed to a lower cadence and a slower overall performance. Even though 50 km walkers have lower walking speeds than 20 km competitors, high-standard performances are still dependent to some extent on flight time. However, 50 km athletes are advised to restrict their step lengths to those within the range of ratios mentioned above to avoid the risk of disqualification due to visible loss of contact.

Disqualification in race walking can also occur if the knee is not fully extended from initial contact to midstance. The data showed that most competitors had full or nearly full knee extension at both of these gait events (although the athlete in 59th position had a knee contact angle of 175° and received three yellow paddles and one red card, indicating he was on the threshold of what would be deemed acceptable). Full knee extension at initial contact did not appear to have a negative impact on performance; rather, knee extension was correlated with decreased contact time and increased flight time. However, this might not indicate that fully extended knees provide a biomechanical advantage to the athlete but rather that the fastest athletes are the most technically proficient, including legal knee movements. The mean swing knee angle (106° ± 4) did not flex to a minimum of 90° as recommended by coaches (Hopkins, 1978), although smaller angles were associated with faster speeds and longer flight distances, suggesting that the knee's movement is important in elite race walking during swing as well as during stance. Other lower limb joint angles at initial contact were associated with key parameters: greater hip flexion and ankle dorsiflexion angles allowed for longer foot ahead distances, and while an athlete might try to augment foot ahead distance by increasing these angles, it should be remembered that foot ahead ratio needs to be optimised to about 21% to prevent reduced cadence.

The movement of the upper limb is also believed to be important in race walking technique (e.g. Hopkins, 1981). In this study, 50 km athletes who swung their arms too far behind the body during shoulder hyperextension at ipsilateral initial contact were found to have reduced speeds and cadences, and greater elbow angles at toe-off were also correlated with lower cadences. These findings contradict earlier coaching advice that suggested that a "strong upward swing of both arms" (Payne & Payne, 1981, p.366) and an elbow angle of 90° (e.g. Villa, 1990) were of benefit to the elite race walker (the mean at toe-off was only 67° ± 6). Instead, it is possible that the swing movement of the shoulders and arms is a passive reaction driven by movement in the legs and pelvis, as suggested in normal walking and running

(Pontzer et al., 2009), and this could be a worthwhile topic for investigation in future research. Regardless, and based on the current research findings, specific focus should be placed on an optimised arm swing that does not result in reduced cadence.

With regard to trunk rotational movements, no associations were found between pelvic rotation and either step length or speed, and contrary to speculation by coaches (Fruktov et al., 1984), cadence was not positively but negatively associated with pelvic rotation. Because one aim of pelvic rotation is to reduce the stride width (Fenton, 1984), it appeared only to be necessary to achieve the amount of pelvic rotation required to walk along a straight line and not beyond it (which could happen with excessive pelvic rotation). It was noticeable that the slowest of the individual athletes analysed (in 59th place) had 7° more pelvic rotation than average, and it is possible that this magnitude was required to obtain the long foot ahead and foot behind distances that he did (because of an absence of flight distance as mentioned earlier). A lack of a flight period might therefore not only result in slower walking speeds, but also require exaggerated movements, such as those of the pelvis, in order to achieve a productive step length (pelvic rotation was indeed correlated with foot behind distance). The magnitude of shoulder girdle rotation was slightly smaller than the pelvic rotation counterbalanced (as was its standard deviation), and did not correlate with any other performance parameters. Each athlete had his own unique style but coaches should be aware that particular aspects of an individual’s technique can be detrimental so the development of both upper and lower body technique should not be ignored.

5.4.2 Kinematic variations during 50 km race walking

The second objective of this study was to measure variations in key mechanical variables at different distances in a separate European Cup event. On average, the competitors in this part of the study slowed down by 0.68 km/h between 18.5 and 48.5 km, with most of this decrease (0.55 km/h) occurring after 38.5 km. Of course, there was variation between athletes; for example, the individual analyses showed that the race winner was fastest at 38.5 km and his speed at 48.5 km was practically the same as at 18.5 km. Mean step length decreased by 5 cm between 18.5 km and 48.5 km, and as mean cadence did not change it would appear that it was the decrease in step length (itself presumably caused by cardiovascular and muscular fatigue) that was the primary reason the athletes slowed down. Despite its reduction, longer step lengths were found to be associated with faster race walking at all four measurement distances, showing that had the athletes maintained their earlier, longer steps, they would have had improved performances, and athletes should thus try to rely on step length for as long as possible (because longer steps allow the muscles to have more time to work). While mean cadence did not change, its positive correlation with race walking speed did increase as the race progressed (from r = 0.42 at 18.5 km to r = 0.70 at both 38.5 km and 48.5 km). The increase in R^2 values for cadence (from 0.18 at 18.5 km to 0.49 at 48.5 km) with the simultaneous decrease in R^2 values for step length (from 0.66 at 18.5 km to 0.39 at 48.5 km) showed that the variance in speed at the end of the race was accounted for more by cadence, and the importance of maintaining a relatively high cadence in elite 50 km race walking is therefore most evident in the latter stages of the race (when walking speeds tend to decrease considerably) and could be what defines the very best athletes in terms of ultimate finishing positions. However, even at 48.5 km, the combined R^2 values for step length and cadence accounted for only 88% of the variance in speed and thus showed that there are other mechanical variables that explain this variance.

One reason why cadence might have been consistent throughout the race was actually because of the decrease in step length (i.e. the steps were shorter and therefore quicker to complete). While contact time did not change (and longer contact times were consistently associated with slower walking), flight time did decrease from 38.5 km to 48.5 km, and it was the resulting decrease in flight distance (3 cm) that seemed to have been responsible for the decrease in step length. This was also quite clear from the results of the individual analyses where the three slower athletes had their slowest speeds and shortest flight distances at 48.5 km. By contrast, the two other main components of step length, foot ahead and foot behind distance, did not change with distance walked and their correlations with step length were relatively consistent. Flight distance and speed were found to be positively correlated at the first three measurement distances, and thus further highlighted (as in the World Cup results) the critical role flight distance plays in elite race walking. Of course, correlations only explain part of the relationship between variables and the derived R^2 values were also informative with regard to the importance of these three distances, and to step length in particular. The foot ahead distance accounted for very little of the variance in step length, whereas between them the foot behind and flight distances accounted for between 76% and 100% of this variance throughout the race and showed the importance of maintaining the length of these distances as the race progressed. Flight distance contributed less of the variance in both step length and speed at 48.5 km compared with earlier distances, and showed that the underlying neuromuscular mechanisms responsible were fatigued as the athletes neared the finish.

With regard to important angular data, the mean knee angles at initial contact were 2° lower at 48.5 km than at 38.5 km. This suggests that there might be an increased risk of disqualification in the closing stages of the race, particularly as eight of the 12 men analysed had initial contact knee angles below 180° at this final distance. However, the judging records showed that only one of these 12 athletes received a red card for bent knees at any time during the race and indicated that the knees might have appeared straightened to the judges at angles slightly less than 180°. The fact that most of the athletes had hyperextended knees by midstance might also be a reason that bent knees at initial contact were not obvious. Regardless, the decrease in initial contact knee angle might have been too small to be meaningful given normal individual variation and measurement error, and in general it can be seen that these elite race walkers were able to maintain legal knee movements during stance that allowed them to finish the competition.

Decreases in mean pelvic rotation (and consequently distortion angle) and ankle plantarflexion at toe-off occurred as the race progressed. These could be indicators that the athletes were no longer able to maintain earlier, optimal joint kinematics because of greater muscular fatigue. This meant that for most athletes there was no means by which pelvic rotation could become a compensatory mechanism to prevent the decreases in step length caused by reduced flight distance; by contrast, the analysis of individuals showed that, for the winner, pelvic rotation and step length increased and decreased in tandem, and might be an indication of less fatigue in the most successful race walkers. Likewise, the reduction in elbow midstance angle throughout the race was possibly an attempt to reduce the moment of inertia and lower the energy required to swing the arms (Hopkins, 1985), thereby preventing even greater reductions in shoulder angular displacement. However, as with the knee joint, the decreases in angular displacement were relatively small, and rather than describing a deterioration of technique, are possibly more indicative of elite 50 km athletes' abilities to maintain high-quality technique despite fatigue. Indeed, the ability to maintain technique might have been one reason why race walking speed did not decrease more than it did in the final stages. It should be noted that the athletes analysed for this part of the study were very much world-class athletes, as the fastest 10 all achieved an 'A' standard in this race for that year's (2007) World Championships in Athletics, while the slower two achieved the 'B' standard and did in fact compete in that year's World Championships (IAAF, 2011a). While there were some clear effects of fatigue in this study (e.g. slower final mean walking speeds, shorter step lengths), such effects might be more noticeable in less well-trained athletes, and coaches should note that training to maintain technique throughout the 50 km race despite fatigue is a fundamental skill that requires considerable practice beforehand.

With regard to practical implications for 50 km athletes and coaches, the key areas an athlete must optimise are step length (and the distances to the support foot at initial contact and toe-off) and cadence (through the reduction of contact time and avoidance of visible flight times). An important finding was that longer steps do not negatively affect cadence if they are within a certain range of step length ratios (between about 66 and 71%). Foot ahead and behind distances were determined partially by lower limb joint angles that the coach must scrutinise to ensure an efficient technique. Monitoring adherence to the straightened knee rule is paramount; ideally, the coach should work with the athlete to ensure that correct technique is developed before competition is attempted. An athlete who struggles to complete shorter races because of disqualification should not attempt the 50 km distance until problematic aspects are corrected. Notwithstanding the importance of being able to maintain an efficient race walking technique, athletes and coaches are also advised to take race tactics such as pacing strategies into account to reduce the likelihood of dropping out or disqualification.

5.5 Conclusion

The 50 km race walk is a highly technical event in which the athletes must optimise a number of interrelated variables while maintaining legal technique despite possible fatigue. The key findings of this study on elite 50 km race walkers are:

- The fastest five athletes had step length ratios between 66 and 71%, foot ahead ratios between 21 and 22%, and foot behind ratios between 26 and 29%;
- Step length was negatively correlated with cadence, but as this correlation was not present when step length was normalised as step length ratio, the range of ratios above is a strong indicator of optimum step lengths and foot positions that can help avoid under- or overstriding;
- While the underlying causes of reduced pace towards the end of the 50 km race might ultimately be physiological in nature (e.g. reduction in

carbohydrate stores, or increased core temperature), slower speeds during the latter stages of the race were ultimately due to decreased step length. Because of this, the importance of maintaining a high cadence in the latter stages was crucial and could be what defines the very best athletes in terms of finishing position (particularly as its association with speed increased with distance walked);

- Flight distance had a critical role in longer steps and faster speeds even though the 50 km athletes tended to have relatively short flight times. The results from the European Cup showed that flight distance and speed were correlated at the first three measurement distances, and furthermore the decrease in flight distance towards the end of the race was a key factor in reduced step length (foot ahead and foot behind did not change);
- Full knee extension at initial contact did not have a negative impact on performance; instead, knee extension was correlated with decreased contact time and increased flight time. The results showed that these world-class athletes were able to maintain their high-quality techniques (including straightened knees) despite fatigue and this is a key indicator of elite 50 km race walking;
- There was evidence that greater angular displacements at the shoulder and pelvic girdle led to reduced cadence, possibly because completing such large movements requires more time and hence increases the duration of each step. Therefore, athletes and coaches should be aware that more pelvic rotation is not necessarily ‘better’ (the mean was 19°) as the effort required to achieve it might detract from more beneficial activity;
- 50 km athletes who swung their arms too far behind the body were found to have reduced speeds and cadences, which contradicted coaching advice that increased arm action improves race walking performance. Instead, coaches should be watchful to ensure that arm movements are not over-exaggerated;
- The mean elbow angle was 80° and therefore less than the 90° recommended by many coaches. Coaching advice should now take into account these new data, particularly as greater elbow angles at toe-off were correlated with lower cadences, and they decreased with fatigue (suggesting arms with elbow angles that are too large can be more difficult to swing).

CHAPTER 6

STUDY 3: JUNIOR 10 KM COMPETITIONS

6.1 Introduction

Most biomechanical research in race walking has been on senior athletes and by contrast there have been very few studies of elite junior race walkers. Understanding aspects of elite junior race walking might not only help appreciate the progression from junior to senior competition (Douglass & Garrett, 1984), but also add to the body of knowledge with regard to which biomechanical variables are important throughout all competitive stages. This is important as many elite junior race walkers become (or aim to become) elite competitors at senior standard (Vallance, 2005). Of course, not all junior athletes are as successful at becoming senior champions or even at qualifying for global championships at senior standards (Hollings & Hume, 2010). It is possible that certain variables are more important to success in junior competition than in senior competition (because of lack of physical or technical development, or because the competitive distance is shorter) and the identification of these variables could inform coaches as to why particular junior athletes do or do not progress to become successful senior athletes. The objective of this part of the study was to analyse junior athletes competing in international competition in order to identify the key kinematic variables, and to compare junior male and female race walkers to see if gender differences were present.

6.2 Methods

6.2.1 Participants

Video data were collected at the 8th European Cup Race Walking. Most athletes in both races were analysed at the 6.5 km distance, although some who were obstructed from the cameras' view at this distance were analysed at 4.5 km instead. It was not possible to obtain the athletes' heights and weights (as in the previous studies on senior athletes) as these data are generally not recorded for junior athletes. This means that it was not possible to calculate normalised variables (e.g step length ratio). Twenty junior men and 20 junior women were analysed in each race. Amongst the junior men, the analysed competitors included the 2008 World Junior champion, the 2009 World Youth champion, and the 2007 World Youth championship bronze medallist (a youth is defined as an athlete 18 years of age or younger in the year of competition). Amongst the junior women, the analysed competitors included the 2008 World Junior champion and the 2007 World Youth championship bronze medallist. From the judging records of the analysed athletes over the course of the race, four junior men received one red card each for loss of contact, and five received one red card each for not straightening their knee correctly. Of the analysed junior women, four athletes received one red card each for loss of contact. With regard to not straightening the knee correctly, one junior woman received two red cards and one other junior woman received one red card.

A summary of the race performances from both events is presented in Table 6.1. The World Junior Record for each event is also presented. No athletes from either competition who did not finish or were disqualified have been included in the study.

Table 6.1. Race performances from the 8th European Cup (mean ± *s*).

	Time (min:s)	Time (min:s)
	Junior men (N=20)	**Junior women (N=20)**
Mean finishing time	45:53 (± 3:06)	51:20 (± 3:20)
Range	41:22 – 52:01	44:16 – 57:13
World Junior Record	37:44	41:57

6.3 Results

6.3.1 Speed, step length and cadence

The values for walking speed, step length and cadence for junior men and women are shown in Table 6.2, and correlations between these and other key race walking variables are shown in Tables 6.3 and 6.4 respectively. In both groups of athletes, speed was positively correlated with step length (Figure 6.1) and cadence (Figure 6.2). With regard to the components of step length, in the junior men's group foot ahead comprised 33% of total step length, foot behind 39%, flight distance 14%, and foot movement 14%. In the junior women's group the respective ratios were 34%, 43%, 9% and 15%.

Table 6.2. Mean (± *s*) and between-subjects effects of key race walking variables. Differences were significant at $p < 0.05$ (bold). Effect sizes were based on Cohen's *d* and indicated when very large (‡), large (†), or moderate (*).

	Junior men	Junior women	*p*	95% CI
Speed (km/h)	13.36 (± 1.04)	11.61 (± .96)	**< .001**	**1.11 to 2.39†**
Step length (m)	1.16 (± .07)	1.01 (± .05)	**< .001**	**.112 to .192‡**
Cadence (Hz)	3.21 (± .15)	3.20 (± .13)	.861	–.084 to .100
Contact time (s)	0.29 (± .02)	0.31 (± .03)	**.010**	**–.038 to –.006***
Flight time (s)	0.03 (± .02)	0.01 (± .01)	**.003**	**.005 to .025***
Contact time (%)	92.0 (± 5.6)	96.7 (± 4.0)	**.004**	**–7.92 to –1.66***
Foot ahead (m)	0.38 (± .03)	0.34 (± .02)	**< .001**	**.025 to .058†**
Foot behind (m)	0.45 (± .03)	0.43 (± .02)	**.040**	**.001 to .034***
Flight distance (m)	0.17 (± .06)	0.09 (± .06)	**< .001**	**.039 to .118†**
Foot movement (m)	0.17 (± .02)	0.15 (± .02)	**.008**	**.004 to .023***

Table 6.3. Correlation analysis of key race walking variables across the 8th European Cup junior men's sample. Correlations were significant at $p < 0.05$ (bold).

	Step length	Cadence	Contact time	Flight distance	Foot ahead (m)	Foot behind (m)
Speed	**$r = .80$ $p < .001$**	**$r = .61$ $p = .004$**	**$r = –.75$ $p < .001$**	**$r = .77$ $p < .001$**	$r = –.07$ $p = .772$	$r = .38$ $p = .100$
Step length		$r = .02$ $p = .937$	$r = –.34$ $p = .143$	**$r = .70$ $p = .001$**	$r = .18$ $p = .461$	**$r = .75$ $p < .001$**
Cadence			**$r = –.79$ $p < .001$**	$r = .36$ $p = .117$	$r = –.32$ $p = .170$	$r = –.38$ $p = .099$
Contact time				**$r = –.79$ $p < .001$**	**$r = .52$ $p = .019$**	$r = .16$ $p = .511$
Flight distance					**$r = –.48$ $p = .034$**	$r = .17$ $p = .477$
Foot ahead (m)						$r = .31$ $p = .178$

Table 6.4. Correlation analysis of key race walking variables across the 8th European Cup junior women's sample. Correlations were significant at $p < 0.05$ (bold).

	Step length	Cadence	Contact time	Flight distance	Foot ahead (m)	Foot behind (m)
Speed	***r* = .91** ***p* < .001**	***r* = .82** ***p* < .001**	***r* = –.93** ***p* < .001**	***r* = .83** ***p* < .001**	*r* = –.33 *p* = .154	*r* = .41 *p* = .075
Step length		***r* = .51** ***p* = .022**	***r* = –.80** ***p* < .001**	***r* = .85** ***p* < .001**	*r* = –.29 *p* = .224	***r* = .56** ***p* = .011**
Cadence			***r* = –.82** ***p* < .001**	***r* = .55** ***p* = .012**	*r* = –.28 *p* = .227	*r* = .10 *p* = .685
Contact time				***r* = –.89** ***p* < .001**	***r* = .48** ***p* = .031**	*r* = –.14 *p* = .546
Flight distance					***r* = –.62** ***p* = .003**	*r* = .27 *p* = .259
Foot ahead (m)						*r* = –.03 *p* = .905

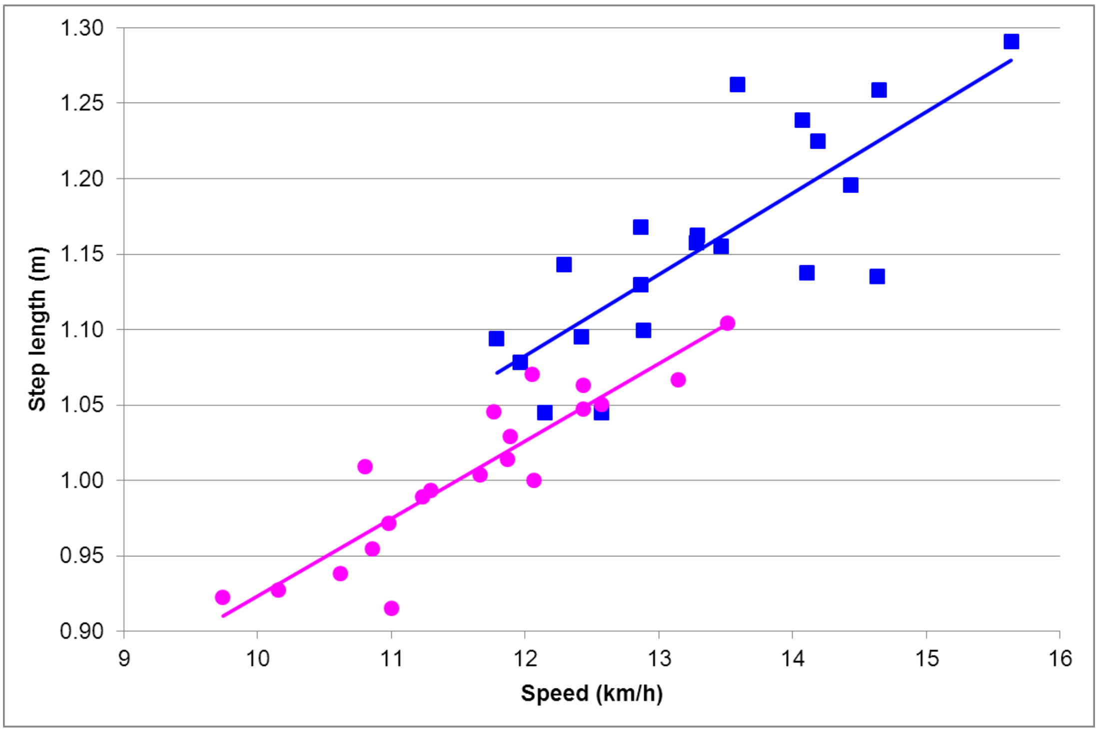


Figure 6.1. Speed was correlated with step length in both junior men (blue squares; *r* = .80) and junior women (pink circles; *r* = .91).

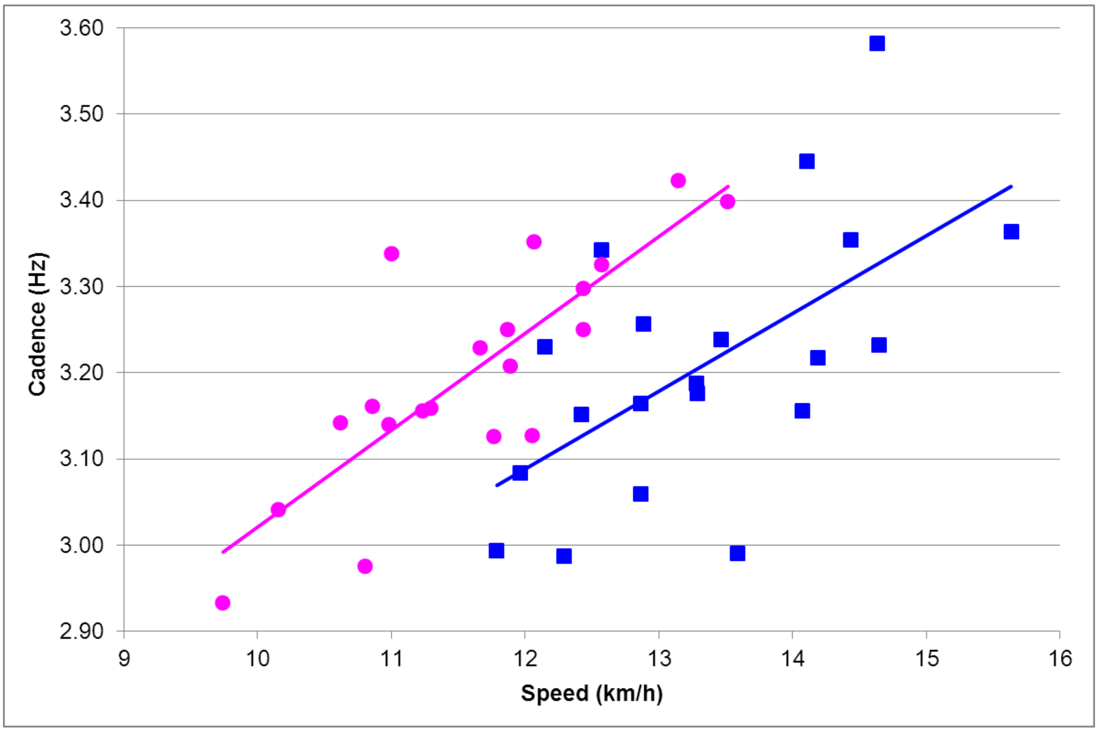


Figure 6.2. Speed was correlated with cadence in both junior men (blue squares; *r* = .61) and junior women (pink circles; *r* = .82).

6.3.2 Relative position of the foot at initial contact and toe-off

The position of the support foot relative to the CM is also shown in Table 6.2 and correlations are shown in Tables 6.3 and 6.4. The mean decrease in velocity during foot ahead in the junior men's group was –0.16 m/s (± .09) and the mean increase in velocity during foot behind was 0.18 m/s (± .08). However, there was no correlation between decrease in velocity and foot ahead distance (r = .37, p = .113) nor was there any correlation between increase in velocity and foot behind distance (r = .03, p = .915). The mean decrease in velocity during foot ahead in the junior women's group was –0.14 m/s (± .07) and the mean increase in velocity during foot behind was 0.16 m/s (± .06). The distance of the foot ahead did not correlate with decrease in velocity in the junior women's group (r = .28, p = .241), but foot behind distance did correlate with the increase in velocity during this phase in junior women (r = .58, p = .008). In addition, foot ahead distance was negatively associated with flight distance in the junior women's sample (r = –.60, p = .005).

6.3.3 Contact time and flight time

The values for contact time and flight time for both junior men and junior women are shown in Table 6.2. As expected, flight distance was correlated with flight time (junior men: r = .94, p < .001; junior women: r = –.82, p < .001), but it was also correlated with foot movement distance in junior men (r = –.56, p = .010). Flight time was correlated with speed and step length in both junior men (speed: r = .58, p = .007; step length: r = .60, p = .005) and junior women (speed: r = .67, p = .001; step length: r = .65, p = .002).

6.3.4 Stance:swing ratio

The mean stance:swing ratio was 46:54 (± 3) for junior men and 49:51 (± 3) for junior women. The stance proportion for the junior men was lower than for the junior women (p = .001, 95% CI = –4.88 to –1.41, ES = 1.00). Lower stance proportions were correlated with higher speeds in both junior men and junior women (r = –.71, p < .001, and r = –.84, p < .001 respectively); and with longer steps (r = –.55, p = .012, and r = –.85, p < .001 respectively), longer flight distances (r = –.95, p < .001 and r = –.96, p < .001 respectively), and shorter foot movements in junior men only (r = .57, p = .009).

6.3.5 Vertical displacement

The mean vertical displacement of the CM for junior men was 53 mm (± 8) and for junior women, 45 mm (± 9). This difference was found to be significant (p = .006, 95% CI = .002 to .013, ES = 0.94). The vertical displacement of the CM was positively correlated with step length (*r* = .49, *p* = .028), flight distance (*r* = .66, *p* = .002) and flight time (*r* = .50, *p* = .025) in the junior women's group only. Vertical displacement did not correlate with any key variables in the junior men's sample.

6.3.6 Pelvic and shoulder girdle rotation

The transverse plane rotation values of the pelvis and shoulder girdles are shown in Table 6.5. Most walkers studied had little pelvic rotation; in fact, 13 junior women and three junior men had 10° pelvic rotation or less. In the junior men's sample, the distortion angle was positively correlated with both speed (*r* = .53, *p* = .016) and step length (*r* = .45, *p* = .049), but neither pelvic nor shoulder girdle rotation was correlated with any other key variables. In the junior women's sample, the distortion angle was correlated with speed (*r* = .49, *p* = .030), step length (*r* = .54, *p* = .014), contact time (*r* = –.53, *p* = .016), and flight distance (*r* = .58, *p* = .007). Pelvic rotation was correlated with foot behind distance (*r* = .52, *p* = .018) and foot movement distance (*r* = –.53, *p* = .015), while shoulder girdle rotation was correlated with speed (*r* = .45, *p* = .047), contact time (*r* = –.59, *p* = .006), and flight distance (*r* = .52, *p* = .019).

Table 6.5. Mean (± *s*) and between-subjects effects of pelvic, shoulder and distortion rotation angles. Differences were significant at *p* < 0.05 (bold). Effect sizes were based on Cohen's *d* and indicated when very large (‡), large (†), or moderate (*).

	Junior men	Junior women	*p*	95% CI
Pelvic rotation (°)	15 (± 5)	9 (± 3)	**< .001**	**3.48 to 8.52†**
Shoulder rotation (°)	17 (± 3)	20 (± 4)	**.004**	**–5.53 to –1.17***
Distortion angle (°)	30 (± 5)	27 (± 5)	.112	–.627 to 5.73

6.3.7 Knee joint angles

Table 6.6 shows the mean knee angles at initial contact, midstance and toe-off. The range of values for junior men at initial contact was between 176° and 187°; for junior women it was between 174° and 182°. Overall, the junior men had hyperextended knees for 69% (± 12) of contact time and junior women 71% (± 14) (*p* = .556, 95% CI = –10.6 to 5.8, ES = 0.19). Knee hyperextension duration (%) was positively correlated with knee angle at toe-off in the junior women (*r* = .67, *p* = .001), but not in junior men. During swing, the maximum knee flexion angle was 101° (± 5) for junior men and 100° (± 5) for junior women. There were no differences between groups for any of these knee angle variables. Furthermore, there were no correlations between knee angle at contact, midstance or during swing with any key race walk variables in either group. However, in both groups, knee toe-off angle was positively correlated with step length (junior men: r = .44, p = .049; junior women: r = .59, p = .006), and it was also correlated with speed (r = .55, p = .012), contact time (r = –.65, p = .002), and flight distance (r = .81, p < .001) in the junior women's group only.

Table 6.6. Mean (± *s*) and between-subjects effects of lower and upper limb joint angles. Differences were significant at p < 0.05 (bold). Effect sizes were based on Cohen's *d* and indicated when very large (‡), large (†), or moderate (*).

	Junior men	Junior women	*p*	95% CI
Knee angle (°)				
Initial contact	180 (± 3)	178 (± 3)	.208	–.624 to 2.77
Midstance	192 (± 5)	192 (± 4)	.785	–2.55 to 3.35
Toe-off	155 (± 5)	158 (± 6)	.141	–6.28 to .926
Hip angle (°)				
Initial contact	169 (± 3)	167 (± 3)	**.019**	**.387 to 4.16***
Midstance	195 (± 3)	192 (± 4)	**.007**	**.923 to 5.43***
Toe-off	193 (± 3)	195 (± 3)	.115	–3.38 to .382
Ankle angle (°)				
Initial contact	103 (± 4)	104 (± 3)	.364	–3.20 to 1.20
Midstance	108 (± 3)	109 (± 3)	.127	–3.33 to .430
Toe-off	129 (± 4)	134 (± 5)	**.002**	**–7.58 to –1.77***
Shoulder angle (°)				
Initial contact	–65 (± 7)	–66 (± 7)	.530	–5.77 to 3.02
Midstance	–22 (± 4)	–25 (± 6)	**.038**	**–6.41 to –.186**
Toe-off	37 (± 7)	36 (± 7)	.702	–3.62 to 5.32
Elbow angle (°)				
Initial contact	80 (± 13)	68 (± 12)	**.006**	**3.56 to 19.49***
Midstance	85 (± 10)	75 (± 8)	**.003**	**3.55 to 15.60***
Toe-off	71 (± 10)	67 (± 6)	.180	–1.76 to 9.06

6.3.8 Hip and ankle joint angles

In Table 6.6, the values for the hip angle represent means of 11° and 13° hip flexion at contact for junior men and junior women respectively, and 13° and 15° hyperextension at toe-off. In junior men, the contact values for the hip and ankle did not correlate with any of the main performance parameters, although in junior women the hip contact angle was positively correlated with flight distance (*r* = .55, *p* = .013). Hip and ankle toe-off angles did not correlate with any key variables.

6.3.9 Shoulder and elbow joint angles

Table 6.6 shows the values for the angles of the shoulder and elbow joints. The shoulder contact values are shown as negative values to signify their hyperextended position. The data in Table 6.6 hence show 65° and 66° of ipsilateral shoulder hyperextension at contact for junior men and junior women respectively, and 37° and 36° of flexion at toe-off respectively. The total range of motion for the shoulder from initial contact to toe-off was 102° for both junior men and junior women. Eighteen of the junior men and 17 of the junior women had their largest (or equal largest) elbow angle at midstance, while 18 of the junior men and 14 of the junior women had their smallest or equal-smallest elbow angle at toe-off.

A correlation was found amongst the junior men between shoulder contact angle and step length (*r* = .52, *p* = .018). The shoulder toe-off angle was correlated in junior men with speed (*r* = .49, *p* = .030), step length (*r* = .78, *p* < .001), and foot behind distance (*r* = .67, *p* = .001). In the junior women sample, shoulder contact angle was correlated with foot ahead distance (*r* = .53, *p* = .016), contact time (*r* = .57, *p* = .009), and flight distance (*r* = –.50, *p* = .025). There were, however, no correlations between the key kinematic variables and shoulder angle at either midstance or toe-off. There were no correlations between the elbow angle at any gait event with any key race walking variable in either group.

6.3.10 Analysis of individual athletes

A selection of five athletes was chosen from each of the junior men's and the junior women's 10 km races and their results for particular variables are shown in Tables 6.7 and 6.8 respectively.

Table 6.7. Sample of individuals' results from the junior men's 10 km.

Finishing position	1	8	19	26	36
Speed (km/h)	15.63	14.44	13.47	13.28	11.97
Step length (m)	1.29	1.20	1.16	1.16	1.08
Cadence (Hz)	3.36	3.35	3.24	3.19	3.08
Foot ahead (m)	0.36	0.33	0.38	0.36	0.39
Foot behind (m)	0.48	0.46	0.43	0.42	0.45
Flight distance (m)	0.30	0.24	0.19	0.22	0.07
Foot movement (m)	0.16	0.17	0.16	0.16	0.18
Pelvic rotation (°)	18	23	13	13	23
Shoulder rotation (°)	17	17	16	17	13
Knee at contact (°)	178	177	180	186	179
Knee at midstance (°)	184	182	197	196	190

Table 6.8. Sample of individuals' results from the junior women's 10 km.

Finishing position	1	7	15	23	28
Speed (km/h)	13.51	12.44	11.89	11.00	10.16
Step length (m)	1.10	1.06	1.03	0.92	0.93
Cadence (Hz)	3.40	3.25	3.21	3.34	3.04
Foot ahead (m)	0.33	0.37	0.35	0.38	0.38
Foot behind (m)	0.44	0.47	0.46	0.41	0.41
Flight distance (m)	0.18	0.08	0.07	0.00	0.00
Foot movement (m)	0.15	0.15	0.15	0.13	0.13
Pelvic rotation (°)	12	10	9	9	11
Shoulder rotation (°)	25	19	19	17	15
Knee at contact (°)	182	179	177	174	182
Knee at midstance (°)	192	193	184	186	196

6.4 Discussion

The aim of this study was to analyse junior race walkers in international competition to identify the key kinematic variables and to compare male and female athletes; doing so would also allow for important aspects of technical development to be observed when compared with senior athletes (covered in Chapter 7). One of the key concerns of all junior athletes and their coaches is how to develop into successful senior athletes. This is particularly important in race walking, as there is an increase in competitive distance to 20 km (and also to 50 km for male athletes), and it is therefore surprising that so little previous research has been carried out on junior race walkers.

The results showed that speed was correlated with both step length and cadence in both groups, and these results are emphasised by the long steps and high cadences achieved by the winners of each race, particularly when compared with the slowest athletes (Tables 6.7 and 6.8). Junior race walkers thus cannot neglect the development of either of these key variables in their pursuit of improving speed and their chances of success. The junior men and women did not have different cadences and therefore the mechanical cause of the difference in speed between them was the junior men’s greater step lengths (because of longer foot ahead, foot behind, foot movement and flight distances). However, although the cadences were the same, other factors that resulted in the faster speeds of the junior men were lower contact time percentages and stance:swing ratios. In essence, the junior men were faster because they used more of their step time in flight whereas the junior women spent a greater proportion in contact. These variables were also important in distinguishing between faster and slower athletes within each group (shorter contact times, longer flight times and lower stance proportions were correlated with speed in both groups). In particular, longer flight times were important in increasing speed because of their association with greater flight distances and step lengths. Of course, these flight times needed to be restrained to avoid visible loss of contact (and particularly in the case of junior women whose flight times correlated with vertical displacement, which is often what is noticed by judges (Hoga et al., 2009)). What was particularly noticeable was the very long flight distance (30 cm) achieved by the junior men’s winner that could place him at risk of disqualification (although he only received one red card during the race). By contrast, many of the junior women had no flight time at all and instead experienced periods of double support, with the inevitable result that no flight distance was achieved (e.g. by the athletes finishing in 23rd and 28th positions (Table 6.8)). These athletes thus have the capacity to shorten their contact times so that cadence is increased with a consequent improvement in speed while still avoiding a visible loss of contact.

As mentioned above, flight distance was correlated with step length, and this was the reason it was also correlated with walking speed. The other key variables that correlated with step length in both junior men and women were foot behind distance and distortion angle. Aside from its association with step length, the foot behind distance was further shown to be important in this sample of junior women as it was positively correlated with the increase in velocity during the propulsion phase of stance. Foot ahead, by contrast, was not associated with step length and instead its positive correlation with contact time in both groups means that athletes should take care not to overstride when placing the foot in front of the CM at initial contact. This suggestion is supported by the results of the individual analyses that showed that the slowest athletes in each race had longer foot ahead distances than all (junior men) or most other competitors analysed (junior women). These slower athletes had little or no flight distance, and their longer foot ahead distances might have been attempts to increase step length in its absence. Of course, these distances are absolute measurements, and data on stature that would have allowed for calculation of foot ahead and foot behind ratios were not available. However, it can be seen that while both winners had foot ahead distances that were 75% of their foot behind distances, the slowest junior man and woman had foot ahead:behind ratios of 87% and 93% respectively. Coaches of junior race walkers should therefore monitor technique to ensure that their athletes are not relying too heavily on foot ahead distance for step length rather than foot behind distance, although such weaknesses might arise partly from muscular qualities rather than purely technical causes such as foot placement.

It is always important to pay attention to knee joint kinematics in race walking because of IAAF Rule 230.1. The initial contact knee angles for junior men and junior women were 180° and 178° respectively and both increased to 192° at midstance, so it was therefore unsurprising that very few red cards (eight) were awarded for unstraightened knees to the athletes analysed. As with prior findings on a much smaller number of female junior walkers (Neumann et al., 2008), variations in this particular measurement (standard deviations of 3° at initial contact) were very small and indicative of a well-trained gait characteristic in even these relatively young race walkers. Of course, not all athletes are as well-trained and the junior woman who finished in 23rd position (Table 6.8) had an initial contact angle of only

174° (this was the lowest value found in either group). However, the knee hyperextension that she then underwent until midstance (186°) might have been what helped her to avoid any red cards. After midstance, the knee flexed to reduce hyperextension and continued to flex until toe-off in preparation for swing. In junior women, the angle of the knee at toe-off appeared particularly important, as greater knee angles were associated with faster speeds, shorter contact times and longer flight times. This might have been because the faster athletes had shorter contact times and therefore less time for the knee to flex after midstance. Passing judgement on the optimal range for the hips and ankles is more difficult as there were very few correlations with the key race walking variables such as speed and step length. However, there were some moderate differences found for lower limb joint angles between junior men and junior women and these might partially differentiate performances between the sexes; coaches of junior athletes should note that these differences highlight the need to individualise technical training regimens, with the athlete’s gender being one of the factors to take into account.

The distortion angle that was correlated with step length in both junior men and junior women was also correlated with speed, suggesting that a certain amount of trunk transverse plane rotation is important for faster race walking. There was no difference in distortion angle between junior men and junior women; however, the relative contributions of the pelvic and shoulder girdles differed as the junior men had more pelvic rotation, whereas the junior women had more shoulder girdle rotation. It was particularly noticeable that rotation of the shoulder girdle in the junior women’s group was more than twice that of the pelvic rotation it functioned to counterbalance. Junior women are therefore advised to develop increased pelvic rotation because of its association with longer foot behind distances, although these variables, like many others in race walking, do not need to be maximised (given anthropometric restrictions) but optimised instead (Williams & Ziff, 1991). Coaches should note the findings of studies on elite 20 km and 50 km athletes to get an indication of the typical ranges of motion achieved by senior competitors that might be a realistic target to aim at.

With regard to the upper limb, the function of the arms in race walking is to counterbalance the anteroposterior movements of the legs. The association between increased step length and larger shoulder flexion and hyperextension angles in junior men was evidence of this. It is recommended that junior race walkers develop their upper body muscular strength and endurance, as an inability to counterbalance the movement of the legs with the arms might result in increased upper torso rotation instead (Pontzer et al., 2009). There was no difference in shoulder angle at initial contact or toe-off between junior men and women (total mean range was 102° for both groups), but it is probable that the junior women's arms had smaller moments of inertia because of less muscle mass (not measured in this study) and smaller elbow angles. It is therefore possible that the reason for the relatively high shoulder girdle rotation magnitudes found in junior women was because the upper torso had to assist the arms in balancing the angular momentum of the lower limbs. The standard deviations for the elbow joint angles at the three identified gait events were larger than at any other joint in both junior men and women, which was similar to earlier results of junior male athletes (Douglass & Garrett, 1984). While the large range of elbow angles might have been an indication of inefficient technique among some athletes, it is also possible that their variation was due to individual responses to counterbalancing the lower limbs, and coaches should monitor training of the arms for effects on whole body movement.

While it was expected that the junior men would be faster than the junior women, it is worth noting that the best junior women's results were comparable to those of many of the junior men. For example, the winner of the junior women's race had a time that would have finished in 14th place (out of 39 finishers) in the junior men's race. It is clear that one difficulty with analysing junior race walkers is the range of abilities amongst the competitors. While many might have little experience of international competition, or of competing over 10 km (at least three of the junior women had never raced over the distance before), others are much more developed. While junior athletes should not be expected to match senior athletes with regard to training loads (e.g. total yearly distance walked), time can be spent on ensuring compliance with the two specific aspects of visible loss of contact and knee straightening. Of all the athletes who competed in the 8th European Cup, four junior men and four junior women were disqualified. It is not sensible for a junior athlete to attempt competing over 20 km at senior level if he or she is unable to comply with the rules to the satisfaction of the judges (who will see the athlete twice as often as in a 10 km race). Fortunately, avoiding loss of visible contact and straightening the knee are skills that can be learned through repeated practice of correct technique, as shown by most of the athletes analysed. Coaches can assist young athletes by ensuring that technical and physical development continue during the transition from junior to senior competition to help prolong their athletic careers.

6.5 Conclusion

Analysing and understanding the kinematics of elite junior race walkers and key features of their techniques is useful for coaches and the athletes themselves, as well as scientists interested in all forms of human gait. The usefulness of such an analysis is that comparisons can be made with successful senior athletes (who compete over longer distances) that show the junior athletes and their coaches where improvements can or should be made, and also adds to the body of knowledge that senior athletes can learn from. The key findings of this study on elite junior male and female race walkers are:

- The best junior athletes had both long step lengths and high cadences. Junior men had longer step lengths than their female counterparts, and although both groups' cadences were the same, one key reason for the junior men's faster speeds was that they used a greater proportion of step time in flight (nearly 5% longer);
- This difference in step time components was particularly important because of the significant role that flight distance played in producing step length and speed; by contrast, some of the slower athletes relied on longer foot ahead distances to increase step length that might have counterproductively resulted in overstriding, with longer and less productive contact times as a consequence;
- Many of the junior women experienced periods of double support, with the result that no flight distance was achieved. Given the importance of flight distance to elite race walking (across both junior and senior athletes), this is a considerable technical weakness. However, it does mean that these athletes have the capacity, with appropriate training, to reduce contact time and either achieve shorter double support times or very brief flight times. This is particularly important for the junior women as cadence had a stronger association with speed than it did in junior men;
- Most of the junior athletes had knee extension angles of approximately 180° at initial contact, and had hyperextended knees at midstance. These results show that even these young athletes were able to achieve legal race walking technique before becoming senior race walkers;
- The relative contributions of the pelvic and shoulder girdles differed as the junior men had more pelvic rotation whereas the junior women had more shoulder girdle rotation. These differences might be because of differing strength levels (e.g. in achieving pelvic rotation), or because of differences in upper body movement (e.g. arm swing mechanics). Overall, the athletes in

this study had relatively small magnitudes of pelvic rotation, and it is possible that these young athletes had not yet developed the pelvic mobility required for the magnitudes achieved by senior athletes;

- Elbow angles varied the most of all angular measurements, indicating that how athletes use their arms to counterbalance the legs' movements is highly individualised and not stereotyped in the same way as the lower limb's movements. This might be due to strength levels or muscle mass, and coaches should not neglect the upper part of the body but develop it with technical and strength training of the lower body.

CHAPTER 7

SUMMARY OF COMPETITION STUDIES

7.1 Introduction

The key kinematic variables in race walking have been identified in previous chapters for five groups of race walkers: 20 km men, 20 km women, 50 km men, 10 km junior men and 10 km junior women. Comparisons have been made between male and female athletes competing over the same distances in Chapter 4 (senior 20 km walkers) and Chapter 6 (junior 10 km walkers). Although the combined sample of 130 athletes analysed at the 23rd World Cup and 8th European Cup (i.e. not including those from the variation samples) could have been used to perform large Pearson's product moment correlation coefficient tests, Atkinson & Nevill (2001) warned that finding correlations in heterogeneous samples (e.g. men and women, seniors and juniors) can often lead to misinterpretations of the determinants of elite performance. However, comparisons between those heterogenous groups might be useful in further assessment of the key kinematic variables. The objective of this chapter therefore is to collate the main findings of the competition studies described in Chapters 4, 5 and 6 and present an overall summary. While no new results are presented, additional comparisons have been reported below to add to those already shown, i.e. between senior men competing over 20 km and 50 km, between senior 20 km men and junior men, and between senior women and junior women.

7.2 Results

7.2.1 Senior men – 20 km and 50 km

There were no differences between the two groups of senior men for height or mass. The results of the comparisons between key kinematic variables for the two groups have been reported in Tables 7.1 and 7.2. While there were quite a few differences for key performance parameters (e.g. 20 km competitors had higher speeds, step lengths, and cadences), there were very few for angular measurements. Those that did differ were hip and shoulder angles at initial contact and shoulder angle at midstance, as well as maximum knee flexion angle during swing (20 km men: 103° (± 4); 50 km men: 106° (± 4)) (p = .027, 95% CI = –4.74 to –.298, ES = 0.75). The stance:swing ratio for the 20 km men was 45:55 (± 2) and for the 50 km men it was 47:53 (± 2) (p = .007, 95% CI = –2.69 to –.456, ES = 1.00).

Table 7.1. Mean (± *s*) and between-subjects effects of key race walking variables in 20 km and 50 km men. Differences were significant at $p < 0.05$ (bold). Effect sizes were based on Cohen's *d* and indicated when very large (‡), large (†), or moderate (*).

	20 km men	50 km men	*p*	95% CI
Speed (km/h)	14.52 (± .86)	13.15 (± .75)	**< .001**	**.958 to 1.79†**
Step length (m)	1.21 (± .07)	1.16 (± .06)	**.002**	**.020 to .085***
Step length ratio (%)	68.0 (± 3.7)	65.3 (± 2.8)	**.002**	**1.13 to 4.56***
Cadence (Hz)	3.34 (± .12)	3.16 (± .16)	**< .001**	**.104 to .252†**
Contact time (s)	0.27 (± .02)	0.30 (± .03)	**< .001**	**–.035 to –.018***
Flight time (s)	0.03 (± .01)	0.02 (± .01)	**.014**	**.002 to .013***
Contact time (%)	91.3 (± 4.4)	94.0 (± 3.0)	**.008**	**–4.63 to –.750***
Foot ahead (m)	0.37 (± .02)	0.38 (± .02)	**.036**	**–.022 to –.001**
Foot ahead ratio (%)	20.6 (± 1.1)	21.3 (± 0.9)	**.011**	**–1.15 to –1.57***
Foot behind (m)	0.48 (± .02)	0.48 (± .03)	.460	–.009 to .020
Foot behind ratio (%)	27.1 (± 0.9)	26.9 (± 1.5)	.483	–.420 to .875
Flight distance (m)	0.19 (± .06)	0.15 (± .05)	**.004**	**.013 to .067***
Foot movement (m)	0.17 (± .02)	0.15 (± .01)	**< .001**	**.010 to .026†**

Table 7.2. Mean (± *s*) and between-subjects effects of angular variables in 20 km and 50 km men. Differences were significant at $p < 0.05$ (bold). Effect sizes were based on Cohen's *d* and indicated when very large (‡), large (†), or moderate (*).

	20 km men	50 km men	*p*	95% CI
Pelvic rotation (°)	18 (± 3)	19 (± 4)	.381	–2.61 to 1.01
Shoulder rotation (°)	16 (± 2)	16 (± 2)	.763	–1.39 to 1.03
Distortion angle (°)	32 (± 3)	34 (± 3)	.098	–3.06 to .305
Knee angle (°)				
Initial contact	180 (± 2)	181 (± 3)	.156	–2.07 to .339
Midstance	189 (± 4)	190 (± 4)	.175	–3.52 to .655
Toe-off	156 (± 5)	154 (± 4)	.198	–.796 to 3.76
Hip angle (°)				
Initial contact	167 (± 3)	170 (± 4)	**.010**	**–4.26 to –.609***
Toe-off	189 (± 3)	190 (± 2)	.145	–2.24 to .337
Ankle angle (°)				
Initial contact	101 (± 3)	103 (± 3)	.062	–2.91 to .073
Toe-off	125 (± 4)	126 (± 4)	.194	–3.20 to .664
Shoulder angle (°)				
Initial contact	–64 (± 7)	–72 (± 7)	**< .001**	**–10.8 to –3.86***
Midstance	–21 (± 4)	–24 (± 4)	**.016**	**–5.09 to –.543***
Toe-off	37 (± 5)	36 (± 4)	.460	–.144 to 3.14
Elbow angle (°)				
Initial contact	79 (± 9)	80 (± 8)	.505	–5.78 to 2.88
Midstance	82 (± 7)	83 (± 7)	.462	–4.76 to 2.19
Toe-off	65 (± 7)	67 (± 6)	.396	–4.84 to 1.94

7.2.2 Senior men (20 km) and junior men

Tables 7.3 and 7.4 show the results of the comparisons between 20 km men and junior men for key kinematic variables. Because no anthropometric data were available for the junior athletes, no comparisons have been made for step length ratio, foot ahead ratio or foot behind ratio. In addition to those variables shown below, the senior men's stance:swing ratio of 45:55 (± 2) did not differ from the junior men's (46:54) (± 3). There was also no difference between maximum swing knee flexion angles (20 km men: 103° (± 4); junior men: 101° (± 5)).

Table 7.3. Mean (± *s*) and between-subjects effects of key race walking variables in senior and junior men. Differences were significant at $p < 0.05$ (bold). Effect sizes were based on Cohen's *d* and indicated when very large (‡), large (†), or moderate (*).

	Senior men	Junior men	*p*	95% CI
Speed (km/h)	14.52 (± .86)	13.36 (± 1.04)	**< .001**	**.623 to 1.71†**
Step length (m)	1.21 (± .07)	1.16 (± .07)	**.012**	**.012 to .091***
Cadence (Hz)	3.34 (± .12)	3.21 (± .15)	**.002**	**.050 to .207***
Contact time (s)	0.27 (± .02)	0.29 (± .02)	**.042**	**–.025 to –0.00***
Flight time (s)	0.03 (± .01)	0.03 (± .02)	.815	–.008 to .010
Contact time (%)	91.3 (± 4.4)	92.0 (± 5.6)	.624	–3.54 to 2.14
Foot ahead (m)	0.37 (± .02)	0.38 (± .03)	.093	–.025 to .002
Foot behind (m)	0.48 (± .02)	0.45 (± .03)	**< .001**	**.020 to .050†**
Flight distance (m)	0.19 (± .06)	0.17 (± .06)	.182	–.011 to .059
Foot movement (m)	0.17 (± .02)	0.17 (± .02)	.254	–.004 to .016

Table 7.4. Mean (± *s*) and between-subjects effects of angular variables in senior and junior men. Differences were significant at $p < 0.05$ (bold). Effect sizes were based on Cohen's *d* and indicated when very large (‡), large (†), or moderate (*).

	Senior men	Junior men	*p*	95% CI
Pelvic rotation (°)	18 (± 3)	15 (± 5)	**.013**	**.675 to 5.39***
Shoulder rotation (°)	16 (± 2)	17 (± 3)	.085	–2.64 to .175
Distortion angle (°)	32 (± 3)	30 (± 5)	.056	–.068 to 5.12
Knee angle (°)				
Initial contact	180 (± 2)	180 (± 3)	.502	–.903 to 1.82
Midstance	189 (± 4)	192 (± 5)	**.009**	**–5.82 to –.884***
Toe-off	156 (± 5)	155 (± 5)	.715	–2.39 to 3.45
Hip angle (°)				
Initial contact	167 (± 3)	169 (± 3)	**.020**	**–3.77 to –.333***
Toe-off	189 (± 3)	193 (± 3)	**< .001**	**–5.59 to –2.49†**
Ankle angle (°)				
Initial contact	101 (± 3)	103 (± 4)	.176	–3.04 to .573
Toe-off	125 (± 4)	129 (± 4)	**< .001**	**–6.56 to –2.03***
Shoulder angle (°)				
Initial contact	–64 (± 7)	–65 (± 7)	.866	–4.40 to 3.72
Midstance	–21 (± 4)	–22 (± 4)	.318	–3.72 to 1.23
Toe-off	37 (± 5)	37 (± 7)	.862	–3.08 to 3.71
Elbow angle (°)				
Initial contact	79 (± 9)	80 (± 13)	.760	–7.29 to 5.35
Midstance	82 (± 7)	85 (± 10)	.251	–7.57 to 2.02
Toe-off	65 (± 7)	71 (± 10)	**.028**	**–11.2 to –.695***

7.2.3 Senior women and junior women

The differences between senior women and junior women (Tables 7.5 and 7.6) were similar to those between senior and junior men. The senior women's stance:swing ratio of 47:53 (± 2) was different from the junior women's ratio (49:51 ± 3) (*p* = .019, 95% CI = –3.15 to .312, ES = 0.82). Senior women also had greater shoulder hyperextension at initial contact and greater shoulder flexion at toe-off (the total range of movement at the shoulder between these two points was 110° for senior women compared with 102° for juniors). There was no difference between maximum swing knee flexion angles (20 km women: 100° (± 4); junior women: 100° (± 5)).

Table 7.5. Mean (± *s*) and between-subjects effects of key race walking variables in senior and junior women. Differences were significant at *p* < 0.05 (bold). Effect sizes were based on Cohen's *d* and indicated when very large (‡), large (†), or moderate (*).

	Senior women	Junior women	*p*	95% CI
Speed (km/h)	12.73 (± .98)	11.61 (± .96)	**< .001**	**.561 to 1.69***
Step length (m)	1.06 (± .06)	1.01 (± .05)	**.002**	**.020 to .085***
Cadence (Hz)	3.34 (± .17)	3.20 (± .13)	**.003**	**.051 to .229***
Contact time (s)	0.28 (± .02)	0.31 (± .03)	**.001**	**–.039 to –.011***
Flight time (s)	0.02 (± .01)	0.01 (± .01)	**.009**	**–.002 to .016***
Contact time (%)	93.6 (± 3.7)	96.7 (± 4.0)	**.005**	**–5.42 to –.991***
Foot ahead (m)	0.33 (± .02)	0.34 (± .02)	.279	–.021 to .006
Foot behind (m)	0.43 (± .02)	0.43 (± .02)	.699	.015 to .010
Flight distance (m)	0.13 (± .05)	0.09 (± .06)	**.010**	**.010 to .073***
Foot movement (m)	0.17 (± .01)	0.15 (± .02)	**.001**	**.007 to .023***

Table 7.6. Mean (± *s*) and between-subjects effects of angular variables in senior and junior women. Differences were significant at *p* < 0.05 (bold). Effect sizes were based on Cohen's *d* and indicated when very large (‡), large (†), or moderate (*).

	Senior women	Junior women	*p*	95% CI
Pelvic rotation (°)	14 (± 4)	9 (± 3)	**< .001**	**2.77 to 6.83†**
Shoulder rotation (°)	19 (± 2)	20 (± 4)	.325	–3.10 to 1.06
Distortion angle (°)	32 (± 4)	27 (± 5)	**.001**	**2.01 to 6.85***
Knee angle (°)				
Initial contact	179 (± 2)	178 (± 3)	.374	–.807 to 2.11
Midstance	190 (± 3)	192 (± 4)	.261	–3.27 to .907
Toe-off	158 (± 4)	158 (± 6)	.904	–3.09 to 2.74
Hip angle (°)				
Initial contact	169 (± 3)	167 (± 3)	.072	–.158 to 3.58
Toe-off	190 (± 3)	195 (± 3)	**< .001**	**–6.27 to –2.98†**
Ankle angle (°)				
Initial contact	104 (± 3)	104 (± 3)	.610	–1.41 to 2.38
Toe-off	129 (± 4)	134 (± 5)	**.001**	**–7.55 to –2.15***
Shoulder angle (°)				
Initial contact	–70 (± 7)	–66 (± 7)	**.023**	**.647 to .835**
Midstance	–23 (± 5)	–25 (± 6)	.094	–5.35 to .438
Toe-off	40 (± 6)	36 (± 7)	**.024**	**.564 to 7.84***
Elbow angle (°)				
Initial contact	72 (± 10)	68 (± 12)	.190	–2.07 to 10.2
Midstance	76 (± 7)	75 (± 8)	.605	–3.38 to 5.75
Toe-off	66 (± 6)	67 (± 6)	.469	–5.07 to 2.37

7.2.4 Analysis of best performances

Key kinematic data for each of the fastest athletes measured in each race are shown collated in Table 7.7. The bronze medallist in the men's 20 km was also the bronze medallist at the World Championships the following year, while the women's 20 km winner was Olympic Champion in 2008. Aside from achieving a World Record in winning the 50 km at the World Cup, the winner also finished 3rd at the 2008 Olympics. The winner of the junior men's race finished 5th in the 2011 World Championships 20 km at the age of 20, while the winner of the junior women's race finished 17th in the 2011 World Championships 20 km aged 21 (IAAF, 2011b).

Table 7.7. Sample of results from the highest-finishing individuals in each race.

Event	20 km men	20 km women	50 km men	10 km junior men	10 km junior women
Finishing position	3	1	1	1	1
Speed (km/h)	15.75	14.79	14.49	15.63	13.51
Step length (m)	1.24	1.19	1.20	1.29	1.10
Cadence (Hz)	3.53	3.47	3.34	3.36	3.40
Foot ahead (m)	0.37	0.36	0.37	0.36	0.33
Foot behind (m)	0.47	0.46	0.51	0.48	0.44
Flight distance (m)	0.27	0.23	0.17	0.30	0.18
Foot movement (m)	0.15	0.16	0.15	0.16	0.15
Pelvic rotation (°)	16	15	18	18	12
Shoulder rotation (°)	17	26	17	17	25
Knee at contact (°)	179	183	179	178	182
Knee at midstance (°)	186	191	187	184	192
Knee during swing (°)	101	108	101	91	98

7.3 Discussion

The results of all three studies showed that, as predicted by the hierarchical model of race walking, speed is significantly determined by step length and cadence. Step length was correlated with speed in all five groups: 20 km men (*r* = .80), 50 km men (*r* = .54), senior women (*r* = .76), junior men (*r* = .80) and junior women (*r* = .91). In the three senior groups of athletes, for whom anthropometric values were available, the association between speed and step length ratio was higher than between speed and absolute step length, showing that shorter athletes can compete successfully against taller rivals (stature was not correlated with walking speed, although it did differ between men and women). Cadence was also correlated with speed in all five groups: 20 km men (*r* = .42), 50 km men (*r* = .58), senior women (*r* = .71), junior men (*r* = .61) and junior women (*r* = .82), and what was noticeable was the greater reliance of both junior and senior women on cadence compared with men. The results of the best athletes in each race (Table 7.7) further highlighted the fact that athletes aiming to be successful must achieve relatively high values for both of these variables, and there is no point in race walkers being "obsessive" about step length (Payne & Payne, 1981, p.366) if this is not matched by equal attention paid to cadence. The relationships found between step length and cadence were not consistent across all five groups: amongst 20 km men, 20 km women and junior men there was no relationship found, suggesting that longer steps did not adversely affect the athletes' abilities to achieve high cadences (and in the junior women they were positively correlated). By contrast, in the 50 km, step length and cadence were negatively correlated, but it should be noted that this association did not exist when step length was expressed as a ratio. This suggests that athletes can prevent any potentially detrimental effects of step length on cadence if they avoid overstriding by basing their step length on the anthropometric constraints of their own stature. While step length ratios of over 70% were common amongst the fastest 20 km walkers, the best 50 km walkers had slightly lower values (between 66% and 71%) and this range might be a better guide in the longer race. It should be noted that the differences in some key variables between 20 km and 50 km men (e.g. step length and cadence) do not indicate that the 50 km competitors were less able athletes, but that they were limited by the necessary balance between walking quickly and avoiding fatigue. There were also differences between 20 km and 50 km men with regard to associations between key variables (e.g. pelvic rotation was only negatively correlated with cadence in 50 km men) and these might have resulted from the need to restrain walking speed (by means of less muscle force per step).

The respective decreases in speed over the course of the 20 km races were 4.2% for men and 6.8% for women. The decreases in step length between 4.5 and 18.5 km were 2.4% and 4.5% respectively (but only the men's difference was significant) and the decreases in cadence were 1.5% and 2.3% respectively (both groups experiencing significant changes between 13.5 and 18.5 km). In the 50 km race, the decrease in speed from 18.5 km to 48.5 km was 4.8%, caused by an overall decrease in step length of 4.0% (there was no change in cadence). In each race, it can therefore be seen that the largest contributor to overall decrease in speed was the reduction in step length (notwithstanding that the 5 cm decrease in the 20 km women was not significant). It could be argued therefore that a primary aim of endurance training for race walkers is to maintain step length over the course of either a 20 km or 50 km race, for example by pacing themselves carefully in the initial stages to avoid early muscle fatigue. However, it is also possible that the reduction in step length was an instinctive mechanism that prevented greater decreases in cadence (and this was then therefore what differentiated better athletes). Although it was not possible to measure muscle activity during these competitions, it is possible that the small changes in cadence were evidence of endurance athletes who have trained to maintain regular muscle firing rates, and that the main effect of fatigue was decreased muscle forces (similar to distance running (Avela et al., 1999; Millet et al., 2003)) that imparted smaller propulsive impulses, and consequently led to reduced step length. The study of muscular activity patterns in elite athletes will help to understand not only which muscle groups are most important in race walking (and hence which might fatigue most), but also the role of the stretch-shortening cycle, which is profoundly affected by muscle fatigue levels (Komi, 2000).

It was clear from each group's results that reducing the duration of the contact phase was essential for faster walking, as shorter times were strongly correlated with speed because they led to higher cadences. In particular, faster gait was typically achieved with lower proportions of stance time compared with swing as shown by the correlations between stance percentage and speed: 20 km men (r = –.81), 50 km men (r = –.57), senior women (r = –.62), junior men (r = –.71) and junior women (r = –.84). Improving the stance:swing ratio is best achieved by shortening the contact phase duration as increasing the swing proportion of each gait cycle can lead to longer flight times and a risk of disqualification. However, it was very obvious that most of the race walkers analysed (whether they were world-class or not) benefitted from experiencing brief but presumably non-visible flight times, and would have been much slower without them. The distance covered during the flight phases contributed substantially to overall step length (from 9% in the junior women to 16% in the 20 km men) and was particularly important for the fastest athletes (e.g. Table 7.7). Furthermore, the decreases in flight distance in the variation studies coincided very closely with the decreases in step length, and thus its importance was shown in both inter-individual and intra-individual differences. Advice to race walk coaches about flight times carries a degree of necessary ambiguity, for while they are undoubtedly a key factor in achieving competitive success, deliberately encouraging athletes to try to achieve flight periods might equally discourage the pursuit of technical proficiency and increases the risk of receiving red cards. In addition, athletes who walk relatively slowly will struggle to improve their race times if their reliance on flight time is so much (e.g. 0.04 s) that it is only by increasing it to visible durations that they can speed up. It is therefore recommended that coaches and athletes should always endeavour to undertake the shortest possible flight times they can at any pace. The benefits of this are three-fold: it encourages the athlete to concentrate on good technique; it lowers the risk of attracting the judges' attention; and it gives the athlete some leeway if they decide to speed up during competition (e.g. to overtake a rival, or during close finishes).

In addition to flight distance, the distance of the foot ahead of the CM at initial contact and the distance of the foot behind the CM at toe-off were identified in the hierarchical model of race walking (Figure 2.3) as important components of step length. Foot ahead contributed approximately 32% of the total step length, and while it differed between men and women competing over the same distance (men's values were greater and this might have been because of better muscular properties), there were no differences between groups of the same gender. Although foot ahead was found to correlate with step length in 20 km men and 50 km men, it did not in any other group. By contrast, foot behind was correlated with step length in all five groups, and at all four measurement distances in the 50 km men. This suggests that not only is foot behind the greatest contributor to step length (means ranging from 39% to 43% across groups), but also that it differentiates between athletes (within groups) more so than foot ahead in terms of step length. Although it was only associated with speed in 20 km women, it did also correlate with increase in velocity during the propulsive phase in both 50 km men and junior women, and on the basis of this evidence a simple suggestion for coaches is to emphasise longer foot behind distances, rather than foot ahead. However, the results also indicated (as with many other variables in race walking) that restraint has to be shown when making such recommendations. This is because longer foot behind distances were correlated with decreased cadence in both groups of senior men, probably because achieving longer distances requires more time spent in contact with the ground (a similar finding occurred between foot ahead and cadence in both groups of senior men). While there were no differences for either of these variables within the groups analysed at multiple measurement distances, the individual analyses did show that there was some variation within walkers for foot ahead, but as with the group correlations these did not follow an easily defined pattern (e.g. with the longest foot ahead distance the best 20 km man was slowest, whereas the best 20 km woman was fastest). The mean values for foot ahead ratio for the senior athletes ranged from 20.3 to 21.3% while the range of mean foot behind ratios was from 26.2 to 27.1%, and these seem to be sensible guides for race walk coaches. Women did however experience more adverse effects of longer foot ahead distances, and achieving this range of values might still result in negative consequences if the athlete is not sufficiently strong to overcome the natural braking effect of the foot ahead position.

The knee angle is the most important angle to measure in race walking kinematics, and was found to be straightened at initial contact in all five groups: 20 km men (180°), 50 km men (181°), 20 km women (179°), junior men (180°), and junior women (178°). Standard deviations for this variable were low in all five groups (between 2° and 3°), and it was one of the few variables that did not differ in any comparison between groups; furthermore, all groups had hyperextended knees of approximately 190° by midstance. It was clear therefore from this study that these elite athletes were able to satisfy the straightened knee rule without negatively impacting on their great speeds, and they therefore displayed technically proficient and legal race walking. The variation data for both the 20 km men and women showed no reduction in knee contact or midstance angle as the race progressed, although there was a small difference found for the contact angle in the 50 km men's sample. Nonetheless, the mean knee angle of 178° recorded 1.5 km from the finish was still within the range of values found for the larger groups of athletes and was thus indicative of legal race walking and the maintenance of excellent technique despite fatigue. The knee angle at toe-off was similar across all groups with a range between 154° and 158°, but during swing the 20 km women flexed their knees more than the 20 km men, who in turn flexed their knees more than the 50 km men. These values, and those of the junior athletes (which did not differ from their senior counterparts), did not reach the 90° angle previously recommended by coaches (e.g. Hopkins, 1978) despite faster walking speeds being associated with more flexed knees in 20 km men and 50 km men. It is possible that even though a speed benefit might accrue from increased knee flexion, the requirement for a straightened knee at initial contact meant the race walkers avoided too much knee flexion during swing that would have made full extension difficult, and which also might have led to a visible loss of contact (a correlation between increased knee flexion and flight time was indeed found in 50 km men (r = .010)). It appears therefore that while IAAF Rule 230.1 obviously affects knee stance kinematics, there is also a knock-on effect on the knee during swing. This could be one of the negative effects of the rule, as other key race walking variables did not seem to be negatively affected (although this could be partly because practically all athletes had straightened knees at contact). The study of knee muscle moments and powers, as well as EMG activity, will give a better indication of the effects of full knee extension during stance on the movement of the lower limb throughout the gait cycle so that advice to coaches is better informed.

There were few differences between similarly-matched groups of athletes for other lower limb joint angular data. For example, the mean hip joint angle at initial contact was relatively consistent across all five groups (ranging from 167° to 170°); more noteworthy was that at toe-off the hip hyperextension and ankle plantarflexion angles were larger in junior men than in 20 km men, and in junior women than in 20 km women. These might be indications of joint angular differences between junior and senior athletes that are partly responsible for differences in key variables (e.g. the greater hip and ankle angles at toe-off in junior athletes might have been responsible for their longer contact times compared with the senior competitors). While there are potential advantages in maintaining longer contact with the ground (e.g. it could reduce flight time), coaches of junior athletes should note that the subsequent decrease in cadence will probably outweigh any small gains in step length, and the progression to senior competition requires the development of less extension at toe-off to shorten contact time. This might be achieved through an earlier initiation of the swing phase (by the hip flexors, for example) that prevents the foot from staying in contact until it is no longer productive. As well as the difference between junior and senior athletes, there were differences between genders for the mean ankle plantarflexion angle at toe-off (between 20 km men and 20 km women, and between junior men and junior women) and for several other joint angles. These suggest that male and female athletes do not have identical race walking kinematics, and while this might not be the underlying cause of differences in speed or step length (overall stature being very important), it does indicate that some caution should be taken by coaches when teaching technique or analysing possible faults. With regard to the variation studies, there were few differences in joint angles with distance walked, and this should be taken as evidence of highly-trained athletes who are able to maintain their techniques despite fatigue.

Pelvic and shoulder girdle rotation are distinctive characteristics of the exaggerated gait adopted in elite race walking, and utilising pelvic rotation is particularly emphasised as it is believed to produce longer steps (e.g. Murray et al., 1983; Knicker & Loch, 1990). The results of the competition studies did provide some evidence that supports this position, aside from the fact that the magnitudes found were greater than those in normal walking (Levine et al., 2012). For example, pelvic rotation was greater in men than in women in both senior and junior competition, and senior athletes of both sexes had greater pelvic rotations than their junior counterparts (where the former group in each comparison had greater step lengths). However, there was no difference in pelvic rotation values between the most homogenous groups (20 km and 50 km men) despite a 5 cm difference in step length. Additionally, there were no correlations within any group between pelvic rotation and step length (or speed), and it did not prove useful in preventing decreases in step length with fatigue. Of course, this does not infer that pelvic rotation is not important to race walking performance (e.g. it was correlated with foot behind distance in 50 km men and junior women) but that there is not necessarily a benefit to obtaining values much greater than average (particularly as pelvic rotation was negatively correlated with cadence in 50 km men). There was therefore no obvious advantage in rotating the pelvis considerably more than other athletes to gain tiny increases in step length (Erdmann, 2007). This might be because, as suggested by coaches (Hopkins, 1978; Payne & Payne, 1981), a function of pelvic rotation is to narrow the stride width and while an optimum pelvic rotation will achieve this, greater than optimum values could cause a ‘crossing’ of the feet that is counterproductive. The optimum magnitude is individual to each athlete, and might be related to body size in some (stature and pelvic rotation were associated in 20 km men). There are a number of insights that can be gained from these results; first, relatively exaggerated pelvic rotation is a feature of elite race walking that is so ubiquitous that it does not differentiate between athletes in the same category as it does between men and women (and therefore greater values might be beneficial for some athletes, but not for others); second, that it could be related to the athlete’s need to achieve a straight line of walking and larger values are not necessarily better (e.g. values too large might lead to decreased cadence as in the 50 km men) and this might correspond to their body size; and third, that it was much smaller in junior athletes and is thus an aspect to improve in the development of younger athletes. With regard to shoulder girdle rotation, its importance was more difficult to ascertain as it was found to correlate only with key performance variables (speed, contact time and flight time) in junior women. This lack of associations might be partially due to the small standard deviations found for shoulder girdle rotation (between 2° and 4° across all five groups), but also because the role of shoulder girdle rotation is as a counterbalance to pelvic rotation, rather than to drive the legs. The larger shoulder girdle rotations in women at both junior and senior level (exemplified by the individual analysis of the fastest athletes in each race in Table 7.7) might have resulted from a need to compensate for less take-up of angular momentum by the arms, and could have been due to smaller moments of inertia throughout the upper body because of lower masses.

The function of the arms in race walking is to counterbalance the movement of the lower limbs by swinging in the opposite direction to the ipsilateral leg. At initial contact of the foot, the shoulder is therefore hyperextended, and in the athletes studied, this angle ranged from a mean of 64° to 72°. While this angle seemed important within samples (e.g. greater angles were correlated with shorter flight times in 20 km women, with longer contact times in junior women, with slower speeds in 50 km men, and with greater step lengths in junior men), the associations were inconsistent across groups, and it is difficult to make any concrete recommendations about optimal hyperextension angles. In addition, there were few correlations between the shoulder flexion angle at toe-off across groups, and overall there was little evidence that race walkers should endeavour to walk with a "strong upward swing" of the arms (Payne & Payne, 1981, p.366) or that the shoulder movements assist walking speed (McGuire, 1989), especially in the men's 50 km race. If, as suggested by Pontzer et al. (2009), the shoulder action is a passive response to the legs, then the key advice to race walk coaches is to ensure that the arms are moving in a manner that appears to balance the legs' movements (an exaggerated shoulder girdle movement as described above could be evidence that they do not). The elbow angle is of course a key contributor to how the upper limb balances the leg's movements because a larger angle increases the arm's moment of inertia (and decreases its angular velocity), and vice versa. The elbow angle is not maintained at a constant angle, but varies throughout its swinging motion; the mean elbow angles at midstance were larger than those at initial contact and toe-off in the vast majority of race walkers (as Fruktov et al. (1984) has suspected), but was less than 90° in all five groups (20 km men: 82°; 50 km men: 83°; senior women: 76°; junior men: 85°; and junior women: 75°), as shown again in more recent research on world-class athletes (Hanley, 2013b) and contrary to the widespread advice of coaches (e.g. Markham, 1989; Villa, 1990; Laird, 1996). The resulting changes in upper limb moment of inertia might have been in response to changes in the leg's movements during the gait cycle, while the decrease in midstance elbow angle in both 20 km women and 50 km men might have been a response to fatigue that allowed for easier arm swing.

7.4 Conclusion

The purpose of Studies 1 to 3 was to analyse a large range of elite male and female athletes competing over the Olympic distances of 20 km and 50 km, as well as over the junior distance of 10 km. The overall key findings of the competition studies are:

- The most important kinematic variables in elite race walking are step length and cadence; step length was the main reason for differences in walking speed between men and women at different age groups, and its decrease was the larger factor in reduced speed in the variation studies. Cadence was found to be a more important variable in terms of faster walking for both junior and senior women ($r = .82$ and $r = .71$ respectively);
- Athletes can prevent potentially detrimental effects of step length on cadence if they attain a step length relative to their own stature. While step length ratios of over 70% were common amongst the fastest 20 km walkers, the best 50 km walkers had slightly lower values (but still above 65%) that might be better suited because of self-imposed restraints on speed;
- These elite athletes relied to a great extent on flight phases for increased speed, as the distance covered during the flight phases contributed substantially to overall step length (means between 9% and 16%). This was particularly important for the fastest athletes, although practically all athletes would have been slower without them;
- In addition, the decreases in flight distance in the variation studies coincided very closely with the decreases in step length and speed, showing again its key role in elite race walking. Despite all this, deliberately encouraging athletes to try to achieve flight periods is not unequivocally recommended because of the increased risk of receiving red cards;
- Faster gait was achieved with lower proportions of stance time compared with swing, to the extent that double support occurred in only the slowest

walkers. The main area for an athlete to focus on if he or she wishes to improve cadence is therefore a reduction in contact time;

- Achieving shorter contact times might require shortening of both foot ahead and foot behind distances, for although both contribute to step length (and foot behind differentiated between athletes more so than foot ahead), overstriding can occur if athletes place their feet too far ahead at either initial contact or toe-off, with the consequence being time spent in unproductive contact and hence lower cadences. The caveat to this is that longer foot ahead distances can be beneficial (by increasing step length) if the athlete is strong enough to overcome the negative effects of the foot position taken;
- All groups obeyed the straightened knee rule largely successfully at both initial contact and midstance, without greatly disadvantaging speed. The requirement for straightening the knee at initial contact also meant that race walkers tried to avoid too much knee flexion during swing that would have made the return to full extension difficult, and so there is a knock-on effect of Rule 230.1 (that officially only applies to stance) that actually also affects the knee and whole lower limb during swing;
- Despite the emphasis on pelvic rotation in the coaching literature, there were no correlations between pelvic rotation and step length or speed, and it did not prove useful in preventing decreases in these variables with fatigue. The values found did however differ between groups (i.e. between men and women), so while it did not differentiate between elite athletes, it still has an important role in race walking. As with foot ahead, greater strength levels in female athletes might allow them to approach the pelvic rotations achieved by men and increase speed. However, the potentially negative outcomes (e.g. decreased cadence) must be borne in mind by coaches;
- Hip hyperextension and ankle plantarflexion angles were larger at toe-off in junior athletes than in their senior counterparts, and it is possible that these were related to longer contact times. These joint angular differences might indicate a lack of development in hip and ankle musculature that needs addressing during the younger athlete’s transition to senior racing;
- There were larger standard deviations in the upper limb angles compared with the lower limb that indicated that the athletes’ torsos and arms responded non-uniformly to their more stereotyped leg movements. As the upper limb acts to balance the movement of the legs, its movement is very important in overall body efficiency and should be monitored as part of technical training, and is an area worth further study.

CHAPTER 8

STUDY 4: LABORATORY-BASED STUDY

8.1 Introduction

There are a number of important mechanical variables that cannot normally be measured in competition such as GRFs, joint moments and muscular activity patterns (via EMG). These data can complement and explain kinematic findings, and improve understanding of the strength training needs of race walking, which should be based on the specificity of its motor-technical demands (Scholich, 1992). Because the present rule governing the knee during stance was introduced in 1995, earlier studies no longer describe either the joint kinetics (White & Winter, 1985; Cairns et al., 1986) or EMG patterns (Murray et al., 1983) in modern race walkers. Furthermore, those studies that have taken place since the introduction of the new rule have not tested sufficient numbers of athletes across junior and senior levels, or both men and women. Therefore, literature on race walking biomechanics is limited, and as a result no clear relationships have been established between key biomechanical parameters and performance criteria. New analyses of modern elite race walkers will allow the mapping of movement patterns in athletes with fully developed and technically sound race walking gaits, and help understand the pattern of muscle activation and the internal dynamics of the key lower limb joints.

None of the small number of studies that measured internal kinetics in race walking (White & Winter, 1985; Cairns et al., 1986; Hoga et al., 2003; Hoga et al., 2006; Preatoni et al., 2006; Donà et al., 2009) have combined the analysis of joint moments, powers or work with EMG, despite the importance of this combination in understanding how muscles coordinate human gait (Zajac et al., 2003). A thorough description and understanding of the patterns of muscular activity in elite international race walkers will allow coaches and athletes to develop training regimens that emphasise correct technique and appropriate strength development, rather than relying on subjective observations as they have predominantly done to date. In addition, this information will prove useful to members of the scientific community with regard to understanding the musculoskeletal limits of the lower limbs in an exaggerated form of gait. The aim of this study was to measure and analyse the lower limb joint moments, powers, work and EMG patterns in elite international male and female race walkers.

8.2 Methods

The main methods for this part of the study have been described in Chapter 3. In contrast with the analyses carried out on the competition data, stride length has been used rather than step length as the focus of this part of the study is on the right leg stride (from toe-off of the right foot to the next successive toe-off of the right foot). Subsequently, stride length ratio has been used instead of step length ratio, and cadence has been calculated as strides per second rather than steps per second (and is still reported in hertz). All other variables (e.g. foot ahead, contact time) were only reported for the right foot contact phase. The distance the CM travelled during flight (flight distance) was measured from the instant of toe-off to the instant of initial contact, and like flight time was only measured between the two contact phases (right foot and left foot). While the timing gates were used to get an indication of race walking speed at the time of testing, the speeds reported were of the CM for one full stride and obtained using the digitised data.

8.2.1 Participants

Twenty international race walkers from six different nations (Australia, Canada, Finland, Great Britain, Ireland and Lithuania) participated in the laboratory study. The 20 athletes comprised 10 men (23 ± 5 yrs, 1.79 ± .06 m, 67.0 ± 9.4 kg) and 10 women (22 ± 5 yrs, 1.69 ± .05 m, 53.9 ± 5.6 kg). The men were taller (p = .001, 95% CI = .050 to .155, ES = 1.81) and heavier (p =.002, 95% CI = 5.70 to 20.4, ES = 1.69) than the women. Each of these groups was further broken down into two groups of five senior and five junior athletes, and their characteristics are summarised in Table 8.1. There were no differences between the heights and masses of the senior men and junior men, or between the senior women and junior women.

Table 8.1. Mean (± *s*) participant heights, masses and personal best times over the senior and junior championship distances. Four of the five senior men had recorded a time over the 50 km distance.

	Height (m)	Mass (kg)	Personal best (h:min:s)
Senior men (N=5)	1.81 (± .06)	70.2 (± 7.1)	20 km – 1:22:53 (± 1:38) 50 km – 3:50:48 (± 3:17)
Senior women (N=5)	1.68 (± .05)	56.7 (± 3.6)	20 km – 1:30:11 (± 0:48)
Junior men (N=5)	1.77 (± .06)	63.9 (± 11.1)	10 km – 44:38 (± 2:16)
Junior women (N=5)	1.69 (± .06)	51.1 (± 6.2)	10 km – 49:53 (± 1:56)

All of the senior men and senior women have competed at the Olympic Games or World Championships in Athletics; four of the senior men were 50 km specialists. Of the junior men, one had competed at the World Junior Championships; and of the junior women, one was World Youth Champion, who with another junior woman has also competed at the World Junior Championships, and one other had competed at the European Junior Championships. All of the other junior athletes had competed at major international competitions such as the World Cup and European Cup.

8.3 Results

8.3.1 Kinematic and temporal variables

The values for the key kinematic and temporal variables are shown in Table 8.2. Race walking speed was correlated with stride length (r = .66, p = .002), stride length ratio (r = .52, p = .018), cadence (r = .77, p < .001), contact time (r = –.59, p = .006), and foot behind (absolute: r = .53, p = .017; ratio: r = .45, p = .047). Stride length was correlated with stature (r = .60, p = .005), foot ahead (r = .57, p = .008), foot behind (r = .78, p < .001) and foot behind ratio (r = .53, p = .016). Longer flight times were associated with shorter foot behind distances (r = –.45, p = .045).

Table 8.2. Mean (± *s*) and between-subjects effects of key race walking variables. Differences were significant at p < 0.05 (bold). Effect sizes were based on Cohen's *d* and indicated when very large (‡), large (†), or moderate (*).

	Men	Women	*p*	95% CI
Speed (km/h)	13.66 ± 0.39	12.49 ± 0.89	**.001**	**.529 to 1.83†**
Stride length (m)	2.44 ± 0.04	2.24 ± 0.08	**< .001**	**.150 to .268‡**
Stride length ratio (%)	135.4 ± 5.3	131.1 ± 5.7	.103	–.935 to 9.42
Cadence (Hz)	1.55 ± 0.05	1.55 ± 0.11	.927	–.169 to .173
Contact time (s)	.297 ± .021	.299 ± .027	.899	–.024 to .021
Flight time (s)	.027 ± .014	.026 ± .008	.805	–.010 to –.012
Contact time (%)	91.5 ± 4.6	92.0 ± 2.5	.739	–4.03 to 2.91
Foot ahead (m)	0.39 ± 0.03	0.35 ± 0.02	**.001**	**.018 to .062†**
Foot ahead ratio (%)	21.8 ± 1.4	20.8 ± 1.1	.104	–.220 to 2.16
Foot behind (m)	0.50 ± 0.02	0.46 ± 0.02	**.001**	**.020 to .062‡**
Foot behind ratio (%)	27.7 ± 1.2	26.9 ± 1.4	.174	–.393 to 2.01
Flight distance (m)	0.13 ± 0.06	0.10 ± 0.02	.267	–.021 to .068
Foot movement (m)	0.21 ± 0.03	0.20 ± 0.03	.331	–.014 to .039
Knee at contact (°)	179 ± 2	182 ± 3	.054	–4.85 to .048
Knee at midstance (°)	185 ± 3	186 ± 4	.530	–4.29 to 2.29

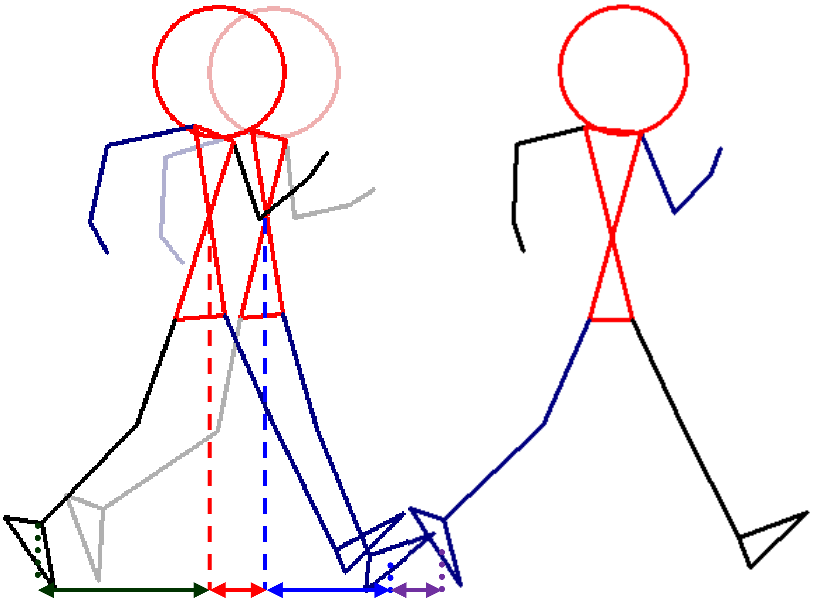


Figure 8.1. The four distances that contribute to step length (as per Figure 2.11).

In Figure 8.1, the green arrow represents the foot behind distance, the red arrow represents the flight distance, the blue arrow represents the foot ahead distance, and the purple arrow represents the foot movement. The mean ratio of each of these distances to the right foot step length respectively was 41:10:32:17 in men and 41:9:32:18 in women. Longer foot movements were associated with longer contact times ($r = .73$, $p < .001$) and shorter flight times ($r = –.70$, $p = .001$), whereas longer flight distances were associated with shorter contact times ($r = –.53$, $p = .018$) and longer flight times ($r = .71$, $p < .001$). Longer foot movements were also associated with longer foot behind distances ($r = .47$, $p = .035$) and lower cadences ($r = –.45$, $p = .046$), while flight distance was correlated with step length ratio ($r = .56$, $p = .010$). The mean stride width for men was 50 mm (± 16) while it was 41 mm (± 30) for women.

8.3.2 GRF variables

The values for key kinetic variables for men and women are shown in Table 8.3 below and a diagram of a typical race walk GRF trace is reproduced in Figure 8.2. The values found for the GRF peaks of interest in all three directions did not differ between men and women. A distinct vertical impact peak was not identified in the GRF traces of four of the participants, three of whom were female. In all those traces with an impact peak, its magnitude was smaller than the loading peak ($p < .001$) whose timing ranged from 14 to 31% of stance time. Additionally, the mean loading peak force was greater than the mean push-off peak force ($p = .002$) which had a magnitude of 90% (± 13) of the mean loading peak force and occurred after 56.6% (± 5.1) of stance time. The vertical impact peak value was found to correlate with peak braking force ($r = –.59$, $p = .016$) and the vertical push-off peak value with the propulsive peak value ($r = .50$, $p = .024$). No individual vertical peak force magnitudes were found to correlate with any key kinematic variables such as step length.

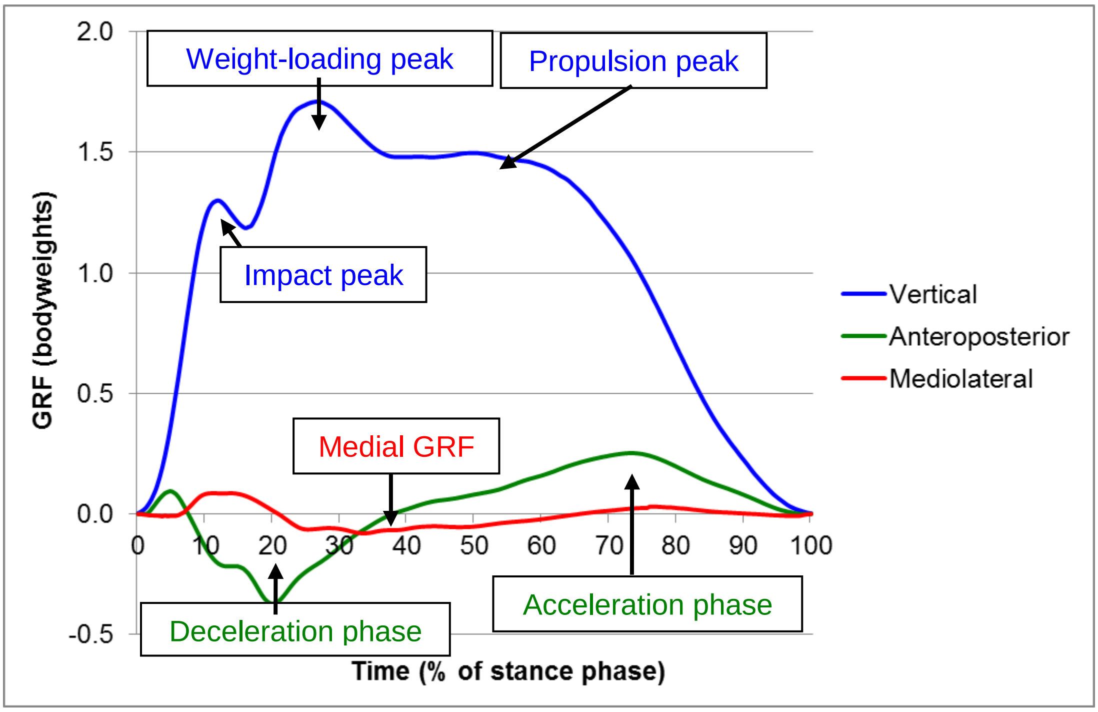


Figure 8.2. A typical race walk GRF trace showing the three components separately (right foot contact).

Table 8.3. Mean (± *s*) and between-subjects effects of kinetic race walking variables. No significant differences were found ($p < 0.05$).

	Men	Women	*p*	95% CI
Vertical force				
Impact peak (BW)	1.29 (± .25)	1.30 (± .15)	.844	–.245 to .203
Loading peak (BW)	1.64 (± .16)	1.69 (± .17)	.494	–.203 to .102
Midstance peak (BW)	1.53 (± .13)	1.54 (± .16)	.953	–.137 to .129
Push-off peak (BW)	1.49 (± .11)	1.47 (± .13)	.838	–.105 to .128
Anteroposterior force				
Braking peak (BW)	–0.37 (± .09)	–0.37 (± .05)	.812	–.075 to .059
Propulsive peak (BW)	0.24 (± .04)	0.26 (± .04)	.274	–.060 to .018
Braking-to-propulsion (%)	42.7 (± 6.7)	42.4 (± 5.4)	.966	–5.77 to 5.97
Decrease in velocity (m/s)	–0.18 (± .04)	–0.17 (± .02)	.654	–.038 to .025
Increase in velocity (m/s)	0.20 (± .05)	0.21 (± .03)	.786	–.043 to .033
Mediolateral force				
Medial maximum (BW)	0.10 (± .05)	0.14 (± .04)	.060	–.080 to .002
Lateral maximum (BW)	0.05 (± .03)	0.05 (± .02)	.935	–.025 to .027
Lateral-to-medial (%)	30.1 (± 6.0)	25.8 (± 2.9)	.066	–.328 to 8.85
Medial-to-lateral (%)	62.0 (± 4.8)	60.2 (± 3.3)	.319	–1.97 to 5.73

In the anteroposterior direction, a GRF trace similar to that found in normal walking was found. A spike impulse at initial contact was recorded in the traces of 19 participants and lasted 19 ms (± 4). The braking peak occurred after 15.5% (± 3.2) of stance time, while the propulsive peak occurred after 73.1% (± 2.7). Correlations between anteroposterior GRF variables and key kinematic variables are shown in Table 8.4. In the mediolateral direction, the medial peak occurred after 40.7% (± 5.4) of stance time, while the late stance lateral peak occurred after 72.3% (± 3.4). The medial peak force was correlated with stride width ($r = .51$, $p = .032$); other correlations are shown in Table 8.4. The peak lateral force magnitude was not correlated with any key variables.

Table 8.4. Correlations between key kinematic and temporal variables and GRF variables; increase in velocity refers to the positive change in velocity that occurred during the propulsive phase. Correlations were significant at $p < 0.05$ (shown in bold).

	Foot behind (%)	Contact time (%)	Flight time	Flight distance	Hip contact angle
Anteroposterior					
Propulsive peak	***r* = .57** ***p* = .008**	*r* = .44 *p* = .052	***r* = –.46** ***p* = .043**	*r* = –.20 *p* = .409	***r* = .54** ***p* = .014**
Braking peak	*r* = –.10 *p* = .668	*r* = .16 *p* = .497	*r* = –.17 *p* = .467	*r* = –.27 *p* = .254	***r* = .46** ***p* = .041**
Time to propulsive peak (%)	*r* = –.36 *p* = .115	***r* = –.69** ***p* = .001**	***r* = .67** ***p* = .001**	*r* = .32 *p* = .174	*r* = –.43 *p* = .060
Duration of propulsive phase (%)	*r* = .35 *p* = .132	***r* = .64** ***p* = .002**	***r* = –.59** ***p* = .006**	***r* = –.58** ***p* = .008**	*r* = .11 *p* = .640
Increase in velocity	***r* = .57** ***p* = .008**	***r* = .47** ***p* = .038**	***r* = –.46** ***p* = .040**	*r* = –.38 *p* = .099	*r* = .44 *p* = .051
Mediolateral					
Medial peak	*r* = .21 *p* = .373	***r* = .51** ***p* = .021**	***r* = –.50** ***p* = .025**	***r* = –.52** ***p* = .018**	*r* = .27 *p* = .242

8.3.3 Muscle moments, powers and work

The muscle moments calculated for the ankle throughout the gait cycle for both men and women are shown below, expressed first in newton meters (N·m) (Figure 8.3) and then as normalised values (Figure 8.4). The dashed vertical line on each graph represents the instant of initial contact, so that the first part of each graph shows swing, and the second shows stance (DeVita, 1994). In order to facilitate the identification of key events during the gait cycle, specific peaks in the trace are labelled on this and successive graphs in a similar fashion to comparable previous studies (e.g. White & Winter, 1985; Bezodis et al., 2008). In Figures 8.3 and 8.4, the peak of the plantarflexor moment has been labelled as AM3; in a subsequent ankle moment diagram (Figures 8.5), this peak has been labelled as both A3 and A4. These labels are used to demarcate the energy absorbing and energy generating phases of the plantarflexor moment, as defined by the accompanying power trace. However, the value used for the plantarflexor moment was the same for both A3 and A4 in terms of analysis.

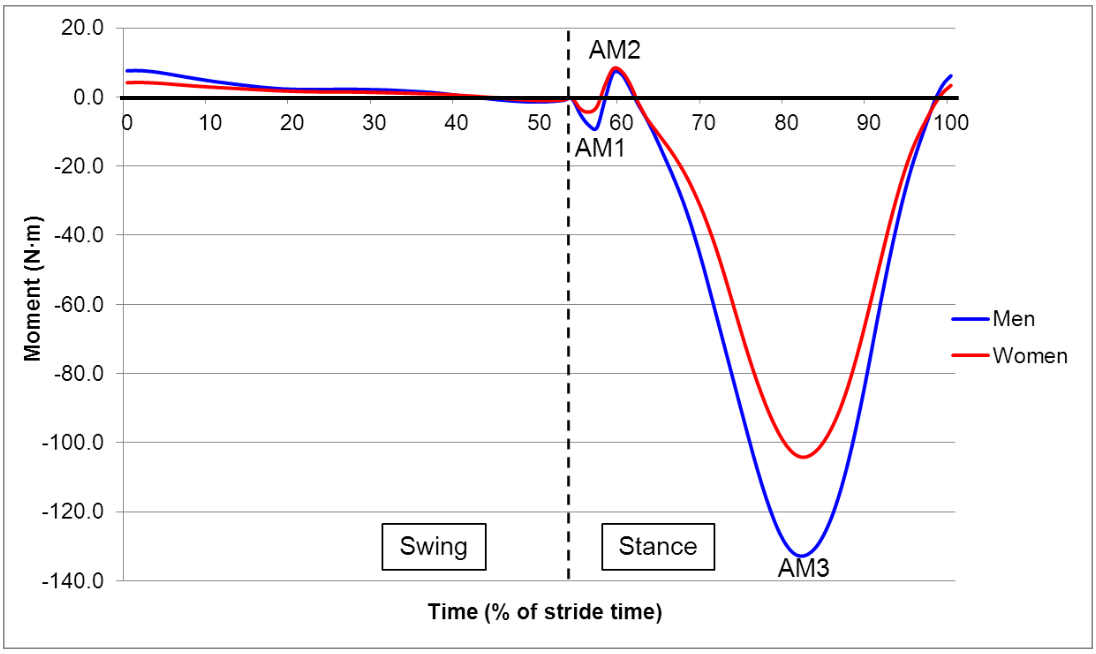


Figure 8.3. Moments (N·m) for the ankle for men and women during a single stride. The dashed vertical line represents the instant of initial contact.

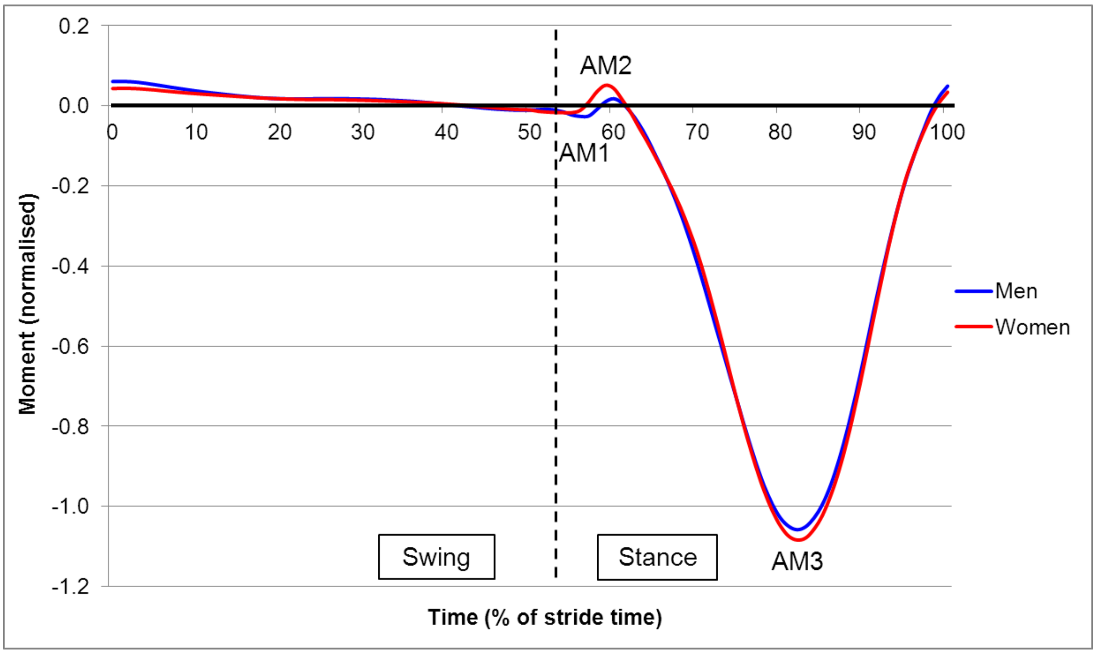


Figure 8.4. Moments (normalised as N/kg) for the ankle for men and women during a single stride. The dashed vertical line represents initial contact.

In Figure 8.3, the moment measured at AM3 had a greater absolute magnitude for men than women (*p* = .008, 95% CI = –48.8 to –9.18, ES = 1.42), but there was no difference when normalised (*p* = .618, 95% CI = –.085 to .138, ES = 0.23) as shown in Figure 8.4. Neither AM1 nor AM2 was different when expressed either way. Similar results were also found for ankle power and work, and at the knee and hip. Therefore, in order to provide an overall description of the patterns of joint kinetics, all moments and powers have been expressed as normalised values. Joint angles and AREMG have also been averaged for all athletes in the Figures and in the descriptions below. Work has been reported for the major power peaks and was normalised as J/kg/m for statistical analysis, although in certain instances the work values have been presented in the more familiar SI unit of joules.

8.3.3.1 Ankle

Figure 8.5 shows the traces of the joint angle, normalised moment, and normalised power of the ankle, as well as the AREMG of key muscles crossing the ankle joint. At toe-off, the ankle was plantarflexed at an angle of 132° (± 6) which decreased as the ankle dorsiflexed by approximately 40° during early swing. The energy generating dorsiflexor moment that caused this action was neither energy generating nor absorbing during midswing and late swing before initial contact, with the result that the total work done during swing was only 1.8 J (± 0.7). There was noticeable tibialis anterior AREMG activity throughout the swing phase.

During early stance, the mean ankle dorsiflexion angle decreased by approximately 20° to reach the anatomical standing position (110°). This movement was initiated by a short energy generating plantarflexion moment (A1) but was quickly followed by a rapid energy absorbing dorsiflexion moment (A2), which itself was followed by another brief energy generating plantarflexion moment. In the midstance phase, the ankle dorsiflexed as the lower leg rotated about the ankle joint; this motion coincided with a plantarflexion moment (A3) that absorbed energy (–8.7 ± 2.6 J) and lasted for approximately 15% of total stride time. The EMG amplitudes of gastrocnemius and soleus increased during this period, indicating an eccentric loading of the triceps surae muscle-tendon unit.

As the athletes moved into late stance, the activity of the triceps surae gradually decreased while the preparation for toe-off was controlled by a powerful plantarflexion moment (A4) that generated energy (16.4 ± 3.8 J) and peaked at about 80% of total stride time. Thereafter, this plantarflexor moment reduced rapidly and a small energy generating dorsiflexor moment occurred with a reversal of the EMG pattern from triceps surae activity to tibialis anterior activity. There were no correlations between any of the identified peak values for ankle moment, power, or work and the variables featured in Table 8.1, although the ankle plantarflexion angle at toe-off was correlated with increased contact time (r = .58, p = .008).

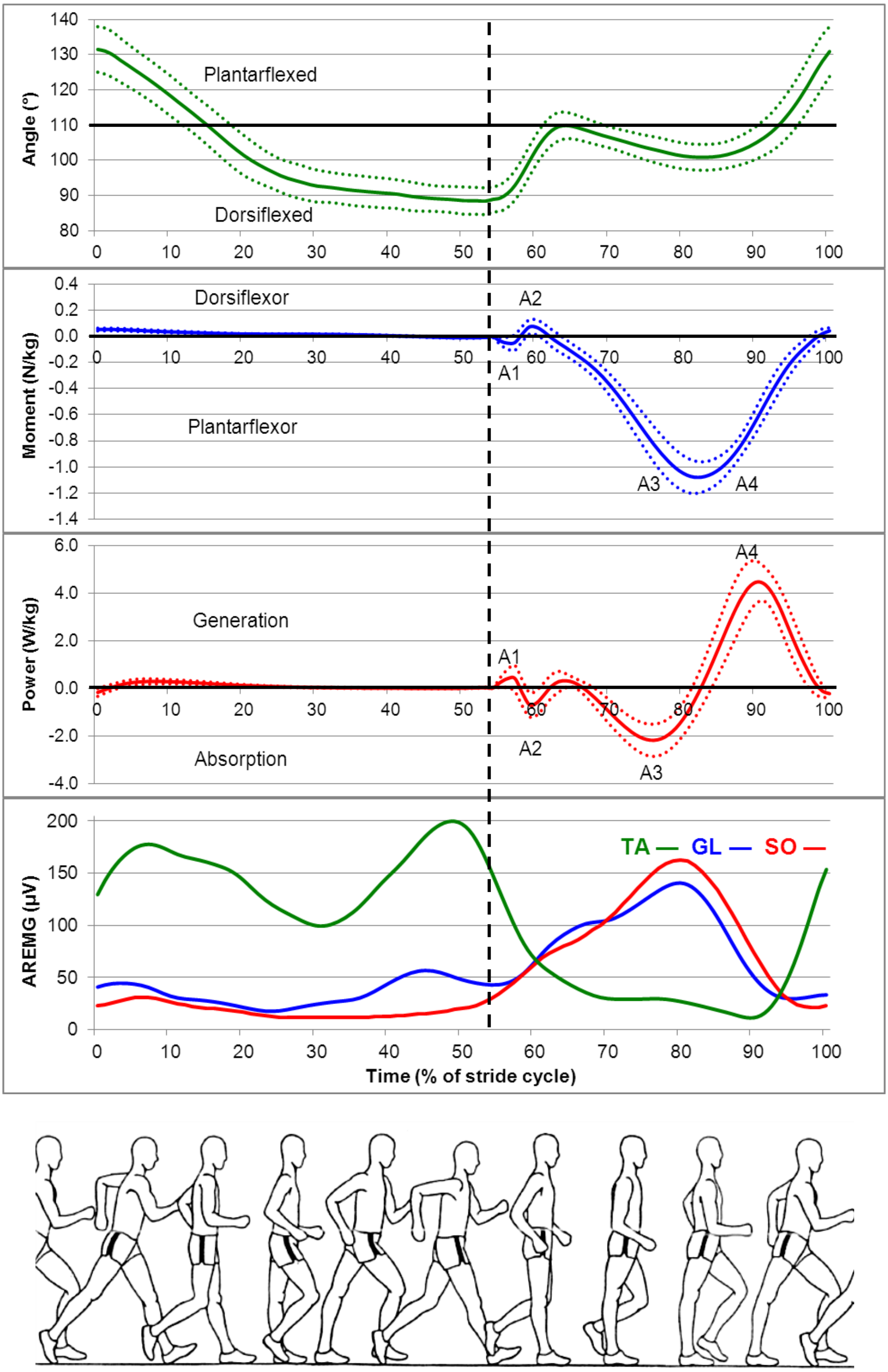


Figure 8.5. Mean ankle joint angle, moment and power (± *s*) and mean AREMG of the right leg during one complete race walking stride (diagram from Laird, 1996).

8.3.3.2 Knee

Figure 8.6 shows the traces of the joint angle, normalised moment, and normalised power of the knee, as well as the AREMG of key muscles crossing the knee joint. Although the gastrocnemius originates above the knee joint, it is considered a very weak knee flexor (Kapandji, 1987) and its EMG trace has therefore not been included in the analysis of knee motion.

In early swing, the knee flexed from a toe-off angle of 145° (± 5) to a maximum flexion value of 107° (± 5). The knee experienced an energy absorbing extensor moment during this phase that actually began in late stance (K1) and decreased in magnitude until approximately 20% of stride time (midswing) before experiencing an energy absorbing flexor moment during late swing (K2) as the knee extended to a mean of 180° (± 3) at initial contact. The mean work done during the swing phase of K1 was –11.1 J (± 3.3) and during K2 it was –35.3 J (± 6.6). The EMG traces showed slight rectus femoris activity during early swing and a high activity of biceps femoris during late swing, while vastus lateralis activity gradually increased towards initial contact. In addition to those correlations shown in Table 8.5, the moments at K1 (swing) and K2 were both correlated with foot behind (*r* = .54, *p* = .015 and *r* = –.48, *p* = .033 respectively), but only the K1 moment was correlated with foot ahead (*r* = .54, *p* = .013). The negative work done during the swing phase of K1 was associated with speed (*r* = –.61, *p* = .004) and cadence (*r* = –.58, *p* = .008). The K2 work was also correlated with cadence (*r* = –.62, *p* = .004).

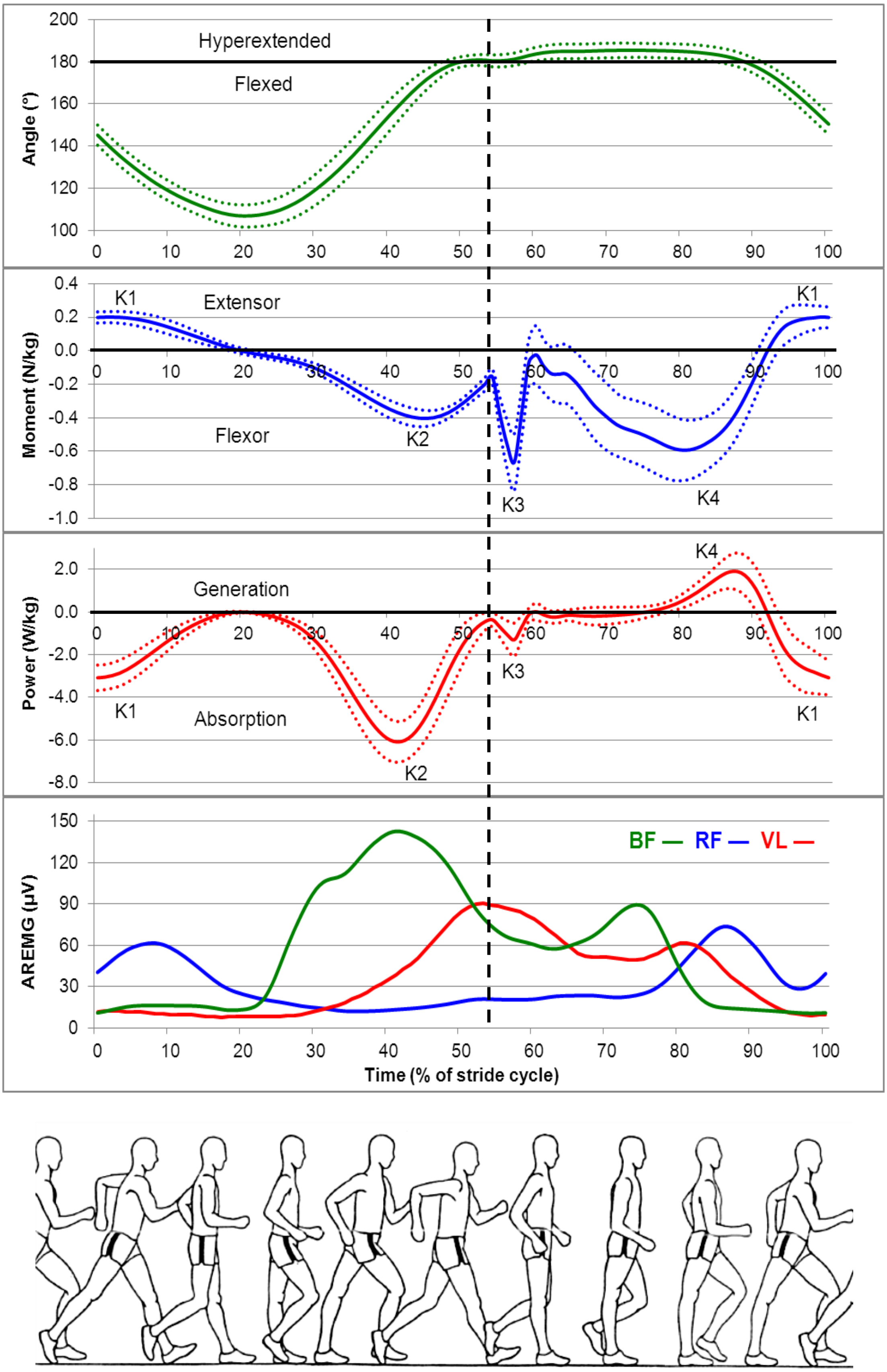


Figure 8.6. Mean knee joint angle, moment and power (± *s*) and mean AREMG of the right leg during one complete race walking stride (diagram from Laird, 1996).

Table 8.5. Correlation analysis of normalised moments and powers with key kinematic variables. Correlations were significant at $p < 0.05$ (shown in bold).

	Speed	Stride length	Stride length ratio	Cadence	Knee at contact	Knee at midstance
Knee						
K1 moment (swing)	**r = .78** **p < .001**	**r = .55** **p = .012**	r = .20 p = .398	**r = .46** **p = .041**	**r = –.54** **p = .014**	r = –.36 p = .119
K1 power	**r = –.77** **p < .001**	r = –.37 p = .109	r = –.11 p = .652	**r = –.63** **p = .003**	**r = .47** **p = .035**	r = .32 p = .169
K2 moment	**r = –.63** **p = .003**	r = –.39 p = .094	r = –.13 p = .580	**r = –.47** **p = .036**	r = .38 p = .097	r = .27 p = .244
K2 power	**r = –.49** **p = .029**	r = .05 p = .834	r = –.13 p = .600	**r = –.65** **p = .002**	r = .27 p = .249	r = .09 p = .705
Hip						
H3 moment	**r = –.70** **p = .001**	r = .13 p = .589	r = –.12 p = .615	**r = –.74** **p < .001**	**r = .45** **p = .047**	r = .20 p = .397
H3 power	r = .35 p = .128	r = –.27 p = .260	r = .06 p = .813	**r = .69** **p = .001**	r = –.23 p = .321	**r = –.46** **p = .039**
H4 moment	r = –.32 p = .171	r = –.33 p = .151	r = .04 p = .877	r = –.07 p = .777	**r = .51** **p = .023**	r = –.11 p = .632
H4 power	r = .38 p = .098	r = .43 p = .060	r = .01 p = .969	r = .04 p = .873	**r = –.53** **p = .017**	r = .14 p = .569

A brief energy absorbing flexor moment (K3) occurred within the first 0.05 s of stance that was followed by a flexor moment of little or no energy generation or absorption as the knee hyperextended to a maximum of 185° (± 3). After midstance, the flexor moment (K4) generated energy (6.8 ± 2.6 J) to allow the knee to flex and prepare for swing. The athletes spent 66% (± 14) of stance time with the knee hyperextended (men: 62 ± 13%; women: 70 ± 14%). During the last 10% of stride time (late stance), an extensor moment absorbed energy (–7.6 ± 5.0 J) as the knee flexed (K1). Vastus lateralis activity was noticeable on the EMG trace during the knee extension phase, although rectus femoris activity was not. The vastus lateralis activity continued to be present for most of the stance phase. Biceps femoris activity was also relatively high, peaking during midstance before diminishing before toe-off. During this late stance phase, rectus femoris activity increased to its highest magnitude during the gait cycle.

The K4 moment was negatively correlated with knee angle at midstance and toe-off (r = –.59, p = .006 and r = –.50, p = .023 respectively) but no other associations were found between the K3 and K4 moment and power values and kinematic variables. However, the K4 work was associated with greater knee midstance angles (r = .75, p < .01) and longer knee hyperextension durations (r = .49, p = .27), while the K3 moment was negatively correlated with initial spike impulse (r = –.49, p = .027), and the K4 moment and power were both correlated with the duration of braking (r = .50, p = .024 and r = –.49, p = .029 respectively) and increase in velocity (r = –.54, p = .014 and r = .47, p = .035 respectively).

8.3.3.3 Hip

Figure 8.7 shows the traces of the joint angle, normalised moment, and normalised power of the hip, as well as the AREMG of key muscles crossing the hip joint.

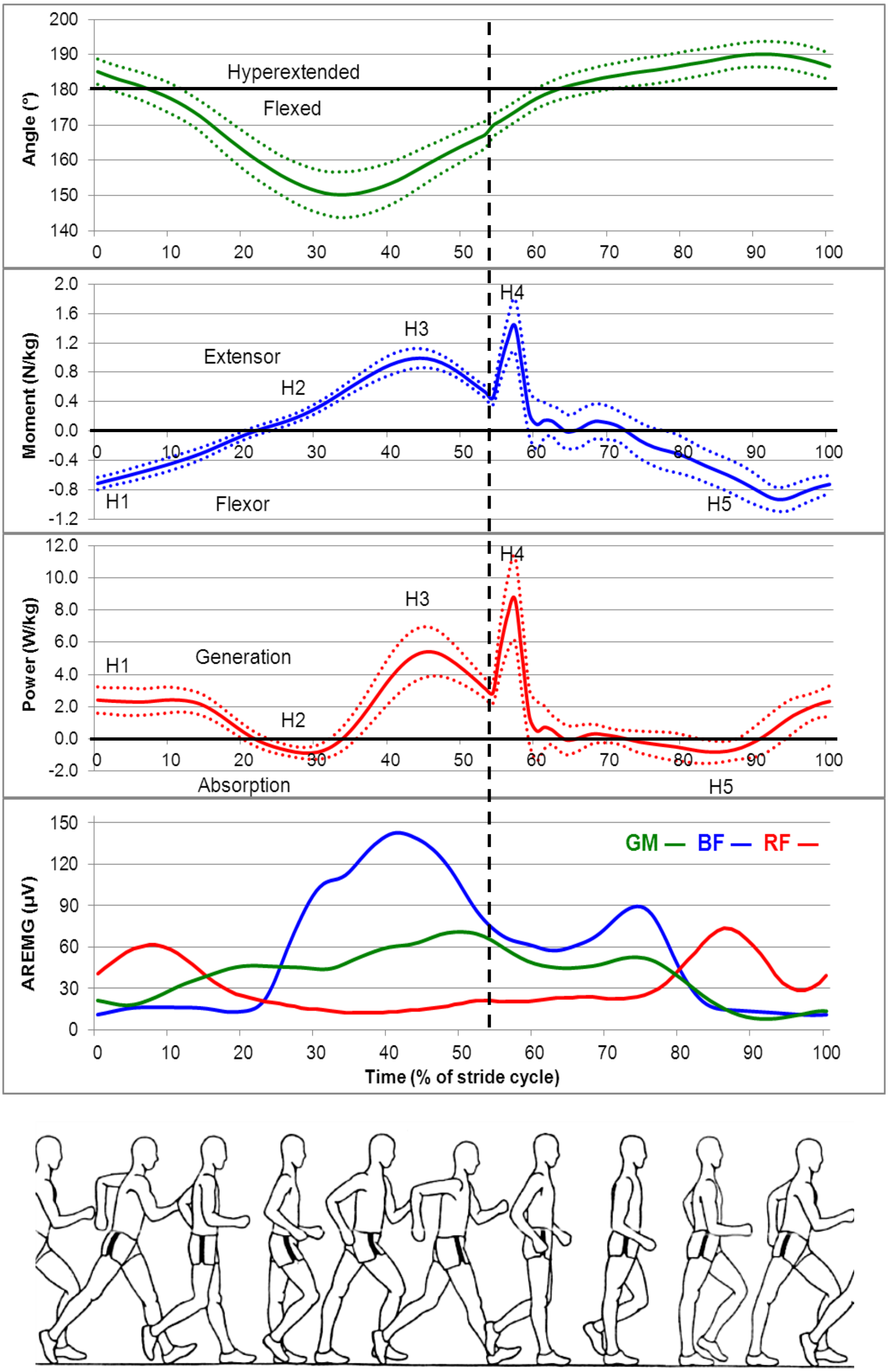


Figure 8.7. Mean hip joint angle, moment and power (± *s*) and mean AREMG of the right leg during one complete race walking stride (diagram from Laird, 1996).

During early swing, the hyperextended hip (185 ± 4° at toe-off) flexed because of a flexor moment (H1) that had begun in late stance, and generated energy (16.3 ± 5.0 J) coincident with activity of the rectus femoris. During midswing, an extensor moment absorbed energy (–3.1 ± 1.3 J) (H2) with increased gluteus maximus activity from about 20 to 35% of stride time. After this the hip flexed to its furthest point of 150° (± 6). During late swing, hip extension occurred because of an extensor moment that generated 28.1 J (± 7.6) of energy (H3) with noticeable EMG activity in the gluteus maximus and biceps femoris. The moments and power peak values at H1 and H2 did not correlate with any key kinematic variables, but the positive work done during H3 was associated with cadence (r = .68, p = .001).

At initial contact, the hip angle was 170° (± 3). A second, larger extensor moment (H4) occurred during the first 10% of the stance phase that generated 14.2 J (± 6.1) of energy and extended the hip to approximately 180° by the end of early stance. Immediately after this, an extensor moment that generated little or no energy occurred as the hip hyperextended, and continued gluteus maximus and biceps femoris activity was observed. During midstance, an energy absorbing flexor moment was observed (H5) that restrained hip extension. The angle of the hip at the vertical upright position was 185° (± 4), after which it reached a maximum hyperextension angle of 190° (± 4), whereupon the flexor moment became energy generating (6.1 ± 4.1 J) and reduced the hyperextension angle before toe-off and continued the flexion movement into early swing. Rectus femoris was markedly active during this flexor moment (peaking during the energy absorption phase) while the activity of the hip extensors was diminished. As well as those correlation shown in Table 8.5, the H4 moment and power peak values were both correlated with initial spike impulse (r = –.53, p = .016 and r = .62, p = .004 respectively). The H4 moment only was correlated with braking peak force (r = .45, p = .048) and the duration of the deceleration phase (r = .47, p = .038).

8.3.3.4 Total work done at each joint

In terms of work performed during the stride, Table 8.6 below shows the totals for the ankle, knee and hip during the whole stride and both stance and swing.

Table 8.6. Total work done (J and J/kg/m) at the ankle, knee and hip joints during one complete race walking stride.

	Swing	Stance	Whole stride
Ankle (J)	1.8 (± 0.7)	7.7 (± 5.2)	9.5 (± 5.6)
Ankle (J/kg/m)	.016 (± .004)	.070 (± .044)	.086 (± .046)
Knee (J)	–46.4 (± 9.5)	–3.6 (± 6.3)	–50.0 (± 12.7)
Knee (J/kg/m)	–.424 (± .064)	–.029 (± .049)	–.453 (± .069)
Hip (J)	41.4 (± 12.0)	15.2 (± 10.2)	56.6 (± 15.8)
Hip (J/kg/m)	.379 (± .106)	.134 (± .079)	.513 (± .120)
Lower limb total (J)	–3.2 (± 8.9)	19.3 (± 11.0)	16.0 (± 9.8)
Lower limb total (J/kg/m)	–.029 (± .084)	.174 (± .089)	.146 (± .088)

Overall, the lower limb was a net generator of energy, with most of the positive work done during stance. The ankle was a net generator of energy, with most of its positive work occurring during stance. The hip was also a net generator of energy, with more positive work done during swing than during stance, but still its contribution to the total during stance was nearly twice that of the ankle. By contrast, the knee was a net dissipater of energy, with noticeably large negative work values occurring during swing; on average, this led to a net dissipation of energy in the lower limb during this phase.

Because muscle groups performed work during different power phases (e.g. the knee flexors did negative work during both K1 and K2 phases), Table 8.7 shows the total work done for each muscle group (some phases have been omitted because the total work done was very small (< 2 J)). This was done to give an indication of the contribution of each muscle group to add to the information about each joint given in Table 8.6. In each case, the phases in Table 8.7 refer to the power bursts that peaked at the annotated positions in each of Figures 8.5, 8.6 and 8.7.

Table 8.7. Total work done (J and J/kg/m) by each of the main muscle groups during either energy generation or absorption. Only those phases where the mean work total was 2 J or more have been included.

	Work (J)	Work (J/kg/m)	Phase
Ankle			
Plantarflexors (generating)	16.4 (± 3.8)	.150 (± .029)	A4
Plantarflexors (absorbing)	–8.7 (± 2.6)	–.080 (± .021)	A3
Knee			
Extensors (absorbing)	–18.7 (± 6.4)	–.167 (± .035)	K1 stance / swing
Flexors (generating)	6.8 (± 2.6)	.064 (± .027)	K4
Flexors (absorbing)	–38.2 (± 7.1)	–.349 (± .049)	K2 / K3
Hip			
Extensors (generating)	42.3 (± 10.1)	.385 (± .073)	H3 / H4
Extensors (absorbing)	–3.1 (± 1.3)	–.028 (± .012)	H2
Flexors (generating)	22.4 (± 7.1)	.202 (± .048)	H1 stance / swing
Flexors (absorbing)	–5.1 (± 4.2)	–.046 (± .039)	H5

8.3.3.5 Timing of joint moments and powers

In order to display better the sequencing of movements throughout the lower limb, Figure 8.8 shows the averaged joint angles, moments, powers and EMG of the ankle, knee and hip for all 20 participants. It can be seen that during midswing, the change in net moment dominance from hip flexors to hip extensors and from knee extensors to knee flexors both occurred at approximately 20% of stride time. The swing hip extensor and knee flexor moments both peaked at approximately 45% of stride time, although the hip was generating energy at this instant while the knee was absorbing it. It was during this late swing phase that maximum biceps femoris activity was evident on the EMG traces. Three conspicuous peaks on both the moment and power traces occurred during early stance: an energy generating plantarflexor moment at the ankle that possibly existed to allow it to move from a maximally dorsiflexed position to a plantarflexed one in preparation for stance; an energy absorbing flexor knee moment that occurred even though the hamstrings contracted during this phase (hence causing a flexor moment), as the hyperextension of the knee meant that it was energy absorbing rather than generating; and an energy generating hip extensor moment, showing the hamstrings' main role during early stance might be to extend the hip (rather than flex the knee). However, as these three moments occurred largely during the first 0.05 s of stance (when impact forces occur), there is a possibility that errors arose in their calculation. Such errors have been found to occur during initial contact in high-impact movements such as jumping (Bisseling & Hof, 2006) and sprinting (Bezodis et al., 2013), and it is also possible that they occur in elite race walking (although the impact forces found in this study (1.3 ± 0.2 BW) were lower than in these other activities). Typically, these errors are due to differences between the filtering frequencies of kinetic and kinematic data that lead to artifacts and cause an increase in the magnitude of the moments calculated (Kristianslund et al., 2012). These errors are thought to be greatest at the hip, and show that magnitudes of muscle moments and powers in gait should be treated with caution, although this does not always affect the overall interpretation of the findings (Hewett & Myer, 2012) and in the present study means the trends found are still valid. After early stance, there was a period of little energy generation or absorption, although absorption at the ankle did begin during midstance as dorsiflexion (and hyperextension at the hip and knee) took place and flexor moments were found at all three joints. Peak hip energy generation occurred during early stance, whereas peak energy generation at the knee occurred at approximately 85% of stride time, followed shortly afterwards by peak ankle energy generation.

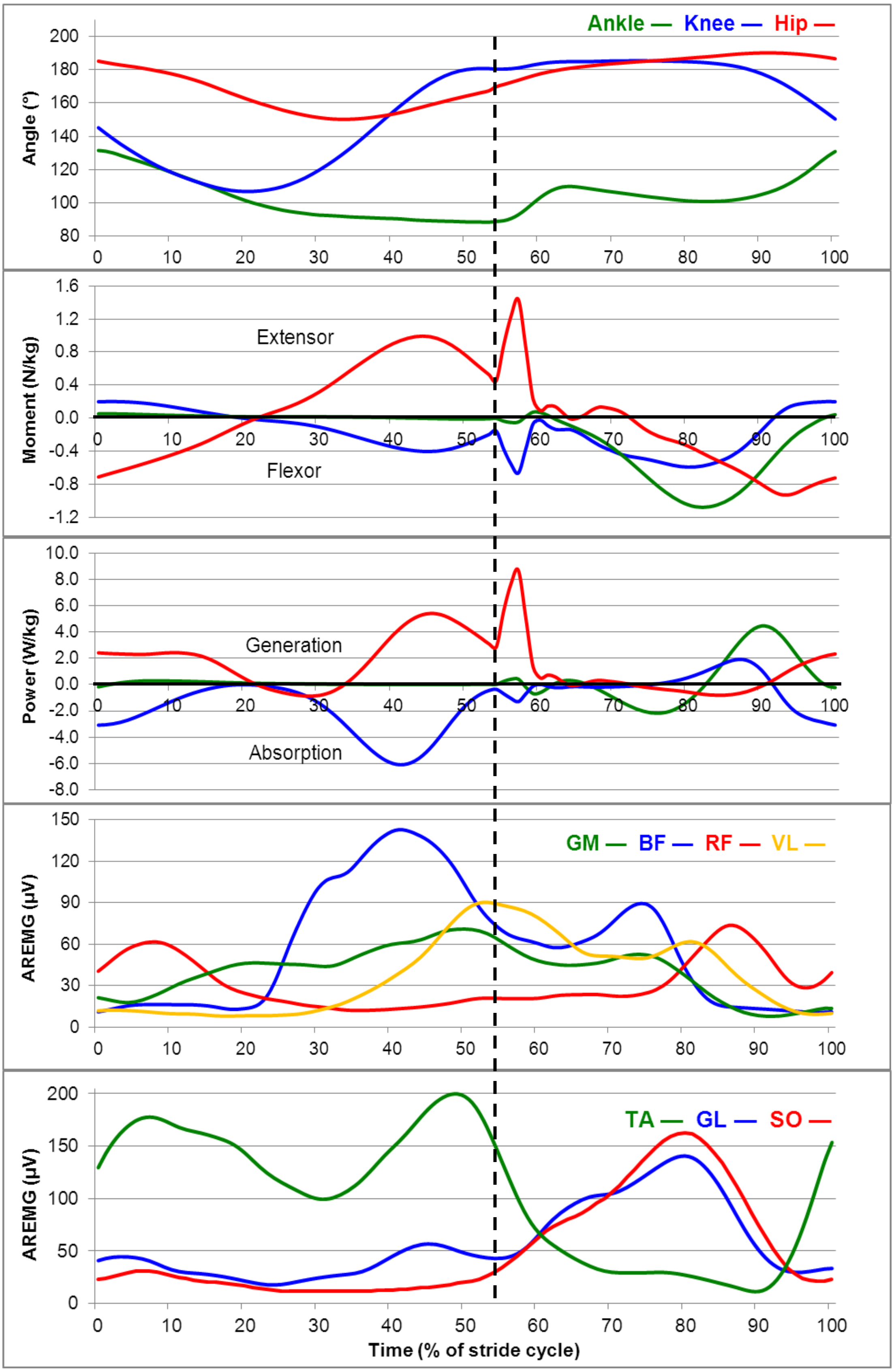


Figure 8.8. Mean joint angles, moments, powers and AREMG at the ankle, knee and hip during one complete race walking stride.

8.3.3.6 Comparisons between the four subgroups of athletes

Figure 8.9 below shows the averaged joint moments, powers and EMG traces at the ankle joint for each subgroup. No differences were found between magnitudes of either moments or powers at any instant (A1, A2, A3 or A4), or any visual differences in EMG traces. With regard to the knee (Figure 8.10), joint angle patterns were also similar across all subgroups. However, the junior women had larger knee angles at initial contact (184 ± 3°) than the senior men (179 ± 2°) (p = .024, 95% CI = 0.55 to 9.05, ES = 1.42). The mean value at the same instant for both the senior women and junior men was 180° (± 2) which was not different from either the senior men or junior women's values. Additionally, the senior men's knee toe-off angles (142 ± 3°) were found to be smaller than those for the junior men (146 ± 3°) (p = .015, 95% CI = –15.7 to –1.49, ES = 1.33) and the junior women (150 ± 4°) (p = .025, 95% CI = –15.1 to –0.89, ES = 2.26), but the values for the senior women (143 ± 5°) were not different.

There were differences between subgroups for some knee peak magnitudes; the extensor moment at K1 was smaller in junior women than in either senior men or junior men (p = .005 and p = .002 respectively) and the magnitude of the power at K1 was also lower in junior women than in senior men (p = .049). The junior women's K2 moment also had a smaller magnitude than the junior men (p = .039) while the junior men had a greater peak moment magnitude at K4 than the senior men (p = .012). However, no differences were found for normalised work values. One noticeable visual difference occurred at approximately 60% of total stride time, where the senior men's subgroup experienced a short, small extensor moment on average where the other subgroups instead experienced flexor moments. The activation patterns of all three muscles were similar across subgroups. However, the activation of the biceps femoris, which began during swing, lasted longer in the senior men's group and the second activation peak during midstance was much smaller than the first. The most noticeable feature of the quadriceps femoris traces was the slightly larger activation pattern observed in junior men during early stance.

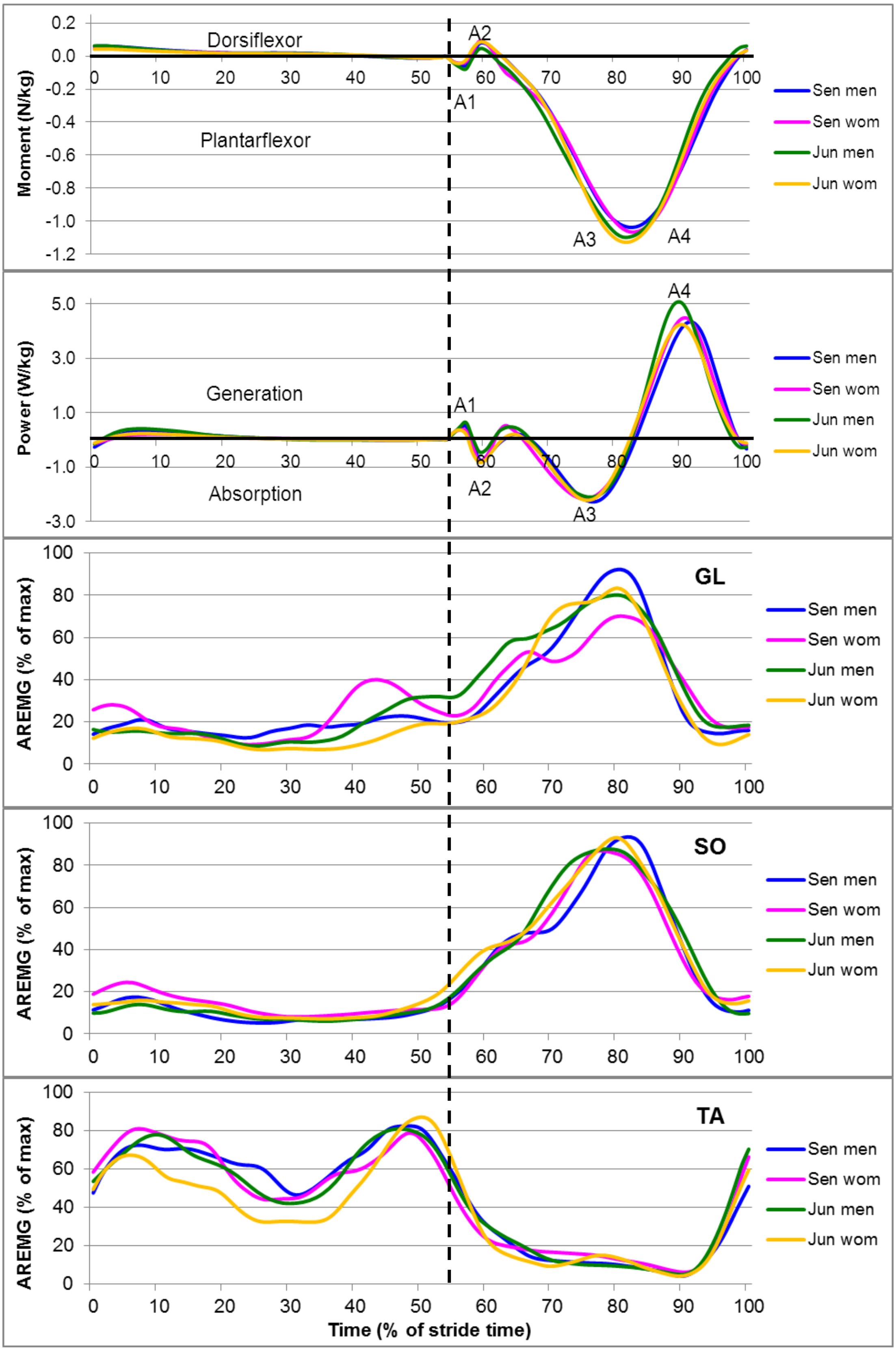


Figure 8.9. Mean ankle joint moments, powers and AREMG traces during one complete race walking stride for each subgroup of athletes.

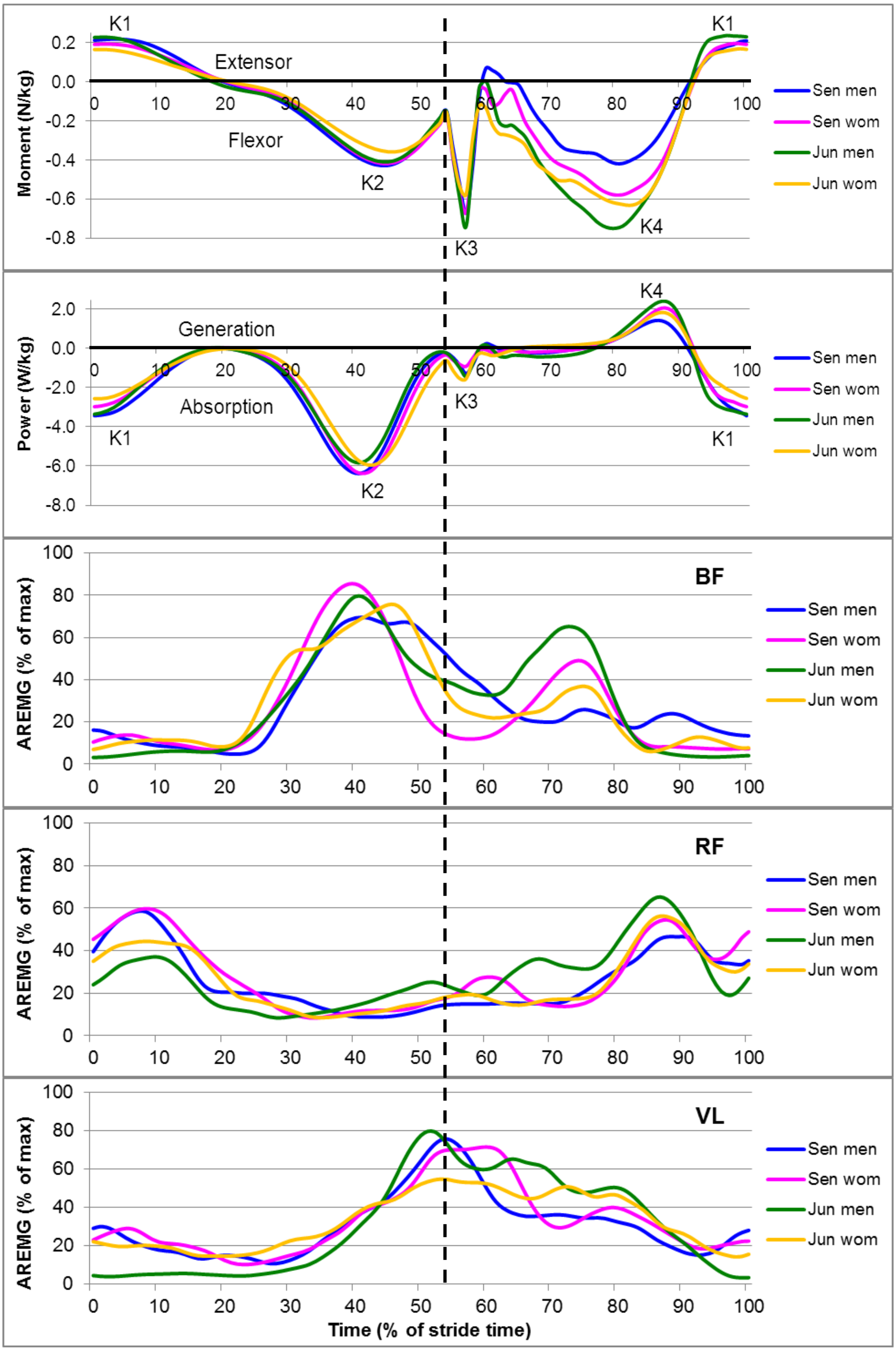


Figure 8.10. Mean knee joint moments, powers and AREMG traces during one complete race walking stride for each subgroup of athletes.

There were no differences between subgroups for the values of the identified peaks on the hip moment and power traces (or for work). However, similar to the knee joint, there were some differences between subgroups with regard to the pattern of the traces (Figure 8.11). In the senior men’s group, the energy generating extensor moment observed after initial contact became an absorbing flexor moment at 60% of total stride time and remained so until approximately 90% of total stride time. By contrast, the other three subgroups continued to experience a predominantly energy generating extensor moment until after 70% of stride time (after which the energy absorbing flexor moment began and continued until about 90% of stride time as in the senior men’s subgroup). The activity of the three hip muscles measured was largely similar across all subgroups, although as with the biceps femoris, the gluteus maximus in senior men seemed to be active for longer during the late swing / early stance phases.

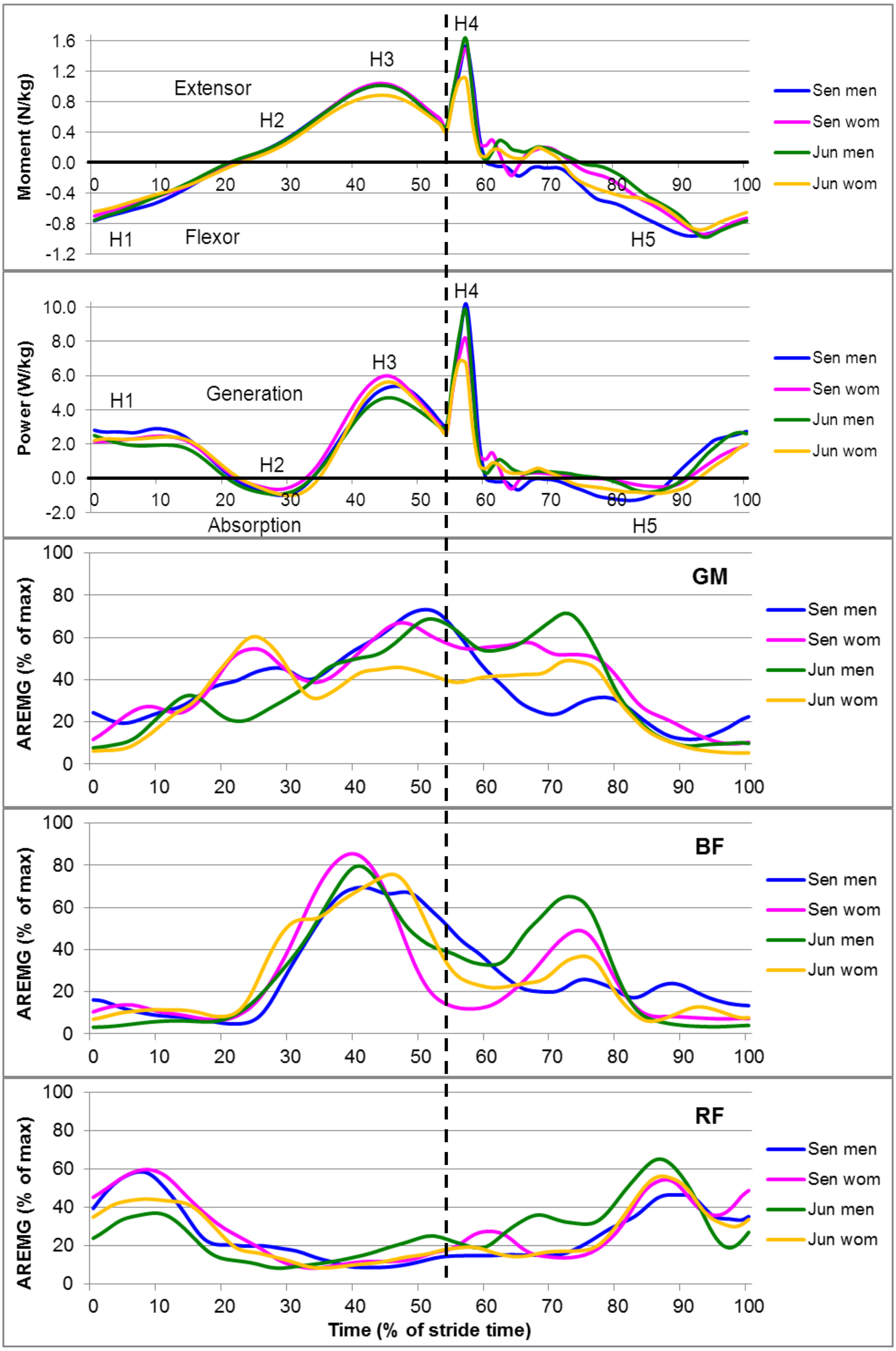


Figure 8.11. Mean hip joint moments, powers and AREMG traces during one complete race walking stride for each subgroup of athletes.

8.4 Discussion

The aim of this study was to measure and analyse the lower limb joint moments, powers, work and EMG patterns in elite international male and female race walkers. Key kinematic and kinetic variables were also measured to link the internal parameters with those that were external. The patterns of muscle activity in the main leg joints gave an insight into the typical demands of the muscles involved in this unique form of competitive gait and will prove very useful to race walk coaches, athletes and biomechanists. The differences between men and women for moment and power peaks were not present when normalised for anthropometric measurements, an important finding replicated for key kinematic variables such as stride length, foot ahead and foot behind distances, and key kinetic variables such as braking and propulsive forces. Therefore, despite performance differences (i.e. men were faster than women), both sexes had similar overall joint moment and power patterns. Differences were found between senior men, junior men and junior women for the magnitudes of a few peak values that might be important in differentiating between athletes, but in general the averaged moment and power patterns represented each group very closely. This suggests that although some kinematic differences were found between groups (e.g. knee angle at toe-off), the fundamental patterns are very similar and can be generalised across elite, well-trained race walkers. Of course, these similarities might not be visually obvious because of the physical effects of differences in body size and muscle strength. This information is nonetheless useful for coaches because it means that while athletes’ training can be individualised (e.g. for different strength levels), the exercises prescribed can be similar within a training group if the aim is to develop the specific movements of race walking.

As well as being used in the calculation of muscle moments, the GRF data were also analysed in their own right. While all peak GRFs (in all three directions) were higher than those typically found in normal walking (Levine et al., 2012), what was particularly striking was how the vertical trace did not increase after midstance with the result that the push-off peak was approximately 90% of the earlier loading peak. This vertical push-off peak also occurred much earlier in the stance phase than in normal walking (Levine et al., 2012). It was inferred in previous research (Fenton, 1984) that this reduced push-off peak was due to efforts by the race walker to minimise vertical force so that visible loss of contact did not occur. While this might be a beneficial consequence of the reduced push-off peak, the corresponding kinematic data (which Fenton (1984) did not record) suggest that the reduction in vertical force during late stance is a result of the knee's movement during this phase, rather than a conscious decision by the athlete to avoid flight. In essence, the knee's movement from hyperextension in midstance to flexion during late stance is the opposite of what occurs in normal walking (Levine et al., 2012), and one result of this abnormal motion is the reduction (and earlier occurrence) of the vertical push-off peak. The knee's kinematics during late stance might therefore prove to be a useful aid in reducing vertical displacement of the CM, and reveal a previously unheralded advantage of the straightened knee to efficient race walking that might also help prevent visible loss of contact (while still being acknowledged as having a negative effect on speed when compared with, for example, distance running).

As endurance athletes, it is important for race walkers to reduce overall movement inefficiency and some features of the vertical GRF pattern (e.g. the slight flattening of its late stance profile) might be an attempt to conserve mechanical energy. Similarly, when maintaining constant walking speed, race walkers should aim to reduce inefficiency in the anteroposterior direction by minimising decreases in velocity during the braking phase so that the effort required to recover velocity during the propulsion phase is minimised. Nearly all athletes experienced a brief propulsive impulse at initial contact that theoretically reduced the need for greater force production in late stance, but its small magnitude meant that no such association was found. The propulsive phase began relatively early but its peak occurred in late stance and therefore did not coincide with the vertical push-off peak. Later propulsive peaks during the foot behind phase were found to be important in this group of elite race walkers as they were associated with increased flight times, which if managed correctly (i.e. within the event's rule) could be a key area for athletes and coaches to develop.

Although there were no phases of double support identified in any of the race walkers' traces, lateral forces were still experienced during early and late stance, as in normal walking (Levine et al., 2012). However, medial forces were also recorded during early stance in some athletes. More consistently, relatively large medial forces were recorded in all athletes during the middle third of stance. As suggested by previous research (Murray et al., 1983), this was possibly due to an acceleration of the CM toward the swing side of the body as a result of pelvic obliquity that occurs to reduce the vertical displacement of the CM in the absence of knee flexion. The medial force peak was smaller in those athletes with their feet following a narrower stride width, and suggests that walking in a straighter line helps to reduce the need to apply (potentially wasteful) forces in this direction (Levine et al., 2012). Incidentally, the stride widths were narrower than those in normal walking (Levine et al., 2012) and in previous research on non-elite race walkers (Murray et al., 1983) and therefore could indeed be a feature of elite race walking as predicted by coaches (e.g. Markham, 1989). The lateral forces experienced during late stance could be an attempt to reverse the pelvic obliquity movement before contralateral initial contact (Murray et al., 1983), although this movement was not measured in this study. These features of both medial and lateral GRFs highlight the requirement for race walkers to develop the pelvic muscles involved (e.g. gluteus medius) so that CM movement efficiency is improved, and also give a direction for future research on the effects of these frontal plane pelvic movements on race walking technique and muscle recruitment.

8.4.1 The ankle joint

The main functions of the ankle joint during swing were to dorsiflex to allow the foot to clear the ground and place the foot in a position for heel-strike to occur. The tibialis anterior maintained a forceful contraction throughout this phase, although little work was done because the ankle quickly reached the end of its anatomical range. It is possible that the athletes needed to reach this limit to ensure ground clearance given the relatively little knee flexion that occurred (e.g. compared with distance running (Williams et al., 1991; Smith & Hanley, 2013)). The prolonged contraction of tibialis anterior might be a source of the shin pain that is frequently reported by race walkers (Levin, 1992; Francis et al., 1998), and similar to the increased stress found in the dorsiflexors during fast normal walking (Prilutsky & Gregor, 2001). During early stance, the foot’s rapid progress from initial contact to a flat foot position was controlled by a short energy absorbing dorsiflexor moment (A2 in Figure 8.5). The brief energy generating plantarflexor moment before this (A1) appeared to be an attempt to ‘unlock’ the ankle from its dorsiflexed position to permit a smooth foot landing movement to occur and engage the ankle earlier in the stance phase. The eccentric contraction of tibialis anterior (during the A2 moment) has also been given as a possible reason for the shin pain found in race walkers, but this might be a less likely source than the swing phase contraction given the very brief duration of the moment, its small magnitude, and the evidence of reduced tibialis anterior activity. However, this moment and the negative work done during it might be considerably greater in some individuals (e.g. novice walkers) and could indeed be a source of pain and injury for them.

During late stance, the ankle plantarflexors did the greatest amount of positive work of any joint during the propulsive phase. Despite this, and in contrast to Hoga et al. (2006), the final plantarflexor moment (A4) was not correlated with race walking speed ($r = .03$). This might have been because the plantarflexor moment (A3) that absorbed energy immediately beforehand was an important source of elastic energy storage in the triceps surae, and whose energy return contributed to the final plantarflexion movement (Zajac et al., 2003). This possible role of the stretch-shortening cycle in the plantarflexors was supported by the EMG graphs that showed diminished activity in the triceps surae before toe-off, and that also probably prevented the ankle from plantarflexing any further.

8.4.2 The knee joint

To aid the ankle in ground clearance and reduce the moment of inertia of the swing leg, the knee started flexing before toe-off (K1 in Figure 8.6), but was later restricted during early swing and midswing by an energy absorbing extensor moment. This movement was probably undertaken so that returning the knee to full extension by initial contact was facilitated. This extensor moment continued and eventually supported the transition from knee flexion to extension after midswing, but this extension was itself restricted by an energy absorbing flexor moment during late swing (K2). This flexor moment recruited the biceps femoris, and the large amount of negative work done during this phase to decelerate the lower leg was by far the largest observed during the race walking stride. Peak biceps femoris activity occurred before the end of the eccentric phase, as is typical for the stretch-shortening cycle in running (Komi, 2000). There is therefore great stress on the hamstrings during late swing given that at the same time this biarticular muscle group contributed to a large hip extensor moment (H3), and coaches should pay attention to the strength of their athletes' hamstrings to try to reduce the risk of injury.

At the end of the swing phase, the knee extended to a fully straightened position. As stated above, this was facilitated by the restraint on knee flexion that occurred during midswing and could thus be a crucial intervention that allows the walker to keep within the rules. The brief energy absorbing flexor moment at initial contact (K3) was in reaction to the sudden large impact force, but this impact did not lead to noticeable knee flexion in these well-trained race walkers. This flexor moment differed from the findings of older studies (White & Winter, 1985; Cairns et al., 1986), and can be attributed to the current requirement for a fully extended knee at initial contact, and further emphasises that some early findings on race walking (and subsequent recommendations) need to be treated with caution. The short and small energy generating extensor moment experienced by the senior men's subgroup was most likely necessary to fully extend the knee during early stance as, unlike the other subgroups, the mean knee angle at initial contact was slightly below 180°. While the small amount of knee extension that then occurred might have provided a benefit to these senior men, it is not recommended that race walkers deliberately make initial contact with a flexed knee because of the risk of receiving red cards. However, landing with a straightened knee and then achieving some hyperextension might accrue similar benefits if the knee is not already hyperextended at heel strike.

After the flexor moment, the knee slowly hyperextended and there was little or no work done during midstance. The biceps femoris contracted to extend the hip and this longer flexor moment appeared to be important in decreasing the duration of braking and increasing CM velocity during late stance. While in this position, the biceps femoris contracted to extend the hip but this did not also lead to knee flexion until after the vertical upright position (K4). As in sprinting (Vardaxis & Hoshizaki, 1989), the rate of knee flexion before toe-off was controlled by an energy absorbing knee extensor moment (K1) that allowed the foot to maintain contact for longer thereby increasing the foot behind distance (*r* = .54) and providing the swing leg with more time to advance before any flight occurred so that foot ahead distance was also increased (*r* = .54). The contribution of this energy absorbing knee extensor moment to stride length is noteworthy and might be one of the discrete factors that enable fast race walking while reducing visible loss of contact.

8.4.3 The hip joint

After the hip flexors contracted to move the thigh rapidly forwards during early swing (H1 in Figure 8.7), the gluteus maximus contracted eccentrically during midswing in order to halt flexion (H2) and then contracted concentrically with biceps femoris to reverse the hip's movement into extension. The magnitude of this extensor moment (H3) was correlated with race walking speed, and both this moment and the positive work done during it were associated with greater cadences. In addition to this, a large energy generating extensor moment occurred during early stance (H4) that continued the extension of the hip. While they were not correlated with speed, this normalised hip moment and its associated power (1.4 ± 0.4 N/kg and 8.7 ± 2.6 W/kg) were the largest observed across all joints during the entire gait cycle and their magnitude shows the hip extensors' crucial role in generating mechanical energy. Furthermore, the results showed that the hip extensors did most of the positive work during the gait cycle and emphasised their central function in elite race walking. The correlations between the H4 moment and the initial spike impulse, braking peak force, and duration of the deceleration phase suggest that this large hip extensor moment served to reduce the amount of braking experienced during initial contact. Kaimin et al. (1983) argue that because of full knee extension the hip extensors are only capable of diminishing the deceleration phase in this way (rather than contributing to propulsion), and so while none of these variables directly correlated with speed, it is possible that the small reduction in braking is important to efficiency when accumulated over thousands of steps. The hip flexion that began in late stance and continued into swing was caused by relatively large amounts of work and might have been assisted by any elastic energy storage that occurred in the hip flexors during the energy absorption phase (H5). This phase began noticeably earlier in the senior men's subgroup, and as with energy storage in the triceps surae during midstance, might be an important contributor to reduced energy cost for these men who mainly compete over 50 km. From the EMG patterns, the rectus femoris seemed to be involved during both hip flexor moments and knee extensor moments, although the dominant role of any of the biarticular muscles is difficult to determine precisely. In practical terms, the results of this study show that race walkers should try to develop a forceful extension of the hip during both late swing and early stance with exercises that increase the dynamic strength and endurance of the hip extensor muscles.

8.4.4 Performance parameters and inverse kinetic data

Only one muscle moment or power value (K1) correlated with both speed and stride length (as it began during stance), and the latter association was no longer present when stride length was normalised. By contrast, four of the five moment and power peaks that correlated with speed were also correlated with cadence, and so these moments and powers might therefore be more important in increasing cadence than step length. Three of the joint moment peaks and two of the power peaks were correlated with speed and cadence (Table 8.3), and all largely occurred during swing. Leg joint kinetics during swing were therefore important as they increased cadence through the rapid forward movement of the midswing leg, and a key component in maintaining whole body forward momentum given the limited contribution of the contralateral midstance leg to energy generation. It was also noticeable that the slowest subgroup of athletes tested (junior women) had lower magnitudes for key knee swing moments and powers than other, faster subgroups and this might be one important muscular component that differentiates them from other athletes (e.g. junior men). This might be because the junior women's slower speeds did not allow for the stretch-shortening cycle to be utilised as well as it was in other subgroups. Correct stance leg technique is obviously important, but athletes and coaches should also attend to the development of swing leg technique, and to the risk of injury inherent in its rapid movements (e.g. to the hamstrings).

The defined role of the knee in race walking has a profound effect on all lower limb joints. Because the knee was extended (or hyperextended) from initial contact to midstance, it could not extend late in stance to propel the CM forwards (as in running) but instead underwent flexion. The hyperextension of the knee also corresponded to a prolonged energy absorption in the triceps surae muscles, as well as early hyperextension and short periods of energy absorption at the hip joint. As a result, the race walkers in this study used the straightened leg as a long rigid lever for most of the stance phase before toe-off. In essence, the function of the knee during stance in race walking is to be straightened, and a main function of the swing phase is to restrict knee flexion to allow for easier knee extension before initial contact. As a result, throughout the whole gait cycle, the knee powers were predominantly energy absorbing. This meant that the main contributor to the generation of energy was the coupling of the hip extensors (during late swing and early stance) and the ankle plantarflexors (during late stance), with an important contribution also made by the hip flexors during late stance and early swing. The activity patterns of the two hip extensors, biceps femoris and gluteus maximus, did appear to differ between the senior men and the other three subgroups, and this is possibly because of differences in muscular qualities. While no muscle groups should be neglected, there is evidence that those directly involved in these movements require particular attention. This is not necessarily meant to infer that they need to be trained to produce large forces, but that coaches and athletes should be aware that race walking speed might suffer if these muscles become fatigued or if there is an imbalance between left and right sides of the body.

8.4.5 EMG results

The results from this study provide the most in-depth description of EMG activity patterns in elite race walking to date. Whilst all-round development is important for elite athletes, highlighting the activity of the predominant muscle groups can inform strength training regimens. Of the muscles analysed, the gluteus maximus and biceps femoris were active from midswing to prevent too great a hip flexion angle before initial contact. These synergist muscles continued as powerful hip extensors from late swing until midstance. The prominence of the biarticular hamstrings was also notable as they were involved in decelerating knee extension by contracting eccentrically during late swing. Therefore, the appropriate training of the hamstrings as eccentric knee flexors and hip extensors together with the gluteus maximus is particularly important, as in running (Belli et al., 2002). Specifically, muscle strength and conditioning exercises that position the hip and knee in a way that replicates race walking movements are advised.

On the anterior thigh, vastus lateralis activity was evident before, during, and after initial contact which suggested that the quadriceps femoris acted to some extent to achieve and maintain full knee extension. However, the biarticular rectus femoris was less involved in knee extension during this phase, and more active as a hip flexor. Considering the amount of positive work done by the hip flexors during early swing, this function of rectus femoris might be more important to develop than its role in knee extension. In the lower leg, the triceps surae muscles were almost silent during swing but contracted during stance to plantarflex the ankle. This contraction was crucial as it caused the large energy generating plantarflexor moment in late stance that coupled with the early stance contraction of the hip extensors to develop forward momentum. The triceps surae activity peaked during midstance and diminished before toe-off, by which time their antagonist, tibialis anterior, began contracting to arrest ankle plantarflexion before swing and prepare for dorsiflexion to ensure ground clearance began as soon as toe-off occurred.

Overall, the EMG patterns were very similar across all four subgroups as the muscles appeared to begin and end contracting at roughly the same times during the gait cycle (taking into account individual differences). As suggested above, the finding that the muscles act in a similar fashion across athletes is of use to coaches, especially as they can adopt these findings when working with athletes on their strength and conditioning without conducting EMG data collection of their own.

8.5 Conclusion

Race walking is a highly technical event where its specific rule has a distinct effect on lower limb joint kinetics and EMG. By conducting a new, unique study combining muscle moments, powers and work with EMG in elite male and female athletes, evidence has been provided for the role of particular leg muscles and associated joint movements. The most important findings of this novel study are:

- The key muscle groups that contributed to energy generation were the hip flexors, hip extensors and ankle plantarflexors, while energy absorption occurred predominantly in the knee flexors and extensors;
- The hip in fact did most of the positive work throughout the gait cycle, with the rectus femoris important in late stance / early swing to drive the thigh forwards, and the gluteus maximus and biceps femoris important in late swing / early stance in preventing too much deceleration at initial contact;
- The large energy generating extensor moment that occurred during late swing / early stance was the largest observed during the entire gait cycle for moment, power and work, showing above all the hip extensors' crucial role in generating mechanical energy before and during heel strike;
- In the senior men's group, the energy generating extensor moment observed at the hip after initial contact became an absorbing flexor moment at 60% of total stride time until approximately 90% of total stride time (in contrast to the other groups). This earlier energy absorption in the hip flexors might be a key factor in senior men's faster walking because of the utilisation of the stretch-shortening cycle in this key muscle group;
- Overall, there were few differences in normalised muscle moments, powers, work or EMG activity patterns between men and women (or between juniors and seniors) and this suggests that techniques are comparable across elite athletes, and thus similar strength and conditioning routines can be used across training groups. It also suggests that the junior participants in this study were quite close to elite senior level in terms of technique and more pronounced differences might have been found with non-elite athletes;
- The total amount of work done by the knee during stance was minimal, and in effect, the straightened knee rule restricted the leg to the role of a rigid lever, around which the body rotated because of the work done by the other leg joints and the forward momentum of the contralateral swing leg;
- The race walking rules influenced a swing pattern that restricted knee flexion and stressed the leg muscles, but was also crucial in generating forward

momentum because the swing leg moments and powers negated the limited contribution of the leg during midstance;

- While there were few differences between muscle moment and power peak values, some of those that did occur were for the knee during swing, and mainly showed that junior women had lower magnitudes than male athletes. These results suggest that such slight differences during these energy absorption phases might be important with regard to overall speed;
- Contrary to earlier studies, the ankle in these elite athletes underwent an important plantarflexor moment during early stance that might have unlocked the ankle from its maximally dorsiflexed position. This allowed it to quickly engage in the stance phase, and the stretch-shortening cycle in the triceps surae during midstance might have helped the plantarflexor moment before toe-off and could be an important source of improved efficiency in these endurance events;
- As noted above, there were periods of energy absorption at all three joints and thus there was evidence of an important role for the stretch-shortening cycle in race walking. This was apparent in the ankle plantarflexors during midstance, the knee flexors during late stance / early swing, the knee extensors during late swing, the hip extensors during midswing, and the hip flexors during midstance. Elastic energy storage in the muscle-tendon units might therefore be important in elite race walking with regard to both speed and efficiency (similar to distance running) and requires further investigation;
- The movement of the knee from hyperextension in midstance to flexion in late stance meant that the vertical GRF trace did not increase after midstance, and this is an important factor that minimises CM vertical displacement and reduces flight time;
- The medial force peak was smaller when a narrower stride width was adopted, and suggests that walking in a straighter line helps to reduce the need to apply wasteful forces in this direction;
- Two possible sources of injury to the ankle have been identified previously; the results of this study suggest that it is the prolonged contraction of the tibialis anterior during swing, rather than its brief eccentric contraction during early stance, that is the primary cause;
- The hamstrings are also frequently injured in race walkers, and this study showed that this was likely due to the considerable negative work done during eccentric contraction by these muscles during late swing.

CHAPTER 9

FINAL DISCUSSION

9.1 Preface

The purpose of this research was to provide a comprehensive analysis of the biomechanics of elite race walking that could contribute to a technical manual, by measuring and identifying key variables in determining success, which involved the analysis of men and women, junior and senior athletes, and 20 km and 50 km athletes, in both competition and laboratory settings. The discussion below combines the results and their interpretation from the three outdoor studies in competition (Studies 1, 2 and 3) with those from the laboratory-based study (Study 4) in coming to an overall analysis of the unique characteristics of elite race walking. The overall conclusions of the research are also presented with a summary of the limitations involved and suggestions for future research.

9.2 Synoptic discussion

The construction of a hierarchical model of race walking, based on biomechanical principles and previous models, helped to identify meaningful variables and build theoretical linkages between them (Figure 2.3). This hierarchical model was the foundation on which the key mechanical variables were chosen for analysis, and has been reproduced here as a reminder of these important variables (Figure 9.1). Previous research on these variables has been sparse or limited, and in most instances coaches have relied on anecdotal information or subjective observations when deciding on training practices for technical development. In keeping with this study's purpose of measuring and identifying key variables that could contribute to a technical manual of elite race walking, the focus throughout has been on identifying the most useful findings that can be used by coaches. The predominant structure of this final discussion breaks the race walking stride into constituent parts (i.e. early stance, midstance, late stance and swing) so that the key technical points of each phase can be explained more easily using the scientific evidence found. In this way, it is intended that coaches can isolate aspects of their athletes' techniques as necessary and use the appropriate information to evaluate them and make corrections.

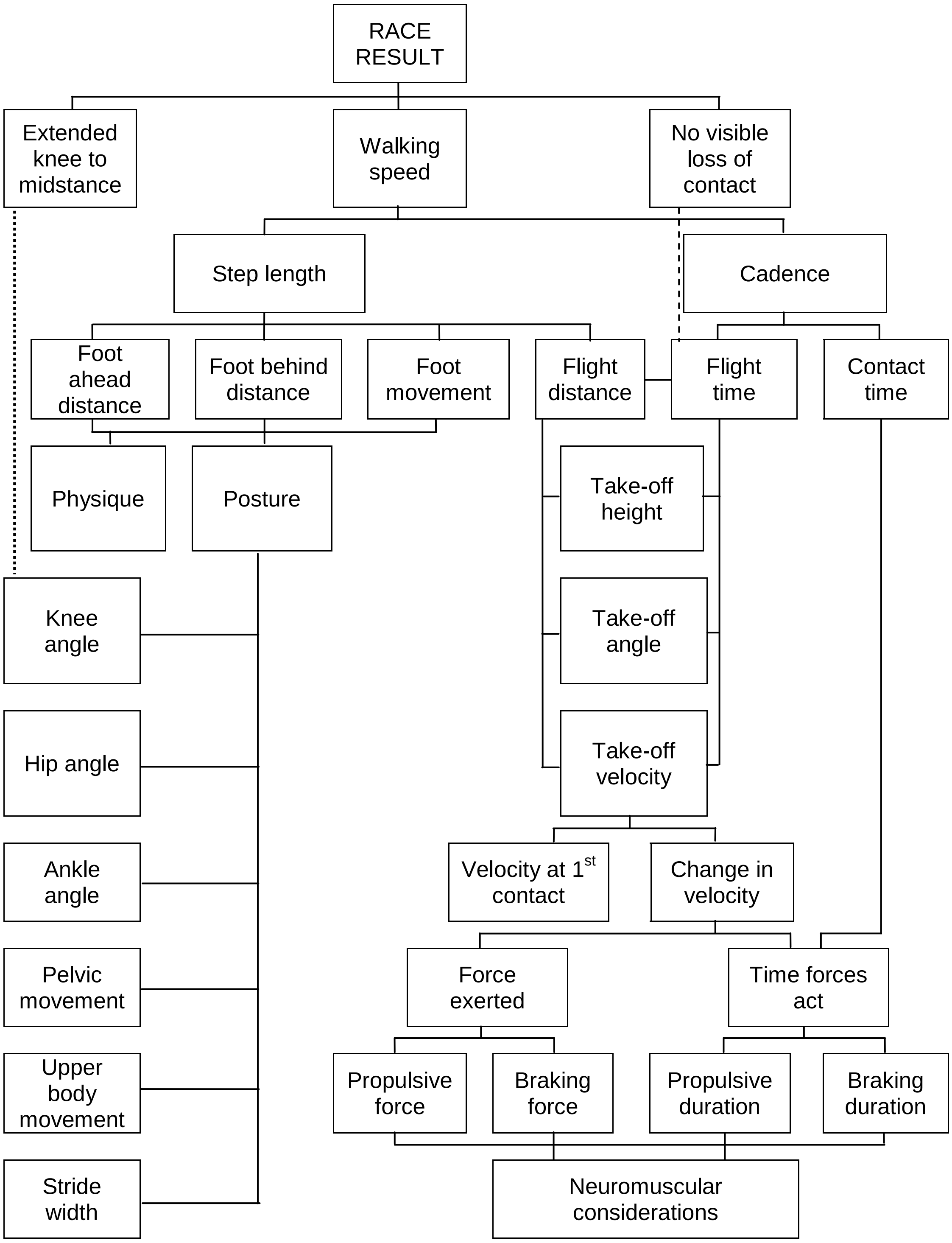


Figure 9.1. Hierarchical model of race walking.

9.2.1 Step length and cadence – overall findings

It has been well established in competitive running that the two main determinants of speed are step length and cadence, and researchers are now often more interested in the interaction between the two (e.g. Salo et al., 2011) or the neuromuscular limits imposed on them (e.g. Mero et al., 1992). By contrast, very few data exist on these two basic factors in elite race walking, and as most of what previously existed was on small numbers of non-elite athletes (e.g. Murray et al., 1983) or restricted to one particular category (e.g. 20 km men (Hoga et al., 2006)), there was a pressing need to clarify their role across a range of athletes. Therefore, one of the most important novel aspects of this study is the provision of useful information about these (and other) key mechanical variables across all categories of race walk competition. By finding associations in large samples of elite athletes, by comparing their results, by measuring changes due to fatigue, and by establishing links with GRF and internal kinetics, it has been possible to bring biomechanical research on race walking to a standard where the roles of step length and cadence are well understood, and future research can now build on this base as in distance running and sprinting.

The results of the competition and laboratory studies showed that the best athletes had both long steps and high cadences. In addition, differences in race walking speed between groups were predominantly due to differences in both step length and cadence; i.e. between 20 km men and 50 km men, between 20 km men and junior men, and between 20 km women and junior women. While the differences between the senior men competing over 20 km and 50 km can be explained by the latter group's need to walk slower to avoid fatigue, the differences between the senior and junior athletes reveal (along with other variables) the performance gaps that exist between the younger and older athletes, and highlight the considerable progress that must be made to advance from one standard to the next. The great development that is needed could explain why so few junior athletes advance to senior competition (Hollings & Hume, 2010), especially when considering the doubling of competitive distance in race walking. While these particular findings are based on averaged data in each group, the individual analyses across race categories further supported the findings that achieving both longer steps and higher cadences were crucial to an individual's chances of success, with cadence being particularly important for female athletes. Although it might have been expected, based for instance on research on sprinting (Hunter et al., 2004), that a negative interaction would be found between increased step length and cadence, this was not generally the case on an inter-individual basis. This might be because one effect of

Rule 230.1's constraints on technique is to restrict flight distance and consequently step length, and another effect is a restriction on the positive work possible at the knee during stance that could make contact time shorter (and hence increase cadence).

With regard to the effects of fatigue, the reductions in step length were identified as the main reason for slower walking, particularly in the latter stages of the men's 50 km. This might be because increased fatigue means that the muscles responsible for energy generation can no longer do the amount of positive work required (especially at the hip and ankle) to maintain propulsive impulse. In addition, not only did the 50 km men manage to maintain cadence despite fatigue, but its association with speed increased with distance walked, showing the significance of sustaining individual walking rhythms so that muscle activity patterns are maintained. This might be because of the importance of continually utilising the stretch-shortening cycle over the course of the race to make use of elastic energy return (Sano et al., 2013) and spare the body's limited glycogen stores (Arcelli, 1996). In terms of advice for coaches, technical and physical training that increases cadence while maintaining step length is required in the development of elite senior athletes. In competition, mean step length ratios ranged from 64.7% for 20 km women to 65.3% for 50 km men and 68.0% for 20 km men, but it should be noted that world-class walkers tended to have step length ratios around or above 70%, and this might be a critical performance indicator in elite race walking given that it was correlated more strongly with speed in the competition studies, and that the fastest walkers did not suffer negative interactions between step length ratio and cadence.

9.2.2 Early stance

The most important functions of the early stance phase in race walking are to contribute to step length by positioning the foot ahead of the CM, to obtain and sustain a fully extended knee, and to reduce the deceleration effects of this foot position and maintain forward momentum. The competition studies showed for the first time that most senior athletes placed their foot slightly more than 20% of their stature anterior to the CM, and similarly in the laboratory based testing the mean foot ahead ratios were 21.8% (± 1.4) for men and 20.8% (± 1.1) for women. These values might be useful guides for coaches, especially as the differences between groups occurred when mean heights were different, and there were no changes in foot ahead position with fatigue in the 20 km and 50 km races. While it was not possible to express foot ahead as a ratio for the junior athletes, it was interesting that their absolute values did not differ from those of their senior counterparts and this might have been because of the elite standard of the junior athletes analysed.

Based on the hierarchical model of race walking (Figure 9.1), longer foot ahead distances lead to longer steps (and in fact make the second-highest contribution after foot behind), but of course one complication in human gait is the consequent negative anteroposterior impulse that occurs from initial contact until midstance (Levine et al., 2012). When measured with the force plates, these negative impulses lasted 42.5% (± 7.0) of stance time in men and 42.4% (± 5.4) in women, leading to decreases in velocity of –0.18 m/s (± .04) and –0.17 m/s (± .02) respectively, not dissimilar to the values found in the outdoor studies (20 km men: –0.13 m/s; 20 km women: –0.12 m/s; 50 km men: –0.13 m/s; junior men: –0.16 m/s; and junior women: –0.14 m/s). These small decreases in velocity occurred consistently throughout all variation studies and showed that this was not one of the key features affected by fatigue. That athletes decelerate during this phase is recognised by coaches (Summers, 1991), but shortening the foot ahead distance considerably (e.g. to 10 cm (Huajing & Lizhong, 1991)) to reduce these braking forces would be entirely counterproductive because of the detrimental effects on step length. The foot ahead phase typically experienced by race walkers therefore is not a wholly negative event and the analysis of the 2008 Olympic women's 20 km champion (Table 4.18) showed that an increased foot ahead distance could be an indicator of world-class performances, but with the caveat that the athlete must be able to overcome (or prevent) the negative effects of such a foot position through better technique or muscle strength. This ability is a key feature that distinguishes between faster and slower race walkers, and possibly also between male and female athletes.

As it was not possible to measure aspects of muscular activity during competition, the laboratory study (that was the first to combine internal kinetic measurements, GRFs and EMG) was particularly insightful in this regard. It was found that to help the athletes reduce the net deceleration experienced, a small positive anterior impulse occurred at the very beginning of initial contact in 19 of the 20 participants. This impulse was produced by the backwards movement of the lower limb at this instant caused by the hip extensor moment that did considerable positive work just before and during early stance. Greater magnitudes of this hip extensor moment were also associated with reduced peak braking forces and shorter braking impulse durations. However, contrary to previous findings on moments during the swing phase in male race walkers (Hoga et al., 2003), there was no correlation between the normalised late swing moment and walking speed, and there was also no suggestion that the benefit of greater energy generation at the hip was a shorter foot ahead distance, as proposed by Lafortune et al. (1989). The results of the present study show instead that a key role of the hip extensors is to minimise the negative effects of the foot ahead distance, and thus highlighted the importance of training the hip extensor muscles from both a strength and endurance perspective using both open and closed kinetic exercises. The small energy generating moment that occurred in the senior men’s subgroup might also have given them an advantage, and while it cannot be recommended that any race walker flexes their knee at initial contact to try to achieve this energy generation, it might still arise through early stance hyperextension provided the knee is not already too hyperextended. As with the flight phase aspect of Rule 230.1, this is an area where being on the threshold of non-legal walking can be of benefit to the athlete but where the athlete and coach might decide that the risk of disqualification is too great for potentially small gains.

The points made above, reinforced by the fact that foot ahead was not correlated with speed in any competition study, suggest that this is a variable that should be neither maximised nor minimised, but rather that there is an optimal, individualised range that contributes an appropriate amount of step length without creating too great a braking force. While race walkers should always be cautious of overstriding (i.e. trying to achieve longer steps that conversely lead to slower walking), it might be possible for elite athletes to increase their foot ahead distance (and step length) through technical changes if they concurrently develop the hip extensor muscles to prevent the otherwise inevitable increases in braking forces.

The results from both competition and laboratory-based studies showed that a knee extension angle ranging from 178° to 182° at initial contact was typical for both men and women and across senior and junior athletes (and shows that full knee extension does now occur, compared with before 1995 (Fruktov et al., 1984)). The EMG pattern of vastus lateralis (the only uniarticular knee extensor muscle tested) showed that peak activity occurred at the instant of initial contact, whereas the EMG activation of rectus femoris was reduced during this gait event compared with late stance and early swing. An athlete who does have to rely on considerable muscular contraction in order to fully extend the knee is at a disadvantage compared with those athletes whose knees extend more easily. For example, their quadriceps femoris might fatigue more quickly and full knee extension could become more difficult or not achieved at all. This might not be an issue for junior athletes who compete over the relatively short distance of 10 km, but the small decrease in knee angle at initial contact in 50 km men in the 7th European Cup suggested that it certainly could become an issue in the latter stages of the longer race. Reducing the effects of any restraints on knee mobility (e.g. inflexible hamstrings) should be a priority for race walkers so that full knee extension is facilitated and muscle activity minimised.

It has been suggested that step length is augmented by way of increased dorsiflexion at initial contact because the heel is projected further forwards (Murray et al., 1983; Fenton, 1984). All of the athletes in both indoor and outdoor studies made initial contact with the heel, which does not always occur in running (Pohl & Buckley, 2008). A positive relationship was indeed found between greater dorsiflexion angles and foot ahead distance in 50 km men, but the absence of this association in the other groups might have been due to the relatively small contribution made by increased dorsiflexion. In the laboratory study, the ankle moments were neither energy generating nor absorbing from midswing until initial contact and this was due to the ankle reaching its dorsiflexion limit. Tibialis anterior activity was actually at its highest magnitude just before initial contact in the senior men, junior men and junior women; the stress on the dorsiflexors that occurs as a result of this prolonged contraction is possibly the source of the shin pain frequently reported by race walkers (Levin, 1992; Francis et al., 1998). The energy generating plantarflexor moment observed during early stance, which has not been reported in previous research, ‘unlocked’ the ankle from its dorsiflexed position to allow a smooth landing movement and engage the ankle earlier in the stance phase. This active landing might be a feature of elite performers (including, in this study, elite juniors) given its absence in studies of less skilled race walkers where a more passive landing took place (White & Winter, 1985; Hoga et al., 2006). The subsequent energy absorbing moment provided a brief restraining action, producing an overall smooth movement. While the eccentric contraction during the latter part of this phase has been previously associated with injury to the anterior shin muscles (White & Winter, 1985; Sanzén et al., 1986), tibialis anterior activity was diminishing during this event in this study, and the sustained contraction of tibialis anterior throughout swing is possibly the primary source of this pain.

Race walking is a whole body activity and important contributions are made by the trunk and arms to overall efficiency. While the ipsilateral shoulder joint angle at initial contact did correlate with a number of important variables in different groups, these were too disparate to identify precisely what role shoulder hyperextension had on performance. However, the large ranges found for the shoulders and elbows in terms of both inter- and intra-group comparisons for both men and women (junior and senior) showed that there were larger individual variations for upper limb movements when compared with the lower limb. These variations, and the differing associations with key variables across all groups with shoulder angles at initial contact, might be a result of different requirements in balancing and compensating the rotational movements of the legs. In effect, all race walkers have very similar lower limb movements because of Rule 230.1 but the upper body responses in counterbalancing them are substantially different because of variations in body size and muscle mass (and therefore moment of inertia). However, the fact that upper body responses to lower limb movements are very much individualised should not be used as an excuse to neglect developing efficient arm movements, and clearly these need to be developed in concert with leg movements so that an easy balance is achieved.

9.2.3 Midstance

As its name suggests, midstance is the middle phase of gait where the leg moves from a decelerating position ahead of the CM to an accelerating position behind the CM. It was found that the knee hyperextended in practically all athletes to a mean range of between 185° and 192° in the competition studies regardless of group (with no changes due to fatigue) and between 185° and 186° in the laboratory study. The 'vertical upright position' as described by the IAAF (2014) therefore rarely exists in elite race walking as there is no instant where the hip, knee and ankle joints form a straight line directly below the CM (as shown in Figure 1.2). Rather, the knee passes below the CM before the foot does, and one recommendation is therefore that the definition of the 'vertical upright position' is altered to consider actual lower limb kinematics in elite race walking so that its meaning is clearer to athletes, coaches and judges. The absence of knee flexion meant that the mean vertical GRF magnitude decreased by only 0.11 BW (men) and 0.15 BW (women) from the weight loading peak to midstance, which were much smaller decreases compared with normal walking (Rodgers, 1993). This indicated that there was little vertical displacement from early stance to midstance, and leg stiffness would have remained relatively constant during this phase, particularly when compared with running (De Wit et al., 2000; Dutto & Smith, 2002). As knee hyperextension lasted on average between 69% and 72% of stance time in the competition studies and between 62%

(men) and 70% (women) in the laboratory study, it was clear that most athletes spent most of the stance phase with their knees hyperextended. This is unsurprising because the process of flexing the knee in returning from a hyperextended position takes time to complete, and the laboratory studies showed a power generating knee flexor moment was involved in this movement. Before this, however, there was little positive or negative work done at the knee and it has little role in forward propulsion.

The hyperextension of the knee in turn caused early hip hyperextension because the thigh's position was moved more posteriorly than in normal walking or running (Figure 9.2). Once the hip had hyperextended in early stance, power generation largely ceased and instead an energy absorbing flexor moment was evident during midstance to arrest hyperextension. This was associated with energy absorption by rectus femoris, which up to this point had not been largely recruited. The hip was therefore unable to drive the athlete forwards during midstance as its range of movement during this gait phase was very narrow; the result was the absence of an active movement and the lower limb acted as a rigid lever instead. Thus, these results underline the importance of the preceding hip extensor work during early stance. Without considerable energy generation during this earlier phase, an athlete could struggle to overcome the braking forces involved, resulting in slower walking.

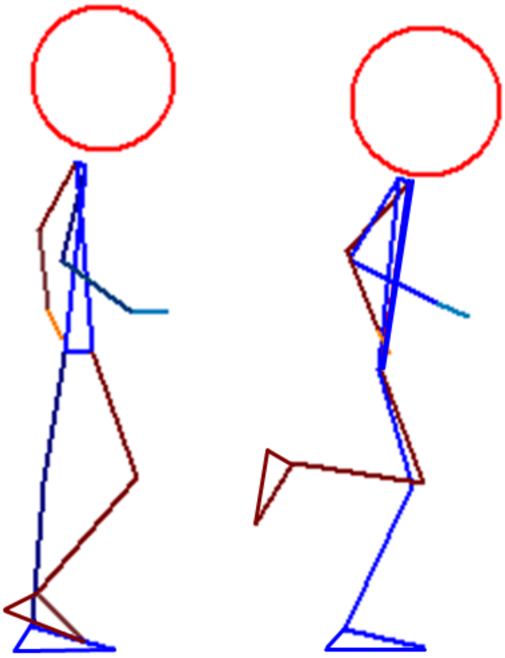


Figure 9.2. The race walker's midstance knee and hip (in blue, left diagram) are hyperextended, whereas the distance runner's knee and hip (right diagram) are flexed. The foot's centre of mass is directly below the CM in both diagrams.

The rather narrow range of hip movement (of about 20°) from the beginning to the end of stance was supplemented by the transverse plane movements of the pelvis. The few correlations found between pelvic and shoulder girdle rotation with key variables does not mean that they are not important aspects of technique. Rather, it seems that these rotations were adopted on an individual basis suggesting there is a limit for optimal trunk rotation beyond which there are diminished returns (i.e. the stride width goes from being optimally narrow to one where the feet cross over one another). This limit might be related to body size and thus a cause of the differences between men and women, and possibly between juniors and seniors (although this is difficult to ascertain because of the lack of anthropometric data for the juniors). Pelvic rotation did not appear to assist in preventing decreases in step length with fatigue, and its negative correlation with cadence in the men's 50 km suggests that it might be over-relied upon, at least for some individuals (its ubiquity therefore not necessarily implying its equal usefulness for all athletes) and coaches should try to identify when their athletes would be better suited to a smaller range of movement.

While the pelvic rotation needed to be individually optimised in order to increase and maintain step length, the role of shoulder rotation seemed to be more important in assisting the upper limbs in balancing the movements of the pelvis and lower limbs, and as such the functions of both girdles differed. Coaches should therefore be aware of these differences so that they are developed in line with the specific role they perform in race walking. With regard to other pelvic movements, the medially-directed GRF that lasted from approximately 28% to 61% of stance acted to decelerate lateral movements that were probably caused by pelvic obliquity. This frontal plane pelvic movement is believed to act in order to minimise vertical displacement when the extended knee is in midstance (Murray et al., 1983), but larger medial forces could be costly in energy terms (Kyröläinen et al., 2001). However, smaller medial forces were associated with a narrower stride width and this new finding could thus be an indicator that this particular element of elite race walking technique provides a benefit beyond that of increasing step length and should continue to be encouraged by coaches.

The hyperextended position of the knee is caused by the obtuse anticlockwise angle found between the thigh and shank (Figure 9.2), and this also affects the ankle. There were no correlations found between the ankle midstance angle and any key performance variables, although there was evidence from the laboratory study that the ankle's movement during this phase was important with regard to forward momentum because it led to the calf muscles being stretched and absorbing energy. Zhang & Cai (2000) suggested that the triceps surae stored energy at initial contact, but this study shows that it is predominantly during midstance that this occurs, although the active unlocking ankle movement that occurred early in stance might indeed have aided the effectiveness of this energy storing phase. The results of this study suggest that the energy absorbed during this phase contributed to the following plantarflexion moment, although White & Winter (1985) had dismissed this notion when observing a similar moment (in a single non-elite male walker) because of its small size. However, the energy absorbed during this study was much greater than that in White & Winter's (1985) study, and might therefore be an indicator of better race walkers, or a difference caused by the new race walking rule. The role of the stretch-shortening cycle could therefore be a key feature of elite race walkers and muscle elasticity might be an area for coaches to develop in their athletes. Overall, the midstance phase was a period of little energy generation at any joint and the energy absorption curve at the ankle was by far the most noteworthy power burst.

9.2.4 Late stance

The main functions of the late stance phase in race walking are to increase step length by moving the foot posterior to the CM, to recover any loss of velocity during early stance, and to achieve a body position that allows for an effective swing phase to begin. The foot behind ratio was found to range between 26.2 and 27.1% in the senior competitions, and similarly the laboratory results showed a mean foot behind ratio of 27.7% (± 1.2) for men and 26.9% (± 1.4) for women. Unlike foot ahead, the absolute foot behind distance differed between senior and junior men and was the largest cause of overall step length difference. In both the competition and laboratory studies, foot behind contributed more to total step length than any other component. Like foot ahead, the foot behind distance is theoretically associated with step length in the hierarchical model of race walking (Figure 9.1) and indeed there was a positive correlation found between absolute foot behind distance and step length in all five competition groups and in the laboratory group. In terms of coaching suggestions, Summers (1991) suggests that race walkers should increase the time spent in propulsion during late stance to increase step length, whereas Villa (1990) believes that the time spent in this phase should be reduced to avoid upward propulsion. The results of this study show that both these apparently conflicting viewpoints had elements of useful technical advice, as while longer foot behind distances did lead to longer steps, 20 km and 50 km senior men with longer foot behind distances in competition also experienced the negative outcome of decreased cadence. The optimum foot behind distance is therefore one that achieves the aim of increasing step length during contact while decreasing the time taken to achieve this.

In terms of recovering the velocity losses that occurred in early stance, the increase in velocity during late stance in the laboratory study was 0.20 m/s (± .05) for men and 0.21 m/s (± .03) for women. These were similar to the results found for the competition studies where they were 0.15 m/s (± .05) for 20 km men, 0.14 m/s (± .06) for 20 km women, 0.14 m/s (± .05) for 50 km men, 0.18 m/s (± .08) for junior men, and 0.16 m/s (± .06) for junior women. While there were no differences in foot behind distances with fatigue, the 20 km men achieved smaller increases in velocity in the second half of the race, probably due to the inability to maintain high enough propulsive impulses as these were caused by positive anteroposterior forces that pushed the CM forwards. The GRF data showed for the first time that those athletes with higher (anteroposterior) propulsive peaks, shorter times to the propulsive peak, and greater increases in velocity had shorter flight times, and the generation of forward momentum (as opposed to upwards) was thus shown to be a key component in avoiding visible loss of contact, as suggested by Villa (1990). In the development of good race walking technique, emphasis should therefore be placed on encouraging athletes to concentrate on ‘driving’ forwards rather than upwards, for example by asking them to focus on minimising upward movements. Of course, it has been highlighted before that flight distance is an important contributor to step length and athletes would be ill-advised to aim to eliminate flight time completely. The reduced (but not absent) peak vertical push-off force probably helped athletes to maintain the appropriate amount of vertical lift at toe-off so that flight times were optimised. Although this reduced vertical push-off force was identified previously (Fenton, 1984), this study’s first use of synchronised GRF and high-speed video data collection showed that this reduction in force was probably caused by the knee’s movement from hyperextension to flexion rather than by a conscious effort on the part of the athletes to avoid flight. It therefore appears that compliance with the straightened knee aspect of Rule 230.1 can actually assist athletes in also complying with the no visible loss of contact aspect and shows the benefit of excellent, legal technique. With regard to other GRF data, the lateral forces experienced during late stance appeared to be an attempt to reverse the pelvic obliquity movement (that occurred during midstance) (Murray et al., 1983) before contralateral initial contact, and therefore features of mediolateral GRFs highlight the requirement for race walkers to develop the muscles involved (e.g. gluteus medius) so that CM movement efficiency is improved.

The largest source of energy generation during late stance occurred at the ankle as it plantarflexed. As mentioned above, the relatively small triceps surae muscles might have been aided in producing the final large energy generation peak by their preceding energy absorption during midstance, and through the transfer of energy from the hip via the knee (Johnson & Buckley, 2001). However, it is important to note that the plantarflexor moment and its power burst decreased in magnitude by toe-off as the effectiveness of the triceps surae declined. Additionally, a very small energy absorbing dorsiflexor moment at toe-off was visible as contraction of the tibialis anterior occurred. While the important role of the plantarflexors in doing positive work during late stance has been recognised (White & Winter, 1985; Hoga et al., 2006), the potential implications of the activity of tibialis anterior during this phase have not been previously identified (partially because EMG was not used in these other studies). The results from these elite race walkers suggest that the tibialis anterior acts in this way to prevent excessive plantarflexion (where no more positive work is done) and hence avoid periods of unproductive contact time. Avoiding too much ankle plantarflexion might therefore be an indicator of better performances and athletes should therefore not try to deliberately prolong the duration of the foot behind phase. Indeed, in the comparisons between the paired groups analysed in competition (Chapter 7), the faster group had less ankle plantarflexion at toe-off, and it is possible that the greater ankle plantarflexion (and hip hyperextension) angles that were found in junior athletes were a means of increasing step length within the limits of techniques that are not yet optimised. These athletes might be able to avoid excessive, unproductive plantarflexion if their stance legs can begin the swing phase earlier, and from a coaching perspective, Villa (1990) recommends achieving this through powerful hip flexion. This viewpoint proved to be quite insightful, as the total positive work done by the hip flexors (22.4 ± 7.1 J) was greater than that done by the ankle plantarflexors (16.4 ± 3.8 J) (contrary to what was found in a single non-elite athlete by White & Winter (1985)). This suggests that this hip flexor moment is important to modern elite race walking in two ways: it performs the obvious role of moving the thigh forwards quickly and maintaining forward momentum, but it also lifts the foot from the ground, hence halting magnitudes of plantarflexion that might unnecessarily increase contact time. At its commencement, this hip flexor moment might have been assisted by the energy absorption by rectus femoris that occurred during midstance, as has been found in running (Belli et al., 2002), and further emphasises the crucial role of the stretch-shortening cycle in elite race walking.

As noted above, an energy generating knee flexor moment, whose function was to return the knee from its hyperextended position to a flexed one before toe-off, began towards the end of midstance. The movement of the knee joint in race walking during late stance could thus be described as the opposite of that which occurs in running, i.e. the knee flexes after midstance until toe-off in race walking, whereas it extends in running (e.g. De Wit et al., 2000). This perceived disadvantage of race walking kinematics has already been shown to be useful in reducing vertical displacement of the CM during late stance, but this new research has found other advantages. First, the knee’s movement from extension to flexion increases the foot behind distance by increasing the effective leg length, and second, it allows the swing leg more time to reach forwards before initial contact so that foot ahead (and thus step length) is increased without causing visible loss of contact. In this way, elite race walkers are able to achieve longer steps than those predicted by Trowbridge (1981) who, by assuming the rear leg stayed straightened, did not take into account the extra distance gained by either the small amount of knee hyperextension at initial contact or the considerably greater degree of knee flexion at toe-off (Figure 9.3). These findings are useful for coaches, as they show that because knee flexion contributes to foot behind (and arises as a natural consequence of legal technique), there is less need to rely on potentially counterproductive ankle plantarflexion for forward propulsion, and athletes can instead concentrate on developing hip flexor power. While improving hip muscle strength had previously been advised by Hoga et al. (2003), this study provides a rationale for doing so beyond the hip flexors’ role in energy generation, and shows its importance across male and female athletes, and at both junior and senior standard. In terms of tangible coaching advice, athletes should try to develop hip flexor strength, for example by race walking on slight inclines or with gym-based exercises that require hip flexion but while restraining knee flexion.

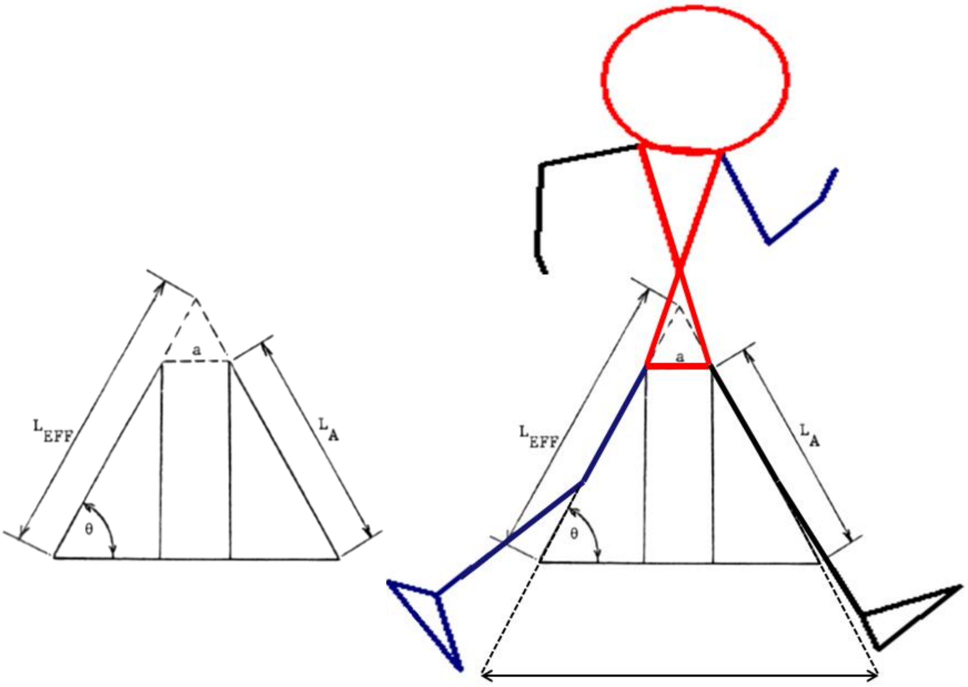


Figure 9.3. Trowbridge's model of step length (left, as per Figure 2.5) with a digitised figure of an elite race walker superimposed (right). The dashed lines on the right-hand diagram are extrapolations of the original L_{EFF} and L_A lines because both diagrams have been rescaled to match the distance between the hip joints ('a').

As expected, the shoulder was flexed at ipsilateral toe-off, while the ipsilateral elbow was found to be at its most flexed at this instant (compared with midstance when the angle was at its greatest). The reduction in elbow angle that occurred in the time between these two gait events was possibly directed towards achieving a reduction in moment of inertia so that a natural balance with the legs was maintained. The decrease in toe-off elbow angle in 20 km women as fatigue occurred (that also occurred at midstance in both 20 km women and 50 km men) might have been an indication that the athletes were trying to reduce moment of inertia to make arm swing easier (Hopkins, 1985). In any case, these values are lower than the 90° angle recommended previously by race walk coaches (Hopkins, 1978; Fruktov et al., 1984; Markham, 1989; Villa, 1990; Laird, 1996), and therefore this angle (or any other specific angle) should not be enforced lest an unnatural arm position is adopted. Instead, the best advice might be to let athletes walk with whatever arm angles feel comfortable, with the coach monitoring the upper limbs to ensure that they appear to be working in concert with the legs, have suitable strength endurance levels to maintain their position, and do not move in a way that would attract the judges' attention.

9.2.5 Swing

The function of the swing phase is to reposition the foot from its position posterior to the CM to one anterior to it (Novacheck, 1998) while clearing the ground and preparing for weight bearing. One swing leg variable that seemed to be particularly important was the stance:swing ratio, with mean values from 45:55 to 49:51 found across all competition groups. As longer swing ratios were indicative of faster walking, and their proportion decreased with fatigue in 20 km women, it would appear that increasing the duration of the swing phase is sound technical advice. However, this presents a problem for race walkers because simultaneous swing phases in both legs lead to flight times. Therefore, because swing times must be kept brief, the swing leg must move in a way that returns the foot rapidly to the ground after toe-off, while at the same time ensuring a straightened knee is achieved by initial contact. The findings of this new research were particularly informative about how elite race walkers are able to combine these complex motor tasks. First, the knee was prevented from flexing too much during early swing by an energy absorbing extensor moment (maximum knee angles ranged between 100° and 107° across studies, with no changes with fatigue); second, the ankle dorsiflexors contracted throughout swing to reduce the need for the knee to be entirely responsible for ground clearance; and third, the hip extensors did positive work during late swing to return the foot to the ground quickly. These results show that how the leg swings is not just important in terms of energy generation or transfer (Hoga et al., 2003), but is crucial in terms of maintaining legal race walking technique.

It should be noted that the swing phase of race walking does not merely function to return the foot to contact but is an essential contributor to maintaining high speeds by increasing cadence. This study found that it is the movement of the swing leg that helps propel the body forwards when the ipsilateral leg is in midstance (and acting as a rigid lever). In particular, the hip flexor moment during early swing not only moves the large thigh segment forwards rapidly, but also contributes to lower limb movement via energy transfer (Johnson & Buckley, 2001). This was the main source of the shank’s forward swing motion, rather than the knee extensors that predominantly absorbed energy during this phase. While the subsequent energy return might have aided knee extension (and this might have contributed to the positive correlation between knee joint moments and powers and cadence), it was clear that the hip flexors were central to initiating this motion and once again highlighted their importance in elite race walking. The fast movement of the swing leg is a defining feature of elite performances and requires careful development of the key muscle groups and specific technique involved.

Achieving the correct swing leg movements at fast speeds is not risk-free or easily done. The fact that the knee has to fully extend while the hip is simultaneously extending presents a considerable physical challenge to the elite race walker. The laboratory study showed that activity of the biarticular biceps femoris was at its peak during this negative work phase and, as in fast running (Chumanov et al., 2011), this could be a cause of the frequent injuries to the hamstrings in race walkers (Francis et al., 1998). These results suggest that strength training of the hamstring muscles is a particularly important component of race walk training that elite athletes should not neglect. In addition, tibialis anterior contracted throughout swing to dorsiflex the ankle and maintain this position until initial contact. This action is considered important in race walking as it helps reduce knee flexion and the appearance of visible loss of contact (Hoga et al., 2009). However, high magnitudes of stress in the dorsiflexor muscles have been found during the swing phase in fast (normal) walking speeds, and in normal circumstances a transition to slow running would take place to reduce this stress (Prilutsky & Gregor, 2001; Hreljac et al., 2008). The added onus on the ankle to ensure ground clearance in race walking might therefore stress the dorsiflexors even more and cause the high incidence of shin muscle pain found (Sanzén et al., 1986; Levin, 1992; Francis et al., 1998) along with (or possibly rather than) the energy absorbing dorsiflexor contraction that occurred during early stance. Improved training regimens for both ankle dorsiflexors and plantarflexors (e.g. through gradual progression of walking distances and speed) are therefore necessary to reduce the risk of injury to these key muscles (Ziv & Rotstein, 2009).

It has been established in prior race walking research that short flight times are an integral part of elite race walking. This study confirmed these findings, as the time spent in flight as a percentage of total step time ranged from 3.6% (junior women) to 8.7% (20 km men) in the competition studies (Figure 9.4), with the values found in the laboratory similar to those of the 20 km men. The data from the competition and laboratory studies showed that most flight times recorded were approximately 0.04 s or shorter, and with the exception of very slow athletes (particularly junior women), some flight time was common to all athletes analysed. However, flight time durations shortened with distance walked in both the 20 km women and 50 km men and flight time is therefore a key variable that is affected by local muscular fatigue (which could actually provide a benefit to those athletes who received red cards for loss of contact earlier in the race). This 0.04 s value was similar to that suggested by Knicker & Loch (1990), but it should still not be taken as a literal threshold below which an athlete will avoid red cards, as providing a definitive guide as to how long flight time can last before becoming visible to the human eye is not possible because of its subjective nature. However, if this proviso is borne in mind, it might be a useful value for coaches to use in conjunction with visual inspection of their athletes.

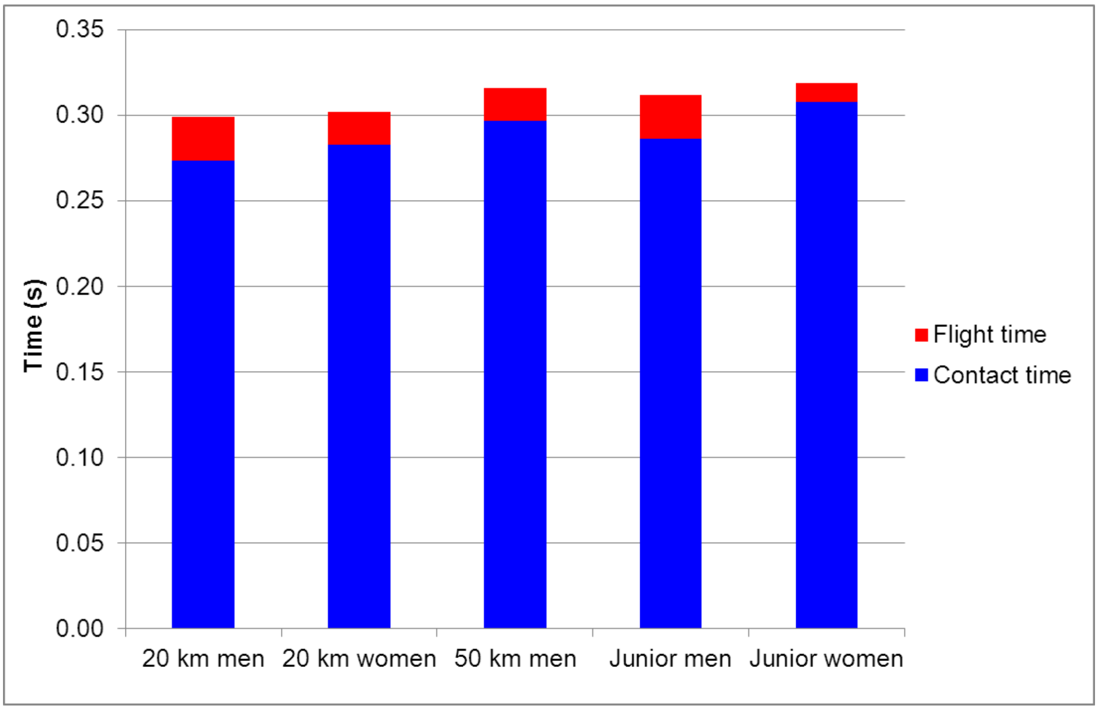


Figure 9.4. Mean step time for each group of athletes; the blue section of each bar represents contact time and the red section represents flight time.

Flight time was an important contributor to step length by way of flight distance, and there might be a temptation for athletes to deliberately increase it. However, the risk of having too long a flight phase is clear and it is not sensible to explicitly advise race walkers to increase its length in an attempt to improve performance. On the contrary, it is preferable for them to develop their techniques in such a way that high speeds are maintained with as little flight as possible. This study's results show how elite athletes can achieve this: the knee's movement from hyperextension to flexion during late stance reduces vertical forces before toe-off; excessive knee flexion during this phase and early swing is restrained by energy absorption in the knee extensors, facilitating its quick return to contact; and the energy absorbing moment that results allows for longer foot ahead and behind distances. These aspects of elite technique can help prevent visible flight times when technique changes, such as when making tight turns, or when increased speed is required, such as in a close finish. Although the two aspects of IAAF Rule 230.1 are often thought of as separate and independent of one another, this study has shown that the enforcement of the straightened knee can actually assist the athlete in avoiding vertical lift, and a technical focus on that aspect is particularly encouraged. One key recommendation to emphasise to coaches is that the development of useful eccentric contractions in elite race walking, such as those that might reduce flight time, requires relatively fast movements and therefore race walking drills should be carried out close to competition speed, provided the athlete is physically ready and free of injury.

9.3 Limitations of the project

The main limitations of this project were:

- Videography methodology used in competition: the nature of the competition studies meant that filming had to take place outdoors (fortunately the weather was sunny and cloudless at all three events) and this meant that the number and choice of cameras was limited to those that were easy to transport overseas and could be used without a mains power supply. The two 3CCD semi-professional, broadcastable Canon camcorders used gave high quality recordings but were limited to 50 frames per second. However, it was felt that these limitations were outweighed by the benefits to external validity in obtaining video data of real performances of the world's best race walkers under genuine competitive conditions. The athletes were naïve to the presence of the cameras, and so as they made no conscious adjustment as they passed the recording points they were in effect captured in their 'natural surroundings';
- Videography methodology used in the laboratory: it was only possible to obtain two-dimensional video data using the high-speed system when conducting the laboratory-based study. This was because of the restrictions on equipment available at the time, and the need to use a system that could be synchronised with the software used for collection of GRF and EMG data;
- Digitisation process: the manual digitising procedure used involved visual identification of anatomical landmarks and the estimation of joint centre locations. In some cases this was not possible because of obstruction by other body parts and this required the joint centre position to be estimated. To reduce the possibility of errors, each video file was digitised at least twice: first using the frame by frame method and then using the points over frame method. In addition, the high reliability of the digitising process was established through repeated digitising and comparison using 95% limits of agreement, coefficient of variation, and intraclass correlation coefficient;
- Recruitment of participants: although the laboratory study was the largest ever conducted on either internal kinetics or EMG measurements in race walking, the four subgroups analysed were restricted to only five participants each. The lack of great differences between junior and senior athletes might be because of the high standard of junior athletes chosen; larger and possibly more informative differences might have been found had a sample of novice or non-elite athletes participated. Unsurprisingly, it was quite difficult to recruit world-class athletes (and took a great deal of time) and this required inviting athletes from various nations to attend.

- The inverse dynamics method used (Winter, 2005) is a well-established technique in biomechanical analysis, particularly in gait. Limitations of the inverse dynamics method adopted include assumptions of pure rotations around ideals hinge joints, constant moment of inertia around the joint, no dissipative forces, and that the intersegmental forces act through the centre of rotation of the joint (Vardaxis & Hoshizaki, 1989). In addition, its indirect nature of calculating muscle moments features some assumptions that can lead to errors in the values calculated. In particular, the method used effectively calculates the net moment (and power) about a joint, rather than the individual contributions of particular muscles (Winter, 2005). This can occasionally result in a picture of little or no muscular activity at a joint, when in fact there is considerable activity (but in co-contracting antagonist muscles). Fortunately, the simultaneous use of EMG in this study meant that any interpretation of muscle activity was supported by an objective means of establishing if a muscle is actually contracting.
- Data collected during biomechanical testing typically contains noise that can adversely affect the analysis and interpretation of measurements found. While a great attempt using established methods was made to reduce the noise levels in the data (e.g. Giakas & Baltzopoulos, 1997a; Winter, 2005), it is inevitable that some remained. In particular, this might have affected the results of the inverse dynamics calculations as the data used were obtained from two separate systems (kinetic and kinematic) and required separate filtering. Using different cut-off frequencies has been found to adversely affect the results of inverse dynamics during high-impact activities at initial contact, and while race walking typically has relatively small impact forces, it is possible that the magnitudes of the values found (if not necessarily the interpretation) were affected because of the non-stationary parts of the signal that led to different frequency contents (Chau, 2001). However, such issues usually only affect the very early phase of stance and most of this phase (along with swing) is unaffected.

9.4 Conclusions

9.4.1 Agreement with previous research

The present study provides accurate and reliable data on elite race walkers in competitive and laboratory conditions to the scientific and athletic community. There have been very few biomechanical studies on this Olympic event and their limitations have been described previously. This study has now supported, through evidence on elite race walkers, some findings from previous research and the beliefs of race walk coaches (while others were contradicted and are detailed in the original contribution section below). In some instances, while aspects of the earlier findings were supported, the interpretation of their role or importance differs:

- Of the two factors affecting race walk speed, step length was the more important contributor with respect to comparisons between men and women, juniors and seniors, and between different distances in the same individuals;
- Many characteristics of gait, such as joint angles, did not alter greatly with changes in speed in the variation studies. This was seen as an indication that these well-trained elite athletes are largely able to maintain their techniques despite fatigue;
- Nearly all elite race walkers experienced a brief but advantageous flight phase (≤ 0.04 s), while a shorter contact phase was crucial for fast race walking speeds;
- There were greater variations in upper limb movements, and the transverse plane movements of the pelvis and shoulder girdle were noticeable elements of elite race walking performances;
- The ankle dorsiflexors are at a high risk of injury because of the movement patterns adopted during swing and early stance;
- The ankle was an important source of energy generation during stance, while the hip was important for energy generation during early swing, late swing, and early stance. Indeed, the forceful backwards movement of the leg before initial contact was important in reducing the effects of foot ahead on braking;
- The knee mostly underwent energy absorption throughout swing (risking injury to the hamstrings) and generated little energy;
- The vertical push-off GRF peak was lower than the earlier loading peak.

9.4.2 Original contribution of the thesis

Considerable gaps were found in prior literature on elite race walking, with the result that coaches had little scientific underpinning on which to base technical training, and the scientific community did not fully understand the idiosyncrasies of this unique and abnormal form of gait (especially given the older studies were conducted before the rule change in 1995). The new, original findings of this thesis provide this evidence and can be used as a justification for adopting or rejecting particular practices. This study analysed the greatest number of athletes in competition of any study on race walking (90 athletes at the World Cup, 36 at the 7th European Cup, and 40 at the 8th European Cup) and the greatest number for a laboratory-based biomechanical study (20 athletes). These athletes, unlike in most previous research, were not sub-elite or of novice standard, but were race walkers competing at elite standard, and in some cases, were Olympic or World Champions. The correlation analyses within groups, and the analysis of differences between them, were useful in assessing the importance of specific variables identified in the hierarchical model, specifically as women's and junior race walking were previously very under-researched areas. In addition, the study of variations within competitions, and especially the inevitable fatigue in the 50 km race, was valuable in ascertaining the truly important variables. No previous research had combined internal kinetic data with EMG recordings, and this study showed that using synchronised EMG, high-speed video, and GRF data was extremely beneficial as it revealed aspects of elite race walking that might have remained unknown if only one or two of these methodologies had been used. The main original findings of this study are:

- The new studies on elite male and female athletes, both junior and senior, showed that there were major kinematic differences between genders and age groups. In both junior and senior competitions, the men's mean absolute step lengths were approximately 15% longer than the women's, and while cadence did not differ between groups of the same age group, female athletes were more dependent on cadence and had longer contact time percentages. Decreases in step length and cadence occurred with fatigue, largely because of reduced flight distances;
- Step length ratio is an important guide for coaches and athletes aiming for improved performances. It was a better predictor of optimum step length than absolute values, and a ratio of approximately 70% was found in the world's best athletes (e.g. Olympic Champions, World Champions, and a World Record Holder). This value might be a critical performance indicator

given its strong correlation with speed in the competition studies (20 km men: *r* = .87; 20 km women: *r* = .77; 50 km men: *r* = .69) and the fastest walkers did not experience negative interactions between step length ratio and cadence;

- The values found for foot ahead and foot behind ratios (20% and 27% respectively) are useful guides for those who aim to ensure optimal foot placement positions with regard to over- and understriding. In particular, increased foot ahead distances need not be overly harmful to performance provided the athlete has appropriate strength levels, and instead can be an extremely useful feature of faster walking. This was one variable that seemed to differentiate men's and women's performances, but also separated the best woman (a World and Olympic Champion) from her competitors. Foot ahead tended to vary much more with different speeds, whereas foot behind was more consistent, showing the greater importance of the foot ahead distance to achieving faster speeds;
- Flight distances contributed about 13% of total step length but in general their durations were too short to result in visible loss of contact. Nonetheless, flight distance was a key factor in longer steps, without which the athletes would have been much slower (e.g. shorter or no longer existent flight distances were observed with fatigue);
- Relatively high magnitudes of pelvic girdle rotation and counterbalancing shoulder girdle rotation were recorded in competition but these were not correlated with performance parameters, showing a ubiquity among elite race walkers. Optimum magnitudes for pelvic rotation of about 15° for senior women and 20° for senior men were found (which junior athletes should strive to achieve) and beyond which there were diminished returns (e.g. decreased cadence in 50 km men, and no prevention of decreased step length with fatigue in 20 km men);
- The measured values for elbow flexion of elite race walkers disagreed with previous coaching literature, being about 10° less than the 90° recommended, and in 20 km women and 50 km men it flexed more with fatigue at some gait events, suggesting the athletes needed to ease rotation of the whole arm. Therefore, coaching advice should be adjusted to these actual values. With regard to the shoulder, there was evidence that increased hyperextension in 50 km men led to reduced speed (*r* = –.50) and cadence (*r* = –.38), and instead it is possible that the swing movement of the shoulders should be a passive reaction driven by movement in the legs;

- Most of the athletes in this study achieved full (or close to full) knee extension (i.e. 180°) from initial contact to midstance, contrary to findings in older research. A small decrease with fatigue in the 50 km men of 2° was probably too small to be meaningful given individual variation and measurement error, and overall the elite athletes analysed maintained their high-quality techniques despite fatigue;
- The two aspects of IAAF Rule 230.1 are not separate but interdependent, and the enforcement of the straightened knee in fact assists elite race walkers avoid visible loss of contact through late stance knee flexion and a consequential reduction in vertical force before toe-off that helps minimise vertical displacement;
- The hip extensors did the greatest amount of positive work during the gait cycle when extending during late swing and early stance (42.3 ± 10.1 J), followed by the hip flexors that were active during late stance and early swing (22.4 ± 7.1 J) and then the ankle plantarflexors that contracted during late stance (16.4 ± 3.8 J). These results thus show the clear importance to coaches of developing hip muscle strength / endurance in elite race walkers;
- The hip extensor moment that generated mechanical energy before and during heel strike at the beginning of stance was important in maintaining the athletes' forward momentum. This was because it minimised the negative effects of the foot ahead position via a small impulse spike at initial contact and also reduced the braking peak force and duration of the negative anteroposterior force;
- Energy absorption and stretch-shortening cycle mechanisms similar to those found in running, as well as energy transfer from the proximal to the distal segments, occurred at all three lower limb joints and could be particularly important in this endurance event with regard to energy return. For instance, the earlier energy absorption in the hip flexors in senior men might be a key factor in their faster walking because of the utilisation of the stretch-shortening cycle in this key muscle group. By contrast, the lower values of knee moments and powers in junior women during early swing might have been caused by their slower walking speeds. The development of fast and efficient technique that can utilise this source of energy requires at least occasional training at speeds close to competition pace;
- The knee extensor muscles do not forcefully extend the knee, and in particular rectus femoris appeared to only have a very small role in knee

extension (it was more important as a hip flexor). This reduced role is possibly because of lessened resistance from the flexors and ligaments, and shows that elite race walkers do not need to engage in extensive training of the quadriceps femoris group;

- The knee had little involvement in energy generation because of its restricted role as a fully extended rigid lever. However, it did provide a small amount of energy generation during early stance in the senior men's group that suggests they benefitted from slightly flexed knees (and that athletes with bent knees could have an advantage over legal walkers in this regard). Furthermore, the late stance knee had an important role in maintaining contact with the ground so that foot ahead and foot behind were increased;
- The movement of the swing leg was of great importance as it was crucial in maintaining forward motion by providing the momentum that rotated the CM about the stance leg, and therefore coaches should always remember to consider the speed and movement of the swing leg during technical and conditioning training. However, during late swing the high powers recorded during the knee's energy absorbing phase could be a contributor to the high incidences of injury to the hamstrings reported;
- A key element during early stance, never observed before, was an energy generating plantarflexor moment at the ankle that occurred at initial contact that allowed both elite junior and senior athletes to bypass a passive landing and improve the ankle's role during stance;
- During midstance, the energy absorbed by the triceps surae contributes to the following plantarflexion moment, reducing the work required of the ankle. In addition, during late stance, the tibialis anterior absorbs energy to prevent excessive and unproductive plantarflexion that would result in unnecessarily long contact times. Coaches should note that what aids the athlete to prevent this unproductive plantarflexion is powerful hip flexion during late stance and early swing, and this movement should be developed by training that necessitates powerful activity, such as walking on slight inclines;
- The shin injuries that are commonly found in race walking might not only be due to the small energy absorbing dorsiflexor moment that stabilises the ankle's motion, but more so because of the high tibialis anterior activity magnitudes found during swing. While these high stresses in the shin muscles, and those in the hamstrings, are to some extent inevitable in elite race walking, coaches should take steps to reduce the risk of injury by developing training slowly with regard to progression and overload.

9.5 Suggestions for future research

The present project measured the kinetics and kinematics of elite race walkers to provide an analysis of the key variables in high-standard race walking. It was not possible to analyse all aspects of race walking, and thus there are other factors that should be studied in order to understand better the important elements and consequent implications for training. Suggestions for future research include:

- Musculotendon profiles of elite race walkers to appreciate architectural changes as a result of long-term race walk training, and therefore internal limiting and contributing factors affecting performance;
- Analysis of frontal and transverse plane movements with regard to internal kinetics and EMG as part of 3D measurements;
- Detailed analysis of foot movements during stance, e.g. angle of the foot, pressure distribution, subtalar joint movements;
- Contributions of pelvic movements to efficiency, and in particular their exaggerated role given full knee extension;
- Longitudinal studies measuring the technical development of junior athletes as they progress to become senior athletes;
- The role of commonly-used race walking drills in training with regard to their efficacy and specificity;
- Analysis of common injuries in race walking, not only to the shin and hamstring muscles, but also with regard to the effects of hyperextension on the knee joint capsule.

CHAPTER 10

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