The biomechanics of elite race walking: technique analysis and the effects of fatigue

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23:4; 17-25, 2008

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ABSTRACT

The aim of this study was to measure and analyse the important kinematic variables in elite race walking. Video recordings of 80 athletes were taken during men's 20km, women's 20km and men's 50km competitions at the 7th European Cup Race Walking in 2007. Stride length, stride frequency, positions of the body segments and joint angles were analysed. Among the findings were that the fastest athletes had stride lengths of approximately 70% of body height and were able to maintain high stride frequencies. Joint angles did not appear to be important to walking speed; instead, the speed of movements at the joints was significant. Twelve competitors in each race were analysed at three other points in their races to assess the effects of fatigue on technique. On average, all groups of athletes slowed down as the race progressed. In men, this was mostly due to shorter stride lengths; in women, it was due to lower stride frequencies. Nearly all athletes adhered to the straight leg rule of race walking but most had short, normally undetectable flight times. The 50km men had knee contact angles that decreased significantly with fatigue; this leads to an increased risk of disqualification.

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Introduction

In race walking, the single most important factor in competitive success is speed, although this is restricted by the two unique rules of race walking technique. At the most basic level, speed is determined by step, or stride, length and stride frequency. Stride length is often considered to be the more important (HOGA et al., 2003), and is affected by factors including leg length and the range of movement of the pelvic girdle. Stride frequency is determined by the time taken to complete each successive step, and as a result a shorter step time (usually the result of a shorter contact time) is associated with higher walking speeds (CAIRNS et al., 1986). The position of the support foot in relation to the athlete's whole body centre of mass is important in maintaining forward speed. A foot landing too far in front of the body at initial contact can cause too great a braking impulse (LAFORTUNE et al., 1989). The distance to the support foot at toe-off is important in generating adequate stride length and forward propulsion (HOGA et al., 2003).

There is a direct link between the position of the foot and the joint angles of the entire leg. First, the hip angle will determine how far in front or behind the body the foot is placed. Increasing hip extension velocity results in a decrease in support time (LAFORTUNE et al., 1989), which in turn allows for much longer strides to be taken. Second, the knee is in many regards the most important joint to analyse during race walking as it is the only joint to which specific technical rules are applied. Although an extended knee is abnormal during normal walking or running, research has shown that a straight knee at landing is of benefit to race walkers (CAIRNS et al., 1986). Finally, the angle of the ankle at different points in the support phase is important: at initial contact for ensuring a straightened knee and at toe-off as its plantar-flexion aids the drive phase of the step (WHITE & WINTER, 1985).

Success in race walking is related more to the efficiency of technique rather than physiological factors (HOGA et al. 2003). The correction and optimisation of technique is therefore of great importance. Modifications in gait patterns may affect the energy cost of walking (BRISSWALTER et al., 1998) and these modifications can be caused by fatigue. When the body is placed under immense physical pressure in endurance events such as race walking, performance can deteriorate due to the effects of fatigue. Athletes can normally continue performing whilst experiencing fatigue but their technique may alter (BRISSWALTER et al., 1998). These changes usually occur at the end of a race or within the final stages, when the final outcome is decided. This is especially important in race walking, where poor technique can lead to disqualification. In order for athletes to improve their overall performance, knowledge of when their technique starts to change and ways to combat changes may help prevent technique deterioration.

The aim of this study was to measure and analyse the key kinematic variables in elite race walking. There were two objectives towards achieving this aim. Each of these was applied to different groups of athletes, with regard to race distance and gender:

- First, to find associations within the important gait variables that can suggest methods of improving performance. A theoretical framework of which variables are most important to race walking success can then be considered and used by athletes and coaches to highlight indicators of success and relevant strengths and weaknesses.
- Second, to measure the decline in these variables as fatigue occurs. Most studies have only looked at athletes at one point in their race, or during testing in a laboratory. The measurement of key variables at different points allows for an appreciation of changes in technique and their consequences.

Methods

The athletes analysed were competitors in the 7th European Cup Race Walking, held at Royal Leamington Spa (GBR) in May 2007. Video data of the men's 50km race and both men's and women's 20km races were recorded. Two stationary cameras (Canon, Tokyo) were placed at the side of the course at approximately 45º and 135º to the plane of motion respectively; the sampling rate was

Table 1: Mean (± SD) ages, heights, and masses of all participants

Race	N =	Age (yrs)	Height (m)	Mass (kg)
Women's 20km	30	26 (± 5)	1.64 (± .05)	51 (± 5)
Men's 20km	29	27 (± 5)	1.80 (± .06)	67 (± 5)
Men's 50km	21	31 (± 7)	1.78 (± .08)	67 (± 6)

Table 2: Points of analysis of fatigue for study participants

Race	N =	1st	2nd	3rd	4th
Women's 20km	12	4.5km	8.5km	13.5km	18.5km
Men's 20km	12				
Men's 50km	12	18.5km	28.5km	38.5km	48.5km

Table 3: Speed, stride length, and stride frequency (mean ± SD)

	Speed (km/hr)	Stride length (m)	Stride length (%)	Stride Frequency (Hz)
Women's 20km	13.29 (± .78)	1.08 (± .05)	66.1 (± 3.2)	3.41 (± .12)
Men's 20km	14.80 (± .52)	1.23 (± .05)	68.4 (± 2.4)	3.35 (± .13)
Men's 50km	14.14 (± .55)	1.22 (± .06)	68.4 (± 3.4)	3.23 (± .17)

50Hz. The reference volume was 5m long, 2m wide, and 2.16m high; this ensured data collection of at least three successive steps and provided a calibration reference for 3D-DLT. The participants' mean ages, heights and masses are shown in Table 1.

Analysis was performed at approximately halfway in each race. For the men's 20km race, this occurred at 8.5km. Because the women's 20km field was not well spread out at this point, 13.5km was chosen instead. In the 50km race, the men were analysed at 28.5km. In each race, twelve athletes were analysed at three other points in order to measure which gait changes occurred. The four points of analysis of these athletes are shown in Table 2. Athletes who did not finish or were disqualified have not been included in the analysis.

The video data were digitised to obtain kinematic data using motion analysis software (SIMI, Munich). The recordings were filtered using a Butterworth 2nd order low-pass filter and DE LEVA's (1996) body segment parameter models were used.

Variables of interest were defined as follows:

- Speed: the average horizontal velocity during one complete stride cycle (two steps).
- Stride length: the distance the body travelled between a specific phase on one leg and the same phase on the other leg.
- Stride frequency, measured by dividing horizontal speed by stride length.
- Angular velocity: the velocity of rotation in a given direction at a joint.

Definitions of specific reference points used in this study are as follows:

- Initial contact: the first visible point during stance where the athlete's foot clearly contacts the ground.
- Toe-off: the last visible point during stance where the athlete's foot clearly contacts the ground.
- Mid-stance: the point where the athlete's foot was directly below the body's centre of mass, used to determine the 'vertical upright position' (IAAF Rule 230.1).
- Foot ahead: the distance from the centre of mass of the landing foot to the body's overall centre of mass.

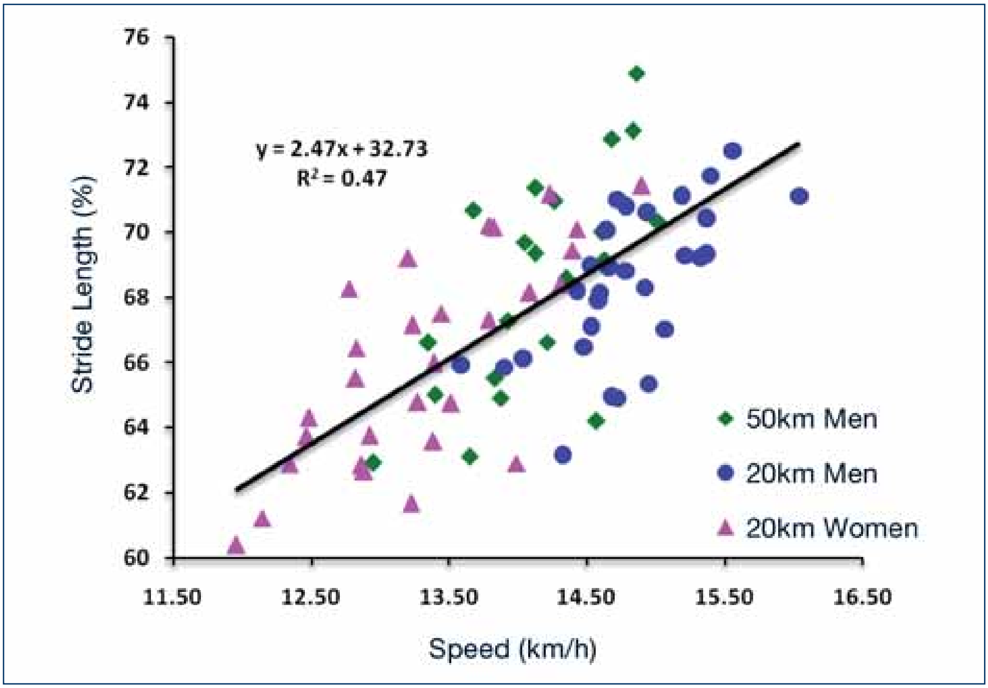

Figure 1: The relationship between speed and stride length (%) for all participants

- Foot behind: the distance from the centre of mass of the toe-off foot to the body's overall centre of mass.

Pearson's product moment correlation coefficient was used to find associations within each group of athletes. One-way analysis of variance was conducted to compare values between the 20km men, 20km women and 50km men. Statistical analysis to measure the effects of fatigue in each race consisted of repeated measures analysis of variance with post hoc pairwise tests using Bonferonni adjustments. For each variable, the data shown are the averages of left and right limb values.

Results

Speed is primarily determined by the two factors of stride length and stride frequency whose values are shown in Table 1. Stride length is also expressed as a percentage of the participants' statures, in order to take into account differing standing heights.

Speed was correlated with stride length in both the 20km men and women's races when expressed as its absolute value and as a percentage of the athlete's height ($p < .01$). Speed was not correlated with absolute stride length in the 50km men ($p = .19$) but it was correlated with stride length percentage ($p < .01$).

Figure 1 shows the correlation between stride length (%) and speed for all participants. The fastest athletes (those at above or just below 15 km/hr) generally walked with a stride length of between 70 and 72% of overall stature.

Stride length and stride frequency were negatively correlated in both men's races ($p < .01$), meaning that the longer the stride length, the lower the stride frequency. In contrast, there was no correlation between these variables in the women's 20km. It was also interesting to note that there was no correlation between stride frequency and stride

Table 4: Walking speed at each stage of analysis (mean ± SD)

	Distance	20km Women	20km Men	Distance	50km Men
Speed (km/hr)	4.5km	13.56 (± 1.21)	15.12 (± 0.53)	18.5km	14.11 (± 0.61)
	8.5km	13.20 (± 0.72)	14.73 (± 0.63)	28.5km	14.15 (± 0.60)
	13.5km	13.08 (± 0.77)	14.66 (± 0.79)	38.5km	13.98 (± 0.76)
	18.5km	12.65 (± 1.03)	14.51 (± 0.85)	48.5km	13.43 (± 0.71)

Table 5: Stride length at each stage of analysis (mean ± SD)

	Distance	20km Women	20km Men	Distance	50km Men
Stride length (m)	4.5km	1.10 (± .08)	1.27 (± 0.02)	18.5km	1.25 (± 0.05)
	8.5km	1.08 (± .04)	1.24 (± 0.04)	28.5km	1.24 (± 0.04)
	13.5km	1.07 (± .06)	1.24 (± 0.03)	38.5km	1.23 (± 0.05)
	18.5km	1.05 (± .07)	1.23 (± 0.04)	48.5km	1.20 (± 0.05)

Table 6: Stride frequency at each stage of analysis (mean ± SD)

	Distance	20km Women	20km Men	Distance	50km Men
Stride frequency (HZ)	4.5km	3.43 (± .11)	3.30 (± .11)	18.5km	3.14 (± .08)
	8.5km	3.40 (± .14)	3.29 (± .11)	28.5km	3.16 (± .09)
	13.5km	3.41 (± .13)	3.29 (± .15)	38.5km	3.16 (± .11)
	18.5km	3.35 (± .16)	3.27 (± .18)	48.5km	3.12 (± .13)

length when expressed as a percentage for any group of athletes. The values for the 20km women's stride lengths were significantly shorter than those of both sets of men when expressed either in absolute terms or as a percentage of their heights ($p < .01$). The 20km and 50km men did not have significantly different stride lengths, but stride frequency was found to be significantly different ($p < .01$). In addition, there was no significant difference in stride frequency between men and women competing over 20km.

The mean values presented in Table 4 show a significant decrease in speed over the course of all three races ($p < .01$). The greatest decrease for the 20km men occurred between 4.5km and 8.5km (0.39km/hr), while the greatest reductions for the 20km women (0.43 km/hr) and 50km men (0.55km/hr) were between the second-last and final measurement points.

Table 5 shows that the largest mean stride length for each set of athletes was observed during the first stage of analysis, and gradually decreased to its lowest level towards the end of the race. The decrease in both sets of men's stride lengths was significant ($p < .01$) but the women's decrease was not ($p = .13$), principally due to the large standard deviations found in this group.

Mean stride frequency values followed a similar trend to stride length (Table 6). Statistical analysis showed the women's values decreased significantly ($p < .01$) whereas the men's values did not. Thus the men had a significant decrease in stride length with fatigue, whereas the women had a significant decrease in stride frequency.

Table 7: Step time, contact time, and flight time (mean ± SD)

	Step time (s)	Contact time (s)	Flight time (s)	Contact (%)
Women's 20km	0.30 (± .01)	0.28 (± .02)	0.02 (± .01)	92.8 (± 4.0)
Men's 20km	0.30 (± .01)	0.27 (± .02)	0.03 (± .01)	89.2 (± 3.8)
Men's 50km	0.31 (± .02)	0.30 (± .02)	0.02 (± .01)	94.2 (± 4.1)

Table 8: Position of the foot in relation to the body's centre of mass in both absolute and relative terms (mean ± SD)

	Foot ahead (m)	Foot behind (m)	Foot ahead (%)	Foot behind (%)
Women's 20km	0.33 (± .03)	0.42 (± .02)	19.8 (± 1.7)	25.9 (± 1.1)
Men's 20km	0.37 (± .04)	0.46 (± .03)	20.8 (± 1.9)	25.8 (± 1.4)
Men's 50km	0.38 (± .04)	0.51 (± .03)	21.2 (± 1.9)	28.6 (± 1.5)

Table 9: Lower limb joint angles (mean ± SD)

	Hip	Knee		Ankle
	Contact (°)	Contact (°)	Mid-stance (°)	Contact (°)
Women's 20km	169 (± 3)	178 (± 3)	189 (± 4)	109 (± 3)
Men's 20km	167 (± 4)	178 (± 3)	188 (± 3)	107 (± 3)
Men's 50km	171 (± 2)	180 (± 3)	185 (± 5)	103 (± 2)

The sampling rate of the cameras was 50Hz, measuring contact and flight durations to an accuracy of 0.02 seconds. It can be seen from Table 7 that flight time was on average 0.02 sec for both the 20km women and the 50km men, and 0.03 sec for 20km men. The 20km men had significantly shorter contact times than either of the other two groups ($p < .01$), and significantly longer flight times ($p < .01$). Keeping in mind that Rule 230.1 forbids loss of contact that is visible to the human eye, only ten of the eighty walkers analysed showed no loss of contact and these tended to be slower athletes. It was found that the shorter the contact time and the longer the flight time, the faster the athlete's stride frequency ($p < .01$ for 20km walkers, $p < .05$ for 50km walkers). This value is summarised as contact time (%) in the table.

Overall, the decrease in speed throughout the races corresponded with increased contact time and decreased flight time. The men in the 50km race had the shortest flight times; only three of these twenty-one athletes had flight times above 0.02 sec.

The position of the support foot is shown in Table 8. Similarly to stride length, the values for foot ahead and foot behind are also expressed as percentages of overall stature to allow comparison between athletes of differing heights.

The 50km men had the longest distances to their support foot at both contact and toe-off. These distances were significantly longer than those found for the 20km men ($p < .05$); they were also significantly longer in 20km men than in 20km women ($p < .01$). Both foot ahead and foot behind distances were negatively correlated with stride frequency in the men's groups ($p < .01$) but not the women. Both sets of 20km athletes analysed on four occasions did not show a significant change in these values; the 50km men's group how-

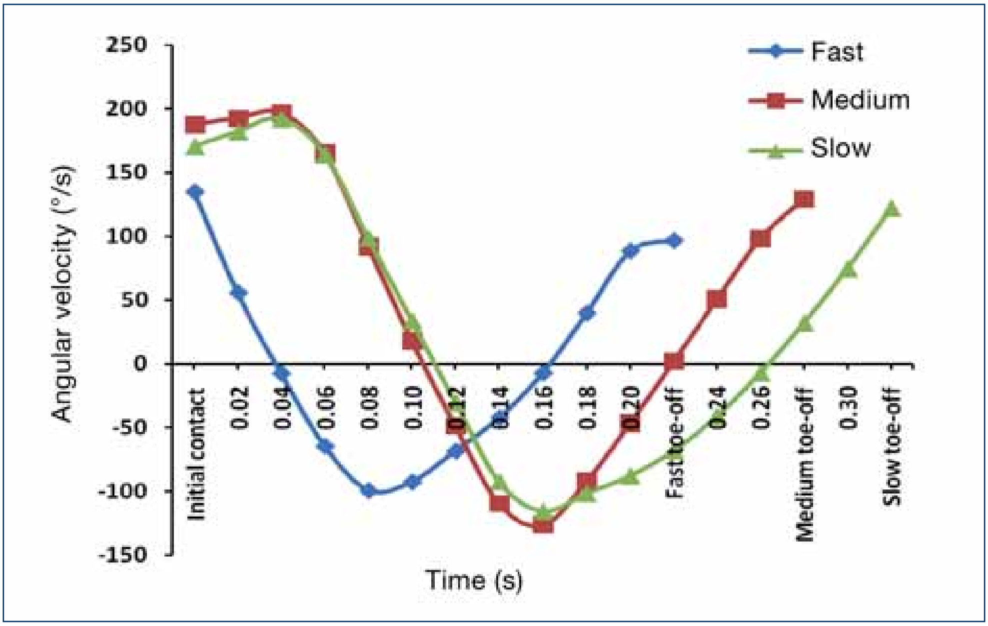

Figure 2: Angular velocities of the right hip from initial contact to toe-off for three athletes in the Men's 20km

ever had a significant decrease in the distance of the foot behind ($p < .05$), dropping from 0.52m at 18.5km to 0.49m at 48.5km.

The leg angle values of most interest are shown in Table 9. The hip was considered to be 180° if fully extended. The figures thus show an average of between 9 and 13° of hip flexion upon initial contact. There was a significant difference in hip contact angles between the 20km women and 50km men ($p < .05$), and between the 20km men and 50km men ($p < .01$). There were no significant relationships between these joint angular data and any of the main performance variables (e.g. stride length, stride frequency) in either the 20km women or the 50km men. However, in the 20km men's group the angle of the hip, knee, and ankle at contact were negatively associated with contact time (and hence step time) ($p < .05$). That is, the larger these angles, the shorter the step time and the higher the stride frequency.

On average, the 50km men achieved full knee extension (180°) at contact. The 20km athletes had values slightly below 180° but it is unlikely that their knees would have been judged as bent. The lowest value found at initial contact was 169° for a 20km man. At midstance (the vertical upright position), all groups had hyper-extended knees, with the women having significantly greater angles than the 50km men ($p < .01$), but not the 20km men.

Two 50km athletes and one woman showed slightly flexed knees at mid-stance (the minimum was 177°). With regard to the effects of fatigue, the only significant change occurred at initial contact for the 50km men, where the value decreased from 181° at 18.5km to 179° at 48.5km. Post hoc tests showed that this decrease was exhibited after 38.5km. In the worst individual case, the knee contact angle decreased from 182° at 18.5km to 175° at 48.5km. Although the average decrease is not considerably large, it could mean that for some athletes their knee angle decreases so much that disqualification in the latter stages is very likely.

Figure 2 shows the hip angular velocities of three 20km men during the stance phase of the right leg. The three men are differentiated in terms of speed; the fast walker's speed was 15.39km/hr, the medium-paced walker's 14.58km/hr, and the slow walker's 13.59km/hr. Only three athletes were chosen for the sake of clarity. The graph shows the angular velocity of the hip from the point of contact (the first data point for each athlete) to toe-off (the last data point for each). The fast athlete has fewer data points than the other two as his contact time is shorter, and the slow athlete has the longest contact time. Steep lines on the graph indicate large changes in angular velocity and show rapid hip extension. 'Flat', horizontal sections are indicative of little change in angular velocity and therefore ineffective in producing forward momentum. The lowest point on each trace (where the trace changes direction) is at the point of or very close to mid-stance.

The fast athlete shows an excellent trace with regard to hip angular velocity: the lines are steep showing high angular acceleration. In contrast, both the medium and slow walkers have an initial period of approximately 0.08 sec where it appears that the hip muscles are not actively extending the hip. The medium athlete's trace then follows a similar pattern to the fast walker right to the end of contact. The slow walker's trace is less steep towards toe-off, which suggests a lack of forceful activity in the hip muscles.

Discussion

The most important factors in race walking success are speed, maintaining visible contact, and the straightness of the knee from initial contact to mid-stance. In this study, the 20km men were the fastest group, followed by the 50km men, and then the 20km women. The 20km men and 50km men had practically identical stride lengths; the difference in speed between them was due to the 20km men's higher stride frequencies. The higher speeds achieved by both groups of men compared to the women were due to longer steps. No difference was found in stride frequency between the 20km men and 20 km women. Although stride length is more important than stride frequency to walking speed (HOGA et al., 2003), a higher frequency is crucial in achieving race success in those athletes with similar stride lengths. Stride length and stride frequency were found to be negatively correlated; a balance between the two is necessary. The finding that stride frequency was not negatively correlated with stride length when expressed as a percentage of stature is helpful. It shows that if athletes can adapt their stride length to a particular proportion of their height (about 70%), high cadences can be achieved without large braking forces and without flight times that will be judged as lifting.

The importance of having an optimal stride length is evident from the effects of the position of the support foot ahead of the body. Too far a distance in front of the body upon initial contact will lead to a braking effect; too near and the athlete is sacrificing stride length. The optimal position of the foot behind the body at toe-off is equally unclear. The fastest group of athletes, the 20km men, had a greater value than the women, but also a lower value than the 50km men. A relatively long distance to the foot at landing will not necessarily produce an unduly detrimental braking force if the athlete strongly extends their hip prior to and upon initial contact. Similarly, having the foot a further distance behind the body at toe-off is not productive if the leg is no longer acting to providing forward propulsion. Athletes should therefore not strive to increase step length for its own sake; short, powerful steps are better than long, slow ones.

How long the foot is in contact with the ground is affected by the positioning of the foot and how quickly it is pulled through from initial contact to toe-off. This is achieved through angular rotation at the hip and ankle and produced by the powerful muscles at these joints. The shorter the contact time and the longer the flight time, the faster the athlete. As flight time must be brief to avoid being judged as lifting, it is necessary instead to reduce contact time. The 20km men and women had similar cadences but crucially the proportion of flight time and contact time differed. The men had significantly shorter contact times and longer flight times. The 50km men had a lower stride frequency than either group and this was due to their longer contact times. The 50km men were thus slower than the 20km men due to maintaining longer contact duration. It must be remembered that the 50km men cannot race as fast as in a 20km race as fatigue would set in sooner, and so this longer contact time may be of benefit in this regard.

There were no differences between the groups in the angle of the knee at initial contact, which is not surprising as all athletes attempt to straighten the knee at this point. While on average the knee was not entirely extended, it may be that the knees (measured for the 20km walkers as slightly below 180°) were considered straight when judging technique. The knee was hyper-extended in all groups by mid-stance, in a deliberate attempt to keep the knee straight. That only three of the eighty athletes had slight flexion at this point shows that this rule is predominantly adhered to.

The very few correlations between joint angles and significant performance variables suggest that although they contribute to efficient technique, it is not the angles themselves that are important, but the angular velocities and timing of movements instead. A deliberate and forceful attempt to extend the hip at contact and continue with this force application against the ground right through to toe-off is paramount to shortening contact time and maintaining high levels of forward momentum (LAFORTUNE et al., 1989). In contrast, athletes who do not apply this force from initial contact onwards waste a certain amount of their contact time in non-productive support.

Conclusion

The optimisation of race walking performance depends greatly on balancing a number of key parameters, in particular stride length and stride frequency. Each of these can only be increased to a certain point before the technical rules are broken. The majority of competitors did not show evidence of bent knees or flight times that would be visible to the naked eye. The different heights of men and women result in subtly different techniques: women rely more on their shorter legs to increase stride frequency, and men rely on their longer legs to increase stride length. As a result, it is sensible to appreciate that male and female athletes may require different approaches in coaching. All walkers, and especially the 50km men, should note that technique deteriorates with fatigue to the point where there is an increased risk of disqualification. The effects of fatigue may be offset by walking at a constant pace throughout the race.

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