TECHNICAL CHARACTERISTICS OF ELITE JUNIOR MEN AND WOMEN RACE WALKERS

B. Hanley, [1] A. Bissas, [1] A. Drake [2]

[1] Biomechanics Department, Carnegie Faculty, Leeds Metropolitan University, Leeds, United Kingdom

[2] National Centre for Race Walking, University Sport, Leeds Metropolitan University, Leeds, United Kingdom

There are no conflicts of interest with this paper.

B. Hanley,

Headingley Campus,

Carnegie Faculty,

Leeds Metropolitan University,

Leeds, LS6 3QS.

Email: B.Hanley@leedsmet.ac.uk

ABSTRACT

Aim. Successful coaching in race walking requires a thorough understanding of the biomechanical principles underlying this unique form of gait. The purpose of this study was to analyze elite male and female junior race walkers and identify key kinematic variables.

Methods. Twenty junior men and 20 junior women were videoed as they competed over 10 km in the 8th European Cup Race Walking. Three-dimensional kinematic data were obtained using motion analysis software (SIMI, Munich).

Results. Step length and cadence were correlated with speed in both sexes, and greater step lengths were the kinematic reason for junior men's faster walking speeds. While cadence did not differ between junior men and junior women, there was a difference in proportion of step time spent in contact. There were some differences between genders for upper body joint angles (e.g. elbow) but there were few differences within lower limb joint angles.

Conclusion. Although some technical aspects (e.g. pelvic and shoulder girdle rotation) appeared undeveloped, it was noteworthy that most athletes achieved full knee extension at initial contact in accordance with the rules. However, in many athletes flight times were evident that might present problems during the transition to the higher standards of senior competition. There was a large range of ability among both sexes and coaches are advised to ensure that technical development continues during the transition to senior competition.

Key words: Athletics, gait, kinematics, motion analysis, young sportspeople

TEXT

Introduction

Race walking is part of the athletics program in the Olympic Games and all other major athletics championships, with competitions held over 20 km for men and women, and 50 km for men only. Because of the physical demands of competing over such long distances, races for junior men and women (under 20 years of age) are held over the shorter distance of 10 km.[1] The rules of race walking state that no visible loss of contact with the ground should occur and that the knee must be straightened from the moment of first contact with the ground until the 'vertical upright position'.[1] Judges issue red cards to athletes who they consider to be losing contact or not straightening the knee fully. An athlete receiving 3 red cards is disqualified.[1]

Successful coaching in race walking depends to a great extent on a thorough knowledge of the biomechanical principles underlying its unique technique. The main determinants of race walking speed are step length and cadence.[2-4] These are in turn affected by other important variables, such as contact time, flight time, and the position of the stance foot with regard to the whole body center of mass (CM) at both initial contact and toe-off.[2,3,5] The majority of previous biomechanical research into race walking has been on senior athletes and in comparison there has been a lack of research on elite junior race walkers. In one notable exception, Douglass & Garrett [6] analyzed 8 international junior male athletes in competition and found that step length and the ability to maintain it as the competition progressed were the main determinants of success. In an attempt to analyze the levels of efficiency in junior walkers, Douglass & Garrett [6] also measured the elbow angle at both midstance and ipsilateral initial contact. Large variations were found both between athletes (standard deviations typically ranged between 9 and 13°) and within each individual at each measurement distance.[6] In a similar study on coordination, Neumann *et al.* [7] measured the variability in race walking variables in 4 junior female walkers who walked at a constant speed on a treadmill. The knee angle at midstance showed the least variability of all variables measured. However, although treadmills have certain advantages, gait kinematics can be significantly different when walking on a treadmill from walking overground [8] and these results might not be replicated in a competitive setting.

Elite junior race walkers often become elite competitors at senior level. For example, Vallance [9] reported 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. Understanding aspects of elite junior race walkers could help coaches appreciate the progression from junior to senior competition, as areas for development (such as step length or joint angular data) can be highlighted and possibly compared with values found for elite senior athletes. Previous research has also found that there are differences between elite senior male and female race walkers [2] and thus it is useful to separate men's and women's results in identifying key variables (averaging across sexes might lead to misleading results such as with step length). There might also be kinematic differences due to body shape that could require different training emphases and identifying these differences could be useful to the coaching community. Very little research has been conducted on junior athletes, and none on junior women in competition; kinematic descriptions of elite junior athletes are therefore required to fill this gap in the research. The aim of this study was to analyze junior athletes participating in international competition in order to identify key kinematic variables and to compare male and female junior race walkers.

Materials and methods

Participants

The study was approved by the Faculty's Research Ethics Committee. Video data were collected at the 8th European Cup Race Walking, held in Metz, France in May 2009. Participants' dates of birth were obtained from the International Association of Athletics Federations (IAAF) [10] although it was not possible to obtain their heights and weights as these data are generally not reported for junior athletes. Twenty junior men (age=18.2±0.8 years) and 20 junior women (age=18.1±0.9 years) were analyzed in each race. Amongst the junior men, the analyzed competitors included the 2008 World Junior champion, the 2009 World Youth champion, and the 2007 World Youth championship bronze medallist. Amongst the junior women, the analyzed competitors included the 2008 World Junior champion and the 2007 World Youth championship bronze medallist.[10] A summary of the race performances from both events is presented in Table I. None of the 4 junior men or 4 junior women who were disqualified has been included in the study.

Procedures

Permission to record video data at the European Cup event was obtained from the European Athletics Association (EAA). The experimental set-up was similar to that used in comparable previous studies.[2,11] Two stationary 3CCD digital camcorders 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 walkers. Based on the recommendations of the British Association of Sport and Exercise Sciences (BASES),[12] the sampling rate was 50 Hz and the shutter speed 1/500 s. The resolution of each camera was 720 x 576 pixels. The section of the course chosen for camera placement was due to the straightness of the course at that part of the course and the absence of obstacles to the view of the cameras. In general, both junior men and women walked in large, bunched groups for the first half of the race and as a result most were analyzed at the 6.5 km distance where they could be seen more easily. However, some athletes who were obstructed from view at this distance were analyzed at 4.5 km instead. Consequently, the results of this study only describe the performances of the athletes at approximately the middle of the race, and different gait characteristics may have been adopted at earlier or later distances (due to fatigue or receiving red cards, for example). The reference volume was 5.20 m long, 2.00 m wide and 2.01 m high. The reference poles were placed so that the 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.[13]

Data analyses

The video data were manually digitized to obtain kinematic data using motion analysis software (SIMI Motion, Munich). The video footage from both cameras was synchronized manually by visual identification. Dropout occurred on the left hand side of the body on some occasions and estimations were made by the single experienced operator. Each file was first digitized frame by frame and upon completion adjustments were made as necessary using the points over frame method.[14] The magnification tool in SIMI Motion was set at 400% to aid identification of body landmarks. Seventeen segment endpoints were digitized for each participant using de Leva's [15] body segment parameter models for males and females.[16] These models were later used to obtain data for the whole body CM and particular limb segments. Joint angular data were also derived from the digitized body landmarks.

The results for each side of the body were averaged for the purposes of this study. The digitized data were filtered as follows: 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 phase-lag) was employed to filter the displacement-time data of each marker prior to the calculations of the first and second derivatives.[17,18] The cut-off frequencies were selected based on residual analysis and values for the variables included ranged from 4.6 – 5.9 Hz.[19]

Walking speed was determined as the average horizontal speed during one complete gait cycle. Step length has been 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. Cadence was calculated by dividing horizontal speed by step length and the proportion of time spent in stance compared with swing was also measured as the stance:swing ratio. 'Foot ahead' was used to describe the distance from the CM of the landing foot to the body's overall CM. Similarly, 'foot behind' was the distance from the CM of the toe-off foot to the body's overall CM. 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, and when the foot was behind the CM from midstance to toe-off. Vertical displacement was calculated as the difference in CM height between its lowest and highest position (which occurred in all cases following toe-off) during each step.

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.[20] 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. Negative values for the shoulder therefore indicated a hyperextended 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. 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.[3]

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. Definitions of these specific events are as follows:

- Initial contact: the first visible instant during stance where the athlete's foot clearly contacts the ground.
- Midstance: the instant during stance where the athlete's foot center of mass was directly below the CM, used to determine the 'vertical upright position' (IAAF Rule 230.1).[1]
- Toe-off: the last visible instant during stance prior to the foot leaving the ground.

Statistical analyses

All statistical analyses were conducted using PASW Statistics 18 (IBM SPSS, Inc., Chicago). Pearson's product moment correlation coefficient was used to find associations in each of the samples of 20 junior men and junior women. One-way ANOVAs were also conducted to compare values between the junior men and women, with confidence levels of 5% adopted for all statistical tests.

Results

Speed, step length and cadence

The values for walking speed, step length and cadence are shown in Table II. Speed was correlated with step length (junior men: $R=.80$, $P<.001$; junior women: $R=.91$, $P<.001$) and cadence (junior men: $R=.61$, $P=.004$; junior women: $R=.82$, $P<.001$).

Contact time and flight time

The values for contact time and flight time are shown in Table II. Speed was correlated with both contact time (junior men: $R=-.75$, $P<.001$; junior women: $R=-.93$, $P<.001$) and flight time (junior men: $R=.58$, $P=.007$; junior women: $R=.67$, $P=.001$). The amount of contact time as a percentage of overall step time is presented as contact time (%) in Table II. Shorter contact times (%) were correlated with speed (junior men: $R=-.62$, $P=.003$; junior women: $R=-.68$, $P=.001$). Periods of double support where no loss of contact occurred were observed in 11 of the junior women and in 3 junior men.

Stance:swing ratio

The average stance:swing ratio was 46:54 for junior men and 49:51 for junior women. The stance proportion for the junior men was significantly lower ($F=13.45$, $P=.001$). In both groups, lower stance proportions were found in athletes with higher speeds (junior men: $R=-.71$, $P<.001$; junior women: $R=-.84$, $P<.001$) and longer steps (junior men: $R=-.55$, $P=.012$; junior women: $R=-.85$, $P<.001$).

Vertical displacement

The mean vertical displacement of the CM for junior men was 39 mm (± 7) and for junior women, 45 mm (± 9). This difference was found to be significant (F=8.38, P=.006). Vertical displacement was positively correlated with step length and flight time in the junior women's group only (R=.49, P=.028 and R=.50, P=.025 respectively).

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

The position of the support foot relative to the whole body CM is shown in Table II. The average decrease in velocity during foot ahead in the junior men's group was 0.16 $m \cdot s^{-1}$ (± .09) and the average increase in velocity during foot behind was 0.18 $m \cdot s^{-1}$ (± .08). The average decrease in velocity during foot ahead in the junior women's group was 0.14 $m \cdot s^{-1}$ (± .07) and the mean increase in velocity during foot behind was 0.16 $m \cdot s^{-1}$ (± .06). Foot behind distance correlated with the increase in velocity during this phase in junior women (R=.58, P=.008). Foot behind distance was also correlated with step length (junior men: R=.72, P<.001; junior women: R=.56, P=.011), while foot ahead distance was associated with contact time (junior men: R=.52, P=.019; junior women: R=.48, P=.031).

Pelvic and shoulder girdle rotation

The transverse plane rotation values of the pelvis and shoulder girdles are shown in Table III. 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). 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 time (R=.72, P<.001). Pelvic rotation was correlated with foot behind distance (R=.52, P=.018), while shoulder girdle rotation was correlated with speed (R=.45, P=.047), contact time (R=–.59, P=.006), and flight time (R=.63, P=.003).

Lower limb joint angles

Table III shows the average hip, knee and ankle angles at initial contact and toe-off, as well as the midstance values for the knee. The range of knee angle 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). 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. 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 with speed (R=.55, P=.012), contact time (R=–.65, P=.002), and flight time (R=.82, P=.002) in the junior women's group only. In junior women the hip contact angle was positively correlated with flight time (R=.54, P=.014).

Shoulder and elbow joint angles

Table III also shows the values for the angles of the shoulder and elbow. A significant 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=.71, 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 time (R=–.53, P=.015).

Discussion

The aim of this study was to analyze junior athletes participating in international competition in order to identify key kinematic variables and to compare male and female junior race walkers. With regard to the most important variables, the results showed that speed was correlated with both step length and cadence in each group as expected from other studies on elite race walkers.[2,21] Junior race walkers therefore 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 cause of the difference in speed between them from a kinematic point of view was the junior men's greater step lengths. Of course, other possible sources of differences between junior men and women such as physiological and anthropometric variables that were not measured in this study are important for the coach to consider.

Although the cadences were the same, other factors that resulted in the faster speeds of the junior men were their significantly lower contact time percentage and stance:swing ratio. Longer flight times were important in increasing speed due to their association with greater step lengths. Of course, these flight times have to be restrained in order to avoid disqualification (and particularly in the case of junior women whose flight times correlated with vertical displacement). More than half of the junior women had no flight time at all and instead experienced brief periods of double support. 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 to remain within the rules. Only 3 of the junior men had periods of double support and so the majority of junior men relied to some extent on a flight phase. While these flight phases were probably too brief to be visible to the human eye, athletes who rely on a flight phase at junior level might struggle to walk faster at senior level without resorting to a visible loss of contact. It is therefore imperative that coaches of junior athletes work to eradicate or at least minimize loss of contact during this developmental stage of technique prior to senior competition (which is also over longer distances). This finding in particular highlights the usefulness of this and any future kinematic analyses of junior race walkers as increased loss of contact at senior level could seriously hinder the athlete's continued progress in the event and is therefore a key technical aspect for coaches to develop.

As stated above, flight time was correlated with step length. The other key variables that correlated with step length in both junior men and women were foot behind distance and distortion angle. However, the correlations between distortion angle and step length were relatively moderate and larger distortion angles might not have been beneficial for all athletes. Aside from its association with step length, the foot behind distance appeared 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. It was also one of the few key variables that did not differ between junior men and junior women. Foot ahead distance, by contrast, was not associated with step length and its positive correlation with contact time means that athletes should take care not to overstride by placing the foot too far in front of the CM at initial contact. Coaches should be therefore aware that forced or exaggerated increases in step length might be detrimental in the development of technique.

Although distortion angles did not differ between the sexes, the relative contributions of the pelvic and shoulder girdles did differ as the junior men had more pelvic rotation and the junior women more shoulder girdle rotation. In addition, it was 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. These variables, like many others in race walking, do not need to be maximized (given anthropometric restrictions) but optimized instead and it is important to note though that just because correlations have been found between angular variables and speed, this does not imply causation, as this would suggest even greater angles would lead to increased speed where instead there is an optimum range.

It is important to pay attention to the knee joint in race walking because of IAAF rule 230.1.[1] There was no difference between junior men and junior women for knee extension at either initial contact or midstance. The initial contact knee angles for junior men and junior women were 180° and 178° respectively, which both increased to 192° at midstance, so it was unsurprising that very few red cards (8) were awarded for unstraightened knees to the 40 athletes analyzed. As with prior findings on a much smaller number of female junior walkers,[7] variations in this particular measurement were very small. Full knee extension thus appeared to be a well-developed characteristic in these relatively young race walkers. Following 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. Rather than the knee angle being the cause, this might instead have been because the faster athletes had shorter contact times and therefore less time for the knee to flex following midstance. This was supported by the fact that knee toe-off angle was also larger in those junior women who spent more time in knee hyperextension.

With regard to the upper limbs, the function of the arms in race walking is to counterbalance the anterioposterior movements of the legs. The standard deviations for the elbow joint measurements at the 3 identified gait events were larger than at any other joint, which was similar to earlier results reported on junior male athletes.[6] The large range of elbow angles might have been an indication of inefficient technique among some athletes, but as there were no correlations between the elbow measurements and the key kinematic variables measured in this study it is difficult to ascertain what effect these arm positions had. While there is an obvious focus on the lower limb in this unique form of gait, coaches should not neglect upper body development as this study highlights that even elite junior race walkers can have quite different ranges of upper limb joint angles.

The junior men were significantly faster than the junior women, although the very best junior women's results were comparable to those of many of the junior men. 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. Related to this fact, the winning time in the junior women's 10,000 m race at the 2008 World Junior Championships bettered the entry standard required for the junior men's event.[10] Out of all athletic events held at that competition, the race walk was the only event in which this occurred.[22] While the disparity between senior men and women over 20 km is much larger,[10] at junior levels there might not be as great a need to differentiate technical training based on gender. Certainly, 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 3 of the junior women had never raced over the distance before), others were much more developed. For example, the Russian winner of the junior men's race (analyzed in this study) was 18 years old at the time of competition. In senior competition, he subsequently became European 20 km champion in 2010 when aged 19 and finished 5th in the 2011 World Championships 20 km at the age of 20.[10] Although not quite as successful, the Russian winner of the junior women's race (also analyzed in this study and aged 18 at the time) nevertheless subsequently finished a very creditable 17th in the 2011 World Championships 20 km a few weeks after turning 21.[10] It is important therefore that coaches assist young athletes by ensuring that technical and physical development continues during the transition from junior to senior competition to help prolong their athletic careers.

Conclusions

The analysis of elite junior race walkers in international competition showed that the fastest athletes had both long steps and high cadences. Slower athletes had longer contact times and quite often no flight times; reducing contact time and increasing flight time can improve race walking speed by increasing both cadence and step length and is a key area for coaches of junior race walkers to focus on. Race walking gait is unnatural and learned and therefore requires a great deal of technical development to be efficient. Certain body movements associated with elite race walking such as pelvic rotation and elbow flexion were ungainly in their appearance and varied greatly between athletes. Race walk coaches should be mindful to pay attention not only to achieving legal technique but also to achieving all-round movement efficiency. This will help junior athletes to progress from the shorter competitive distance of 10 km to the senior distances of 20 and 50 km.

REFERENCES

1. IAAF: Competition Rules 2012 – 2013 [Internet]. Monte Carlo: International Association of Athletics Federations; 2011 [cited 2012 Sep 12]. Available from: http://.www.iaaf.org/.

2. Hanley B, Bissas A, Drake A. Kinematic characteristics of elite men's and women's 20 km race walking and their variation during the race. Sports Biomech 2011; 10:110-24.

3. Knicker A, Loch M. Race walking technique and judging - the final report to the International Athletic Foundation Research Project. New Stud Athlet 1990; 5(3):25-38.

4. Padulo J, Annino G, D'Ottavio S, Vernillo G, Smith L, Migliaccio GM, et al. Footstep analysis at different slopes and speeds in elite race walking. J Strength Cond Res 2013; 27:125-9.

5. Lafortune M, Cochrane A, Wright A. Selected biomechanical parameters of race walking. Excel 1989; 5(3):15-7.

6. Douglass BL, Garrett GE. Biomechanics of elite junior race walkers. In: Terauds J, Barthels K, Kreighbaum E, Mann R, Crakes J, editors. Proceedings of the II International Symposium on Biomechanics in Sports. Del Mar: Research Center for Sports; 1984:91-6.

7. Neumann HF, Krug J, Gohlitz D. Influence of fatigue on race walking stability. In: Kwon Y-H, Shim J, Shim JK, Shin I-S, editors. Proceedings of the XVII International Symposium in Sports. Seoul: International Society of Biomechanics in Sports; 2008:428-31.

8. Alton F, Baldey L, Caplan S, Morrissey MC. A kinematic comparison of overground treadmill walking. Clin Biomech 1998; 13:434-40.

9. Vallance B. The men's 20 km walk. Modern Athlete and Coach 2005; 43(2):12-7.

10. IAAF: Biographies - IAAF World Athletics Series athletes: 1999 onwards [Internet]. Monte Carlo: International Association of Athletics Federations; ©2011 [cited 2012 Sep 12]. Available from: www.iaaf.org/athletes/biographies/index.html.

11. Hanley B, Smith LC, Bissas A. Kinematic variations due to changes in pace during men's and women's 5 km road running. Int J Sports Sci Coaching 2011; 6:243-52.

12. Payton CJ. Motion analysis using video. In: Payton CJ, Bartlett RM, editors. Biomechanical Evaluation of Movement in Sport and Exercise. Leeds: The British Association of Sport and Exercise Sciences; 2008: 8-32.

13. Abdel-Aziz YI, Karara HM. Direct linear transformation from comparator coordinates into space coordinates in close range photogrammetry. In: American Society of Photogrammetry, editors. Proceedings of the Symposium on Close Range Photogrammetry. Falls Church: American Society of Photogrammetry; 1971:1-18.

14. Bahamonde RE, Stevens RR. Comparison of two methods of manual digitization on accuracy and time of completion. In: Schwameder H, Strutzenberger G, Fastenbauer V, Lindinger S, Müller E, editors. Proceedings of the XXIV International Symposium on Biomechanics in Sports. Salzburg: International Society of Biomechanics in Sports; 2006: 650-3.

15. de Leva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J Biomech 1996; 29:1223-30.

16. Hanley B, Bissas A. Differences between body segment parameter models in analysing elite race walkers in competition. Gazz Med Ital – Arch Sci Med 2012; 171:541-50.

17. Giakas G, Baltzopoulos V. A comparison of automatic filtering techniques applied to biomechanical walking data. J Biomech 1997; 30:847-50.

18. Giakas G, Baltzopoulos V. Optimal digital filtering requires a different cut-off frequency strategy for the determination of the higher derivatives. J Biomech 1997; 30:851-5.

19. Winter DA. Biomechanics and motor control of human movement. 3rd edition. Chichester: Wiley; 2005.

20. Cairns MA, Burdette RG, Pisciotta JC, Simon SR. A biomechanical analysis of racewalking gait. Med Sci Sports Exerc 1986; 18:446-53.

21. Hanley B, Bissas A. Analysis of lower limb internal kinetics and electromyography in elite race walking. J Sports Sci 2013; 31:1222-32.

22. Vallance B. Transitional factors in race walking. European Athletics Association Summit Series: European Walks Conference; 2010 November 5-7, Leeds.

TITLES OF TABLES

TABLE I. *–Race performances from the 8th European Cup (mean ± SD).*

TABLE II. *–Means (± SD) and between-subjects effects of key race walking variables. Differences were significant at P<0.05 (bold).*

TABLE III. *–Means (± SD) and between-subjects effects of rotation, leg and arm joint angles. Differences were significant at P<0.05 (bold).*

TABLE I. –*Race performances from the 8th European Cup (mean ± SD).*

	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

TABLE II. –*Means (± SD) and between-subjects effects of key race walking variables. Differences were significant at p<0.05 (bold).*

	Junior men	**Junior women**	**F**	P
Speed (km·h^{-1})	13.36 (± 1.04)	11.61 (± .96)	30.51	**< .001**
Step length (m)	1.16 (± .07)	1.01 (± .02)	58.19	**< .001**
Cadence (Hz)	3.21 (± .15)	3.20 (± .13)	0.03	.861
Contact time (s)	0.29 (± .02)	0.31 (± .03)	7.30	**.010**
Flight time (s)	0.03 (± .02)	0.01 (± .01)	10.11	**.003**
Contact time (%)	91.6 (± 5.2)	96.4 (± 4.5)	9.60	**.004**
Foot ahead (m)	0.38 (± .03)	0.34 (± .02)	25.69	**< .001**
Foot behind (m)	0.44 (± .03)	0.43 (± .02)	3.63	.064

TABLE III. *–Means (± SD) and between-subjects effects of rotation, leg and arm joint angles. Differences were significant at P<0.05 (bold).*

	Junior men	**Junior women**	**F**	**P**
Pelvic rotation (°)	15 (± 5)	9 (± 3)	23.75	**<.001**
Shoulder rotation (°)	17 (± 3)	20 (± 4)	9.76	**.003**
Distortion angle (°)	30 (± 5)	27 (± 5)	2.64	.112
Knee angle (°)				
Initial contact	180 (± 3)	178 (± 3)	1.64	.208
Midstance	192 (± 5)	192 (± 4)	0.08	.785
Toe-off	155 (± 5)	158 (± 6)	2.26	.141
Hip angle (°)				
Initial contact	169 (± 3)	167 (± 3)	5.95	**.019**
Toe-off	193 (± 3)	195 (± 3)	2.60	.115
Ankle angle (°)				
Initial contact	103 (± 4)	104 (± 3)	0.84	.364
Toe-off	129 (± 4)	134 (± 5)	10.59	**.002**
Shoulder angle (°)				
Initial contact	–65 (± 7)	–66 (± 7)	0.40	.530
Midstance	–22 (± 4)	–25 (± 6)	4.60	**.038**
Toe-off	37 (± 7)	36 (± 7)	0.15	.702
Elbow angle (°)				
Initial contact	80 (± 13)	68 (± 12)	8.57	**.006**
Midstance	85 (± 10)	75 (± 8)	10.37	**.003**
Toe-off	71 (± 10)	67 (± 6)	1.87	.180