Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 147 (2016) 544 – 549

Procedia Engineering

www.elsevier.com/locate/procedia

11th conference of the International Sports Engineering Association, ISEA 2016

Outdoor tests for the validation of an inertial system able to detect illegal steps in race-walking

Giuseppe Di Gironimo[a,*], Teodorico Caporaso[a], Giuseppe Amodeo[b], Domenico Maria Del Giudice[a], Antonio Lanzotti[a], Stephan Odenwald[b]

[a]*University of Naples Federico II – Fraunhofer JL IDEAS, DII, P.le Tecchio 80, Naples 80125, Italy*
[b]*Chemnitz University of Technology, Reichenhainer Str. 70, Chemnitz 09126, Germany*

Abstract

Aim of this study was to validate an inertial system able to detect the loss of ground contact (LOGC) in race-walking through outdoor tests in real training conditions. An inertial sensor was placed at L5/S1 of the vertebral column of a Italian national team athlete to acquire timing measurements of the LOGC. Data were encoded by a well-defined protocol. After a preliminary laboratory study, the athlete performed outdoor-field-tests at different velocities. A specific e-bike with a high-speed camera allowed to acquire a video and to validate sensor measurements. Results indicate that the inertial system can improve the accuracy in detecting the visible LOGC.

Peer-review under responsibility of the organizing committee of ISEA 2016

Keywords: **Race walking; loss of contact; inertial sensor; video analysis;outdoor test**

1. Introduction

Race-walking is a long-distance discipline, included in the athletics program of the Olympic Games since 1908. As defined by the rule 230 of Competition Rules 2014-15 of International Association of Athletics Federations (IAAF), "*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*" [1]. Not complying with the first part of this rule (no visible loss of contact) represents the most common violation at elite-level in this discipline, named loss of ground contact (LOGC). The LOGC is defined as the time between two temporal gait events, "toe off", i.e. the last toe-contact with the ground, and the following "heel strike", i.e. the first instant of heel contact with the ground, within a sequence step as shown in Fig.1.

During competitions, the control of the rule is committed to several judges present at the racing track. They can show to the race walker a yellow paddle (i.e. a caution) or they can give a red card (i.e. proposal for disqualification). The athlete is disqualified when three red cards are given from three judges. In the last World Championships in Beijing, approximately 60% of red cards were caused to a LOGC, in particular, with a peak of over 80% in the men's 20km race [2]. Many efforts have been made to evaluate the LOGC during the elite-racewalkers' training or competition. A video-analysis study on sixteen international-level athletes, including ten men and six women, during training sessions, has shown a range for LOGC values from 30ms up to 45ms (i.e. average speed from 12.0 km/h to 15.0 km/h) [3]. During the 25th World Race Walking Cup, in Saransk, Russia on May 2012, the LOGC was evaluated for medallists (both men and women) of the 20 km race-walk, and of the men's 50km race-walk. The LOGC value was equal to 50ms for the male in the 20 km race, to 30ms for the female in 20km race and to 40ms for male ones in 50km race; the average speed of 15.2, 13.2 and 13.9 km/h, respectively [4].

* Corresponding author. Tel.: "+39 0817682461" ; fax: +39 0817682470.
*E-mail address:*giuseppe.digironimo@unina.it

Peer-review under responsibility of the organizing committee of ISEA 2016
doi:10.1016/j.proeng.2016.06.236

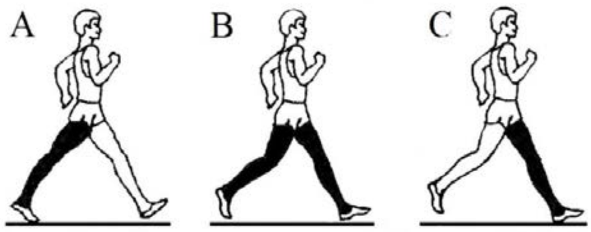

Fig. 1 –Temporal gait events: A) the toe-off and C) the heel-strike; B) shows a LOGC

It is worth noting that judges can rely only on subjective observations (i.e. by human eyes) and no technology is used to support their decisions. The short duration of gait events makes a proper identification of LOGC very difficult. Previous researches explain how people can perceive a movement in different ways [5, 6]. Experimental tests on professional athletes of a first-person shooter have found that for refresh rates over 30fps (i.e. about every 33ms) the visual perception of the human eye does not show significant improvements [5]. On the other hand, the examination of limits of the visual resolution in natural scene viewing [6] has shown that the detecting image for human eye did not occur for fixations below 100ms. In [7] researchers have studied the assessment of three judges about the race-walking technique. Each judge made 100 evaluations of step sequences in according to IAAF recommendation to give a red card only when the athlete continues to break the rules of race-walking, not only for a step. A long observation area of 30 m (i.e. about 30 steps) was defined. Actions of racewalkers were simultaneously filmed with a standard video camera at 200fps. The study indicates a difficulty in recognizing LOGC shorter than 50 ms.

Therefore, basing the control of the rule on a subjective human observation represents a critical point in race-walking discipline, especially thinking that an incorrect application can lead to the disqualification of the athlete. The aim of the present study is to validate an inertial system capable to detect the LOGC in accord with limits of the human eye.

2. Background

In a preliminary study [8] referring to device architecture, an inertial sensor was chosen, whose the conceptual design was conducted through the Kansei Engineering after the analysis of properties and characteristics of the device, required by race-walking experts (i.e. athletes, trainers and judges). During preliminary tests at the Laboratory of Advanced Measures on Ergonomics and Shapes of the University of Naples Federico II, inertial, dynamic and kinematic measures were collected. An elite race walker, member of Italian national team, to acquire timing measurements of LOGC, used an inertial sensor (i.e. the model type G-Sensor2, BTS) with a sampling frequency of 200Hz. The response of the sensor, which it was placed at L5/S1 of the vertebral column of the athlete, was encoded, processed and optimized by means of a well-defined protocol that concerns the filtering and the correlation between the acceleration and gait events. The validation of the sensor was made by eight integrated force platforms (i.e. model type P-600, BTS, sampling rate 680Hz). The study consisted of fifteen sessions; twenty-two valid steps were collected. The analysis considered 25Hz as the limit of the human eye. The dynamic system identified twenty-two LOGC, three of them evaluated as illegal. The inertial system identified 100% of the LOGC and the system reported an accuracy of 73% in the evaluation of steps.

3. Material and Methods

3.1. Experimental set-up

An athlete of Italian national team performed outdoor race-walking tests. The specific purpose of the experiment was to analyse LOGC events for long sequences of steps on paved road (in training conditions) at different walking speeds. LOGC values were firstly deduced from the kinematic study of the human centre of mass (CoM) by using an inertial system (i.e. the model type G-Sensor2, BTS) set at sampling frequency of 200Hz, ±8g for the tri-axis accelerometer, ±300gps for the tri-axis gyroscope sensor, and ±6 Gauss for the tri-axis magnetic sensor [9, 10]. The sensor was located at the bottom of athlete vertebral column in correspondence of the L5–S1 inter-vertebral space.

Acquired data were transmitted via Bluetooth to a laptop mounted on an electrical bicycle that accompanied the athlete during the test. It was provided with a motor system including a torque sensor that permits to obtain instant seamless power without noise, to follow the athlete at constant speed.

The e-bicycle was also equipped with a high-speed camera (i.e. the model type GoPro Black Hero4, Woodman Lab.) operating at 240fps with a resolution of 848x480 in 16:9, fixed on rear dropout and controlled remotely via wireless connection with a mobile device (i.e. the tablet, Samsung Galaxy Note 2014 Edition) positioned on the handlebars. The high-speed camera video of the athlete's performance allowed evaluating a precise visual assessment of the LOGC. Finally, a webcam (i.e. the model type HD C310, Logitech International S.A, resolution of 320x240 at 30 Hz) was connected with the laptop and fixed on the e-bike carrier (with the optical axes parallel to the one of the high-speed camera) in order to obtain a video of the race-walking, synchronized with data of the inertial system. The race-walker was also equipped with a GPS watch (i.e. the model type Forerunner 305, Garmin) with heart rate monitor.

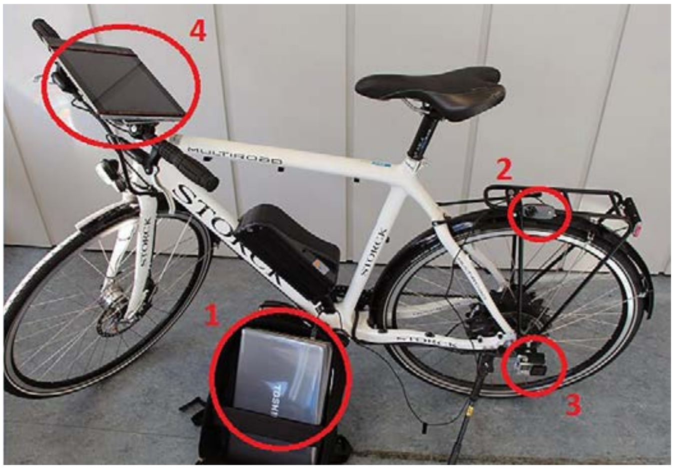

Fig.2 Data collection setting: 1) the laptop with software for acquisition of inertial data and the USB Bluetooth; 2) the webcam; 3) the high-speed camera; 4) the tablet

3.2. Test protocol

Tests were performed near the Chemnitz University of Technology campus on a long paved road, straight and flat in according to recommendations of the IAAF about race walking courses [11]. After a standard twenty minutes warm-up routine, the athlete performed four tests of three-hundred meters race-walking each, at four different speeds (i.e. mean values of 12.0, 12.9, 13.7, 14.6 km/h that represent, respectively, the 93%, 100%, 106% and 113% of the athlete's racing pace (RP)). By means of the GPS watch, the athlete controlled the performance and tried to keep a mostly constant speed during the test. A rest time of 90s between two consecutive tests allowed the athlete to recover completely. It was controlled that the athlete's heart rate before each test was less than 60% of his theoretical maximum heart rate [12]. At the beginning of each test, the athlete has kept an orthostatic position in order to calculate the offset error of the inertial sensor. The Fig.3 shows highlights of the race-walking technique during tests.

Fig. 3 – In the sequence: 1) the heel-strike event, 2) the midstance phase, 3) the start of propulsive action, 4) the toe-off event

3.3. Data processing

After the offset error correction, acceleration data of the inertial sensor were converted from device-based units to meters per square second. A fourth order Butterworth low pass filter was applied with a cut-off frequency of 20Hz for x-axis (i.e. the vertical acceleration of CoM) and 30Hz for z-axis (i.e. the anterior-posterior acceleration of CoM) according to [13] that used for the similar application a low pass filter at 20Hz. The filtering allowed identifying gait temporal events. Over the 70% of the signal is lower the cut-off frequency, as shown in Fig.4a. In order to delete the phase shift, signals were filtered two times (in both the directions, Fig.4.b). From the inertial sensor, LOGC was calculated as the time difference between the minimum of the vertical component of the CoM acceleration and the consecutive peak of anterior-posterior acceleration, that corresponding to the heel-strike event [14], minus a threshold, which fixed to three hundredths of a second in the literature [13,15], as shown in Fig.5.

From high-speed camera data, LOGC was evaluated through video analysis tools (i.e. Kinovea© software, by Joan Charmant&Contrib.) as the time difference between the frame of the toe-off event and the following frame at the heel-strike event. The comparison between the webcam and the high-speed camera data allowed associating LOGC of the inertial sensor with the correspondent LOGC event on the high-speed camera video.

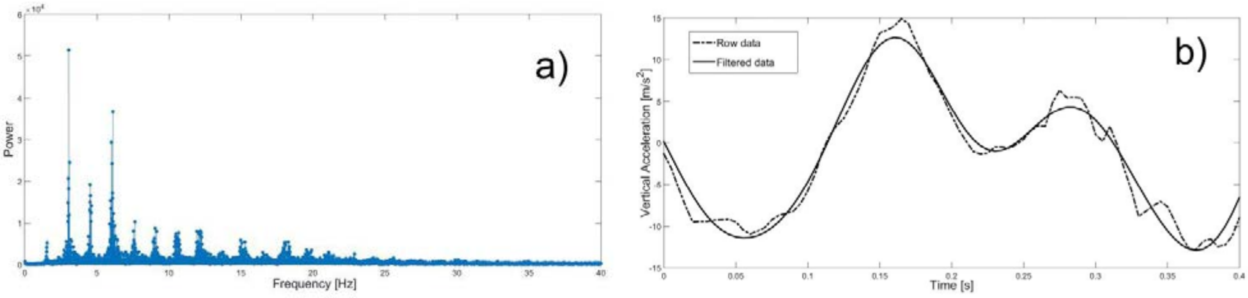

Fig. 4 – In (a) the power spectrum for accelerations on the x-axis; in (b) the comparison between the vertical acceleration based on raw data and the one two-times filtered.

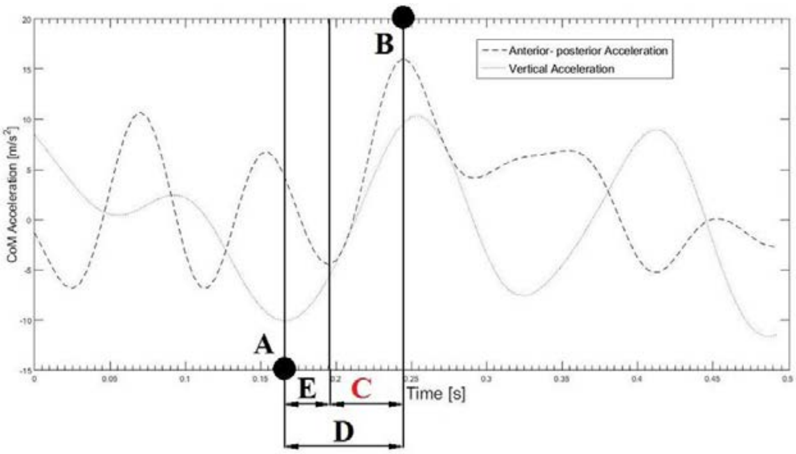

Fig.5 Vertical and anterior-posterior accelerations of CoM versus time in a typical test: A) the minimum value of the vertical acceleration; B) the hell-strike event; C) the LOGC; D) the time between A and B; E) the threshold time.

Afterwards all steps were classified as 'legal' or 'illegal' according to the IAAF rule. The step was identified as 'legal' when the corresponding value of LOGC was under the human eye limit (i.e. no visible LOGC) and as 'illegal' when the corresponding value of LOGC was over the human eye limit (i.e. the visible LOGC). In this study, the human eye limit was defined as 25Hz, (i.e. 0.04s), according to specialized literature [3, 7]. It was also possible that the LOGC did not occurs (i.e. the LOGC value equal or minor to 0). This case was indicated as double support.

4. Results and discussion

A total amount of 720 athlete's steps were evaluated. For each race-walking test and excluding the initial acceleration phase of the athlete, 180 consecutive steps were considered. For each step, the LOGC value was evaluated both by the inertial sensor (named $LOGC_I$) and by the high-speed camera (named $LOGC_C$). Table 1 shows the total number of cases, mean values with standard deviations of $LOGC_I$ and $LOCG_C$ stratified for four different test RP. In the last column, there is the mean difference between $LOGC_I$ and $LOCG_C$ with standard deviation.

Table 1. LOGC data collected during trials.

RP (%)	Cases of $LOGC_I$	$LOGC_I$ (ms)	Cases of $LOGC_C$	$LOGC_C$ (ms)	Mean difference (ms)
93	180	35±10	179	17±8	20±10
100	176	40±10	180	29±8	10±15
106	180	45±15	180	37±8	10±15
113	178	45±15	180	41±8	5±20

Of 720 steps analysed by the camera, 719 steps were characterized by a LOGC event. Only one-step was a double support. The inertial system allowed identifying correctly the 99% of LOGC events, with seven errors (i.e. six LOGC classified as double support and one double support classified as LOGC). Both $LOGC_I$ and $LOGC_C$ duration were directly proportional to the test speed. This correlation is consistent with the literature [3].

The mean difference appears to decrease when RP increases: it takes the highest value to the lowest speed (i.e. 20ms at RP of 93%); then, it takes the lowest value to the highest speed (i.e. 5ms at RP of 113%). This result may be due to the threshold value set in accordance with [13]. However, such threshold should be expressed as a variable depending on the speed.

As mentioned above (*cf.* section 3.3) each step was classified as legal or illegal according to the inertial sensor data ($LOGC_I$) and to the camera data ($LOGC_C$). For the derived step classifications a contingency table was carried out for each trials and reported in Table 2. The two-way table if it is read for rows depicts illegal and legal cases recorded by the high-speed camera; instead, if it is read for columns represents illegal and legal cases viewed from inertial system.

Table 2. Steps' classification according to contingency table for the trials at RP equal to 93%, 100%, 106% and 113%.

RP 93%	Legal inertial system	Illegal inertial system	Sum
Legal high-speed camera	155	25	180
Illegal high-speed camera	0	0	0
Sum	155	25	180
RP 100%			
Legal high-speed camera	131	43	174
Illegal high-speed camera	2	4	6
Sum	133	47	180
RP 106%			
Legal high-speed camera	78	69	147
Illegal high-speed camera	13	20	33
Sum	91	89	180
RP 113%			
Legal high-speed camera	34	39	73
Illegal high-speed camera	57	50	107
Sum	91	89	180

Starting from the data in table 2, and assuming as "true" the high speed camera classification the false alarm rate, the miss alarm rate and the accuracy were obtained (Table 3). The false alarm rate is the proportion of high-speed camera legal cases that are predicted illegal from inertial system. The miss alarm rate is the proportion of high-speed camera illegal cases that occur as predicted legal from inertial system. The accuracy is the proportion of true results (both true legal and true illegals) among the total cases observed.

Table 3. Statistical errors and accuracy of the inertial system classification compared to the high speed camera classification for RPs.

	RP= 93%	*RP= 100%*	*RP= 106%*	*RP= 113%*
False Alarm	14%	25%	47%	53%
Miss Alarm	0%	33%	39%	53%
Accuracy	86%	75%	55%	47%

Table 3 shown a decreasing trend of the accuracy rate with the respect to the trials speed (Accuracy > 75%, RP ⩽ 100%; Accuracy < 55%, RP > 100%). The frequency of miss alarm and false alarm with the respect of test speed (both increasing to 53% for the highest speed) confirmed previous findings. It is worth noting that at lowest speeds (RP ⩽ 100%) illegal steps are very unusual (e.g. zero cases at RP of 93%) as also recognized in other studies [3,16]. Moreover, accuracy values provide a good classification of legal steps. On the other hand, tests at highest speeds (RP > 100%) showing illegal steps, have allowed a complete assessment of the inertial system as effective classifier. Results indicated that the correct characterization of the athlete's steps represents a critical point for the inertial sensor when the LOGC values were near to the human eye limit (despite a more accurate LOGC assessment).

It must be said that the correct analysis within a range of RP extended around the value of 100% is important since these paces are functional both in the construction of the training programs that during the race (*viz.* the change of pace for advantage over their rivals in the race).

Finally, identifying for each of our tests six step sequences (each one consisting of 30 steps) and evaluating the mean value of $LOGC_I$ and $LOCG_C$, the following results were obtained:

Table 4 Step sequences classification according to contingency table and statistics.

	Legal inertial system	Illegal inertial system	Sum	Statistics	
Legal high-speed camera	13	5	18	False Alarm	28%
Illegal high-speed camera	0	6	6	Miss Alarm	0%
Sum	13	11	24	Accuracy	79%

Analysing data about judges evaluations [7] with our method of classification, judges achieved the following accuracy rate: 73%, 68% and 54% (i.e. the mean value of 65%). Therefore, in a similar experiment, the inertial system seems to get higher values of accuracy despite a more strict classification of step sequences legal, i.e. LOGC $\leq$ 40ms vs LOGC < 50ms. However, further studies on the evaluation accuracy by judges are required to assess a specific target to the accuracy needed.

5. Conclusion

Results obtained agree with values achieved in laboratory tests. Both studies confirm that an inertial system could represent a useful tool for the LOGC judgment during race-walking competitions. In particular, the inertial sensor together with the proposed data analysis protocol represents a valuable tool to identify legal steps in race-walking training session at low speed (at these speeds we have seen that illegal steps are very unusual). Furthermore at greater speed (where occurred a large number of illegal steps) the error in assessing the LOGC value appears to be small, but the accuracy is lower (<55%). Finally, the step sequence analysis shows that the classifier performance is encouraging to help coaches in the training session and judges in monitoring race-walking competitions. Further developments will be centred on testing with a greater number of athletes with different anthropometric characteristics and also in race conditions; designing a sensor data fusion algorithm to correct accelerations data according to the body orientation and to improve the LOGC measure; and introducing a correlation between the threshold adopted for the LOGC assessment and the athlete speed.

6. Acknowledgements

The authors would like to thank the anonymous reviewers for their precious suggestions. This study was partially funded by the Italian D.M. n°976 of the 29.12.2014, Int. agr. TUC and FII (for the mobility of university students for studies of research). This work was also supported by the State of Saxony (European Social Fund ESF).

7. References

[1] International Association of Athletics Federations. IAAF, Competition Rules 2016–2017. Imprimerie Multiprint: Monaco: Principality of Monaco, 2013,Web access on 10January 2016. <http://www.iaaf.org/about-iaaf/documents/rules-regulations>.

[2] Timetable/results of 15th IAAF World Championships in Beijing (National Stadium)PR of China, 22–30 aug. 2015,Web access on 10 January 2016.<http://www.iaaf.org/competitions/iaaf-world-championships/15th-iaaf-world-championships-4875/timetable/byday>.

[3] DeAngelis M., Menchinelli C. "Times of flight, frequency and length of stride in racewalking". Proceedings of the X International Symposium of Biomechanics in Sports; Milan: 1992

[4] Hanley B, "A Biomechanical Analysis of World-Class Senior and Junior Race Walkers". New Studies in Athletics 2013; 28 (1/2): 75-82.

[5] Claypool M, Claypool K, Damaab F. "The Effects of Frame Rate and Resolution on Users Playing First Person Shooter Games." In Proceedings of ACM/SPIE Multimedia Computing and Networking Conference. International Society for Optical Engineering; San Jose:2006.

[6] Loschky L.C., McConkie G.W., Yang J, Miller M.E. "The limits of visual resolution in natural scene viewing. Visual Cognition 2005;12(6): 1057-1092. DOI:10.1080/13506280444000652

[7] Knicker A., Loch M. "Race walking technique and judging – The final report of the International Athletic Foundation research project." New Studies in Athletics 1990; 5(3): 25-38

[8] Di Gironimo, G., Caporaso T., Del Giudce D.M., Lanzotti A. "Validation of an Electronic Device to Control Loss of Ground Contact in Race-Walking", in proceedings of Virtual Concept International Workshop on MAJOR TRENDS IN MECHANICAL DESIGN (Bordeaux, March 2016).

[9] Zijlstra W, Hof L." Assessment of spatio-temporal gait parameters from trunk accelerations during human walking." Gait & Posture 2003; 18(2): 1–10

[10] Wixted A.J., Billing D.C., James D.J. "Validation of trunk mounted inertial sensors for analyzing running biomechanics under field conditions, using synchronously collected foot contact data." Sports Engineering 2010; 12(4):207–212

[11] IAAF. The judging of Race Walking and the organization of a Race Walking event. A guide for judges, officials, coaches and athletes. 5th Edition ,2006.

[12] Benson R, Connolly D. "Heart Rate Training." Champaign: Human Kinetics; 2011. p.10-12.

[13] Lee J.B., Mellifont R.B., Burkett B.J., James D.A. "Detection of illegal race walking: a tool to assist coaching and judging." Sensors 2013; 13(12): 16065-16074

[14] Kavanagh J.J, Menz H.B. Accelerometry: A technique for quantifying movement patterns during walking. , Gait & Posture 2008; 28(1): 1–15

[15] Little C, Lee J.B, James D.A., Davison K. An evaluation of inertial sensor technology in the discrimination of human gait. Journal of Sports Sciences 2013; 31(12): 1312-1318

[16] Cazzola D., Pavei G., Preatoni E. "Can coordination variability identify performance factors and skill level in competitive sport? The case of race walking." Journal of Sport and Health Science, 2016 - Elsevier