

The effect of different first 200-m pacing strategies on blood lactate and biomechanical parameters of the 400-m sprint

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Abstract The purpose of the present study was to evaluate the effect of three pacing strategies upon performance of the 400-m sprint. Eight healthy male physical education students participated in this study. Each participant performed a 200-m maximal test (200_{MAX}) and three 400-m running tests in a random counterbalanced design. The 400-m tests were run with the first 200-m pace set at 98% ($400_{98\%}$), 95% ($400_{95\%}$), and 93% ($400_{93\%}$), respectively, of the effort for 200_{MAX} . The stimulation of the lactate system was assessed by post-test blood lactate concentration (BLa). Running speed (RS) was controlled with time-keeping devices. Stride frequency (SF), stride length (SL) and lower extremity kinematics were acquired with video cameras operating at 100 fps at the 125 and 380-m marks of the tests. A two-way analysis of variance (ANOVA) with repeated measures was used to identify modifications caused by the pacing strategies used. Non-significant differences were revealed for BLa. The fastest 400-m race was run in $400_{93\%}$, but performance was not significantly different ($p > 0.05$) among the examined pacing strategies. RS, SF and SL had significantly ($p < 0.05$) lower values in the 380-m mark when compared with the 125-m mark. In $400_{98\%}$, both SF and SL decreased by approximately 13%, while SF and SL dropped 2.4 and 9.2%, respectively, in $400_{93\%}$. In conclusion, lower peak BLa and less unfavorable modifications of running mechanics were recorded in

$400_{93\%}$, where time differential between the halves of the 400-m race was smaller, which eventually resulted in better performance.

Keywords Performance · Pace strategy · Running kinematics · Blood lactate concentration · Muscle fatigue · Biarticular muscle function

Introduction

The thrilling finish of the men's 400-m final of the 2010 European Athletics Championships, with first through seventh place constantly altering in the home straight and finally decided at the very last meter of the race by just 0.27 s, is a reminder of the importance of maintaining high levels of running speed (RS) under the fatiguing conditions occurring at the last meters of long sprint running.

RS is a function of stride frequency (SF) and stride length (SL). SF is defined by stride time (TS), which is the sum of the duration of the support and flight phases within the stride. On the other hand, SL is composed of the stance distance and the flight distance (Hay 1985). Segment positions at touchdown and takeoff are influencing stance time and stance distance, while ground reaction forces and air resistance during the stance influence the flight time and flight distance (Hunter et al. 2004). Flight distance is defined by speed, height and angle of takeoff, so the kinematics of the Body Center of Mass (BCM) is a basic factor for sprinting (Hay 1985). BCM kinematics is defined by segment positioning, which could be expressed as the angles formed between body segments. Running mechanics are partially studied by examining the kinematics (i.e. position, displacement, velocity, acceleration) of the joints and the body segments during the stride (Kollias 1997a).

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During a 400-m race, RS, SF and SL reach their maximum values during the first 100–150 m, followed by a significant decrease in the last stages of the race (Graubner et al. 2009; Hanon and Gajer 2009; Hanon et al. 2010; Hobara et al. 2010; Nummela et al. 1996). RS is in particular by far lower in the final 50 m of the race (Ferro et al. 2001; Gajer et al. 2007; Hanon and Gajer 2009; Hobara et al. 2010; Muller and Hommel 1997). These trends, along with experimental data, led to the conclusion that a 400-m race places a considerable demand on the lactate system for energy production. Hence, fatigue prevention is an important factor for maintaining RS, SF and SL (Nummela et al. 1992, 1994, 1996).

In the 400-m race, a high percentage (93–94%) of $\text{VO}_{2\text{max}}$ is achieved (Hanon et al. 2010; James et al. 2007). The decrease of VO_2 in the second half of the race has been found to be related with peak lactate (Hanon et al. 2010), since approximately after the first 200 m, the contribution of glycolysis to energy production is increased (Hirvonen et al. 1992). As soon as the athlete enters the second half of the race, RS decreases because of the decreased rate of ATP resynthesis and the change in the requirement of different muscle fibres (Hirvonen et al. 1992). The maximum rate of muscle lactate accumulation has been found to be attained after about 35 s and conversely in blood after about 27 s (Hirvonen et al. 1992). At the end of the 400-m sprint, CP stores are depleted and lactate concentration attains an individual maximum (Hirvonen et al. 1992). The relative aerobic/anaerobic contribution to the 400-m race has been reported to vary from about 30/70% (Lacour et al. 1990; Reis and Miguel 2007) to 64/36% (Weyand et al. 1994), with most of the studies concluding to a percentage of about 40/60% (Duffield et al. 2005; Nummela and Rusko 1995; Spencer et al. 1996; Spencer and Gastin 2001).

The physiological parameters determine how the 400-m sprint is performed. Thus, depending on the “pacing strategy” (the distribution of work and energy throughout the running distance, Abbiss and Laursen 2008), two types of 400-m runners occur (Schiffer 2008): (a) the “speed-based” athlete, who covers the first 200-m fast and then tries to maintain speed for as long as possible, hoping that fatigue will emerge at the very last stages of the race, and (b) the “endurance-based” athlete, who either utilizes an even-paced race, with the time for covering the second half of the race being roughly similar to the time of the first half, or speeds up in the second half, running the first in a steady or slow pace (Smith 1994). In competition, a fast first 200-m is generally followed by a slow second half of the race and vice versa (van Coppenolle 1980). It has been shown that top athletes, when compared with sub-top runners, are faster in the second 200 m of the 400-m race, with a less time differential between the two halves of the race (Hanon and Gajer 2009; van Coppenolle 1980). Findings based

upon time-intervals of the 400-m race suggest that world class runners adopt a more aggressive pacing strategy and demonstrate greater fatigue, when compared with national or regional level athletes (Hanon and Gajer 2009). In particular, high level, national level and regional level sprinters ran the first 200 m with an effort of 97.6, 94.4 and 93.9%, respectively, of their 200-m personal best (Hanon and Gajer 2009). These observations support the recommendation that runners should run the first half of their 400-m race at 94% of the personal best in the 200-m sprint (Brooks 1977, cited in Gambetta 1978; Jarver 2005).

Pacing strategies have an impact on physiological parameters that determine running performance (Abbiss and Laursen 2008; Hausswirth et al. 2010; Sandals et al. 2006). The question that emerges is what the optimum pacing strategy should be for a 400-m sprinter, in order to avoid the disadvantageous effects of fatigue at the last stages of the race and thus to improve performance. The results of the present study could provide further insight and a more detailed understanding of pacing strategies in the 400-m sprints, in order to optimize training and thus enhance performance.

The aim of the present study was to evaluate and to compare three pacing strategies of running the 400-m sprint, with respect to (a) the stimulation of the lactate system, and (b) the alterations to running kinematics due to fatigue. Blood lactate concentration (BLa) and selected biomechanical parameters, i.e. SL, SF, BCM velocity, lower extremities’ angular kinematics, etc., were assessed in order to support the hypothesis that differences will occur in the stimulation of the lactate system and the running mechanics due to the modification of running speed (RS) during the first 200 m of a 400-m race. It was hypothesized that an “endurance-based” (with a small time difference between the halves of the race) approach of the 400-m sprint will allow athletes to rely more on aerobic than anaerobic mechanisms during the slower first 200 m of the 400-m sprint. Slower first 200 m would lead to a delayed peak BLa, with consequent limited fatigue-induced alterations in running kinematics between the halves of the race and eventually better performance than running the distance with a “speed-based” strategy.

Methods

Subjects

Eight healthy male physical education students, with previous experience as track runners, participated in this study. Mean \pm SD of the subjects for age, body height and body mass were 21.3 ± 1.8 years, 1.78 ± 0.03 m and 71.0 ± 4.6 kg, respectively. All participants were in good

physical condition, with no apparent or reported injury or disability. Prior to the investigation, they were informed of the experimental risks and signed an informed consent document. The investigation was conducted under the institutional research committee guidelines for use of human subjects.

Procedure

Each participant performed, in a random counterbalanced design, three 400-m running tests aiming at maximum performance. The running tests were executed on an oval 400 m outdoor track with a rubber surface and consisted of (a) 400-m sprint, with the first 200 m pace set at 98% of the effort for a 200-m maximal test ($400_{98\%}$), (b) 400-m sprint, with the first 200 m pace set at 95% of the effort for a 200-m maximal test ($400_{95\%}$), and (3) 400-m sprint, with the first 200 m pace set at 93% of the effort for a 200-m maximal test ($400_{93\%}$). After the 200-m mark, subjects were asked to cover the distance with maximum effort.

Prior to the 400-m tests, a maximal 200-m sprinting test (200_{MAX}) was executed in order to retrieve a reference running speed (RS) value. When 200_{MAX} was completed, RS for 98, 95 and 93% of the 200_{MAX} was calculated. Additional 200-m running tests were executed ($200_{98\%}$, $200_{95\%}$, $200_{93\%}$), so that the subjects were familiarized with the RS of the different 400-m pacing strategies.

In preparation for the sprinting tests, the participants attended a 4-week training program comprising two sessions per week. The aims of this program were to improve physical fitness and to instruct the pacing strategies, in order to properly distribute speed over the racing distances of the sprinting tests. Each test was preceded by a 40-min warm-up consisting of slow running for 8–10 min, stretching with emphasis on the leg muscles for 10–12 min, neuromuscular coordination drills (skipping and heel-to-butt kicks), and three 80-m runs at gradually increasing speed. The tests were spaced 4 days apart and were performed between 12:00 and 14:00 h in late spring, at an ambient temperature of 22–24°C. The middle lanes of the track were used in order to avoid environmental effects (Quinn 2004). During the 3 days preceding each test, the volunteers participated in a common program of active recovery from the previous test and preparation for the next one.

In each trial 200-m sprint, the participants followed a specific pacing strategy focused on maintaining, as much as possible, the RS in accordance to the pacing strategy selected. This was accomplished by a controlled submaximal start, followed by a progressive increase in RS that never reached maximal. Oral feedback was provided at the first 100 m of the 200-m runs, so that participants could adjust and sustain their RS to the goal set by the pacing strategy selected.

Measurement of time intervals

Running time (T) was assessed electronically using (a) five pairs of photocells (Tag Heuer, La Chaux-de-Fonds, Switzerland), with the respective reflectors placed on tripods at a height of 1–1.2 m at intervals of 100-m (0-m/start line, 100, 200, 300, 400-m/finish line), and (b) an electronic chronometer with capacity to measure thousandths of a second (Omega, Geneva, Switzerland), which was connected to the photocells and a printer (Chronoprinter 503). The participants started each test from the standing position and 1 m behind the first pair of photocells, in order to avoid the effect of reaction time on performance. Average RS was calculated as the ratio of distance to time for every 100 m and over the entire running distance.

Measurement of blood lactate concentration

For the determination of peak BL_a, the participants provided capillary blood samples from a fingertip before and 3, 5, 7 and 9 min after each running test. The blood was immediately mixed with a tenfold volume of 0.3 mol/L perchloric acid and was stored at –20°C until analyzed. On the day of analysis, the samples were thawed and centrifuged at 1,500 g for 5 min. Lactate was measured in the supernatant according to an enzymic photometric method from Sigma Diagnostics (St. Louis, MO, USA; method no. 826-UV). The coefficient of variation for lactate was 3%.

Acquisition and analysis of biomechanical parameters

The participants were recorded at the 125 and 380-m marks of each 400-m test. The recordings included three consecutive support phases of the participants. At both recording points, a stationary JVC GR-DVL 9600EG (Victor Co., Japan) digital video camera, placed perpendicular to the plane of motion, was fixed on a tripod at a height of 1.2 m and operating at a sampling frequency of 100 fields/s. The two cameras were positioned 20 m from the inside lane of the track. For the execution of a 2D-DLT kinematic analysis (Kollias 1997b), a 2.5 m × 2.5 m calibration frame with 16 control markers was placed, throughout the filming view, at the middle of the lane and perpendicular to the camera's axis. x -axis represented the direction of running and y -axis was vertical to x -axis. Twenty-two anatomical points of the body (tip of the toe, fifth metatarsal, heel, ankle, knee, hip, shoulder, elbow, wrist, fingers on both sides of the body and the head) and selected points in the filming view were manually digitized in each field. The coordinates of the Body Center of Mass (BCM) were calculated for every field using a combination of segment parameters and anatomical data (Clauser et al. 1969; Dempster 1955; Whitsett 1963). A 6-Hz cut-off frequency, based on

residual analysis (Winter 1990), was selected for smoothing. The accuracy of the 2D reconstruction was determined by Root Mean Square error, after randomly re-digitizing 5% of the captured frames. An error of 6.2 and 6.8 mm was found for the x and y axis, respectively. Digitization, smoothing and analyses were conducted using the A.P.A.S. System 2007 software (Ariel Dynamics Inc., Trabuco Canyon, CA, USA).

Stride time (TS) was defined as the time between consecutive take-offs of opposite feet. The time instant of touchdown was defined at the first field where the foot had clearly contacted the ground. The time instant of take-off was defined at the first field where the foot had clearly left the ground. Thus, contact (T_C) and flight (T_f) time for each stride were determined. Stride frequency (SF) was defined as the strides taken per second.

Additionally, the following parameters were calculated based on the xy coordinates extracted for the digitized anatomical points:

- Stride length (SL): horizontal distance between the touchdown point of the feet between two consecutive supports.
- Touchdown distance (S_{TD}): horizontal distance of the toes of the support foot to the BCM projection at the instant of touchdown.
- Take-off distance (S_{TO}): horizontal distance of the toes of the support foot to the BCM projection at the instant of take-off.
- Horizontal take-off BCM velocity (Vx_{TO}): horizontal velocity of BCM at the instant of take-off.
- Vertical take-off BCM velocity (Vy_{TO}): vertical velocity of BCM at the instant of take-off.
- Angle of take-off (AngPr): Arc-tangent of vertical/horizontal BCM velocity at the instant of take-off.
- Horizontal ankle touchdown velocity (Vx_{ankle}): horizontal velocity of the ankle at the instant of touchdown.
- BCM height: the height of the BCM at the instants of touchdown (H_{TD}), of maximum lowering (H_{AM}) and take-off (H_{TO}).
- Knee joint angle: angle formed between the thigh and the shank at the instants of touchdown ($\theta_{knee_{TD}}$), of maximum amortization ($\theta_{knee_{AM}}$) and take-off ($\theta_{knee_{TO}}$). The minimum knee angle of the swing leg during the support phase was also calculated ($\theta_{knee_{MIN}}$).
- Ankle joint angle: angle formed between the shank and the foot at the instants of touchdown ($\theta_{ankle_{TD}}$) and take-off ($\theta_{knee_{TO}}$).
- Knee joint angular velocity (ω_{knee}). The angular velocity of the swing leg's knee joint at the instant of take-off
- Thigh inclination (φ_{thigh}): angle formed by the horizontal axis and the thigh of the swing leg at the instant of take-off.

Statistical analyses

Data are presented as mean \pm SD. For all statistical procedures, the SPSS 12.0 software (SPSS, Chicago, IL, USA) was used. RS of the first 200 m of each 400-m test were compared with the RS of the respective 200-m test by two-way (order \times intensity) analysis of variance (ANOVA) with repeated measures on order. RS over the entire running distance in the three 400-m tests and BLa after the tests were compared by ANOVA with repeated measures. The biomechanical parameters of the two halves of each 400-m test were compared by two-way (order \times intensity) ANOVA with repeated measures on both factors. Significant differences were followed up with simple contrasts. Correlations between BLa and the kinematic parameters were examined by Pearson's correlation analysis. The level of statistical significance was set at $p = 0.05$ for all analyses.

Results

The subjects run the 200_{MAX} in 24.6 \pm 1.2 s (Table 1). The deviations of RS with regard to the achievement of the RS goals set for the 200-m tests were ± 0.9 , ± 0.7 , and $\pm 1.3\%$ for 200_{98%}, 200_{95%} and 200_{93%}, respectively. BLa was similar between 200_{MAX} and 200_{98%} (16.1 mmol/L). Significantly lower values were recorded for 200_{95%} and 200_{93%}.

Regarding the first 200-m pacing accuracy in the 400-m tests, statistical analysis revealed no significant difference between the RS of the 200-m tests and the RS of the 400-m tests' first half. Specifically, RS goal for the first 200 m of the 400_{98%} was 7.90 \pm 0.37 m/s and the participants run the distance with an average RS of 7.96 \pm 0.38 m/s ($p > 0.05$). The same accuracy was revealed for the 400_{95%} (7.74 \pm 0.38 vs. 7.76 \pm 0.37 m/s) and 400_{93%} (7.56 \pm 0.40 vs. 7.55 \pm 0.32 m/s). Nevertheless, performance was not different ($p > 0.05$) between the different pacing strategies tested in the present study (Table 2). Additionally, non-significant differences were revealed for BLa. However, the fastest 400-m race was run when the 400_{93%} pacing strategy was utilized.

The analysis of time in the 100-m intervals revealed that RS peaked in the 100–200-m section of the race in all three pacing conditions. During the second half of the race, RS dropped significantly ($p < 0.05$) in every pacing strategy, being even lower in the last 100-m of the race. In that stage, RS was significantly higher in 400_{93%}, when compared with 400_{95%} and 400_{98%} (Table 2). RS in the 400_{95%} condition was also higher than 400_{98%}. SF and SL had significantly lower values in the 380-m mark, when compared with those of the 125-m mark (Table 3). In the 400_{98%} pacing strategy, both SF and SL decreased by approximately 13%. For the

Table 1 Performance, average running speed (RS) and peak post-test blood lactate concentration (BLa) for the 200-m tests

200 m test	200 _{MAX}	200 _{98%}	200 _{95%}	200 _{93%}	p	η^2	α
200-m Perfomance (s)	24.6 ± 1.2	25.2 ± 1.2 [§]	25.8 ± 1.3 ^{§,†}	26.5 ± 1.1 ^{§,†,‡}	0.001	0.982	1.000
200-m RS (m/s)	8.1 ± 0.4	8.0 ± 0.4 [§]	7.8 ± 0.4 ^{§,†}	7.6 ± 0.3 ^{§,†,‡}	0.001	0.953	1.000
200-m BLa (mmol/L)	16.1 ± 2.3	16.1 ± 2.2	14.6 ± 2.2 [§]	13.5 ± 1.9 ^{§,†}	0.001	0.699	1.000

Values are expressed as mean ± SD

Significantly different from 200_{MAX}, [§]p < 0.05

Significantly different from 200_{98%}, [†]p < 0.05

Significantly different from 200_{95%}, [‡]p < 0.05

n = 8, p significance level, η^2 effect size, α observed statistical power

Table 2 Performance, time (T) and time differential (T_{diff}) for the 200-m intervals, average running speed (RS) for the 100-m and 200-m intervals and peak post-test blood lactate concentration (BLa) for the 400-m sprints

Pacing strategy	400 _{98%}	400 _{95%}	400 _{93%}	p	η^2	α
400-m Perfomance (s)	55.0 ± 2.7	54.7 ± 2.5	54.1 ± 2.3	0.148	0.293	0.373
T _{0–200m} (s)	25.3 ± 1.1	25.8 ± 1.1 ^a	26.2 ± 1.3 ^{a,b}	0.001	0.855	0.981
T _{200–400m} (s)	29.7 ± 1.5 [§]	28.9 ± 1.3 ^{§,a}	27.9 ± 1.0 ^{§,a,b}	0.002	0.763	1.000
T _{diff} (s)	4.4 ± 0.8	3.2 ± 0.9 ^a	1.7 ± 0.8 ^{a,b}	0.001	0.945	1.000
RS _{0–100m} (m/s)	7.9 ± 0.3	7.7 ± 0.4	7.6 ± 0.4	0.001	0.969	0.999
RS _{100–200m} (m/s)	8.0 ± 0.4	7.9 ± 0.3	7.7 ± 0.4	0.587	0.221	0.395
RS _{200–300m} (m/s)	7.2 ± 0.3 [†]	7.2 ± 0.5 [†]	7.3 ± 0.4 [†]	0.001	0.061	0.109
RS _{300–400m} (m/s)	6.4 ± 0.4 ^{†,‡,‡}	6.7 ± 0.3 ^{†,‡,‡,a}	7.1 ± 0.2 ^{†,‡,‡,a,b}	0.001	0.690	0.981
RS _{0–200m} (m/s)	8.0 ± 0.3	7.8 ± 0.3 ^a	7.6 ± 0.4 ^{a,b}	0.001	0.841	0.999
RS _{200–400m} (m/s)	6.7 ± 0.4 [§]	6.9 ± 0.3 ^{§,a}	7.2 ± 0.3 ^{§,a,b}	0.001	0.686	0.996
400-m BLa (mmol/L)	20.5 ± 1.4	20.2 ± 2.0	18.9 ± 2.1	0.029	0.397	0.682

Values are expressed as mean ± SD

Significantly different from 400_{98%}, ^ap < 0.05

Significantly different from 400_{95%}, ^bp < 0.05

Significantly different from 0 to 200 m, [§]p < 0.05

Significantly different from 0 to 100 m, [†]p < 0.05

Significantly different from 100 to 200 m, [‡]p < 0.05

Significantly different from 200 to 300 m, [#]p < 0.05

n = 8, p significance level, η^2 effect size, α observed statistical power

slowest pace (400_{93%}), SF dropped by only 2.4% and SL by 9.2% in the 380-m mark.

TS and T_C in particular were significantly higher in the second half of the 400_{98%} and 400_{95%} tests. In the 400_{93%} pacing strategy, T_f decreased in the 380-m mark, since T_C increased within the constant TS.

Horizontal BCM take-off velocity was significantly lower in the 380-m than the 125-m mark, but with non significant differences among the pacing strategies. A trend was revealed for the AngPr and V_{yTO}, since their values increased in the 380-m mark when the first half of the race was covered with a slower pace. Although not statistically significant, a trend was revealed for an increase of S_{TD} in the fatiguing conditions of all the pacing strategies tested.

BCM height in the different phases of the stride cycle was shown to be constant, since only H_{TD} and H_{AM} were

significantly lower in the 380-m mark in 400_{98%}. No differences were revealed for the BCM lowering (ΔH_{AM}) at the mid-support phase.

θ_{kneeTO} was significantly larger in the 380-m mark than in the 125-m mark in all pacing conditions (Table 4). Although θ_{kneeTD} and θ_{kneeAM} were significantly lower in the second half of 400_{98%} and 400_{95%}, the range of motion of the knee joint between touchdown and maximum amortization ($\Delta knee_{AM}$) was non significant.

Significant differences were not revealed for the ankle joint kinematics, with the exception of its range of motion during the support phase ($\Delta ankle_{TO}$) in 400_{93%}. In this case, $\Delta ankle_{TO}$ was increased by approximately 4–5 degrees in the 380-m mark compared with the 125-m mark in all running tests.

$\theta_{kneeMIN}$ was significantly higher in the 380-m than the 125-m mark in the 400_{98%} and 400_{95%} conditions, but with

Table 3 Kinematic parameters at the 125-m (1st 200-m) and 380-m (2nd 200-m) marks of the 400-m sprints

Pacing strategy	400 _{98%}		400 _{95%}		400 _{93%}		<i>p</i>	η^2	α
	1st 200-m	2nd 200-m	1st 200-m	2nd 200-m	1st 200-m	2nd 200-m			
Stride length (SL, m)	2.13 ± 0.04	1.84 ± 0.05*	2.15 ± 0.05	1.89 ± 0.05*	2.12 ± 0.04	1.92 ± 0.04*	0.430	0.113	0.174
Stride frequency (SF, Hz)	3.78 ± 0.11	3.26 ± 0.21*	3.66 ± 0.16	3.31 ± 0.22*	3.48 ± 0.22 ^a	3.38 ± 0.16	0.007	0.503	0.863
Stride time (TS, s)	0.27 ± 0.01	0.31 ± 0.02*	0.27 ± 0.01	0.30 ± 0.02*	0.29 ± 0.02 ^a	0.30 ± 0.01	0.009	0.487	0.840
Contact time (T_C , s)	0.12 ± 0.01	0.17 ± 0.01*	0.14 ± 0.02 ^a	0.16 ± 0.01*	0.13 ± 0.02	0.15 ± 0.01*	0.007	0.505	0.866
Contact time (T_C , %TS)	46.7 ± 4.9	54.1 ± 3.7*	49.9 ± 7.0	51.6 ± 3.9	45.8 ± 4.5	52.1 ± 5.5*	0.111	0.296	0.429
Flight time (T_f , s)	0.14 ± 0.01	0.14 ± 0.02	0.14 ± 0.02	0.15 ± 0.02	0.16 ± 0.01	0.14 ± 0.02	0.139	0.246	0.385
Horizontal BCM takeoff velocity ($V_{x_{TO}}$, m/s)	8.0 ± 0.5	6.0 ± 0.6*	7.9 ± 0.5	6.3 ± 0.5*	7.6 ± 0.1	6.4 ± 0.6*	0.006	0.515	0.880
Vertical BCM takeoff velocity ($V_{y_{TO}}$, m/s)	0.6 ± 0.1	0.6 ± 0.2	0.6 ± 0.1	0.7 ± 0.2	0.6 ± 0.1	0.8 ± 0.3	0.040	0.368	0.624
Angle of projection (AngPr, deg)	4.2 ± 0.5	5.3 ± 2.1	4.5 ± 0.7	6.1 ± 2.4	4.3 ± 0.9	6.9 ± 3.0	0.161	0.230	0.357
Touchdown distance (S_{TD} , m)	0.38 ± 0.02	0.42 ± 0.02	0.41 ± 0.02	0.44 ± 0.02	0.44 ± 0.03	0.46 ± 0.03	0.747	0.041	0.088
Takeoff distance (S_{TO} , m)	0.57 ± 0.02	0.52 ± 0.02*	0.58 ± 0.01	0.56 ± 0.02	0.54 ± 0.04	0.56 ± 0.02	0.334	0.145	0.218
BCM height at touchdown (H_{TD} , m)	1.00 ± 0.03	0.99 ± 0.02*	1.00 ± 0.03	1.00 ± 0.03	1.00 ± 0.02	1.01 ± 0.04	0.165	0.227	0.352
Minimum BCM height during support phase (H_{AM} , m)	0.97 ± 0.03	0.94 ± 0.03*	0.97 ± 0.03	0.96 ± 0.03	0.96 ± 0.02	0.96 ± 0.03	0.054	0.386	0.572
Lowering of BCM during support phase (ΔH_{AM} , m)	0.03 ± 0.01	0.04 ± 0.01	0.04 ± 0.01	0.04 ± 0.01	0.05 ± 0.01	0.05 ± 0.01	0.636	0.073	0.160
BCM height at takeoff (H_{TO} , m)	1.03 ± 0.02	1.02 ± 0.03	1.03 ± 0.03	1.03 ± 0.03	1.02 ± 0.02	1.03 ± 0.03	0.290	0.162	0.244

Values are expressed as mean ± SD

Significantly different 125-m versus 380-m mark in the same pacing strategy; **p* < 0.05

Significantly different from 400_{98%}, ^a*p* < 0.05

Significantly different from 400_{95%}, ^b*p* < 0.05

n = 8, *p* significance level, η^2 effect size, α observed statistical power

non significant differences among the pacing tactics. Significant differences were observed between the halves of the 400-m tests for ω_{knee} and φ_{thigh} . ω_{knee} was lower and φ_{thigh} was higher at the 380-m mark, respectively.

Correlation analysis revealed a strong relationship between post-test BL_a and $\theta_{knee_{TD}}$ in the first half of the tests (Table 5). BL_a was also related with AngPr and $\theta_{knee_{AM}}$ for the last meters of the 400_{98%} and 400_{95%} tests. It is worth noting that in the 400_{93%} pacing strategy, strong relationships were revealed among BL_a and SL, T_C , $\theta_{knee_{MIN}}$, ω_{knee} and φ_{thigh} .

Discussion

Although pacing accuracy is relevant to experience and fitness (Green et al. 2010), the participants achieved to run the first half of the 400-m tests in the time defined for the accomplishment of the 400_{98%}, 400_{95%} and 400_{93%} pacing strategies. Performance was not different (*p* > 0.05) between the different pacing strategies tested. However, a

trend was revealed for improving performance by covering the first half of the race with the slower pace tested. A detailed study of the present results revealed the fact that six subjects did run the 400-m race faster, clocking a mean 1.2 ± 0.9 and 0.8 ± 0.4 s faster in 400_{93%} with respect to 400_{98%} and 400_{95%}. Furthermore, in the case of 400_{93%}, where time differential between the two halves of the 400-m race was significantly lower than the other pacing strategies, lower peak BL_a and less unfavorable modifications of running mechanics were recorded which eventually resulted to better performance. The smallest RS difference occurred in 400_{93%} with respect to the other 400-m pacing strategies, confirming the results of simulation studies suggesting that better 400-m performance is achieved with keeping a constant RS (Harman 2002).

When compared with other studies, a similar 400-m performance was recorded previously (Nummela et al. 1994). However, the subjects of the present study were slower than subjects in the majority of 400-m sprint studies (Hanon et al. 2010; Hirvonen et al. 1992; Hobara et al. 2010; Nummela et al. 1992; Nummela et al. 1996;

Table 4 Lower extremities' joint kinematic parameters at the 125-m (1st 200-m) and 380-m (2nd 200-m) marks of the 400-m sprints

Pacing strategy	400 _{98%}		400 _{95%}		400 _{93%}		<i>p</i>	η^2	α
	1st 200-m	2nd 200-m	1st 200-m	2nd 200-m	1st 200-m	2nd 200-m			
Knee angle at touchdown ($\theta_{\text{knee}_{\text{TD}}}$, deg)	152 ± 3	146 ± 5*	152 ± 6	146 ± 5*	148 ± 9	150 ± 4	0.092	0.532	0.553
Minimum knee angle during support phase ($\theta_{\text{knee}_{\text{AM}}}$, deg)	140 ± 4	133 ± 6*	140 ± 6	135 ± 6*	137 ± 7	138 ± 7	0.103	0.277	0.445
Knee angle amortization ($\Delta_{\text{knee}_{\text{AM}}}$, deg)	12 ± 2	13 ± 2	11 ± 2	11 ± 2	11 ± 3	13 ± 2	0.860	0.017	0.065
Knee angle at takeoff ($\theta_{\text{knee}_{\text{TO}}}$, deg)	157 ± 6	163 ± 7*	158 ± 6	163 ± 7*	156 ± 6	163 ± 5*	0.672	0.055	0.103
Ankle horizontal velocity at touchdown (V_{xankle} , m/s)	1.2 ± 0.4	1.5 ± 0.5	1.2 ± 0.4	1.6 ± 0.6	1.3 ± 0.5	1.6 ± 0.7	0.887	0.017	0.065
Ankle angle at touchdown ($\theta_{\text{ankle}_{\text{TD}}}$, deg)	103 ± 3	97 ± 4	102 ± 5	97 ± 4	102 ± 5	100 ± 5	0.380	0.129	0.195
Ankle angle at takeoff ($\theta_{\text{ankle}_{\text{TO}}}$, deg)	125 ± 4	121 ± 3	125 ± 3	126 ± 5	125 ± 5	125 ± 5	0.203	0.204	0.312
Ankle joint range of motion ($\Delta_{\text{ankle}_{\text{TO}}}$, deg)	22 ± 1	24 ± 2	23 ± 2	28 ± 1	22 ± 2	26 ± 2*	0.417	0.117	0.179
Minimum swing leg's knee angle during support ($\theta_{\text{knee}_{\text{MIN}}}$, deg)	33 ± 8	40 ± 7*	34 ± 8	38 ± 7*	36 ± 8	37 ± 11	0.115	0.316	0.343
Maximum swing leg's knee angular velocity (ω_{knee} , rad/sec)	16.9 ± 0.5	13.8 ± 0.6*	16.8 ± 0.4	13.3 ± 0.3*	17.0 ± 0.6	14.0 ± 0.5*	0.841	0.024	0.672
Thigh inclination (φ_{thigh} , deg)	18 ± 6	31 ± 5*	20 ± 4	30 ± 6*	21 ± 6	29 ± 6*	0.164	0.227	0.353

Values are expressed as mean ± SD

Significantly different 125-m versus 380-m mark in the same pacing strategy; * $p < 0.05$

$n = 8$, p significance level, η^2 effect size, α observed statistical power

Table 5 Correlation coefficients between peak post-test blood lactate concentration (BLa) and selected kinematic parameters at the 125-m (1st 200-m) and 380-m (2nd 200-m) marks of the 400-m sprints ($n = 8$)

Pacing strategy	400 _{98%}		400 _{95%}		400 _{93%}	
	1st 200-m	2nd 200-m	1st 200-m	2nd 200-m	1st 200-m	2nd 200-m
Average running speed (RS)	0.087	-0.083	-0.113	0.089	-0.334	-0.278
Stride length (SL)	-0.185	-0.136	0.358	-0.081	0.010	-0.800*
Stride frequency (SF)	-0.095	-0.060	-0.432	-0.311	-0.135	0.387
Contact time (T_C)	0.006	-0.314	0.147	0.258	0.131	0.821*
Flight time (T_f)	0.058	0.376	0.109	0.218	0.043	-0.710*
Vertical BCM take-off velocity ($V_{y_{\text{TD}}}$)	-0.129	0.666	0.417	0.698	-0.470	-0.005
Angle of projection (AngPr)	-0.157	0.710*	0.331	0.721*	-0.435	0.176
Touchdown distance (S_{TD})	-0.465	-0.245	0.721*	0.501	0.196	0.181
Takeoff distance (S_{TO})	0.059	-0.596	0.088	-0.699	0.650	-0.454
Knee angle at touchdown ($\theta_{\text{knee}_{\text{TD}}}$)	0.717*	0.692	0.863**	0.844**	0.781*	0.410
Minimum knee angle during support phase ($\theta_{\text{knee}_{\text{AM}}}$)	0.496	0.822*	0.342	0.801*	0.294	0.149
Minimum swing leg's knee angle during support ($\theta_{\text{knee}_{\text{MIN}}}$)	-0.011	0.238	0.514	0.639	0.702*	0.923**
Thigh inclination (φ_{thigh})	0.065	0.689	0.157	0.503	0.680	0.950**
Swing leg's knee angular velocity at take-off (ω_{knee})	0.091	-0.421	0.152	0.111	0.335	-0.734*

* $p < 0.05$

** $p < 0.01$

Reis et al. 2004) since they were faster only than the “Slow Males” group in the study of Nummela et al. (1996).

Post-test BLa in the 200-m tests (13.5–16.1 mmol/L) was higher than those reported from Duffield et al. (2004) and Hautier et al. (1994). This could be a result of the

longer time to finish the 200-m tests in the present study, since the average performance was close to 27 s, where the maximum rate of BLa is attained (Hirvonen et al. 1992). On the other hand, post-test BLa in the 400_{98%} and 400_{95%} tests were in agreement with those reported elsewhere (Hanon et al. 2010; Lacour et al. 1990; Mero and Peltola 1989; Nummela et al. 1994; Nummela et al. 1996; Ohkuwa et al. 1984a). It is worth noting that much lower BLa values were presented in other studies (approximately 14–15 mmol/L, Hirvonen et al. 1992; Nummela et al. 1992; Reis et al. 2004; Reis and Miguel 2007; Sarlasanidis et al. 2009).

RS dropped during the last 100 m in all 400-m tests (Ferro et al. 2001; Gajer et al. 2007; Graubner et al. 2009; Hanon and Gajer 2009; Hanon et al. 2010; Hobara et al. 2010; Muller and Hommel 1997; Nummela et al. 1996). Despite the fact that RS and BLa were correlated in untrained subjects (Ohkuwa et al. 1984a), no correlation was revealed in the tested pacing strategies (see also Ohkuwa et al. 1984b). However, in the pacing strategies with the larger BLa (400_{98%}, 400_{95%}), subjects were on average slower by 11–15%. This can be supported by several previous studies, which have shown an approximate 15% decrease for RS (Hirvonen et al. 1992; Mero and Peltola 1989; Nummela et al. 1992), while other studies report a much larger decrement of 19–25% (Hobara et al. 2010; Nummela et al. 1994, 1996; Tupa et al. 1995). The decrease of RS was found to be more related with the decrease of SL than the decrease of SF, especially in the 400_{95%} and 400_{93%} pacing strategies, being in agreement with Hanon et al. (2010), Mero and Peltola (1989), Nummela et al. (1992) and Nummela et al. (1996). It is noteworthy that there are contradicting findings in the literature, since the importance of SF over SL has been suggested as the dominant determinant of RS in the last stages of the 400-m race (Hanon and Gajer 2009; Hobara et al. 2010; Mero et al. 1988; Tupa et al. 1995). It has been hypothesized (Hanon and Gajer 2009) that it is more important to maintain SF, because of the difficulty to attain a high level of SL aiming to run economically while running with near to maximal velocity under fatigue. It has also been documented that lower RS under fatigue for female 400-m athletes was associated with various combinations of changes in SL and TS (Chapman 1982).

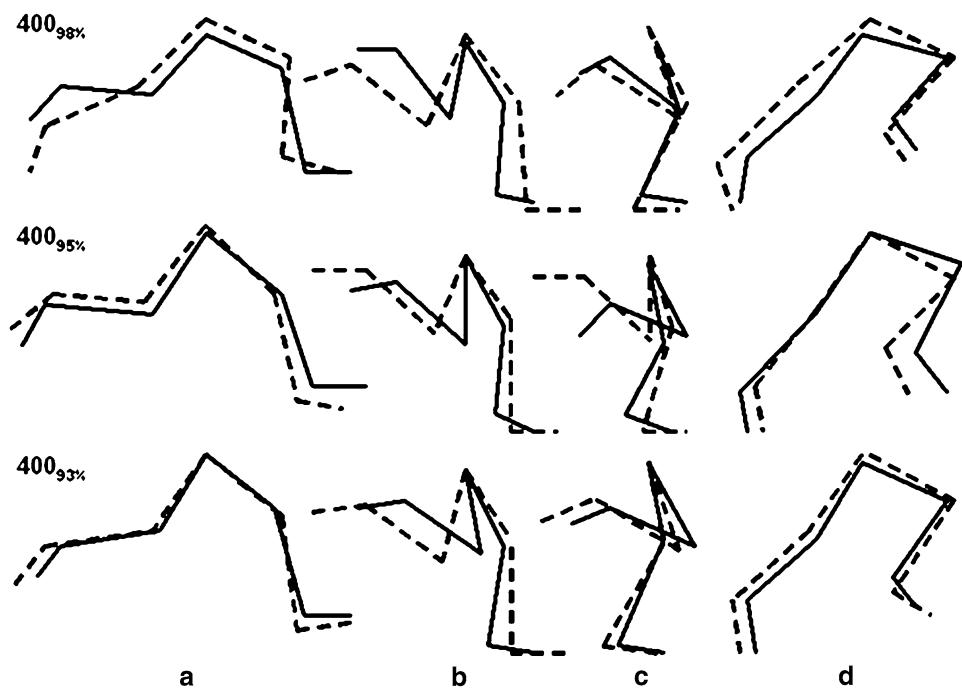
Further investigation concerning the interaction between SF and SL and its effect on the RS decrease in fatiguing conditions is essential. As expected (Girard et al. 2010; Hirvonen et al. 1992; Hobara et al. 2010; Kadono et al. 2008; Mero et al. 1988; Morin et al. 2006; Nicol et al. 1991; Nummela et al. 1992, 1996; Pinniger et al. 2000; Sprague and Mann 1983), T_C increased in the fatigued stage of the running tests. T_C expressed with respect to T_f (Nummela et al. 1992) was also increased, with the exception of 400_{95%}. The relative proportion of slow-twitch fibres

involved in force generation has been suggested to increase at the end of the 400-m run and that might be the reason for the increase in T_C (Hirvonen et al. 1992; Nummela et al. 1992). Force generation results in the production of sufficient impulse for supporting the body weight and in pushing off for the execution of the stride cycle. A higher V_{yTO} might be advantageous when an athlete is fatigued and struggling to maintain a high SF (Hunter et al. 2004), since enough aerial time during the non-support phase is needed for repositioning the swing leg (Weyand et al. 2000). In the present study, a greater V_{yTO} was achieved in the last meters of the pacing tests. This resulted to an increased AngPr, which was highly correlated with BLa in the 400_{98%} and 400_{95%} tests. However, there were no indications that T_f increased at the end of the race, as reported by Sprague and Mann (1983).

Since RS is related to SL, T_C , SF, and not to T_f (Weyand et al. 2000), a further insight should be given to SL, SF, T_C and T_f , which are influenced by stiffness (i.e. the resistance of a body to change in length, Brughelli and Cronin 2008). Stiffness, along with high muscle preactivity, is thought to play an important role in the toleration of the high-impact loads and in enabling the effective utilization of tendon-muscular elasticity during the short contact phase (Mero and Komi 1986). In a 400-m run, both vertical and leg stiffness peak at 50–100 m, with vertical stiffness decreasing 40% in the last 50 m (Hobara et al. 2010), since fatigue affects stiffness regulation because of the changes in the vertical BCM displacement, the reduced ground reaction forces and the changes of muscle preactivity (Bruggemann 1996; Girard et al. 2010; Nummela et al. 1994). This mechanism can be translated as the failure of muscle stiffness in the eccentric contraction, which results in the reduction of the amount of elastic energy stored during the braking phase (Nummela et al. 1994). The increased acidosis and the repetitive stretch loads during the 400-m run decrease the capacity of the neuromuscular system to generate force and to tolerate the impact forces. This decrement in force production is thought to be due to the processes within the skeletal muscle, located at the level of motor unit (Nummela et al. 1994), rather than in the central nervous system (Mero and Peltola 1989; Nummela et al. 1992). Since maintaining a high level of leg stiffness is important for maximum sprint velocity (Bret et al. 2002; Chelly and Denis 2001), a more extended knee angle at touchdown has been proposed for preventing vertical stiffness decrement throughout the 400-m race (Hobara et al. 2010).

Lower extremities' segment configuration is an important aspect for the coordination of the sprinting technique. In particular, φ_{thigh} reaches its minimum value during the support phase at the instant of take-off, the maximum height of the heeling during the backward swing is accomplished at the instant of touchdown, and the foot is

Fig. 1 Representative stick-figures of a participant's lower extremities at the instants of maximum flight height (a), touchdown (b), maximum flexion of the support leg's knee (c), and take-off (d) at the 125-m (solid lines) and 380-m (dashed lines) marks during the $400_{98\%}$, $400_{95\%}$, and $400_{93\%}$ tests



“actively” placed below the BCM, with the lower limbs being almost vertical to the ground (Schmolinsky 1983). Figure 1 presents the modifications of the running mechanics between the first to the second half of the 400-m tests. During the flight phase and the touchdown (Fig. 1a, b), a more “passive” leg placement was observed at the fatigued phase of the runs (380-m mark). S_{TD} increased with fatigue, as documented in the literature (Mero et al. 1988; Pinniger et al. 2000; Simonsen et al. 1985; Tupa et al. 1995). The swinging leg had to displace more during fatigue, since its hip and knee joints were more extended than in the unfatigued part of the tests (Fig. 1b, c). With fatigue, S_{TO} was smaller and a more extended knee for the support leg was noted for the take-off (Fig. 1d). In general, the values of the kinematic parameters were within the range of the values reported (Hanon and Gajer 2009, Hanon et al. 2010; Hobara et al. 2010; Mero et al. 1988; Nummela et al. 1992; Slawinski et al. 2008; Stukolov and Mansvetov 1981; Tupa et al. 1995) and the participants sustained the coordination pattern of the leg placement in fatiguing conditions, as also mentioned by Mero et al. (1988).

During the swing of the leg, the hip and the knee joints are flexed, so that the thigh and the shank are positioned closer to the hip axis of rotation, in order to decrease the moment of inertia and thus an efficient (quick and economical) for the given energy leg movement is accomplished. The biarticular thigh muscles (rectus femoris, biceps femoris), acting at both the hip and the knee joint, are evolved in the swing. During the backward swing, the knee is flexed by external forces, probably generated as reaction forces at take-off and by the remaining muscle tension due to the

muscles' relaxation time (Simonsen et al. 1985). During the forward swing of the thigh, the knee flexors function strenuously, in order to control the momentum of the leg and to prepare for an efficient foot placement (Thelen et al. 2005; Wood 1986; Yu et al. 2008). These biarticular thigh muscles (rectus femoris, biceps femoris) are the muscles that show the earliest signs of fatigue during running (Hanon et al. 2005). In fatigue, an inability to move the thigh as far forward in preparation for the touchdown, because biceps femoris has an earlier onset, while rectus femoris has an earlier cessation (Pinniger et al. 2000). Furthermore, the differences of the kinematic patterns shown in Fig. 1 could be attributed to the alterations of RS, which modify the lower limb joint angles and thus the function of the hamstring muscles (Thelen et al. 2005), whose muscle action is an important limiting factor in sprint running (Wiemann and Tidow 1995).

It is possible that the inability of leg muscles to generate enough force, in order to maintain sprint kinematics in the late stages of the 400-m run, is caused by fatigue-induced processes within the muscles. 400-m running strategy affects the changes in RS, reflecting fatigue-induced changes in the force generation capacity of the neuromuscular system (Nummela et al. 1996). Muscle fatigue was found to be related with lactate accumulation (Tesch et al. 1978) and force production is affected when muscle lactate increases to 10–15 mmol/L (Nummela et al. 1992). Lactic acidosis, indicated by high BLa, is considered to have an effect on the contractile machinery and thus being a cause of fatigue in the 400-m run (Nummela et al. 1992; Nummela et al. 1994). In the present study, significant correlations

were revealed between BL_a and the kinematics of the knee of the swing leg ($\theta_{\text{knee}_{\text{MIN}}}$, φ_{thigh} , and ω_{knee}) during the fatiguing stage of the 400_{93%} test. This could be an indication that lactic acidosis affects the muscle action of the muscles of the lower extremities, which consequently alter the stride kinematics, since BL_a, SL, T_c and T_f were significantly correlated.

The processes described above might have led to insufficient muscle preactivation and stiffness, resulting in inadequate eccentric muscle function and consequently resulting in a more flexed knee during the support phase. The higher knee flexion was highly correlated with BL_a in the 400_{98%} and 400_{95%} tests, with this larger knee flexion having an effect to the larger lowering of the BCM during fatigue (Mero et al. 1988; Sprague and Mann 1983). The consistency of H_{TO} and of the ankle joint kinematics revealed an effort to maintain the running kinematic pattern. The combination of the above factors and the need to generate enough impulse for the take-off, led to an increase of support time and to a more extended knee of the push-off leg at the instant of take-off. This extending contributed to a larger, highly correlated with lactate concentration, take-off angle. As for the swing leg, the fatigued thigh muscles' function could not result in the decrement of the moment of inertia, leading to an extended knee joint and eventually to a lower lifting of the swing leg's thigh at take-off (Pinniger et al. 2000). The reduced RS at the end of the 400-m could be a result of some or of a combination of the above circumstances. The fitness level of the participants could be a limiting factor, since better sprinters maintain their kinematic patterns more sufficiently during the run in fatiguing conditions (Sprague and Mann 1983).

Summarizing, fatigue prevention is an important factor for maintaining RS in the 400-m race (Nummela et al. 1992, 1994, 1996), with fatigue been an important factor when BL_a is above 20 mmol/L (Lacour et al. 1990). Muscle acidosis, revealed by the high peak BL_a, must be one of the causes of fatigue (Nummela et al. 1994). It is noted that a decrease of RS is evident after 200–300 m, when BL_a is about 10 mmol/L (Nummela et al. 1992). Other important factors that affect RS and its components are the CP depletion and the increase of the contribution of glycolysis to energy production (Hirvonen et al. 1992). In the last 100 m of the race, blood metabolic perturbations, which reflect changes in the muscles, could contribute to greater muscle fatigue (Hanon et al. 2010). In order to avoid fatiguing in the last stages of the effort, athletes should focus to adjust their pace so that they reach their critically low values of pH near the end of the race (Foster et al. 1994).

The main finding of the present study was that the optimum pacing tactic for the 400-m race was to run the first 200 m with an average speed of 93% of the personal best in the 200-m run. The limiting factor was that physical edu-

cation students participated in the study, so this percentage is suitable for individuals of the same level of physical fitness. However, this 93% percentage is almost identical with the recommended 94% of the personal best in the 200 m for a 400-m sprinter (Brooks 1977, cited in Gambetta 1978; Jarver 2005). It could be possible that for highly trained athletes, who have larger creatine phosphokinase activity levels (Ohkuwa et al. 1984b) and better alactic anaerobic capacity, the ideal first 200-m pacing strategy might be about 94–95% of the personal best of the 200-m dash. However, some of the changes of the running mechanics have been found to be independent of athletic capability (Nummela et al. 1996), suggesting that the fatigue-induced changes observed in the present study could be also present in high level athletes.

Training programs for the 400-m event aim at maximizing the anaerobic lactic capacity for energy production. The contribution of the lactate system to energy production depends on exercise intensity (speed), duration and rest intervals (Saraslanidis et al. 2009). Athletes may improve their 400-m performance by improving their running economy during high-speed running, thus adapting the more effective running technique (Reis and Miguel 2007). Set pace 300-m runs and rhythm running of various distances have been proposed as well (Smith 1994). Furthermore, intermittent workouts such as 2 × 200 m with a high RS have been found superior to continuous runs of the same total distance with respect to the ability to increase the energy production through the lactate system. Therefore, these 2 × 200 m intermittent runs were recommended for 400-m athletes in order to develop specific (speed) endurance (Saraslanidis et al. 2009). Finally, acclimatization to altitude and normoxic training also improves 400-m running performance (Nummela and Rusko 2000). Based on the results of the present study, all these training methods for the development of performance in the 400-m sprint should take into consideration the optimum first 200 m pacing strategy, in order to be as effective as possible.

Conclusion

The main finding of the present study was that the optimum pacing tactic during the first half of the 400-m race was to run the first 200 m with an average speed of 93% of the personal best in the 200-m dash, since the fastest 400-m race was run with the smallest 200-m differential, i.e. using the 400_{93%} pacing strategy. The effort for running the first half of the 400-m race must result in a sustained delay of the appearance of a high lactate accumulation for as far as possible in the race. Therefore, the development of specific speed endurance is essential for 400-m athletes. Future research must evaluate a greater range of intensities (%) of

the athlete's personal best in the 200-m dash), in order to define the optimum first 200-m pacing strategy in the 400-m race.

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