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ORIGINAL ARTICLE

Biomechanical indices represented on radar chart for assessment of performance and infringements in elite race-walkers

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Abstract

Nowadays, technology in sport plays an important role to help training and judgement processes. This study proposes the use of a wearable inertial system to derive novel biomechanical indices for the assessment of performance and infringements in race-walking. These indices are built from five inertial-based parameters: loss of ground contact time, loss of ground contact step classification, step length ratio, step cadence and smoothness. The biomechanical indices are customized for elite race-walkers, and represented on a radar chart for an intuitive analysis of performance and infringements. From the radar chart, a synthetic index regarding the athlete's overall gesture is derived. The validation of the biomechanical indices is carried out in field tests, involving nine elite race-walkers wearing an inertial sensor located at the end of the column vertebra (L5–S1). A statistical analysis is used to determinate the quality and reliability of the proposed indices and of their representation. The results show that these biomechanical indices can be implemented on a wearable inertial system for assistance in training and judgement in race-walking.

Keywords Race-walking · Performance · Infringements · Biomechanics · Graphical data analysis · Field tests · Wearable sensors

1 Introduction

Race-walking, born in Great Britain in the sixteenth century, is a discipline part of athletics sporting events. Two possible infringements exist in race-walking according to the rule 230 of IAAF Competition rules [1]: "bent knee" and "Loss Of Ground Contact" (LOGC).

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During competitions, the current practice is to entrust the infringements to the subjective human observations made by judges, relying solely on their eyesight. However, the short duration of the LOGC events (in the order of few hundredths of a second [2]), generates difficulties in their correct identification, due to human physiological limitations of vision [3]. For this reason, the judgements are often based also on biomechanics patterns (e.g., excessive knee lift [4]).

Referring to performances, the literature underlines the relationship between performance and kinematic parameters amongst race-walkers. In [5], the authors pool together data from eleven different studies, showing a linear descriptive equation between the step cadence, step length and the race-walking speed. Another important parameter is the smoothness of the center of mass (CoM), which is related to the time derivative of acceleration. In race-walking, the smoothness on the anterior–posterior axes also relates to the ground reaction force, which could discriminate the "fluidity" of the athlete. The latter provides a measure of the braking related with the maximum anterior–posterior deceleration [5].

The assessment of both performance and infringements in race-walking is possible under laboratory or field test conditions. In laboratory conditions (with a treadmill [6] and without a treadmill [3]), previous authors have studied performance and infringements through accurate instrumentations (i.e., motion capture and force platform systems). However, field data represent the benchmark for the analysis of the gesture; indeed, field tests allow us to study the gesture with the real ground interaction. Field tests allow for collecting a larger number of steps, with varying walking speeds. In the field test scenario, the critical points are due to the limitations of the available instrumentation devices as well as to the quality of the data and the more variable conditions.

For the evaluation of infringements in field conditions, past works have presented different solutions. In [7], the authors proposed a system consisting of a pair of insoles with piezoelectric sensor to identify gait temporal events, and consequently LOGC. An inertial sensor can be used for the non-direct assessment of gait temporal events [8, 9]. Recently, the authors in [10] have proposed the use of two inertial sensors placed on the shanks for the evaluation of both infringements: LOGC and bent knee.

From the other side, i.e., evaluation of performance in field conditions, researchers have used high-speed cameras [2]. Video analysis provides reliable results and allows the evaluation of kinematic parameters. However, video analysis can be time-consuming and difficult to use in real conditions (e.g., competitions), where a real-time assessment of performance and infringements is required. Thus, the use of a wearable inertial system could be preferable. As examples, in different sports, wearable inertial systems have been used to estimate performance, as in running [11] and skiing [12].

In summary, the race-walking context lacks simple tools that are able to estimate, in real time and simultaneously, parameters related to infringements and performance of the athletes. To fill this gap, this study proposes: (1) the use of a wearable inertial sensor system for measuring meaningful parameters related to infringements and performance; (2) a methodology for assessment of performance and infringements based on biomechanical indices customized for elite race-walkers; (3) a radar chart representation of the biomechanical indices useful for a quick evaluation of performance and infringements in typical training or competition scenarios. The results of this paper are validated in outdoor experiments involving nine elite race-walkers.

2 Methodology

This section describes the development of the biomechanical indices and their representation on a radar chart, as assessed during the pilot tests (cf. Sect. 3.2). The biomechanical indices can be obtained during race-walking field tests using a wearable inertial sensor located at the end of the column vertebra. The inertial sensor should have the following features: (1) sample frequency at of least 200 Hz, to achieve a good assessment of performance and infringement parameters; (2) small volume and light weight (no bigger in size than a typical sport wearable devices, such as a wrist watch, i.e., about 60 cm^3 in volume and 70 g in weight [13]), to guarantee the athlete's comfort.

2.1 Assessment of parameters for infringements and performance

The biomechanical indices are based on the following kinematic parameters obtained from the inertial system: (1) the approximated LOGC timing (referred to as $LOGC_{T,a}$); (2) the LOGC with the step classification ($LOGC_C$); (3) the smoothness for anterior–posterior linear movement (S); (4) the step cadence (SC); (5) the step length ratio over athlete's height ratio (SLR). The first two parameters are connected with infringements, while the last three with performance. According to the International Association of Athletics Federations (IAAF) recommendations, the judgements must consider a sequence of steps, such that all parameters are related to the mean values of a sequence of 30 steps [1].

The $LOGC_{T,a}$ is an approximated value for estimating the LOGC timing. $LOGC_{T,a}$ is defined as the time interval after which it is possible to consider that the "flight is deemed to have occurred", as described in [8]. Therefore, it is not strictly defined as "the duration of loss of ground contact". Thus, according to [8, 14], the $LOGC_{T,a}$ is carried out starting from the definition of the heel strike event (seen on the anterior–posterior acceleration profile, occurring at the temporal instant t_{max}) and the bottom point in vertical acceleration (occurring at the temporal instant t_{min}) as:

$$LOGC_{T,a} = \frac{1}{30}\sum_{i=1}^{30}\left(t_{max_{i+1}} - t_{min_i} - E\right), \quad (1)$$

where E is a threshold value which is fixed to three hundredths of a second [8].

For the assessment of $LOGC_C$, each step i was classified as "legal" or "illegal" according to the classification proposed in [3], as:

$$\begin{cases} LOGC_{T,a_i} > 40\,\text{ms} & \text{Illegal step} \\ LOGC_{T,a_i} \leq 40\,\text{ms} & \text{Legal step.} \end{cases} \quad (2)$$

Therefore, the $LOGC_C$ for each sequence of steps is fixed equal to:

$$LOGC_C = \frac{\text{Illegal steps}}{30}. \quad (3)$$

Based again on the definition of the heel strike event seen in anterior–posterior acceleration, the SC and SLR are computed as:

$$SC = \frac{1}{30}\sum_{i=1}^{30}\frac{1}{t_{\max_{i+1}} - t_{\max_i}}, \quad (4)$$

$$SLR = \frac{1}{30}\sum_{i=1}^{30}\frac{v_{\text{mean}}}{h}(t_{\max_{i+1}} - t_{\max_i}), \quad (5)$$

where v_{mean} is the mean test speed and h is the athlete's height.

Finally, the smoothness parameter S is evaluated using the normal jerk according to [15] through the following equation:

$$S = \frac{1}{30}\sum_{i=1}^{30}\sqrt{\frac{(t_{\max_{i+1}} - t_{\max_i})^5}{(v_{\text{mean}}(t_{\max_{i+1}} - t_{\max_i}))^2}\int_{t_{\max_i}}^{t_{\max_{i+1}}} j^2(t)\mathrm{d}t}, \quad (6)$$

where $j(t)$ is the jerk related to the anterior–posterior acceleration.

2.2 Biomechanical indices and radar chart representation

The previously defined five parameters are normalized such that each one assumes a value between 0 (best score) and 1 (worst score).

For the normalization of $LOGC_{T,a}$, the index δ is defined as:

$$\delta = \begin{cases} \delta = 0 & LOGC_{T,a} \leq (LHE - \frac{2}{f}) \\ \delta = 0.4 & LOGC_{T,a} = LHE, \end{cases} \quad (7)$$

where f is the sample frequency of the inertial device (defined as $f = 1/T_s$, where T_s the sample timing) and LHE is the limit threshold for the human eye fixed equal to 40 ms [3]. Then, a linear equation between $\delta = 0$ and $\delta = 0.4$ is constructed, such that the following system equations are used to describe δ:

$$\delta = \begin{cases} \delta = 0 & LOGC_{T,a} \leq \left(LHE - \frac{2}{f}\right) \\ \delta = \frac{1}{40-\frac{5}{f}} \cdot \left(LOGC_{T,a} - \left(40 - \frac{2}{f}\right)\right) & \left(LHE - \frac{2}{f}\right) > LOGC_{T,a} > \left(LHE + \frac{3}{f}\right) \\ \delta = 1 & LOGC_{T,a} \geq \left(LHE + \frac{3}{f}\right). \end{cases} \quad (8)$$

Instead, the parameter $LOGC_C$ is just defined in the range between 0 and 1, and the corresponding biomechanical index is called α:

$$\alpha = LOGC_C. \quad (9)$$

For the normalization of SLR and SC, the linear regressions presented in [2] and [5] are used; from these, using elite competition data, the following equations are derived:

$$SLR = 2.47v + 32.73, \quad (10)$$

$$SC = 0.259v + 2.253, \quad (11)$$

where v is the race-walker's speed expressed as [km/h] in (10) and as [m/s] in (11). From (10) and (11), the optimal value ($SLR_{\rho=0}$) and the one which is border line ($SLR_{\rho=0.4}$) are obtained for all types of race competitions:

$$\begin{cases} SLR_{\rho=0.4} & \text{with } v = v_E \\ SLR_{\rho=0} & \text{with } v = v_R, \end{cases} \quad (12)$$

$$\begin{cases} SC_{\gamma=0.4} & \text{with } v = v_E \\ SC_{\gamma=0} & \text{with } v = v_R, \end{cases} \quad (13)$$

where v_E is the speed of the entry standard time for the last World Championship for the 50 km male competition ($v_E = 12.20$ km/h; 3.39 m/s) and v_R is the speed of the world record for the 20 km male competition ($v_R = 15.76$ km/h; 4.38 m/s). These values are chosen to cover speeds of interest. Notice that speeds in the equations are expressed in (km/h) for the Eqs. (10, 12) and in (m/s) for Eqs. (11, 13). Consequently, $SLR_{\rho=0.4}$ and $SLR_{\rho=0}$ are set equal to 62.8 and 71.4; $SC_{\gamma=0.4}$ and $SC_{\gamma=0}$ equal to 3.13 step/s and 3.38 step/s respectively. Finally, the indices ρ and γ from the values of SRL and SC are defined as:

$$\rho = \begin{cases} \rho = 1 & SLR \leq (-1.5 \cdot SLR_{\rho=0} + 2.5 \cdot SLR_{\rho=0.4}) \\ \rho = -0.4\,\frac{SLR - SLR_{\rho=0.4}}{SLR_{\rho=0} - SLR_{\rho=0.4}} + 0.4 & \\ \rho = 0 & SLR \geq SLR_{\rho=0}, \end{cases} \quad (14)$$

$$\gamma = \begin{cases} \gamma = 1 & SC \leq (-1.5 \cdot SC_{\gamma=0} + 2.5 \cdot SC_{\gamma=0.4}) \\ \gamma = -0.4\,\frac{SC - SC_{\gamma=0.4}}{SC_{\gamma=0} - SC_{\gamma=0.4}} + 0.4 & \\ \gamma = 0 & SC \geq SC_{\gamma=0}. \end{cases} \quad (15)$$

For the normalization of the smoothness parameter S, a correlation equation where $S_{\min}$ is set equal to 1 (ideal value of smoothness) and $S_{\max}$ is fixed equal to 10 (since no references are provided) is applied; therefore, the normalization parameter μ is defined as:

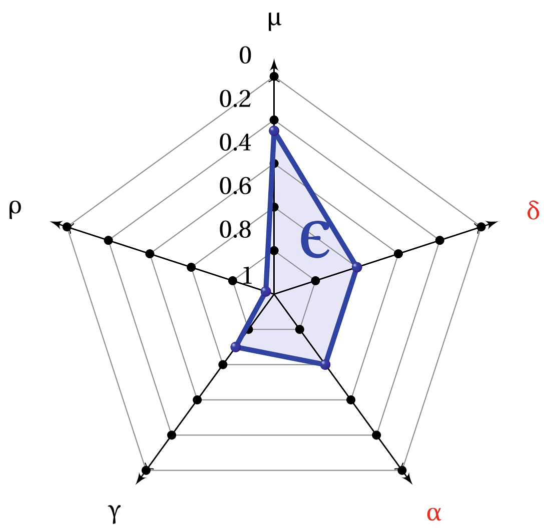

Fig. 1 Radar chart representation of biomechanical indices for race-walking. The red indices are related to infringements, the black indices are related to performance. The blue transparent area (ϵ) represents the synthetic index (color figure online)

$$\mu = \frac{S - S_{min}}{S_{max} - S_{min}}. \tag{16}$$

All the parameters are shown in a synthetic radar chart (see Fig. 1). The calculation of the polygon area, defined in the following as A, allows us to obtain a synthetic index ϵ for the gesture evaluation. Indeed, it allows us to take into consideration the constraints given by infringement in performance. This index is expressed as:

$$\epsilon = \frac{A}{A_{max}}, \tag{17}$$

where A_{max} is the maximum possible area (area of a regular pentagon with unitary radius). In summary, the minimum conditions to guarantee an acceptable level of correct technique are fixed (assuming the threshold values of 0.4 for the infringements parameters δ and α) and the definition of the best acceptable ϵ value (ϵ_{opt}) is carried out:

$$\begin{cases} \epsilon_{opt} = \frac{A}{A_{max}} \\ \alpha \leq 0.4 \\ \delta \leq 0.4. \end{cases} \tag{18}$$

3 Experiments

In this section, the experimental validation is described to evaluate the biomechanical indices in a field scenario. Furthermore, a statistical analysis is presented.

3.1 Participants

Nine world-class Olympic race-walkers were included in this study: seven males (three specialized on 20 km and four on 50 km); two females (specialized on 20 km) from Italy, Germany and Czech Republic agreed to participate in this study. All race-walkers were member of their national team; seven race-walkers possessed the World Championship Entry Standard for London 2017 (1:24:00 in 20 km male, 4:06:00 in 50 km for male and 1:36:00 in 20 km female) and the other two possessed a personal best proximally to entry standard. The participants had not suffered severe injuries in the 12 months before the testing day. The race-walkers were informed about all tests and possible risks involved and provided informed consent before testing, in accordance with the Committee of the University of Naples Federico II, who approved the study. After an initial briefing, the test leader collected the informed consent from volunteers as well as their personal details (i.e., personal best on 20 km: 13.8 ± 0.7 km/h, age: 25.3 ± 4.7 years, experience: 11.7 ± 5.5 years) and anthropometric characteristics (i.e., stature: 174.3 ± 4.0 cm). All values are expressed as mean ± standard deviation.

3.2 Experimental set-up

Data were collected using an inertial system (i.e., the model type G-Sensor2, BTS) with the following technical features: mass of 62 g, dimension of $7.8 \times 4.8 \times 2.0$ cm, set at frequency f of 200 Hz (1/5 ms), ± 8 g for the tri-axis accelerometer, ± 300 gps for the tri-axis gyroscope sensor. The sensor was located at the bottom of the athletes vertebral column in correspondence of the L5-S1 intervertebral space. Trials were performed on a long-paved road, which was straight and flat in accordance to the IAAF recommendations about race-walking courses [1]. After a standard self-selected warm up of 15 min (including mobility exercise) the athletes performed four trials of 300-m race-walking each, at different incremental mean speeds (from 12.0 to 14.5 km/h). These speeds for each race-walker to cover a range from at least 93–100% of their racing pace for 20 km (evaluated with respect to the best results achieved by the athlete in the last two seasons). For the speeds between 12.0 and 14.0 km/h, the speed incremental gain was fixed equal to 1.0 km/h, then it became 0.5 km/h. Tests with a difference over ± 0.2 km/h (for the speed from 12.0 to 14.0 km/h) and over ± 0.1 km/h (for the speed from 14.5 km/h) were excluded from the evaluation. The test-run order of each athlete was randomized. Using a GPS watch (Forerunner 310XT, Garmin [13]), the test leader controlled the performance (checking the mean speed every 50 m) and helped the athlete to keep close to a constant speed during the test. A rest time of 90 s was fixed between two consecutive trials and allowed the race-walker to recover.

3.3 Statistical analysis

Statistical analyses of data were performed using MATLAB (MathWorks, Natick, USA). To obtain a specific description of the participants' experimental phase, their percentile was related to the stature height variable. For this, the reference male and female elite race-walkers populations were screened for normality of distribution using the Anderson–Darling normality test [16]. The screening of the performance and infringement data is carried out: (1) for normality of distribution using the normality test of Kolmogorov–Smirnov; (2) for the homogeneity of variances using the Levene's test. The magnitude of differences, or effect sizes (ES), for each performance and infringement parameter (and for the related key performance index), at different speeds, were calculated according to Hedges' g value and interpreted as trivial (ES < 0.25), small (ES ≥ 0.25 and ES < 0.5), moderate (ES ≥ 0.5 and ES < 1.0) and large (ES ≥ 1.0), according to the scale proposed by Fröhlich [17] for highly trained participants. Finally, to assess the weight of the key performance indices (μ, ρ, γ, α and δ) on the race-walking overall index (ϵ), the κ index is introduced as:

$$\kappa_i = \frac{H_i^{12,14.5}}{\sum_i H_i^{12,14.5}}, \tag{19}$$

where H_i represents the Hedges' g value for a generic key performance index i evaluated between the groups at the minimum speed (12.0 km/h) and maximum one (14.5 km/h).

4 Results and discussion

Two world-class Olympic race-walkers reference population (male and female) were derived, starting from the personal cards data of 140 males (176.6 cm ± 7.5 cm, AD equal to 0.369 and p value equal to 0.422) and 72 females (163.1 cm ± 6.2 cm, AD equal to 0.478 and p value equal to 0.229) Olympic race-walkers in Rio de Janiero [18]. The analysis underlined how the participants of our research study were representative of the reference population. Indeed, they cover a large range from 8th to 97th percentile (in detail: 8th M, 19th M, 27th M, 57th M, 60th M, 63th M, 68th M, 92th F, 97th F). The sample size of nine athletes is also sufficient. Indeed, it is comparable with previous works: a recent review on biomechanics in race-walking states that over 65% of the studies on this topic present a number of participants smaller than 10 [5].

For each race-walking test, excluding the initial acceleration phase of the athlete (fixed equal to 10 s), 180 consecutive steps (e.g., six sequences of step for each trial) were considered. So, 24 sequences of steps (720 steps) for each athlete were evaluated. A total of 36 tests (144 sequences of step, for a total of 25,920 steps) were evaluated. Table 1 shows performance and infringement parameters for the four speeds of the trials (cf. Sect. 2.1). It shows an increasing trend of the $LOGC_{T,a}$, $LOGC_C$, SC and SLR values with growing speeds; this is in accordance with previous literature [2, 5]. At speeds slower than 13 km/h, the mean $LOGC_{T,a}$ of step sequences is under 40 ms, and only a few sequences have $LOGC_{T,a}$ greater than 40 ms ($LOGC_C$ value close to 0). In accordance with the literature, with increasing step frequencies, the smoothness improves (decreasing jerk values).

Figure 2 reports the key performance indices (for all nine athletes) evaluated according to the proposed equations (cf. Sect. 2.2) and plotted on radar charts. According to the literature [2, 5], they show a decreasing trend for infringement indices (α and δ) and, on the other side, an enhancement of the performance indices (μ, ρ and γ) as the speed increases. From the performance analysis point of view, the radar chart allows us to understand strong and critical points that characterize the technique of the athlete. For example, the radar charts underline how Athlete 2 and Athlete 9 have step length values (ρ) better than step cadence values (γ); therefore, step length values represent their strong point. Indeed, Athletes 5, 6 and 7 have the strongest technical feature in step cadence. Moreover, the derivation of custom strategies diversified for the main type of race competition (men and women 20 and 50 km) could improve the athlete's gesture analysis. From the infringement analysis point of view, at the starting speed, the considered indices are at their optimum (around zero); then they worsen with growing speeds, sometimes suddenly. Finally, ϵ allows to individuate the speed where the graph area has the maximum value. Indeed, this value can suggest the speeds of the best compromise to

Table 1 Performance and infringements indices as collected during trials

Speed (km/h)	$LOGC_{T,a}$ (ms)	$LOGC_C$ (–)	SC (steps/s)	SLR (%)	S (–)
12.0	21 ± 7	0.08 ± 0.09	3.10 ± 0.07	61.9 ± 2.8	6.28 ± 1.40
13.0	34 ± 7	0.34 ± 0.25	3.20 ± 0.08	64.6 ± 3.2	5.39 ± 1.44
14.0	45 ± 8	0.63 ± 0.26	3.29 ± 0.07	67.3 ± 3.1	4.65 ± 1.12
14.5	51 ± 9	0.75 ± 0.26	3.34 ± 0.07	69.3 ± 3.3	4.44 ± 1.19

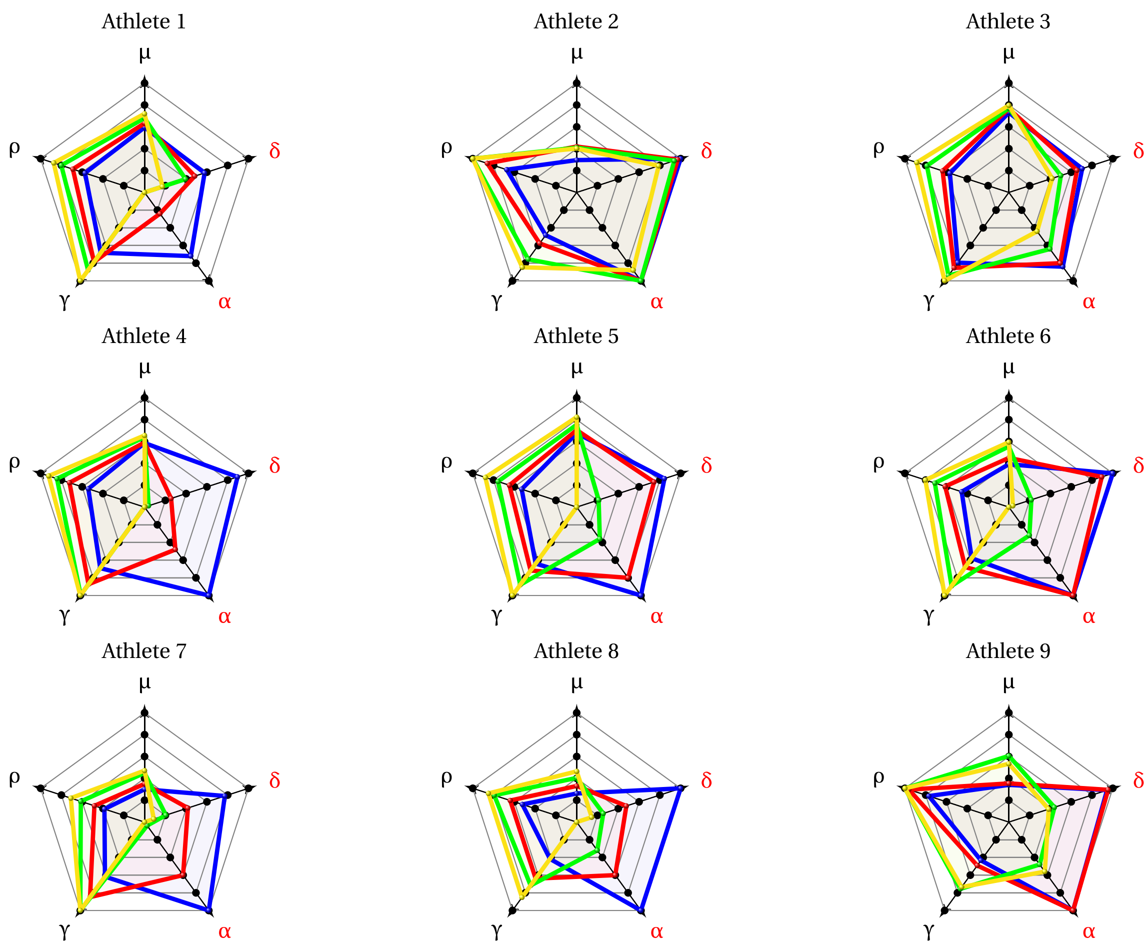

Fig. 2 Radar charts of the nine athletes involved in the experimental tests. The colored areas graphically show the trend of the indices at different speeds (blue: 12.0 km/h, red: 13.0 km/h, green: 14.0 km/h, yellow: 14.5 km/h). The greater the area is, the better the gesture is (color figure online)

achieve at the same time both the optimal SLR and SC values, while ensuring an acceptable level of correct technique (ϵ_{opt} see (17)). From the diagrams, this speed varies between athletes with values between 12 and 14 km/h.

The ES analysis underlines that the performance indices ρ and γ always have moderate ES (except for γ having large ES between 13 and 14 km/h). Moreover, Fig. 3 shows a reduction of ES in the last pair of speeds (14.0–14.5 km/h), characterized by a fixed smaller gain of speed. The third performance index (μ) shows a trivial ES with a small value only between 13 and 14 km/h. For the smoothness, to analyze possible more significant variance, an additional investigation could be carried out on smoothness rotation indices (related to the vertical angular velocity). Indeed, infringement indices show large ES for speed pairs of 12.0–13.0 km/h and 13.0–14.0 km/h. Instead, in the last comparison (14.0–14.5 km/h), smaller ES values arise (small for δ and moderate for α). It is important to notice that the reduction of ES value in the last comparison (underlined both in infringement parameters (δ and α) and in the performance ones (ρ and γ) is also related with the reduction of speed incremental gain (from 1.0 to 0.5 km/h).

Then, according to (19), the κ indices shown in Fig. 4 are derived. The pie graph shows how, even if the infringement indices are fewer than the performance ones (2 compared to 3, respectively), their weight represents almost 50% of the total. This demonstrates their important role in the definition of the total area ϵ, as well as a good balance between performance and infringement indices contribution in the radar chart structure. This study was related to objective evaluation of the indices: a future study will be based on the ranking of relative importance of the indices from an end-user perspective, involving the subjective evaluation of judges, trainers and athletes [19].

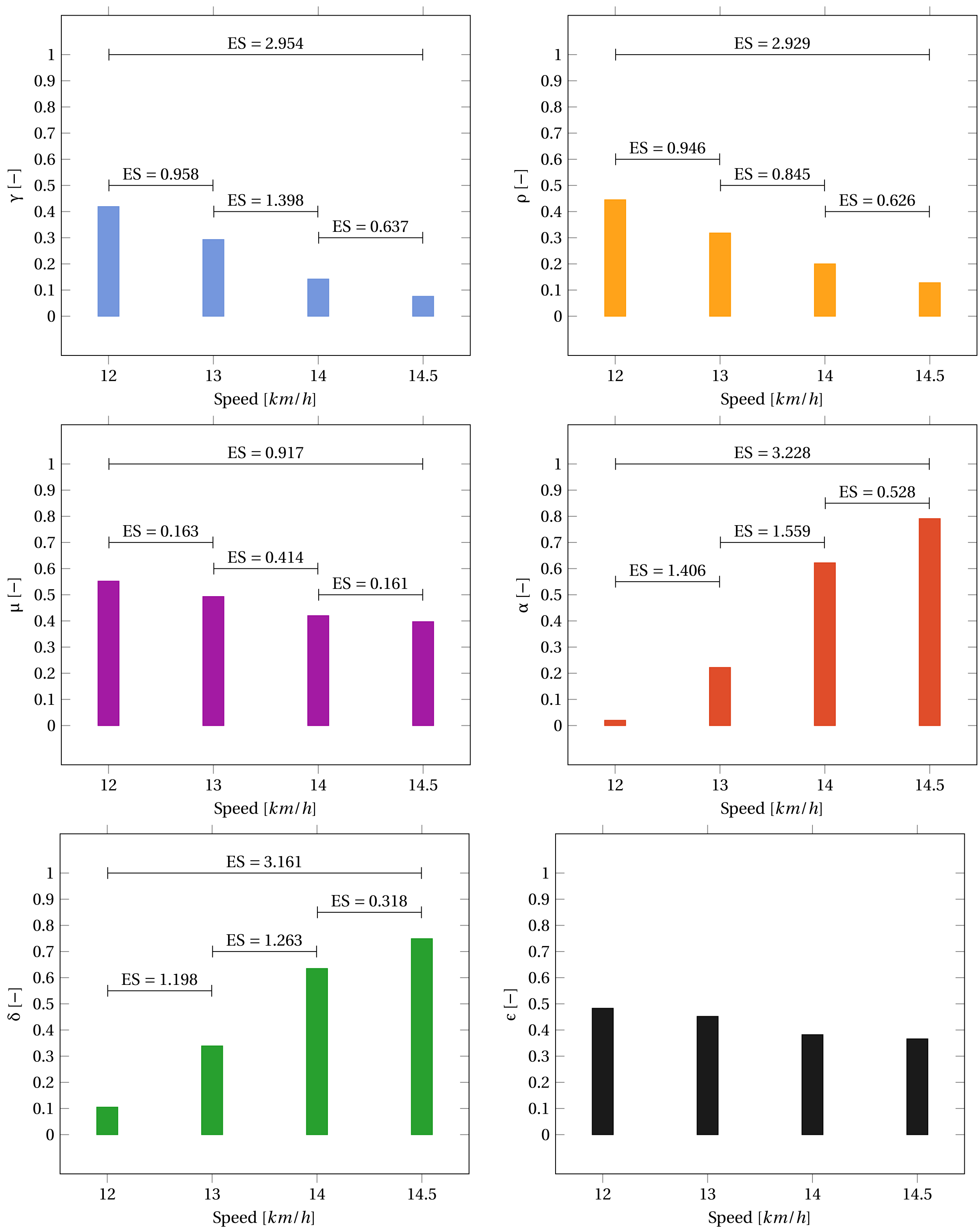

Fig. 3 Effect sizes ES, according to Hedges' g value, related to performance (μ, ρ, γ), infringement (α, δ) and overall (ϵ) indices, computed at different speeds

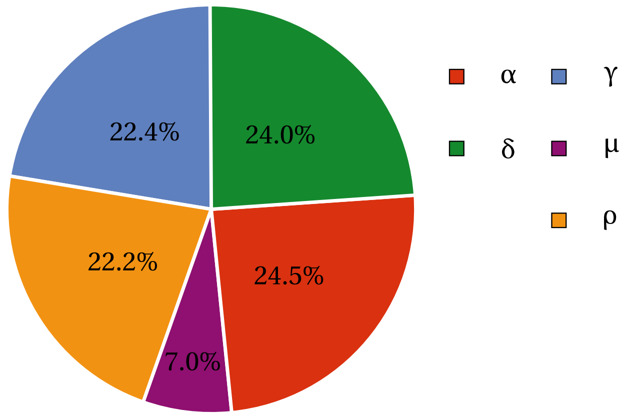

Fig. 4 Pie graph showing the percentage values of κ for all the biomechanical indices

5 Conclusions

In this paper, the definition of five biomechanical indices and their intuitive representation for judging and training purposes in race-walking are presented. Two indices describe infringements (α and δ), and three others performance (μ, ρ and γ). These indices allow the user to understand when the speed becomes critical for a correct execution of the gesture, as well as strong and critical points that characterize the technique of the athlete. The statistical analysis underlines the reliability of the proposed method, which shows a good balance between infringement and performance contribution to the athlete's assessment. The synthetic index ϵ (in combination with an acceptable level of infringement parameters) could allow to individuate the best quality of gesture with the possible optimal race pace speed. The proposed biomechanical indices are ready for the implementation on a wearable inertial-based system to assist training and judgement processes in race-walking.

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References

1. International Association of Athletics Federations (2016) Race walking a guide to judging and organising. A guide for judges, officials, coaches and athletes
2. Hanley B, Drake A, Bissas A (2008) The biomechanics of elite race walking: technique analysis and the effects of fatigue. New Stud Athl 4:17–25
3. Di Gironimo G, Caporaso T, Giudice DMD, Lanzotti A (2017) Towards a new monitoring system to detect illegal steps in race-walking. Int J Interact Design Manuf (IJIDeM) 11(2):317–329
4. Di Gironimo G, Caporaso T, Giudice DMD, Tarallo A, Lanzotti A (2016) Development of a new experimental protocol for analysing the race-walking technique based on kinematic and dynamic parameters. Procedia Eng 147:741–746
5. Pavei G, Cazzola D, La Torre A, Minetti AE (2014) The biomechanics of race walking: literature overview and new insights. Eur J Sport Sci 14(7):661–670
6. Hanley B (2015) Gait alterations during constant pace treadmill racewalking. J Strength Cond Res 29(8):2142–2147
7. Santoso DR, Setyanto TA (2013) Development of precession instrumentation system for differentiate walking from running in race walking by using piezoelectric sensor. Sens Transducers 155(8):120
8. Lee JB, Mellifont RB, Burkett BJ, James DA (2013) Detection of illegal race walking: a tool to assist coaching and judging. Sensors 13(12):16065–16074
9. Di Gironimo G, Caporaso T, Amodeo G, Giudice DMD, Lanzotti A, Odenwald S (2016) Outdoor tests for the validation of an inertial system able to detect illegal steps in race-walking. Procedia Eng 147:544–549
10. Taborri J, Palermo E, Rossi S (2019) Automatic detection of faults in race walking: a comparative analysis of machine-learning algorithms fed with inertial sensor data. Sensors 19(6):1461
11. Wixted AJ, Billing DC, James DA (2010) Validation of trunk mounted inertial sensors for analysing running biomechanics under field conditions, using synchronously collected foot contact data. Sports Eng 12(4):207–212
12. Seeberg TM, Tjønnås J, Rindal OMH, Haugnes P, Dalgard S, Sandbakk Ø (2017) A multi-sensor system for automatic analysis of classical cross-country skiing techniques. Sports Eng 20(4):313–327
13. Specifications—garmin forerunner 310xt. https://www.manualslib.com/manual/253140/Garmin-Forerunner-310xt.html?page=48. Accessed 20 Dec 2019
14. Little C, Lee JB, James DA, Davison K (2013) An evaluation of inertial sensor technology in the discrimination of human gait. J Sports Sci 31(12):1312–1318
15. Balasubramanian S, Melendez-Calderon A, Burdet E (2012) A robust and sensitive metric for quantifying movement smoothness. IEEE Trans Biomed Eng 59(8):2126–2136
16. Newell J, Aitchison T, Grant S (2014) Statistics for sports and exercise science: a practical approach. Routledge, London
17. Fröhlich M, Emrich E, Pieter A, Stark R (2009) Outcome effects and effects sizes in sport sciences. Int J Sports Sci Eng 3(3):175–179
18. Personal cards of olympic race-walkers, xxxi olympic summer games, Rio de Janiero 2016. https://www.sports-reference.com/olympics/athletes/. Accessed 25 Nov 2019
19. Caporaso T, Grazioso S, Vaccaro D, Di Gironimo G, Lanzotti A (2018) User-centered design of an innovative foot stretcher for ergometers to enhance the indoor rowing training. Int J Interact Design Manuf (IJIDeM) 12(4):1211–1221

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