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The biomechanics of race walking: literature overview and new insights

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Abstract

This review aims to provide both researchers and coaches with a comprehensive overview of race walking biomechanics, and to point out new viable route for future analyses. The examined literature has been divided into three categories according to the method of analysis: kinematics, ground reaction forces, and joint power/efficiency. From an overall view, race walking athletes seem to adhere to the “straightened knee” rule, but at race speed they do not observe the “no-flight time” rule. The coach-oriented analysis highlights that stride length is more important than stride frequency for increasing speed and it is mainly obtained by ankle and hip joint power. Moreover kinematic differences (stride frequency, stride length and flight time) between male and female athletes were shown. Also, we found that the maximal speed prediction according to dynamic similarity theory with walking (Froude number) is not applicable as the 3D trajectory of the body centre of mass does not follow an arc of circumference as in walking. The analysed literature shows some shortcomings: i) the data collection is often unreliable because of the mixture of gender and performance level, and ii) the analysis has sometimes been performed on a limited number of strides and speeds. These limitations lead to a scattered and incomplete gait description and a biased application of the results. The research strategy adopted so far is promising but further rigorous analyses need to be approached to obtain a fully comprehensive picture of race walking and to provide coaches with consistent results and reference values.

Introduction

"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" (International Association of Athletics Federation, IAAF, 2013). This rule was introduced in 1995, and before this revision the leg had to be straightened only in the vertical position. Those constraints (no flight time and straightened knee) forced athletes to develop a characteristic locomotors pattern widely known as "race walking style". Despite being a worldwide discipline - in London 2012 forty-three nations representing the five continents competed – race walking has been investigated in few scientific studies and an explicit comparison to walking or running is still missing. Moreover some of them were published before 1995, hence they could not be fully relevant to the current race walking analysis, being based on the old rules.

The aim of this review is to provide coaches and researchers with an overview on race walking biomechanics and to give original insights concerning the gait dynamics. The studies evaluated in this review were split up in three sections regarding to the methodology used for the biomechanical analysis of race walking: i) the technique investigation based on stride lengths, stride frequencies and angular displacements measurements (table I, 'K'); ii) the analysis of the forces exerted during the support phase (table I, 'GRF'); iii) the gait analysis of joint power and efficiency (table I, 'JPE').

Kinematics

The kinematic analysis of race walking has been largely employed to monitor the athletes' technique by measuring rotational and linear parameters during training sessions or competition. The first message emerging from kinematics concerns the athletes' adherence to the rule that relies on i) flight time detection and ii) knee joint angle 'constraint'.

The flight time has been detected in several studies and its duration (0.01 – 0.05 s) varied with speed (Cairns, Burdett, Pisciotta, & Simon, 1986; Cavagna, & Franzetti, 1981; De Angelis & Menchinelli, 1992; Hanley, Bissas, & Drake, 2011a, 2011b; Phillips & Jensen, 1984; Neumann, Krug & Gohlitz 2006, 2008). In race condition, Hanley et al. (2011a, 2011b), found a flight time of 0.03 s for a male 20 km race (speed = 4 $m\cdot s^{-1}$, 14.5 $km\cdot h^{-1}$) and 0.02 s for a female 20 km and male 50 km race (3.5 – 3.6 $m\cdot s^{-1}$, 12.7 $km\cdot h^{-1}$ – 13.1 $km\cdot h^{-1}$ respectively). It should be noted that judges could not detect such short flight durations due to psychophysiological limitations of vision (Cairns et al., 1986; Phillips & Jensen, 1984; De Angelis & Menchinelli, 1992).

The knee 'constraint' was highlighted in the studies after 1995, where the lower limb was straightened at heel strike (Hanley et al., 2011a, 2011b; Neumann et al., 2006, 2008; Zhang & Cai, 2000) and the knee hyperextended for almost the 70% of the contact time, with a peak at midstance of about 10° (Donà, Preatoni, Cobelli, Rodano, & Harrison, 2009).

The stride length (SL, m) and the stride frequency (SF, Hz) are the positively correlated determinants of walking speed, but they seem not to correlate with each other (Hanley et al., 2011a). By pooling together data from these studies (Cairns et al., 1986; Cavagna & Franzetti, 1982; De Angelis & Menchinelli, 1992; Hanley et al., 2011a, 2011b; Murray, Guten, Mollinger, & Gardner, 1983; Padulo et al., 2013a; Padulo et al., 2013b; Preatoni, La Torre, Santambrogio, & Rodano, 2010a; Phillips & Jensen, 1984; Rodano & Santambrogio, 1987) we computed a descriptive equation (Figure 1, $SL = 0.345v + 1.041$; $R^2 = 0.77$) which estimates SL value (m) at a given speed (v, $m \cdot s^{-1}$). SL was better correlated than SF to speed (SL: $R = 0.882$, $p < 0.001$; SF: $R = 0.65$, $p < 0.001$) as shown by Hanley et al. (2011a) in their narrow range of speed. The steeper SL slope compared with SF at increasing speed was related to an increase in flight time and, consequently, a decrease in contact time (Cairns et al., 1986; Padulo et al., 2013a; Phillips & Jensen, 1984).

The effect of fatigue on race walking kinematics with relation to effort/exercise duration is an important factor during the competition: Brisswalter, Fougeron and Legros (1996, 1998) found no changes in SL and SF after 3h race walking at constant speed ($3.3\ m \cdot s^{-1}$; $12 – 12.2\ km \cdot h^{-1}$). In competitions something different occurs: Hanley et al. (2011a) reported a race speed reduction in the 20 km race initially due to a drop in SL, and successively to a SF decrease. Douglass and Garrett (1984) pointed out similar results in a short distance (10 km) where the winner was the athlete capable of increasing SL in the last part of the race. In the 50 km both speed and SL decreased with a significant reduction of flight time, whereas SF was steady over the race; moreover ankle plantarflexion at toe off and the pelvis rotation were decreased (Hanley et al. 2011b). Therefore, race pace, which is affected by a decrease in SL during the race, was more influenced by muscular fatigue than constant training speed. Further analysis of the pacing strategy showed opposite finding with a “negative split” (an increase in speed in the last part of the race) in 20 km men and women winners. On the contrary, in 50 km race speed decreased at the end (Hanley 2013). Finally Hanley et al. (2011a) observed that race speed (20 km race) difference between men and women was due to a smaller flight time in women, hence a smaller SL also due to a smaller athletes’ height. Moreover, De Angelis and Menchinelli (1992) found, at each speed, a shorter step length (0.09 m), a higher step frequency (0.2 Hz) and flight time (0.006 s) for women with respect to men.

Stance phase (or contact time) was divided in braking and propulsive phases depending on the relative position of the foot and the body centre of mass in the sagittal plane. Braking phase takes place when the foot is ahead of the centre of mass, whereas race walkers accelerate the body in the progression direction when the foot is behind body centre of mass (Hanley et al., 2011a, 2011b; Phillips & Jensen, 1984; Preatoni et al., 2010a) as in walking and running. The values presented in most of these studies denote the athlete's ability to spend more time in the propulsive phase, hence coaches should check this parameter during the training sessions.

Recently Padulo et al. (2013a) extended the kinematics analysis, measuring SL and SF at the same speed at level and on gradient (2% and 7%): SL decreased, probably due to a reduction of swing phase because of the incline, contact time decreased, whereas SF increased. Later Padulo et al. (2013b) found also a decrease in SF with an increase in contact time that was addressed to a decrease in speed from level to 7% in order to maintain the "iso-efficiency speed", which is the speed value that leads to a constant energy cost across the slopes. These investigations are the only ones that evaluate race walking on gradient, which is a training methodology employed by coaches.

In literature there are several studies dealing with joint angles but an overall quantitative description is lacking and affected by the different speeds involved (Cairns et al., 1986; Douglass & Garret, 1984; Hanley et al., 2011a, 2011b; Murray et al., 1983; Padulo et al., 2013b; Preatoni, La Torre & Rodano, 2006; Neumann et al., 2006, 2008; Phillips & Jensen, 1984; Zhang & Cai, 2000). In this section the angles are presented at the key stride phases (heel strike, midstance and toe off) in three planes of motion (sagittal, frontal and transverse plane).

In the sagittal plane, at heel strike the ankle is dorsiflexed compared with the standing position, the knee is fully extended and the hip is flexed relative to the standing position; the contralateral shoulder is extended and the elbow is reported to have an angle of 79°±9° (Hanley et al., 2011a). At midstance the ankle is still dorsiflexed, the knee is hyperextended of about 10°, the shoulder is flexed and the elbow has almost a flexion of 82°±7° (Hanley et al., 2011a). At toe off the ankle is plantarflexed, the knee is flexed, the hip is extended, the contralateral shoulder is flexed and the elbow is flexed 67°±7° (Hanley et al., 2011a).

In the frontal plane the motion of the trunk and the pelvis were described: the hip is in the highest position over the support leg and in the lowest when over the swinging leg (pelvic tilt), whereas the shoulder ipsilateral with the support leg is in the lowest position and the contralateral shoulder in the highest, so the column formed a S-shape curve (Murray et al., 1983; Phillips & Jensen, 1984). The pelvic tilt is about 7°±4° at 3.6 $m \cdot s^{-1}$ (13 $km \cdot h^{-1}$), but tends to increase with speed (Cairns et al., 1986). From these investigations, trunk and pelvis adjustments are supposed to minimize the vertical excursion of the body centre of mass during the single support, even though a quantitative analysis/proof is still missing.

In the transverse plane the pelvic rotation was described with controversial results: Hanley et al. (2011a), reported an angle of 18°±3°, whereas others reported greater pelvic rotation: 44° (Murray et al., 1983) and 35°±8° (Cairns et al., 1986). It can be addressed to a varying reference selection for joint angle measurement: Hanley et al. (2011a) estimated pelvic angle using hip joint coordinates, whereas Murray et al. (1936) and Cairns et al. (1986) calculated the whole angular rotation of the same marker. Differently Murray et al. (1983), White and Winter (1985) and Hanley and Bissas (2013) showed hip, knee and ankle joint angular time course during a stride, which may be an important functional parameter for a more complete picture of the locomotion pattern and to provide coaches and athletes with a further technical feedback suitable in training.

The overall kinematics data proved that the IAAF rule was followed for the knee constraint but some flight time actually occurred.

A further approach, based on sophisticated mathematical methods applied to race walking biomechanics, has been carried out in several investigations (Preatoni et al., 2010a; Preatoni, Ferrario, Donà, Hamill & Rodano, 2010b; Donà et al., 2009). Their outcomes may support researchers with functional guidelines and provide coaches with quantitative tools for skill prediction (Donà et al., 2009) and technique assessment (Preatoni et al., 2010b): i) a sequential estimation procedure defined that at least 15 trials are necessary for a reliable description of the kinematical parameters investigated, ii) a non-linear analysis based on entropy (measurement of the motor variability) may reflect the athletic condition and the performance enhancement due to a motor learning/adaptation, iii) a multivariate data analysis (functional Principal Component Analysis, fPCA) found differences in knee joint kinematics across athletes level.

Despite of all these innovative methodologies, the impact of those tools in training and motor learning strategies will need to be checked throughout practical validation with a further and active cooperation among researchers and coaches.

Ground Reaction Forces Analysis

One of the most distinctive sign in locomotion dynamics assessment is the pattern of ground reaction forces (GRF) vertical component, but considering race walking also the anterior-posterior component could give information about the “fluidity” of the technique.

Indeed, the first biomechanical investigation compared the GRF curves during a race walking single support, to walking and running (Payne, 1978). Since then, six studies concerning GRF analysis

(Cairns et al., 1986; Fenton, 1984; Payne, 1978; Preatoni, et al., 2006; Rodano & Santambrogio, 1987; Witt & Gohlitz, 2008), highlighted dynamic parameters to help coaches and specialists in performance assessment.

Cairns et al. (1986), Rodano and Santambrogio (1987) and three subjects of Fenton's study, defined as less-trained, (Fenton, 1984) showed a "M" shaped vertical force (Fy, International Society of Biomechanics, ISB guidelines), with a local minimum between the two peaks, which is typical of walking. Payne (1978) and Fenton, in further four subjects, described a more consistent GRF vertical component, with a notable first peak and a lower relative maximum, similar to running GRF pattern (Figure 2). Overall, the average peak magnitude was around 1.5 body weight (BW), but force traces are speed-dependent so they must be clustered across the speed. Fenton divided his participants in two groups according to Fy timing peak appearance: a group showed an earlier and higher Fy peak, whereas the second group showed also a second peak corresponding to forefoot contact. First group participants were less-trained athletes, whereas well-trained athletes were gathered in the second one. Fenton's investigation was conducted at different speeds, but only a sample relative to 3.35 $m \cdot s^{-1}$ (12 $km \cdot h^{-1}$) was shown, therefore there are not experimental evidences that Fy peak value may increase with speed, as it actually happens in walking and running.

From a technical point of view, Fenton described the first peak timing and its magnitude as indicators of smoothness and "fluidity" of the stride. Additionally, the second force peak reduction (0.5 BW smaller than the first one) is comparable in magnitude to the one assessed in walking, and may be addressed to the athletes' ability to push in the progression direction: the more force is exerted vertically the more a flight phase could occur (Fenton, 1984).

Antero-posterior forces (Fx) pattern is divided in three portions: a braking action, a plateau and a propulsive action (Figure 2). The braking action occurs within the first 43% (3.3 – 3.6 $m \cdot s^{-1}$) of the stance phase with a peak magnitude of about 0.4 BW (Cairns et al., 1986; Fenton, 1984). The plateau coincides with the knee hyperextension during midstance (Fenton, 1984) and the propulsive peak force was slightly smaller, 0.3 BW (3.3 – 3.6 $m \cdot s^{-1}$) than the braking one. The timing of transition between the braking and pushing phases and the smaller Fx fluctuation are informative in analysing the athletes' technique (Fenton, 1984).

The medial-lateral (Fz) direction of the force turned from lateral at heel strike to medial at midstance, possibly balancing the pelvis' lateral shift when the knee was straightened, and lateral again at toe off.

Even if most of the GRF studies were published before 1995, the forces patterns on three axes are comparable with those reported by Preatoni et al. (2006) and Witt and Gohlitz (2008) in later studies. In the literature, further investigations on race walking dynamics, lead to an interesting analysis of the foot centre of pressure (CoP). Cairns et al. (1986) and Rodano and Santambrogio (1987) described also its motion during the contact time: at heel strike the CoP was in the rear part of the shoe sole, subsequentially in the first 30% of the stance it migrated toward the medial part of the sole. At midstance (30% - 60%) it had a fast forward and lateral progression and finally (60% - 100%) CoP pathway returned to the mid-line until toe off.

Joint Power, Energy Flow & Efficiency

The mechanical power of lower limbs and the related energy flow were considered the most promising analysis for race walking technique, both to compare its features with normal walking (Cairns et al., 1986; Murray et al., 1983; Preatoni et al., 2006; White & Winter, 1985) and to provide useful suggestions for coaching (Hoga, Ae, Enomoto, & Fujii, 2003; Hoga, Ae, Enomoto, Yokozawa, & Fujii, 2006; Hanley & Bissas, 2013). Compared with walking, race walking showed i) an higher ankle joint moment both in dorsiflexion and plantarflexion, ii) an higher joint moment in knee flexion/hyperextension and iii) a greater hip abduction moment (Cairns et al., 1986). The oldest studies (Cairns et al., 1986; White & Winter, 1985) reported no impact peak in hip extensor torque, but observed a further knee extensor torque in the first half of the support phase. On the contrary, recent investigation (Hoga et al., 2006; Hanley & Bissas, 2013) showed i) enhanced peaks in the hip extensor torque and knee flexor torque in the initial part of the support phase (Figure 3), ii) an extra knee flexor torque during the support phase in order to prevent hyperextension of the knee joint (principal effect of knee constrain).

Several authors (Hoga et al., 2006; White & Winter, 1985) emphasized the ankle joint moment as a unique biomechanical property of race walking: in this gait the ankle is a key joint that plays the same role as the knee joint in running (Cairns et al., 1986). During ankle joint dorsiflexion, in the early phase of the stance period, the body decelerated while the plantar flexor torque, from 60 to 100% of stance period, is fundamental to gain the forward propulsion (Cairns et al., 1986; White & Winter, 1985), and it is strongly correlated to the speed (Figure 3). However recently Hanley and Bissas (2013) proved that ankle torque is not the only power generator, but hip extensors and ankle plantarflexors moments are also fundamental to accelerate the body centre of mass through an energy transfer from the hip to the ankle via the straightened knee. The absorbing power obtained during the knee flexion before toe off is crucial to provide more time to the swinging leg in order to land ahead and avoid flight phase. Moreover Hanley & Bissas (2013) focused their investigation on the functional role of the swinging leg: peak joint moment and power of knee and hip correlated with speed occurred during swing and could be a defining feature of better performances. They also interestingly found no differences in normalized joint moments and power between male and female athletes (Hanley & Bissas 2013). Finally, the overall increase of joint moments in race walking, demonstrated how the faster speed than walking was reached through a costly muscular activity, also characterized by a different and major activation sequence and timing.

Regarding the investigation of energy flow, Hoga et al. (2003, 2006) employed inverse dynamics method to identify technical factors to increase walking speed and to enhance the performance. In those studies they measured the joint torque power both in the "recovery leg" (i.e. the swinging limb) (Hoga et al., 2003) and in the support leg (Hoga et al., 2006), and the related energy flow through the anatomical segments of the thigh, shank and foot. This accurate analysis of mechanical energy flow allowed them to subdivide the support period in five distinct phases, based on the dynamics of movement, and to suggest how to enhance performance race walker should: i) increase the plantar flexor torque in the middle of the support phase and ii) generate the knee extensor and the hip flexor torques in the final part of the support phase (Hoga et al., 2006). Another technical factor, not completely proved, for enhancing the mechanical energy flow from the "recovery leg" to the support leg, might be the exertion of the "recovery hip" extensor torque in the final part of the support phase (Hoga et al., 2003). Unfortunately, the authors could not demonstrate their theory because of the 2D analysis, and speculated only about the role of trunk rotation torque and of the reaction force of the arm swing, which might enhance rotation of the pelvis and increase the forward joint force of the support hip. These speculations might potentially improve training strategy, but further studies are required to fully validate those hypotheses.

The mechanical work and the metabolic demand are the principal factors describing the economy and efficiency of locomotion, they could equally represent the determinants in achieving the best performance. Cavagna and Franzetti (1981) investigated the dynamics of race walking in the attempt to explain the lower speed dependency of energy expenditure, when compared to walking. The mechanical external work has been measured analysing the patterns of potential and kinetic energies of the body centre of mass during the step at increasing speeds (0.5 – 5.3 $m \cdot s^{-1}$), and it resulted higher than walking even if it reached almost a plateau above 3.9 $m \cdot s^{-1}$. The overall resulting efficiency was greater than walking, (40 – 50%) and its value slightly increased over the speed, but without reaching the running values. Moreover, the potential/kinetic energy exchange typical of pendulum-like gaits was not found, thus a negligible "% Recovery" was obtained. For this reason they concluded that the extra efficiency calculated could be due to some storage/release of mechanical energy in the elastic structures. This efficiency should be called "apparent efficiency" (as in running) because it exceeds the muscular one (25%). Almost simultaneously, Marchetti, Cappozzo, Figura, & Felici (1982) calculated race walking efficiency by employing the inverse dynamic method (Winter, 1979). They found that the efficiency of race walking, related to speed, smoothly follows the last values reported for normal walking, thus never reaching the much higher values typical of running. Their apparent efficiency values were lower than Cavagna and Franzetti study, probably because of the different method applied. Anyway, the mechanical and metabolic data provided in those studies refer to a thirty years old race walking technique, which need to be updated with further analysis on present-day athletes. Moreover, an other interesting topic is the role of elastic energy in race walking mechanics: since this gait resembles running, with an in phase time course of both kinetic and potential energy (Cavagna & Franzetti 1981), the imposed heel strikes and straight knees prevent any use of leg tendons compliance. However the inconclusive results published so far about apparent efficiency of race walking excides muscle efficiency, indirectly demonstrating the potential role of elastic structures, it is a challenge for the future studies to find where it occurs in the muscular-skeletal system.

Pavei et al. (2012) have recently defined how race walking is able to exceed the theoretically maximal walking speed, by analysing the trajectory of the body centre of mass. This maximal velocity is set by Froude number (Alexander 1989), which takes into account the leg length, the velocity and the gravity ($Fr = v^2 \cdot g^{-1} \cdot L^{-1}$), equal to 1. Above this value in the pendulum like gait, as walking, a flight time occurs because the centrifugal force is greater than the centripetal one (due to gravity) and therefore the body centre of mass is raised upwards. Race walkers normally achieve faster velocity than the one theoretically allowed at $Fr = 1$ and this is made possible because the trajectory of the body centre of mass does not draw an exact arc of circle during the stance phase, but shows a vertically lower path than in “normal” walking. Thus race walking is not resembled to a pendulum like motion and can not undergo the Froude number (Pavei et al. 2012). This number was used to compare the progression speed of different size animals (and also humans) since it normalise for the leg length and could be interestingly to employ this approach when comparing female and male athletes. Finally, the high apparent efficiency and the differences from “pendulum like” mechanics make race walking dynamically closer to running than walking.

Conclusions

This review provides a comprehensive overview of the published data in the biomechanical research on race walking, and comprehensive description of such a gait in comparison with walking and running. The major limitations and lacks in knowledge have been pointed out and all the findings have been discussed in order to give functional hints to coaches and researchers.

Practical applications for coaches rely on the influence of race walking technique analysis on performance: i) race speed can be increased mainly by developing a longer SL, which can be generated by a higher propulsive time phase and longer flight time (even if is not allowed), ii) women adopted a different technique with higher SF and shorter SL than men, hence training methodology should be gender specific, iii) GRF analysis could discriminate athletes' level (peak timing of the vertical force) and their "fluidity" (braking to propulsive force inversion), iv) joint power analysis showed ankle and hip as the main determinant of propulsive torque and speed, and leg swing seems to play a role on speed generation. These findings potentially guide training of specific muscles groups, and v) studies about GRF and specific kinematical analyses in the propulsive step phase (behind leg vertical position) are valid even if published before 1995. Rather results from joint power analysis, should be gathered in the most recent studies.

This review encourages coaches to quantitatively focus on training specifically SL and SF, also in relation to fatigue, rather than rely only on the typical drills only qualitatively checked. Moreover gender differentiations should be taken into account for neuromuscular parameters on training program: in male athletes SL and SF could be both optimised for improving their performance, but specific training to increase SL could gain even major benefits to female performance.

The major limitations of the studies so far published are i) the number of subjects and their performance level, ii) the number of step and speed analysed, and iii) the bi-dimensional analysis employed most of the time. As the recruitment of elite race walkers is difficult, most of the studies analysed few subjects sometimes of different level leading to scattered results. Regarding gender mixture, some studies included women in the analysis assuming no differences between genders, even though De Angelis & Menchinelli (1992) showed contrasting results in terms of kinematics. Recently Hanley and Bissas (2013) underlined that joints moment and power normalization is fundamental to provide an unbiased gender comparison. A further observation concerns range of speeds so far examined. In most of the investigations, athletes were tested at training speeds, quite lower than nowadays race speeds, and the number of stride analysed is small or not reported: in most of the studies only one step had been considered, while Preatoni and colleagues (2010a) showed how at least 15 trials would be necessary to properly describe kinematics parameters as angles and lengths. With a small step number it is difficult to obtain a representative average pattern and/or to give coaches decisive data because the results are not representative of the actual situation. The bi-dimensional analysis is a convenient tool, but nowadays three-dimensional instrumentation is very well diffused and could be useful in the angular analysis and also in the energy flow estimation (for examples to shed lights on the speculation about the trunk transfer).

The most recent studies are focused on elite athletes and the assessment of their technique during international events, a reliable kinematic/kinetic description at increasing speeds, based on an adequate number of strides, is missing. Moreover, a strong relationship between any biomechanical parameter and athlete's level has not been shown yet. For these reasons, work is still needed in order to obtain a more comprehensive view on race walking gait, with also latest relevant information useful to coaches, established by validated methodologies.

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Authors	Methods	N° subjects	Performance Level	Equipment	Sampling frequency (Hz)	N° trials collected; speed (s, m•s^{-1})	Aim
Murray et al. 1983	K	2 M	National team USA	1 camera	128	2 trials: 1 stride; 3.3 m•s^{-1}	Changes in movement patterns in two race walkers to provide scientific basis for training.
Douglass & Garret 1984	K	6 M (junior)	National team	1 camera in competition	48	3 trials: 1 stride; 3.5 m•s^{-1}	Analysis of junior race walkers technique, and the influence of fatigue.
Phillips & Jensen 1984	K	3 M	Nationally ranked	1 camera	115	2 trials: 1 stride; $4.7 < s < 5.5$ m•s^{-1}	Kinematics of elite race walking performance.
Cairns et al. 1986	K; GRF; JPE	8 M 2 F	46’25” – 55’14” (10 km)	3 cameras with markers; 1 force plate	50	2 trials: 1 stride; 2.9 and 3.6 m•s^{-1}	Kinetics description of race walking and comparison with walking and running.
De Angelis & Menchinelli 1992	K	10M 6F	International level	Conductance-footboard		M:60 strides 2.3 – 4.16 m•s^{-1} F: 36 strides: 3.5 – 3.9 m•s^{-1}	Determine if top level athlete can race walk at race speeds without adopting lifting phases.
Brisswalter et al. 1996	K	7 M	Elite	Impact monitor		20 strides: 3.4 m•s^{-1}	Investigation of changing in physiological parameters after 3h
Brisswalter et al. 1998	K	9 M	4:08’24” (12’ SD) (50 km)	1 camera with markers	50	3 strides: 3.3 m•s^{-1}	Relationship between kinematics variation and energy cost with exercise duration
Zhang & Cai 2000	K	7 F	National level	1 camera in competition	120	1 step	Analysis of the lower limb biomechanics to provide information to coaches for improvement in performance.
Neumann et al. 2006	K	20M	Experienced	1 camera, treadmill	25	2 m•s^{-1} step 0.25 m•s^{-1}, 30”	Investigate the relationship between occurrence of flight time and knee straightening
Neumann et al. 2008	K	4 F	National level	1 camera, treadmill	25	6 – 10 km constant speed	Investigate the adherence to the rule under the influence of increasing fatigue
Donà et al. 2009	K	4 M 3 F	40’56” – 48’34” (10 km)	8 cameras BTS 2002 system	100	20 trials: 10 stride $2.4 < s < 3.3$ m•s^{-1}	Validation of f-PCA method to analyse the intra-individual variability, and the influence of athletic skill in (inter)national athletes rank.
Preatoni et al. 2010a	K	4 M 3 F	40’56” – 48’34” (10 km)	8 cameras BTS 2002 system	100	20 trials: 10 stride $2.4 < s < 3.3$ m•s^{-1}	i) determination of the number of trials needed to attain stability of individual biomechanical parameters (for a robust description of individual

							peculiarities). ii) refinement of functional feedback process for coaches and physicians.
Preatoni et al. 2010b	K	4 M 3 F	40’56” – 48’34” (10 km)	8 cameras BTS 2002 system	100	20 trials: 10 stride $2.4 < s < 3.3$ m•s^{-1}	Analysis of the nature of movement variability and assessment of entropy estimated as a valuable and synthetic index of neuromuscular organization.
Hanley et al. 2011a	K	42 M 42 F	International	2 cameras in competition	50	1 trial: 1 stride (30) 4 trials: 1 stride (12) 4 m•s^{-1} M; 3.5 m•s^{-1} F	Kinematic analysis of elite men and women 20km race, and the influence of the distance on biomechanical variables.
Hanley et al. 2011b	K	42 M	International	2 cameras in competition	50	1 trial: 1 stride (30) 4 trials: 1 stride (12)	Kinematic analysis of elite men 50km race and the influence of the distance on biomechanical variables.
Padulo et al. 2013a	K	12	Elite	1 camera	210	9 trials: 400 steps; 3.61 – 3.89 – 4.16 m•s^{-1}; 0 – 2 – 7%	Effects of both speed and slope on SL, SF and CT during race walking.
Padulo et al 2013b	K	12 M	High level	1 camera	210	3 trials: 400 steps; 3.5 – 3.3 – 2.9 m•s^{-1}: 0 – 2 – 7%	Effect of slope on kinematic parameters and HR at iso-efficiency speed
Hanley & Bissas 2013	K, JPE	10 M 10 F	Elite	1 camera 2 force plates	100 100	3 trials: 1 stride	Measure and Analyse the lower limb joint moments and powers in elite international male and female race walkers
Payne 1978	GRF	1 M		1 force plate 3D		1 trial: 1 step; 4.7 m•s^{-1}	GFR as affected by sport regulation and its comparison with walking and running
Fenton 1984	GRF	6 M 1 F	Nationally ranked	1 force plate 3D	200	4 trials: 1 step; 3 – 3.35 – 3.8 – 4.5 m•s^{-1}	GRF analysis in race walking and its influence on technique.
Rodano & Santambrogi	GRF	6 M	National level	1 force plate 3D	1000	1 trial	Identify and compare typical biomechanical features associating with the athletic level

o 1987							
Preatoni et al. 2006	GRF, K, JPE	2 M 2 F	National level	8 cameras BTS2002 1 force plate 3D	100 500	17 trials: 1 step 2.85 m•s^{-1}	Analysis of kinematic and kinetics variables in race walking and comparison with normal walking
Witt & Gohlitz 2008	GRF	3 F	National level	force plate		20 strides	Examine the extent of different training on technique.
Cavagna & Franzetti 1981	JPE	8 M	National International	8 force platforms		5 – 15 trials each speed: 0.5 – 5.3 m•s^{-1}	Analysis of race walking lower speed dependency of energy expenditure, if compared to walking.
Marchetti et al. 1982	JPE	4		camera			Search for determinants of the race walking efficiency.
White & Winter 1985	JPE	1 M	National	1 camera with marker; 1 force plate	50; 500	3 trials: 1 step	Mechanical powers at hip, knee and ankle joint in race walking, normal walking and jogging.
Hoga et al. 2003	JPE	28 M	1:18’32” – 1:31’08” (20 km)	1 camera in competition	60	1 step	Mechanical energy flow in the “recovery leg” and its relationship with performance.
Hoga et al. 2006	JPE	12 M	40’52” – 48’50” (10 km)	1 camera; 1 force plate	250; 500	1 step	Joint kinetics and the mechanical energy flow in the support legs of skilled race walkers. Technical factors enhancing the energy flow and increasing walking speed.

Table I. The biomechanical studies of race walking partitioned according to the different analysis methodology: K kinematics; GRF ground reaction force; JPE joint power and efficiency.

Figure captions

Figure 1. Stride Length (SL, filled circles) and frequency (Sf, crosses) variation at increasing speed and their regression lines obtained by data present in literature (see text).

Figure 2. Ground Reaction Forces (GRF) pattern in the three axes (Fy vertical, Fx antero-posterior, Fz medial-lateral) expressed as body weight (BW) and normalise to stance phase are shown. The two different patterns emerging from literature (Cairns et al., 1986 vs. Fenton, 1984) are presented. The data were manually digitalised (Graphclick 3.0, Arizona Software).

Figure 3. Hip joint torque (upper panel), knee joint torque (middle panel) and ankle joint torque (lower panel) normalised using athletes' body mass (kg) and height (m), during the normalised support phase (heel strike to toe off). The extensor torque or dorsiflexor torque for the ankle is positive, whereas the flexor or plantarflexor torque is negative. Data were manually digitalised (Graphclick 3.0, Arizona Software) from White and Winter (1985) and Hanley and Bissas (2013) in order to show the joint torques pattern before (White & Winter) and after (Hanley & Bissas) the rule change.

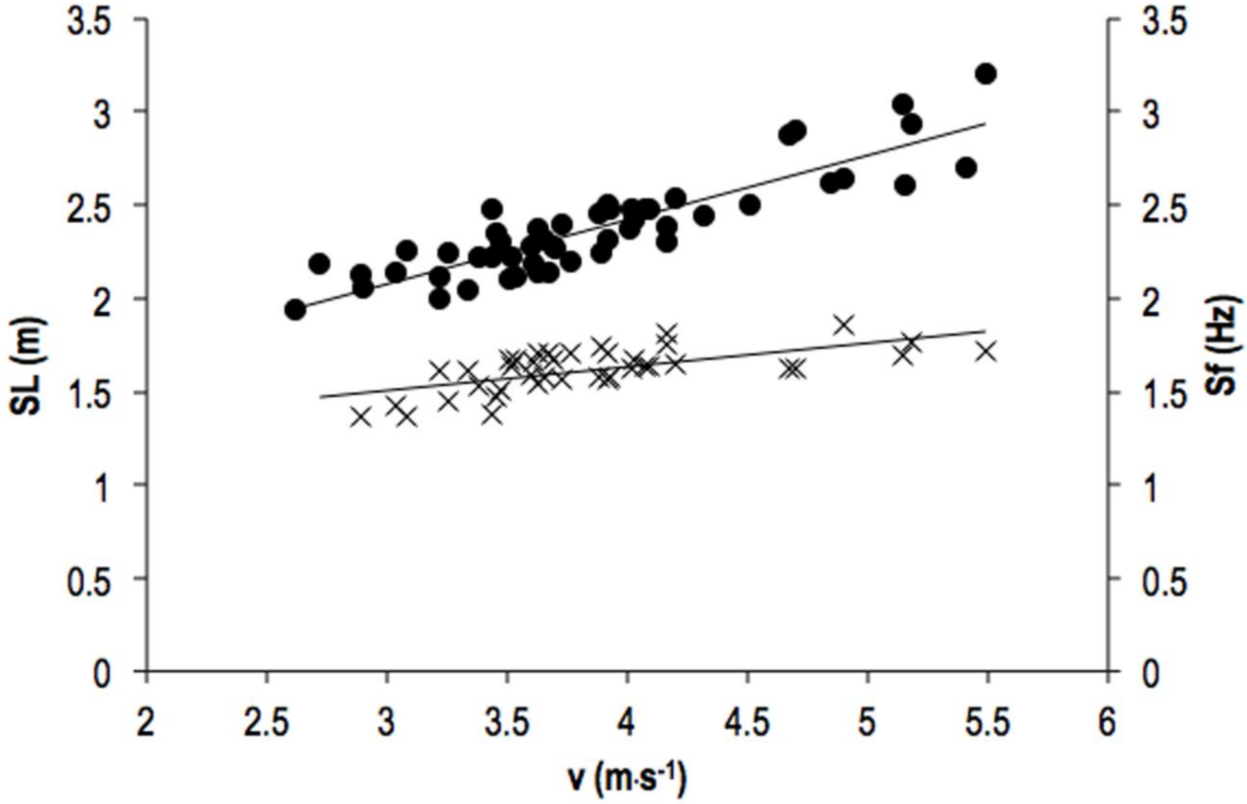

Figure 1.

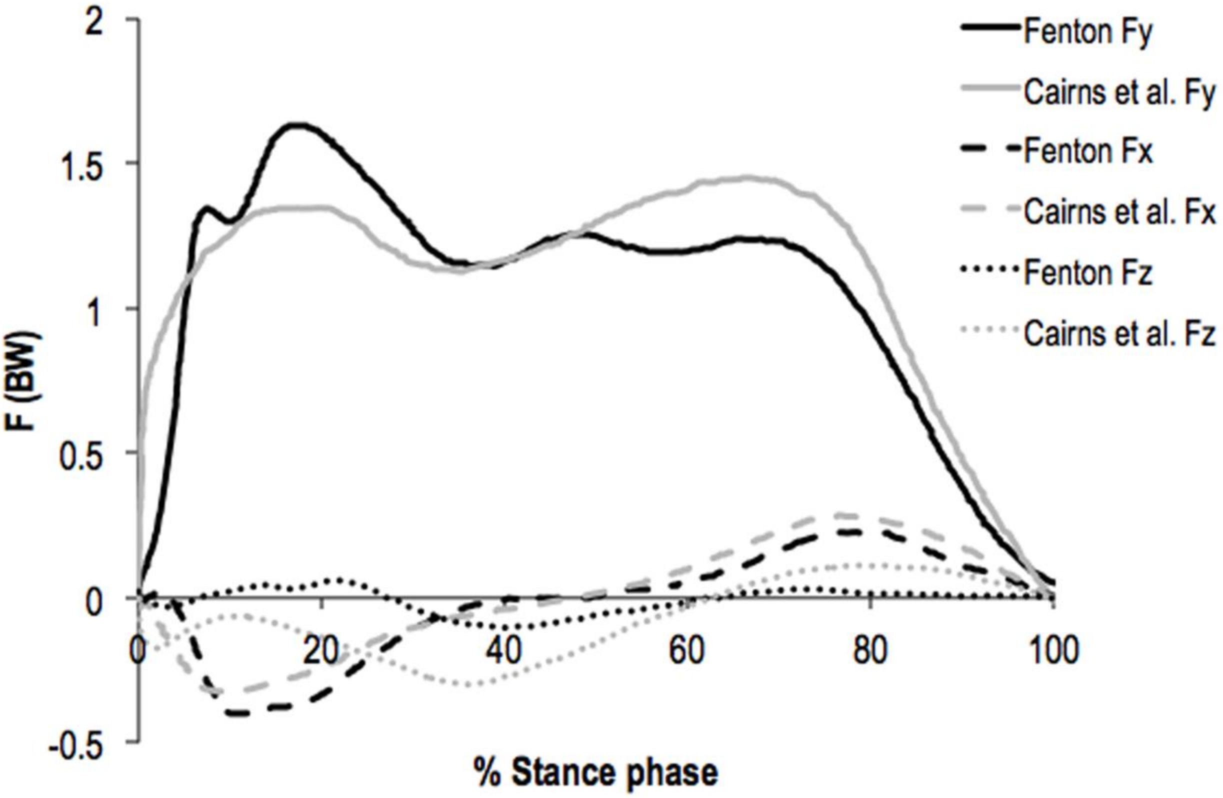

Figure 2.

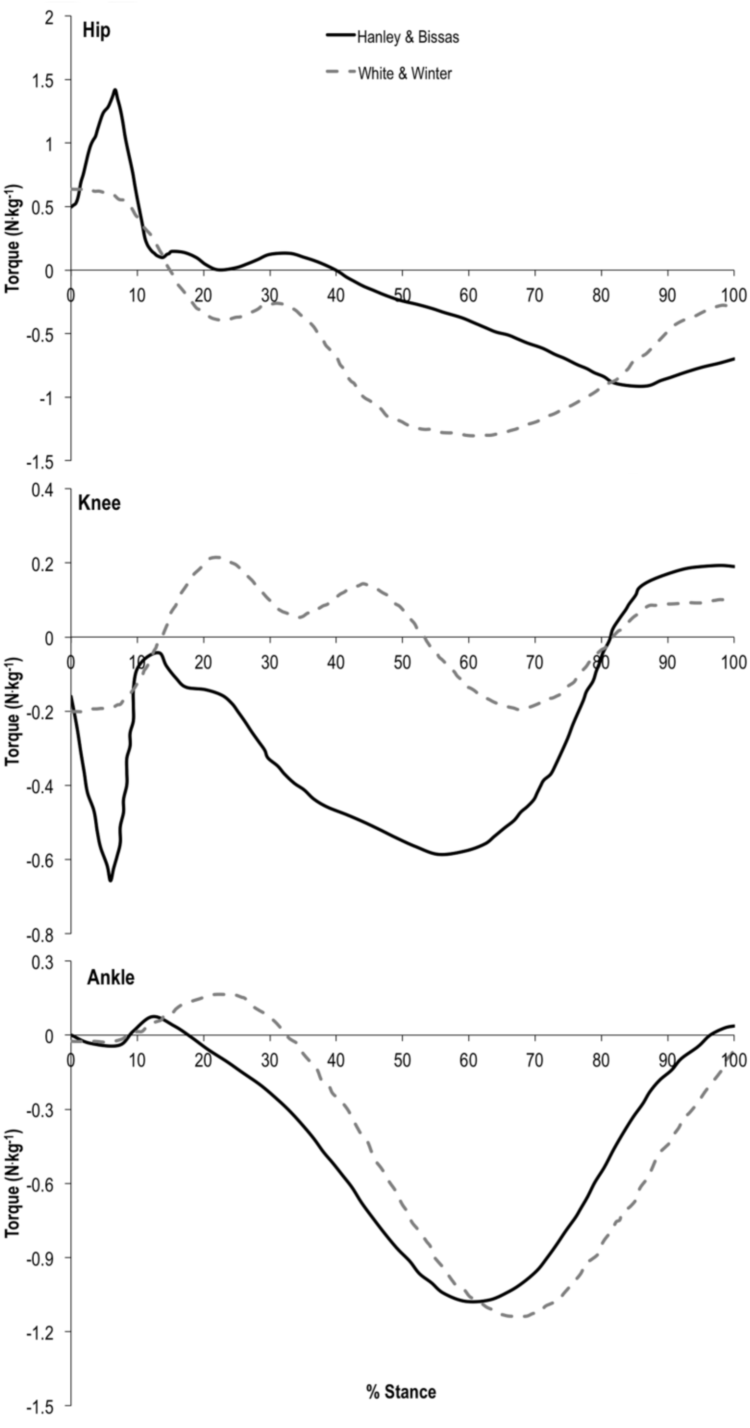
Hip
Hanley & Bissas
White & Winter
Torque (N·kg⁻¹)
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
10
20
30
40
50
60
70
80
90
100
Knee
Torque (N·kg⁻¹)
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
Ankle
Torque (N·kg⁻¹)
0.3
0
-0.3
-0.6
-0.9
-1.2
-1.5
% Stance

Figure 3.