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Development of a new experimental protocol for analysing the Race-walking technique based on kinematic and dynamic parameters

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Abstract

This paper describes a new motion analysis protocol for race-walking. The protocol has been tested under laboratory conditions on a real athlete of the Italian national race-walking team. The experimental setup included a motion capture system and a force platform to record both kinematic and dynamic aspects of the athletic action. Thus, any infringement of the rules can be detected, based on the measure of knee flexion-extension and the loss of ground contact. The biomechanical efficiency can be determined from the joint angles and the temporal components of gait. The results of experiments show that the protocol can be a valuable tool to assist athletes and trainers in improving race-walking technique.

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Keywords: Race-walking; Experimental protocol; Biomechanics; Kinematics; Dynamics; Motion Capturing; Gait Analysis

1. Introduction

Race-walking has a long history in international competitions. It became a permanent Olympic event in 1908 and has been included in the International Association of Athletics Federations (IAAF) World Championships since their creation in 1983 [1]. In this sport, more so than in any other athletic discipline, the technique is strictly determined by the rules of the competition. In particular, rule nr.230 states that "*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*" [2]. Before the introduction of such a formulation for that rule in 1995, the leg had to be straightened only in the vertical position. These locomotor constraints have forced athletes to develop a characteristic pattern widely recognized as 'race-walking style' [3]. Thus, they are highly focused on training drills specifically targeted to refine particular motor behaviours. All this makes race-walking a very technical discipline [4]. Even a small infringement of that rule on track may indeed result in disqualification of the athlete. The most common rule breach is the loss of ground contact (i.e. the flight phase) [1].

Forty-three nations from the five continents competed in race-walking at London 2012 Olympics. Despite being a worldwide discipline, in last three decades few scientific studies have investigated the race-walking. Some of them were published before 1995; hence, being based on the old rules, they cannot be fully relevant to the current analyses [3]. Moreover, few researchers [5–7] attempted to describe race-walking kinematics because of its peculiar characteristics and to investigate the technical factors that can influence the athletes' performance [4]. In this context, our studies focused on a new motion analysis protocol for race-walking aimed at improving the biomechanical efficiency and recognizing any infringement of IAAF competition rules.

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2. Materials and methods for race-walking protocol

The kinematics and dynamics of race-walking have been widely studied under laboratory conditions as well as during training sessions and real competitions [3, 4, 5]. The different patterns of race-walking can be roughly divided into primary and secondary movements. The first ones (which comprehend the phases of front support, rear support and thrust, swing and double support) are those that allow the body to move forward and thus involve lower limbs and pelvis. The second ones (*i.e.* the hip action, the arm movement, the positioning of the trunk and foot) involve mainly the trunk and the upper limbs and are necessary to counterbalance the primary movements. To develop a motion analysis protocol, the parameters (*cf.* section 2.3) that determine the athletic performance according to IAAF rules must be preliminarily identified through laboratory experiments.

2.1. Experimental set-up

The experimental activity was conducted at the Laboratory of Advanced Measures on Ergonomics and Shapes of the University of Naples Federico II. The laboratory includes an optical motion capture (MOCAP) system for kinematic analysis and a force platform for dynamic measures, both provided by BTS Spa, Italy. The first one (BTS SMART-DX 4000) is endowed with ten infrared digital cameras. In order to achieve the maximum image resolution their sampling frequency was limited to 340 Hz. The force platform system (BTS P-600) consists of eight integrated force platforms. Their sampling frequency was set to 680 Hz (maximum value). This system measured ground contact forces. Table 1 summarizes their technical characteristics.

Table 1. Data sheet of measurement systems.

MOCAP system		**Force platform system**	
Sensor resolution	2048×1088 pixel	Sensitive area for each sensor	600×400 mm
Acquisition frequency at maximum resolution	340 Hz	Capacity (X and Y) for each sensor	up to ±2000 N
Maximum acquisition frequency	2000 Hz	Capacity (Z) for each sensor	up to 2000 N
Accuracy	<0.1mm on a volume 4000×3000×3000 mm	Sensitivity deviation over plate surface	<1,0% full scale output

The two systems were synchronized with each other and were properly calibrated. At the end of the calibration process, the overall measurement volume resulted in 2.3×2.5×8.8 m (*cf. figure 1*) with a mean error of 0.3 mm.

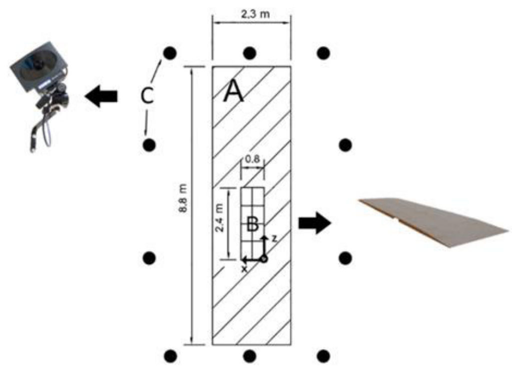

Fig. 1 The experimental setting of laboratory: the A zone shows the control volume, the B zone depicts eight integrated platforms of force, and the cape letter C indicates ten infrared digital cameras. The bottom right corner of the B zone matches with the origin of the laboratory reference system. Axes *z* and *x* show the anteroposterior direction and the medio-lateral direction, respectively; and the axis *y* (not visible since leaving the plane) indicates the vertical direction.

A 28-years old racewalker of Italian national team has been involved in the experiments. The athlete is a man, 166 cm tall, with body mass of 61 kg and centre-of-mass (CoM) at 101.7 cm from ground. He performed twenty test-runs, one test-run for each session.

The race-walker did a fifteen minutes warm-up before the first experimental session. At the beginning of each test run, he was requested to stand upright in order that the motion capture system could acquire the reference posture for his pelvis, hip, knee, elbow and ankle. Then, he race-walked on the force platforms inside the measurement volume for acquiring ten full strides of the right side and ten for the left one. In figure 2 some highlights of a race-walking test are shown.

Fig. 2 An example of race-walking run test.

2.2. The new motion analysis protocol for race-walking

The authors have adapted the well-known motion analysis protocol by Davis [8] to the study of race-walking. In particular, the number of anatomical sites observed has been increased. The Davis protocol, compared to those providing the same accuracy, limits the discomfort caused by optical markers attached to the skin, and makes the identification of anatomical reference points very easy. It is generally used for the analysis of walking with valid and reliable results. The standard marker-set includes twenty-two markers for the static acquisition and twenty-one for the gait.

However, for the purpose of the present study, eight more markers were added to measure also the flexion-extension of the biceps brachii muscle, which is an important parameter for the race-walking; the marker on the heel (which is only used for orthostatic acquisition in Davis protocol) was maintained even during the walking in order to achieve a more accurate estimation of step length.

In particular, four additional markers have been used for each side: two on the arm around the medial and lateral epicondyles of the humerus, and two on the forearm in correspondence to the radial and ulnar styloid. Figure 3 shows the postioning of markers on racewalker’s body (on the left) and the virtual reconstruction of the body (on the right).

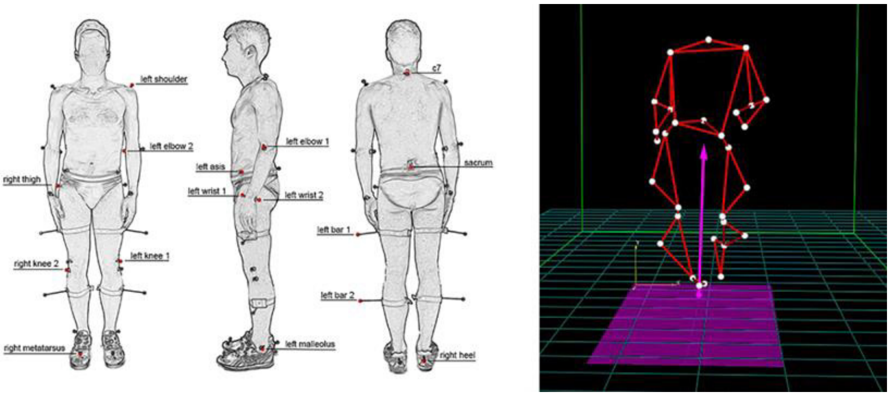

Fig. 3 Front, left side, back and virtual views of the markers-set used.

2.3. Data processing and analysis

Kinematic and dynamic signals were processed as follows. An interpolation of the third-order was applied to kinematic data for ensuring their continuity. In order to reduce the digital noise, data were filtered with a second-order Butterworth low-pass filter [9]. The cut-off frequency used is six-times the frequency of stride (*i.e.* 10 Hz).

CoMs of body segments were identified and evaluated according to the table by Zatsiorsky *et al.* [10, 11] with the correction of De Leva [12]. In order to estimate rotational angles between two adjacent body joints (*i.e.* elbow flexion, ankle dorsi-plantar flexion, knee flexion-extension, hip flexion-extension, pelvic tilt, pelvic obliquity, and pelvic rotation), we have adapted an algorithm (from Davis protocol) based on the evaluation of: (a) racewalker anthropometric data, (b) CoMs of body segments, (c) anatomical reference systems [8] and (d) Euler angles.

Ground contact forces (*i.e.* vertical, medial, lateral, anterior, and posterior) were obtained from dynamic data. A threshold of 5N was applied for reducing the digital noise. In order to decrease other noises caused by several potential artefacts (e.g. environmental, electrical, electronic, computer, physiological), dynamic signals were filtered with a smoothing filter under a triangular window.

The heel-strike and toe-off events were evaluated from dynamic signals. The heel-strike event is the stage in gait at which the heel of the foot first makes contact with the walking surface. The toe-off event is the final period of foot contact during stance phase that is preceded by forefoot loading and is followed by swing phase. Based on these temporal events, some components of gait were evaluated (*i.e.* the time of stride, stance, swing, and flight, the stride length and the cadence). In particular, the flight time was calculated as the time between the end of a step (*i.e.* the toe-off event) and the beginning of the next one (*i.e.* the heel-strike event). In addition, the speed of the race-walker was calculated as the derivative with respect to time variable of the signal of the sacral marker. The outcome is a vector of three components, to which was applied the modulus operator.

To evaluate the efficiency of the athletic performance the push-off angle and the attack angle were evaluated similarly to [4]. The push-off angle (POang) was defined as the position of the rear leg (pushing leg) at toe-off event. It was evaluated as the angle in the sagittal plane between two segments: the first one is defined by joining the CoM of whole body with the point located in the projection of the malleolus to the end of the rear support; the second one is the vertical axis passing through the same CoM. The attack angle (ATTang) was defined as the position of the front leg at heel strike event. It was obtained as the angle in the sagittal plane between two segments: the first one is defined by joining the CoM of whole body with the point located in the projection of the malleolus to the front support; the second one is the vertical axis passing through the same CoM. The last was calculated as the midpoint between the sacral marker and the origin of the reference system of the pelvis.

3. Results and discussion

The flexion-extension of the knee and the loss of ground contact were the main parameters considered to detect the most common infringements of the race-walking rules. The joint angles and the spatial-temporal parameters and the angles of attack and thrust (or push-off) were instead used to measure the biomechanical efficiency of the athletic action. It is understood that average values were considered to cope with the slight differences measured for the right and the left side of the body.

Among the diverse joint angles, the flexion-extension of the knee is broadly recognized as a crucial parameter to evaluate the compliance of the athletic action with the rules of the competition. For a correct execution, the knee joint must indeed remain extended from the moment of the first contact with the ground (heel-strike event) until the passing through the vertical position (mid-stance). This stage lasts as long as about 35% of the stance phase [13]. Several studies provide reference values for knee angles. Knicker and Loch in [14] consider knee joint as straightened for angles between -5° to 5°. Cairns et al. [5] define it as "*hyperextended*" for joint angles greater than -5°, while Hanley et al. [7] give the same definition for angles greater than 0°.

In real race conditions they have found values between -6° and + 6° at the heel-strike event and values between -17 ° and 3 ° at mid-stance. Figure 4 shows a trend curve for the flexion-extension of the knee consistent with the published literature, which highlights values at heel-strike of -0.5° and -3.4° at mid-stance.

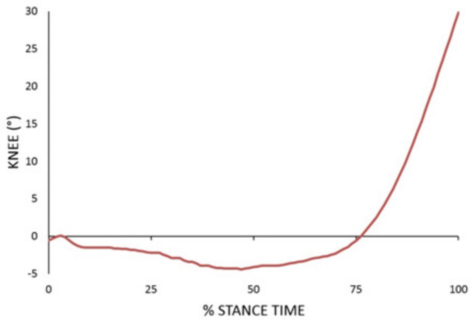

Fig. 4 Mean knee flexion-extension during the stance phase.

In particular, Preatoni *et al.* [15] conducted a study involving four national-level athletes (two males and two females) with a motion analysis protocol developed by Frigo [16]; Pavei and La Torre in [4] involved 15 athletes of different levels (regional, national and international) in a study of a twenty-markers protocol developed by Padulo *et al.* [17]. The curve of the knee flexion-extension showed in these studies is consistent with the ones depicted in figure 4.

The flight time resulted in 20ms with a standard deviation of 10ms. Other studies have also identified the loss of ground contact at different speeds both in training conditions [18] and in actual competitions [7]. This measure is crucial for the purposes of the present study because, as mentioned, a loss of contact visible to the human eye (i.e. a flight time of about 40ms [14, 18]) can result in disqualification of the athlete.

The angle of flexion-extension of the elbow was evaluated mainly for its strong visual impact in race. Hanley *et al.* [6] estimated values of 79°±9° at heel-strike event and 67°±7° at toe-off events; Pavei and La Torre [4] estimated values of 85.4°±11.5° and 99.3°±10.5° respectively.

In this study, we have estimated values of 83.3°±1.9° and 65.6°±1.0° respectively. This angle might influence the decisions of competition judges. The published literature seems not to properly consider this aspect and sometimes provides questionable values. The trend for the angle of flexion-extension seems to be affected by the 'race walker style' of each athlete. Several angles were evaluated at heel-strike and toe-off events. Table 2 shows a comparison between our results and the data provided by Pavei and La Torre [4] under similar speed conditions.

Table 2. Mean ± SD angles at heel-strike and toe-off events in the sagittal plane of motion are compared with Pavei and La Torre [4].

Joint angle	Present study		Pavei and La Torre in [4]	
	At heel-strike event	*At toe-off event*	*At heel-strike event*	*At toe-off event*
Ankle dorsi-plantar flexion	-4.5 ± 1.0	27.4 ± 0.5	-9.4 ± 3.2	25.4 ± 6.3
Knee flexion-extension	-0.5 ± 0.2	29.9 ± 3.8	-2.4 ±2.6	35.7 ± 5.1
Hip flexion-extension	21.8 ± 0.7	-14.4 ± 0.2	22.9 ± 6.1	-11.7 ± 6.8
Pelvic tilt	20.0 ± 0.6	19.2 ± 1.2	Not available	Not available
Pelvic obliquity	-8.8 ± 0.3	3.3 ± 0.1	-2.7 ± 2.3	0.4 ± 1.85
Pelvic rotation	5.7 ± 0.2	-8.1 ± 1.1	21.2 ± 3.9	-17.6 ± 4.0
Elbow flexion-extension	83.3 ± 1.9	65.6 ± 1.0	85.4 ± 11.5	99.3 ± 10.5
ATTang	15.3 ± 0.1	-	19.5 ± 1.4	-
POang	-	30.3 ± 0.2	-	24.8 ± 1.3

The values of the attack and push-off angles are also highlighted. These parameters are very interesting because they provide an immediate measure to evaluate the braking and the propulsive phases [4]. In facts, the technique used by race walkers to increase their speed involves high push-off angles and low attack angles.

Spatial-temporal parameters were obtained. Table 3 compares our outcomes with the ones provided by Cairns et al. and Pavei and La Torre [4, 5]. The stance time shows the highest deviation. This difference could be ascribed to the fact that our experimentation was conducted under laboratory conditions, while the experiments in [4] and [5] were carried out on treadmill and on the race track respectively.

Table 3. Comparison of spatial-temporal components of gait.

Component	Present study	Training racewalk by Cairns *et al.* 1986 [5]	Pavei and La Torre, 2015 [4]
Speed ($m \cdot s^{-1}$)	2.94 ± 0.02	2.89 ± 0.39	2.78
Cadence ($strides \cdot s^{-1}$)	1.53 ± 0.01	1.36 ± 0.09	1.37±0.05
Stride length (m)	1.98 ± 0.05	2.13 ± 0.26	2.02±0.08
Stride length/height ratio	1.19± 0.03	Not available	1.13
Stride time (s)	0.65 ± 0.01	0.78	0.73
Stance time (s)	0.29 ± 0.01	0.42 ± 0.06	0.40±0.03
Swing time (s)	0.36 ± 0.01	0.36 ± 0.04	0.33±0.01
Stance time/swing time ratio	0.81 ± 0.03	1.15 ± 0.22	1.21

Based on the recommendations for race-walking judges [19], some parameters characterizing an inefficient technique are:

- the interruption of the line “trunk-pelvis-pushing leg” (that it strictly related with push off angle);
- the lateral hip sway (that it strictly related with the obliquity pelvic);
- very short steps that have the effect to emphasize no loss of contact (that it strictly related with the stride length/height ratio).

The final step of our protocol is the evaluation of ground contact forces (figure 5). It is worth noticing that the characteristics of signals measured and the mean peak ground-reaction force values (see Table 4) are consistent with the ones in [5]. Despite the revision of rule nr. 230 in 1995, some researchers [15, 20] showed that the comparison with [5] is well founded.

Table 4. Comparison of mean peak ground reaction forces (× body weight) in stance.

Ground Reaction Force	Present study	Training racewalk by Cairns *et al.* 1986 [5]
Vertical	1.53 ± 0.03	1.48 ± 0.20
Anterior	0.23 ± 0.03	0.26 ± 0.04
Posterior	0.30 ± 0.02	0.36 ± 0.10
Medial	0.14 ± 0.02	0.14 ± 0.04
Lateral	0.09 ± 0.01	0.07 ± 0.05

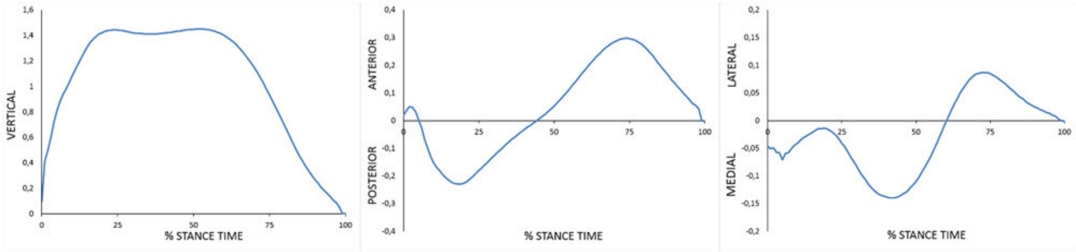

Fig. 5 Mean ground contact forces expressed as multiples of body weight and plotted as a percentage of stance time

4. Conclusions

In this paper, a new motion analysis protocol for race-walking has been illustrated. This protocol was tested on an Italian national team athlete under laboratory conditions. Data analysis concerned the evaluation of the knee flexion-extension and the loss of ground contact (*i.e.* the flight phase) for detecting infringements, and the estimation of push-off and attack angles, joint angles of pelvis, hip, ankle, elbow and, and temporal components of gait for assessing the biomechanical efficiency. Our results are quite consistent with other ones found in the specialized literature, even though they differ in methods and experimental protocols used. The motion analysis protocol developed can improve the knowledge of race-walking technique and could be a valuable tool to assist athletes in enhancing their performance and trainers in analysing motion characteristics.

Future research will involve a larger sample of athletes and will define a correlation between laboratory data and data collected “on the field", under real race-walking conditions.

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