Kinematic characteristics of elite men's 50 km race walking

Race walking is an endurance event which also requires great technical ability, particularly with respect to its two distinguishing rules. The 50 km race walk is the longest event in the athletics programme at the Olympic Games. The aims of this observational study were to identify the important kinematic variables in elite men's 50 km race walking, and to measure variation in those variables at different distances. Thirty men were analysed from video data recorded during a World Race Walking Cup competition. Video data were also recorded at four distances during the European Cup Race Walking and twelve men analysed from these data. Two camcorders (50 Hz) recorded at each race for 3D analysis. The results of this study showed that walking speed was associated with both step length (r = .54, P = .002) and cadence (r = .58, P = .001). While placing the foot further ahead of the body at heel strike was associated with greater step lengths (r = .45, P = .013), it was also negatively associated with cadence (r = –.62, P < .001). In the World Cup, knee angles ranged between 175 and 186° at initial contact and between 180 and 195° at midstance. During the European Cup, walking speed decreased significantly (F = 9.35, P = .002), mostly due to a decrease in step length between 38.5 and 48.5 km (t = 8.59, P = .014). From this study, it would appear that the key areas a 50 km race walker must develop and coordinate are step length and cadence, although it is also important to ensure legal walking technique is maintained with the onset of fatigue.

Keywords: Athletics, gait, motion analysis, walking stride

Introduction

Race walking is contested at all major athletics championships. It is an event that requires great endurance and technical ability. The exaggerated gait used is a function of the rules that govern the event (Cairns et al., 1986). These rules dictate that no visible loss of contact with the ground should occur and that the knee must be straightened from the moment of first contact until the ‘vertical upright position’ (IAAF, 2009a). Judges issue red cards to athletes who lose contact or don’t straighten the knee correctly. Three red cards lead to disqualification (IAAF, 2009a). The 50 km race walk is the longest race in the athletics programme. The percentage of competitors failing to finish at the six World Championships from 2001 to 2011 ranged between 34 and 51%. Disqualifications accounted for an average of 54% of these non-finishers (IAAF, 2011). Correct pace judgement is crucial for 50 km competitors to avoid large decreases in speed towards the end (Hopkins, 1990).

There is little biomechanical research on elite race walkers, and in particular 50 km competitors. In a study of elite 20 km race walkers, Hanley et al. (2011) found that speed was correlated with both step length and cadence, and that shorter contact times were particularly important. Lafortune et al. (1989) found in laboratory studies that the positioning of the support leg in relation to the athlete’s centre of mass (CM) was important in maintaining forward speed, as shorter distances to the foot at initial contact reduced braking forces. Optimal positioning of the support leg requires optimal hip, knee and ankle joint angles (Murray et al., 1983; White & Winter, 1985; Preatoni et al., 2006).

Race walking speed can decrease during a 50 km race due to factors such as reduced aerobic power (Arcelli, 1996). Hanley et al. (2011) measured kinematic variables in elite 20 km competitors and found that although speed and step length decreased during the race there were few variations in joint angles. However, greater decreases may occur in the longer 50 km race. To measure any effects of fatigue caused by a 50 km race walker's typical training session, Brisswalter et al. (1998) tested nine national-level 50 km race walkers using a treadmill moving at 12 km.h^{-1}, both before and after a three hour race walk also at 12 km.h^{-1}. Similar to earlier research (Farley & Hamley, 1979), they found there was an increase in energy cost, but no general alterations in the few gait kinematics measured. However, laboratory-based studies cannot take into account the effects of competition which can have a distinct influence on technique (Knicker & Loch, 1990).

With regard to coaching recommendations, it has been suggested that transverse plane pelvic rotations increase both step length and cadence, as they lead to narrowing of the stride width (Fenton, 1984) and the employment of additional leg muscle groups (Fruktov et al., 1984). A shoulder girdle movement occurs in opposition to pelvis rotation to counterbalance it and provide economy of movement (Schmolinsky, 1996). With regard to upper body joint kinematics, very few studies have reported values for the shoulder and elbow joint angles. From a coaching viewpoint, Hopkins (1985) advocated an elbow angle of approximately 90° as he believed the reduced moment of inertia would lower the energy required to swing the arms at the same frequency as the legs.

To date, the kinematic characteristics of the world's elite 50 km race walkers have not been analysed. New research on these athletes in competition is therefore crucial to understanding the technical demands of the event. It is also important to measure the kinematic changes that occur during a race as these can provide a greater indication of the influence of key variables. The aims 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 in a second step to measure variation in those variables at different distances (in a European Cup event).

Methods

Participants

The study was approved by the university's Research Ethics Committee. Video data were collected at two separate events. 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; this part of the course was chosen as it was straight and flat, free from obstructions, and close to the half-way distance. Participants' heights, body masses and dates of birth were obtained from the IAAF (2009b). Thirty competitors (age 29.5 ± 5.7 years; height 1.78 ± 0.07 m; mass 66.1 ± 5.3 kg) were analysed, including the 2008 Olympic champion and the 2005 and 2009 World Champion. The mean finishing time was 3:57:35 ± 11:59. The current world record of 3:34:14 was set during this competition by one of the analysed athletes.

The men's 50 km race was recorded at the 7th European Cup Race Walking. Twelve competitors (age 28.4 ± 5.5 years; height 1.81 ± 0.07 m; mass 67.2 ± 4.0 kg) were analysed on four occasions: 18.5 km, 28.5 km, 38.5 km and 48.5 km. These athletes were the only competitors who could be seen clearly at all recording distances; their mean finishing time was 3:52:32 ± 7:18. The finishing times from both races were compared using an independent *t*-test which found no difference (t_{40} = 1.352, p = .184). In both competitions, athletes who did not finish or were disqualified were not included.

Data collection

For each event, the set-up was similar. Two stationary 3CCD DM-XL1 digital camcorders (Canon, Tokyo) were placed on one side of the course, approximately 45º and 135º respectively to the plane of motion. Each camera was approximately 8 m from the path of the athletes. The sampling rate was 50 Hz and the shutter speed 1/500 s. The resolution of each camera was 720 x 576 pixels. For the World Cup, the reference volume was 5.20 m long, 2.00

m wide and 2.01 m high. For the European Cup, the volume was 5.00 m long, 2.00 m wide and 2.16 m high. These volumes were used later for calibration for 3D Direct Linear Transformation (Abdel-Aziz & Karara, 1971). At each competition, calibration rods of known length were digitised within the calibration volume and compared to their known lengths. In the European Cup, the root mean square (RMS) of the difference between the known and calculated values was 0.8% of the rod's length in the x-direction (length), 1.0% in the y-direction (height) and 0.9% in the z-direction (width). In the World Cup, the RMS of the differences were 0.2%, 0.5% and 0.6% of the rod's length in the x-, y- and z-directions respectively.

Data analysis

The video data were manually digitised to obtain kinematic data using motion analysis software (SIMI, Munich). Video footage from each camera were synchronised manually by visual identification: for each athlete initial contact and toe-off of both feet 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 so that these 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 first digitised frame by frame by a single experienced operator and upon completion adjustments were made using the points over frame method (Bahamonde and Stevens, 2006). 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. Seventeen segment endpoints were digitised for each participant and de Leva's (1996) fourteen segment body segment parameter model used to obtain data for the whole body CM and limb segments. The results for each side of the body were averaged in this study. A cross-validated quintic spline was used to smooth the data prior to displacement calculations whereas a recursive second-order, low-pass Butterworth digital filter (zero phaselag) was employed to filter the displacement-time data of each marker prior to the calculations of the 1st and 2nd derivatives (Giakas & Baltzopoulos, 1997a; 1997b). The cut-off frequencies were selected based on residual analysis (Winter, 2005) and ranged from 4.6 – 5.9 Hz.

In order to ensure reliability of the digitising process, repeated digitising (two trials) of one sequence 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 prior to 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. The LOA (bias ± random error), CV and ICC (3,1) values for CM horizontal velocity were 0 ± 0.02 $m.s^{-1}$, ± 0.04%, and 1.00 respectively, for the right foot horizontal coordinates (ratio) 1.00 ×/÷ 1.00, ×/÷ 1.09, and 1.00 respectively, and for the left foot horizontal coordinates 0.001 ± 0.006 m, ± 0.08%, and 1.00 respectively. The results showed minimal systematic and random errors and therefore confirmed the high reliability of the digitising process.

Race walking speed was determined as the average horizontal speed during one complete gait cycle. Step length was measured as the distance between successive foot contacts. 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. 'Foot ahead' was used to describe the horizontal distance from the CM of the landing foot to the body's overall CM at initial contact. Similarly, 'foot behind' was the horizontal distance from the CM of the foot leaving ground contact to the body's overall CM at the final point of contact. Both foot ahead and foot behind distances were also expressed as a proportion of stature. Each of these variables was measured for both left and right legs and averaged in this study.

With regard to angular kinematics, the knee angle was calculated as the sagittal plane angle between the thigh and leg segments. The hip angle was defined as the sagittal plane angle between the trunk and thigh segments and was 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 measured approximately 110° in the anatomical standing position. 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. The rotation values of the pelvis and shoulder girdle (transverse plane) were calculated using the left and right hip joint coordinates and the left and right shoulder joint coordinates respectively.

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

- Initial contact: the first visible point during stance where the athlete’s foot clearly contacts the ground.
- Midstance: the point where the athlete’s foot was directly below the body’s CM, used to determine the ‘vertical upright position’. Only knee angle results have been reported at midstance.
- Toe-off: the last visible point during stance where the athlete’s foot clearly contacts the ground.

Statistical analysis

Pearson's product moment correlation coefficient was used to find associations in the World Cup sample of thirty men; alpha was set at 5%. One-way repeated measures ANOVA was conducted on the European Cup variation data with repeated contrast tests conducted to establish significant changes between successive measurement points (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. The effect size was reported using partial eta-squared (η_p^2).

Results

World Cup data

Speed, step length, cadence and temporal variables

The values for speed, step length and cadence for the World Cup participants are shown in Table I, and correlations between these and other key variables shown in Table II. Athletes' heights were correlated positively with step length and negatively with cadence. Step length ratio ranged from 60 to 71%, with a mean of 65.3 ± 2.8%. Speed was positively correlated with step length when expressed as its absolute value and as the step length ratio. Cadence was positively correlated with speed and negatively correlated with step length as an absolute value but not as step length ratio. Table I also shows that athletes experienced a mean loss of contact of 0.02 s; in total twenty-five of the thirty athletes had some loss of contact. Contact time accounted for 93.8 ± 3.2% of total step time; it was found that the shorter the contact time, the faster the athlete. Flight time was correlated with both speed and step length ratio.

Positioning of the foot at initial contact and toe-off

In Table I, the position of the support foot relative to the whole body CM is shown. Table II shows that both foot ahead and foot behind distances were positively correlated with height and step length, and negatively correlated with cadence. However, there were no correlations between cadence and either foot position distances when they were expressed as a proportion.

Knee, hip and ankle joint angles

The lower limb joint angles are shown in Table III, and relevant correlations between these and other key variables are shown in Table IV. Knee angle values at initial contact ranged between 175 and 186°, and between 180 and 195° at midstance. The knee angle at contact was positively correlated with flight time and negatively correlated with contact time (and foot behind distance). In Table III, the hip angle figures of 170 and 190° represent averages of 10° flexion at contact and 10° hyperextension at toe-off respectively. The contact values for the hip correlated positively with cadence, flight time and foot behind distance, and negatively with contact time. Both hip and ankle contact angles were negatively correlated with foot ahead distance.

Shoulder and elbow joint angles and pelvic and shoulder rotation

Table III shows the shoulder, elbow, and pelvic and shoulder rotation values; relevant correlations are shown in Table IV. The shoulder angle at contact was negatively correlated with both speed and cadence. The elbow angle at toe-off was negatively correlated with cadence and flight time, but positively with contact time, foot ahead, and foot behind distances. Pelvic rotation was negatively correlated with cadence and positively with foot behind distance, but shoulder rotation was not correlated with any of the key performance parameters.

European Cup variation data

Speed, step length, cadence, temporal variables and foot positioning

Table V shows the variations in speed, step length and cadence for the twelve athletes analysed at the European Cup. Repeated measures ANOVA showed that the values for speed and step length decreased as the race progressed. One-way repeated contrasts revealed that both these variables decreased significantly from 38.5 to 48.5 km (t_{11} = 9.24, P = .011 and t_{11} = 8.59, P = .014 respectively) with no other changes. One-way repeated measures ANOVA also found that cadence did not decrease over the course of the race. Flight time was 0.02 ± .01 s at the first three measurement points, and decreased from 38.5 km to 48.5 where it was 0.01 ± .01 s (t_{11} = 5.50, P = .039). The number of athletes experiencing loss of contact decreased from ten at 18.5, 28.5 and 38.5 km to six at 48.5 km. There were no changes for either foot ahead ($F_{1.79,19.69}$ = 0.11, P = .872, η_p^2 = .01) or foot behind distances ($F_{3,33}$ = 1.74, P = .178, η_p^2 = .14).

Angular data

The initial contact knee angle was 179 ± 2° at 18.5 km and 28.5 km, and 180 ± 2° at 38.5 km. It then decreased significantly to 178 ± 2° at 48.5 km (t_{11} = 11.00, P = .007), but this

Table I. Mean values for speed, step length, temporal and foot positioning values

Speed ($km.h^{-1}$)	Step length (m)	Cadence (Hz)	Step time (s)	Contact time (s)	Flight time (s)
13.15 (± .75)	1.16 (± .06)	3.16 (± .16)	0.32 (± .02)	0.30 (± .03)	0.02 (± .01)

Foot ahead (m)	Foot ahead (%)	Foot behind (m)	Foot behind (%)
0.38 (± .02)	21.3 (± 0.9)	0.48 (± .03)	26.9 (± 1.5)

Table II. Correlation analysis of key race walking variables across the World Cup sample. The correlations for foot ahead and foot behind are for absolute values only. Correlations were significant at $P < 0.05$ (shown in bold)

	Step length	Step length ratio	Cadence	Contact time	Flight time	Foot ahead	Foot behind
Stature	***r* = .55** ***P* = .003**		***r* = –.61** ***P* = .001**	***r* = .48** ***P* = .011**	*r* = –.23 *P* = .243	***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* = .57** ***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* = .34 *P* = .071	***r* = .45** ***P* = .013**	***r* = .69** ***P* < .001**
Step length ratio			*r* = .12 *P* = .540	*r* = –.36 *P* = .065	***r* = .61** ***P* = .001**	*r* = –.13 *P* = .528	*r* = .29 *P* = .143
Cadence				***r* = –.84** ***P* < .001**	*r* = .30 *P* = .102	***r* = –.62** ***P* < .001**	***r* = –.60** ***P* < .001**
Contact time					***r* = –.68** ***P* < .001**	***r* = .69** ***P* < .001**	***r* = .57** ***P* = .001**
Flight time						***r* = –.46** ***P* = .011**	*r* = –.23 *P* = .229
Foot ahead							***r* = .69** ***P* < .001**

difference was probably too small to be meaningful. 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 (t_{11} =

5.21, P = .043). At initial contact, the elbow angle was 81 ± 5° at 18.5 km and 79° at both 28.5 and 38.5 km (± 4 and ± 5 respectively), with a decrease to 76 ± 6° at 48.5 km; the overall decrease of 5° was significant ($F_{3,33}$ = 3.76, P = .020, η_p^2 = .26). Table V shows the values for pelvic rotation at each of the four distances; the decrease in rotation was significant. The shoulder rotation values however were not found to alter as the race progressed.

Discussion

The aims of this study were to identify and measure key kinematic variables in determining success in elite men's 50 km race walking and to measure variation in those variables at different distances. The results from this particular study 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 a too great step length might have a negative effect on speed. However, this would suggest that taller athletes with naturally longer steps would be at a disadvantage compared with shorter athletes. 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 a proportion of stature. With an average speed of 14.17 km.h^{-1}, the fastest five athletes had step length ratios between 66 and 71%, foot ahead distances between 21 and 22%, and foot behind distances between 26 and 29%. Athletes should be mindful of developing technique with these ratios in mind to minimise any negative effects on cadence, and consequently race walking speed.

Table III. Mean values for upper and lower limb joint angles

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)

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

Table IV. Correlation analysis of key angular variables across the World Cup sample. The correlations for foot ahead and foot behind are for absolute values only. Correlations were significant at $P < 0.05$ (shown in bold)

	Speed	Step length ratio	Cadence	Contact time	Flight time	Foot ahead	Foot behind
Knee (contact)	*r* = .28 *P* = .142	*r* = .26 *P* = .187	*r* = .19 *P* = .304	***r* = –.52** ***P* = .003**	***r* = .44** ***P* = .015**	*r* = –.36 *P* = .053	***r* = –.44** ***P* = .014**
Hip (contact)	*r* = .23 *P* = .227	*r* = .06 *P* = .773	***r* = .46** ***P* = .011**	***r* = –.52** ***P* = .001**	***r* = .54** ***P* = .002**	***r* = –.59** ***P* = .001**	***r* = .62** ***P* < .001**
Ankle (contact)	*r* = .05 *P* = .811	*r* = .05 *P* = .790	*r* = .11 *P* = .555	*r* = –.30 *P* = .114	*r* = .33 *P* = .073	***r* = –.39** ***P* = .035**	*r* = .29 *P* = .116
Shoulder (contact)	***r* = –.50** ***P* = .005**	*r* = –.27 *P* = .180	***r* = –.38** ***P* = .037**	***r* = .45** ***P* = .012**	*r* = –.25 *P* = .190	*r* = .24 *P* = .196	*r* = .12 *P* = .519
Elbow (toe-off)	*r* = –.08 *P* = .691	*r* = –.23 *P* = .259	***r* = –.38** ***P* = .039**	***r* = .40** ***P* = .030**	***r* = –.39** ***P* = .033**	***r* = .57** ***P* = .001**	***r* = .47** ***P* = .009**
Pelvic rotation	*r* = –.26 *P* = .173	*r* = .19 *P* = .345	***r* = –.61** ***P* = .001**	***r* = .58** ***P* = .001**	*r* = –.12 *P* = .526	*r* = .34 *P* = .065	***r* = .51** ***P* = .004**
Shoulder rotation	*r* = .32 *P* = .086	*r* = .32 *P* = .105	*r* = .11 *P* = .550	*r* = –.24 *P* = .199	*r* = .21 *P* = .268	*r* = .04 *P* = .821	*r* = .00 *P* = .988

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 in the interests of race walkers to reduce its duration. Longer flight times were positively correlated with speed due to their association with longer step length ratios. However, athletes must be careful to restrict their step lengths to those within the range of ratios mentioned above. In particular, shorter athletes should take care to limit their step lengths as attempts to match taller athletes would require longer flight periods, increasing the risk of disqualification. Disqualification can also result if the knee is not fully extended from initial contact to midstance. The data showed that the analysed competitors had full or nearly full knee extension at both of these instants. 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. 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.

The movement of the upper limbs is also important in race walking technique. In this study, athletes who swung their arms too far behind the body during shoulder hyperextension at ipsilateral heel strike were found to have reduced cadences and speeds, and greater elbow angles at toe-off were correlated with lower cadences. 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 negatively associated with pelvic rotation. Because one aim of pelvic rotation is to reduce the walking base of support (Fenton, 1984), it appeared to be only 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). The magnitude of shoulder rotation was slightly smaller than the pelvic rotation counterbalanced, and did not correlate with any other performance parameters. Each athlete had their own individual style but coaches should be aware that particular aspects of an individual's technique can be detrimental so the development of upper and lower body technique should not be neglected. Based on the current findings, specific focus should therefore be set on an optimised arm swing that does not result in reduced cadence.

Table V. Mean values for variation in speed, step length, cadence, and pelvic rotation. Differences were significant at $P < 0.05$ (bold)

	Speed (km.h^{-1})	Step length (m)	Cadence (Hz)	Pelvic rotation (°)	Shoulder rotation (°)
18.5 km	14.11 (± .61)	1.25 (± .05)	3.14 (± .08)	21 (± 3)	18 (± 3)
28.5 km	14.15 (± .60)	1.24 (± .04)	3.16 (± .09)	19 (± 2)	19 (± 3)
38.5 km	13.98 (± .76)	1.23 (± .05)	3.16 (± .11)	18 (± 3)	18 (± 3)
48.5 km	13.43 (± .71)	1.20 (± .05)	3.12 (± .13)	17 (± 3)	18 (± 3)
Difference (%)	+0.3, –1.2, –3.2	–0.8, –0.8, –2.4	+0.6, 0.0, –1.3	–10, –2, –5	+1, –4, –2
ANOVA	**$F_{1.71,18.76} = 9.35$**	**$F_{3,33} = 10.88$**	$F_{3,33} = 1.91$	**$F_{3,33} = 5.75$**	$F_{3,33} = 1.86$
	$P = .002$	**$P < .001$**	$P = .147$	**$P = .003$**	$P = .156$
	$\eta_p^2 = .46$	**$\eta_p^2 = .50$**	$\eta_p^2 = .15$	**$\eta_p^2 = .34$**	$\eta_p^2 = .15$

On average, the competitors in the variation study at the European Cup slowed down by 0.68 km.h^{-1} between 18.5 and 48.5 km, with most of this decrease occurring after 38.5 km (0.55 km.h^{-1}). This reduction in speed occurred in line with a significant decrease in step length. The gradual decrease in step length as the race progressed also coincided with significant decreases in flight time, pelvic rotation, and ankle plantarflexion at toe-off. These could be indicators that the athletes were no longer able to maintain earlier, optimal joint kinematics due to greater muscular fatigue. Likewise, the reduction in elbow 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). With regard to other angular data, the average knee angles at initial contact were lower at 48.5 km than at previous distances. This suggests that there might be an increased risk of disqualification in the closing stages of the race.

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 heel strike 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 which the coach must scrutinise to ensure an efficient technique. Monitoring adherence to the straight 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 due to disqualification should not attempt the 50 km distance until problematic aspects are corrected.

A main strength of the study was that the analyses were of a large number of elite athletes in high-level competitions. Recommendations for future research are the analyses of variables which cannot be measured in competition such as ground reaction forces, muscle activity, and joint torques. Such data will complement these kinematic findings and improve understanding of the strength training needs of race walking, which should be based on the specificity of the motor-technical demands of race walking technique (Scholich, 1992).

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. It would appear from this study that performing well requires the balancing of step length and cadence with efficient limb movements. Slower speeds during the latter stages of the European Cup were mostly due to decreased step length, but there were other more subtle changes in joint kinematics which could have had an effect on performance. Athletes and coaches are advised to take race tactics such as pacing strategies into account to reduce the likelihood of dropping out or disqualification.

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