Model for Individual Pacing Strategies in the 400 Metres

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In Memoriam et ad Honorem Prof. Carlo Vittori

ABSTRACT

Coaches have traditionally used the athlete's personal best time for 200m as a reference to establish the ideal 200m split that will minimize the loss of velocity in the final 100m of a 400m race. However, this method has certain practical limitations as evidenced at the elite level by the two most recent World records in the men's 400m race – 43.18 by Michael Johnson (USA) in 1999 and 43.03 by Wade Van Niekerk (RSA) in 2016 – which were achieved with very different pacing strategies. This article describes a model for individualising the pacing strategy for the 400m tested in the early 1990s with elite female Spanish 400m runners, including two-time European indoor champion Sandra Myers. The model utilises test data such as the maximum velocity achieved after accelerating for 30m (Vmax30), the Specific Useful Strength Index (SUSI), and kinematic variables obtained from 2x300m tests, which are compared to actual racing data. The result is a customised strategy aimed at allowing the athlete to act voluntarily within the optimal stride length/frequency ratio during competition and at providing training guidance and monitoring.

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Introduction

Athletics coaches have traditionally considered the 400m to be a speed-endurance event and most agree that it is among the most physiologically and psychologically demanding of all the athletic disciplines[1]. According to the well-respected Italian coach Carlo Vittori, success in the 400m requires a combination of strength, speed and endurance, and the appropriate distribution of effort during the race[2].

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[1] Carlo Vittori (1931-2015): One of the fathers of modern sprint training. As Italy's national sprints coach, he coached athletes who won a total of 47 international medals and achieved four World records. Mennea, Tilli, Pavoni, Fiasconaro, Sabia, Semionato, and Urlo, among others, trained under his direction. He served as an expert consultant for sprints and relays in Spain from 1986 to 1996

The initial effort and velocity in a 400m race determine energy availability with respect to time, and the runner's ability to sustain velocity in the last 100m of the race. A distribution of effort that is as close as possible to the metabolic, neuromuscular and psychological potential of each individual athlete allows the best use of the energy available throughout the entire race.

The main purpose of this paper is to present a model that responds to the needs of 400m training. This model has not been published before, but it has been implemented with good performance results. It is a model for estimating individual strategies for times, velocities and/or stride length and frequency in each section of the 400m, while also being an instrument for guidance and control of specific endurance and strength training. In addition, this model tries to simultaneously monitor metabolic and mechanical training parameters for each athlete's fitness level throughout the season. It is suitable for both national-level and international-level athletes.

Background

Metabolic aspects

At an international level, the duration of the 400m races ranges from 44 to 47 sec for men (an average speed of over 8.5 m/sec) and from 49 to 52 sec for women (an average speed of over 7.7 m/sec). From the muscular perspective, the running pattern deteriorates during the race[3] while neuromuscular activation and muscle function have been shown to be impaired after the event[4]. The effort in such demanding conditions calls for maximum output from both the anaerobic and aerobic energy metabolisms, as the phosphocreatine (PCr) stores are almost completely exhausted before the end of the race[5]. Muscle and blood lactate concentrations can reach values of 15 to 25 mmol/l and oxygen consumption (VO_2) reaches near-maximum individual levels[6].

The main energy source during the first 100m of a 400m race is PCr breakdown, which supplies the energy for ATP resynthesis. The second ATP-delivery system (the anaerobic-glycolytic pathway) provides the main portion of the required energy over the next 200m. As the contribution of these systems becomes limited in the last 100m, the running velocity drops and the aerobic metabolism becomes more important. Evidence shows that the aerobic metabolism provides, on average, ~41-43% (male) and ~37-45% (female) of the total energy needed to run the 400m while the anaerobic metabolism provides ~57-59% (male) and ~55-63% (female)[6–8].

The crossing-over point in the predominance of energy yield from the anaerobic mechanisms to the somewhat more aerobic occurs approximately 30 sec after the beginning of intense exercise[6,9], coinciding with the highest rate of velocity loss in the 400m race[10]. In terms of energetics, 400m running involves maximal oxygen uptake[11] but it also requires a significant energy supply from the nonoxidative glycolytic pathway[11,12]. Accordingly, elevated post-race muscle and blood lactate (and proton) concentrations have been reported[5,11–13]. Interestingly, post-exercise blood lactate concentrations have been shown to correlate positively with average velocity during a 400m event[12]. It was estimated that the energy substrates used to resynthesize ATP are mostly PCr stores and muscle glycogen (anaerobic and aerobic glycolysis)[12,14]. Maximum oxygen consumption (VO_2max) values of over 60 ml/min·kg (78 ml/min·kg in a European indoor champion, unpublished personal data) have been recorded in international-level 400m athletes[15].

When the race was studied in 100m segments, HIRVONEN et al. (1992) found that in the first 100m, muscle PCr decreased by almost half, and muscle lactate increased relative to resting levels by one to four times. After 200m PCr greatly decreased but reserves were not completely depleted, while lactate concentration reached its maximum value. At the end of the race PCr had decreased by 89%. After the race muscle lactate concentration reached ~18–25 mmol/l on average, acidifying both muscle tissue and blood[5,12,16-18]. Phosphofructokinase (PFK) blocks the glucose to lactic acid transformation reaction, supporting the drop in hydrogen potential (pH). Reflecting this, the race pattern of elite athletes shows a great reduction in velocity over the last 100m segment[19,20].

When comparing the peak rate of VO_2 change over time, HANON & THOMAS observed a decrease up to 16%, showing a significant correlation with the maximum blood lactate concentration[56]. When comparing peak VO_2 of 400m runners taken in a 300m run at 400m race pace, and during a 400m race, HANON et al. observed a significant decrease in peak VO_2 in all subjects during the last 100m, most likely related to an increase in fatigue[11]. CALBET et al. suggest that the limitation to VO_2max during prolonged sprint lies in the mechanisms regulating mitochondrial respiration, which is inhibited by 50 to 65%[21]. MORALES-ALAMO et al. have reported that towards the end of progressive exercise to exhaustion there is still a considerable functional reserve for generating muscular energy, i.e., the resynthesis capacity of the remaining ATP is higher than the ATP consumption rate. Nonetheless, the loss of efficiency at the end of maximal excercise is not due to lactate accumulation and the associated muscle acidification, suggesting that it depends more on central than peripheral mechanisms[22]. Although neither aerobic metabolism nor glycolysis are blocked at exhaustion, the rate of ATP production is lower than required to maintain high power output.

Kinematic aspects

In a 400m race, the stride frequency/amplitude ratio attain high values and there is considerable interdependence of efficiency between the technique, or useful force, and the metabolism involved. This efficiency decreases when the stretch-shortening cycle (SSC) is affected in the final race stages due to peripheral and central alterations of the muscle contraction mechanism. NUMMELA et al. recorded neural activation (EMG) and stride characteristics at 100, 200, 300, and 400m at 400m race pace, concluding that the generation of leg muscle strength was maintained between 200 and 300m and then decreased rapidly affecting the running velocity, and that this was due to fatigue caused by intra-muscular processes[23]. It is now known that in adapted subjects the reduction of maximum voluntary contraction (MVC) in a prolonged sprint test is primarily due to the central nervous system (CNS) mechanisms[24]. The CNS regulates and harmonises all functions affecting performance[25,26] by controlling the afferent and efferent stimuli that regulate homeostasis during intense, long-lasting efforts[27,28]. These factors all contribute to the increased perceived effort by the athlete, which would finally adjust mechanical demands and energy conservation. TUCKER suggested that this central control is based on a mechanism of anticipation provoked by perceived effort, and that the athlete can control the effort rate and regulate energy expenditure[29].

In 400m athletes, the effects of fatigue on stride kinematic parameters appear to occur at the point where race velocity begins to decrease. NUMMELA et al. analysed the effects of different partial-pass velocity strategies, and identified several velocity loss profiles[30]. HANON & GAJER compared the mean stride amplitude (length) and frequency in the sector corresponding to in the highest velocity on a 400m race with (125-175m) and at the end of the race (325-375m), showing a significant decrease in stride length (11.5±3.7%) and frequency (5.1±3.8%)[31]. These findings suggest that the largest difference in performance between world-class and lower-level athletes lies in stride length.

The best possible fit between the capacity to produce and transmit energy, in terms of both physiological and kinematic factors, would consist of a strategy that allows the athlete to express the highest level of energy delivery with the minimum level of fatigue during the race. Figure 1 summarises the complexity of the factors (bioenergetic, information, psychosocial) and interactions explaining fatigue as a limiting factor of 400m performance.

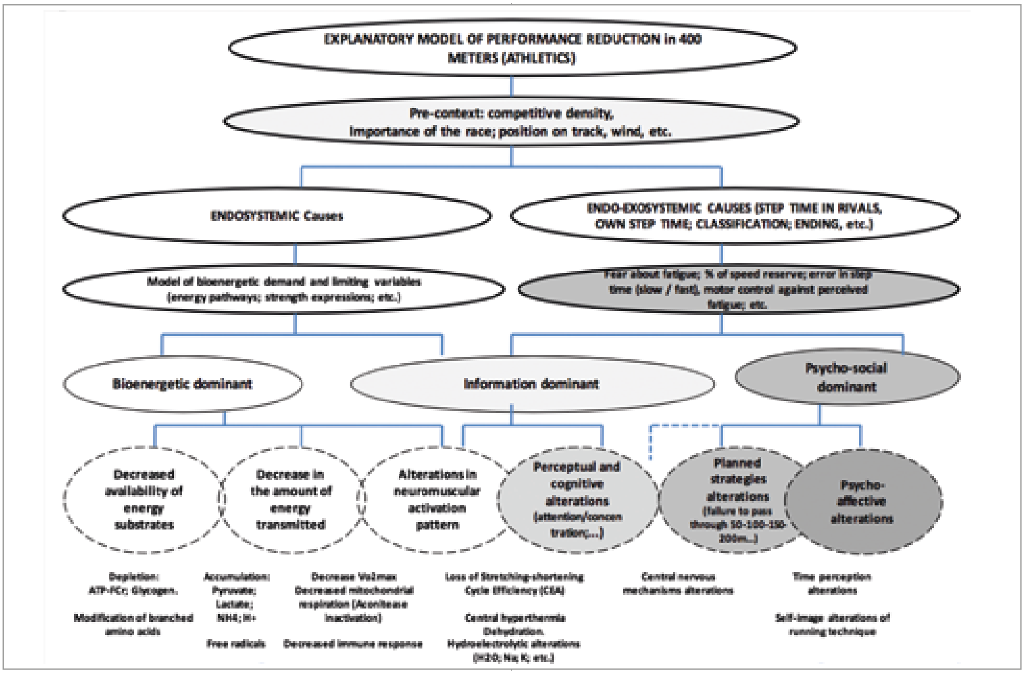


Figure 1: Explanatory model of the complex phenomenon of fatigue as a limiting factor of performance in 400m races

Speed distribution strategy

Research on 400m racing and training has led to many studies on bioenergetic parameters and some on biomechanical ones, but little research has been conducted on control and decision mechanisms for individual speed distribution and energy expenditure during the race.

The two most recent world records in the men's 400m - 43.18 by Johnson (USA) in 1999 and 43.03 by Van Niekerk (RSA) - in 2016 were achieved using very different pacing strategies. The indicator most commonly used to indentify pacing strategy is the percentage difference between the time for the athlete to reach the halfway point (200m) and his/her personal best time over 200m. This percentage was 90% for Johnson's record and 95% for Van Niekrek's[32], which suggests that ~93% may be considered as "ideal". However, an individual strategy model needs to be analysed deeply and cannot be based merely on the athlete's best time in a 200m race.

Based on analysis of the velocity of each 100m segment in world-class 400m competitions conducted by the IAAF[33] and then by BRÜGGEMANN & GLAD[19], HANON & GAJER, observed that maximum velocity was reached between 100 and 200m: 9.66 m/sec (men) and 8.62 m/sec (women) in the 1987 IAAF World Championships in Athletics (WCA), and 9.63 m/sec (men) and 8.61 m/sec (women) in the 1988 Olympic Games. Velocity begins to decrease significantly after 200m, and especially in the last 100m. Between 300m and the finish line, it decreases by around 15% relative to the average in the 200m to 300m section. In the last 100m of the race there is a systematic decrease in velocity resulting in a reduction of 13-20% of the maximum. Overall, the average velocity in the 400m is approximately 80% of the athlete's maximum possible velocity[31].

HANON & GAJER also observed that maximum velocity in the 400m was obtained with a stride frequency of 3.74 Hz and a stride length of 1.98m in females completing the distance in 53.8 sec[31], while NUMMELA et al. found 3.48 Hz and 2.28m in males with a time of 52.8 sec[23]. The decrease in velocity was related to decreases in both stride frequency and length. The world's best 400m runners are characterised by a pacing strategy that is more aggressive and risky than that used by lower-level runners (96% of their personal best time over 200m), and by a longer stride length.

Analysing 400m races at the highest level in the female category, it appears that there has been little progress or innovation in racing strategy, with times remaining steady (Table 1). In the 1991 IAAF World Championships in Athletics 400m races, two of the three best times over the last 100m were placed second and third at the end of the race; in the 1997 IAAF World Championships in Athletics, the first three athletes were also the fastest in the last 100m; in the 2016 Olympic Games the second and third classified were the fastest athletes in the final 100m section.

Sustaining a high relative velocity for as long as possible[35] is an important aim in choosing a pacing strategy, but it is assumed that in a 400m race it is not possible to complete the entire race at maximum effort[36]. Some recommend a high-velocity start[10], while others recommend a more contained and progressive start in an effort to delay rapid lactate accumulation[37].

SARASLANIDIS et al., researched how to estimate the best pacing strategy over 400m but with non-athletes (healthy adults). They analysed the effect of different pacing strategies on blood lactate and biomechanical parameters in the first 200m of a 400m test. They took the personal best for each participant at 200m (200max) as a reference then had the subjects run several 400m tests passing at 200m at 93, 95 and 98% of their personal 200max. The best result over 400m was when 200m velocity was 93% of 200max; this gave the shortest time difference between the first and second half of the 400m. However, overall performance was not significantly different between the three strategies, which showed that the lowest values for speed, frequency, and stride length, measured when passing through the 380m mark, were significantly lower than the values measured when passing through the 125m mark. In the pacing strategy using 93% of the 200max speed, the stride frequency and length decreased approximately 2.4% and 9.2%, respectively. These results are consistent with long-standing suggestions that optimal mid-point pace is 93% of the personal best[40]. This trend has greatly influenced training approaches, assuming that if the personal record for 200m is improved, performance will also improve over 400m[39,41,42].

Only a few of the world's top 400m runners have achieved a 200m split at a pace that is higher than 96% of their personal best over 200m[38]. WILLIS & BURKETT analysed the effect of the initial race speed on performance at 400m[36]. The correlation found between the ability to sustain speed between 200 and 300m and the final 400m time was significant, coinciding with the findings of NUMMELA et al.[20] and the tendency of coaches to recommend starting the 400m at high velocity[10]. In

Mean	WCA 1991	WCA 1997	Olympic Games 2016
300m (sec)	36.24	36.19	35.94
300 to 400m (sec)	14.10	13.96	14.44
300m (m/sec)	8.28	8.29	8.35
300 to 400m (m/sec)	7.09	7.16	6.93
400m (sec)	50.34	50.31	50.38

Table 1: Average segment times and velocities of the first three athletes in the women’s 400m finals of two IAAF World Championships in Athletics (1991 and 1997) and 2016 Olympic Games

addition, WILLIS & BURKETT found differences between men and women with respect to the pacing strategy, where women chose a faster pace than men in relation to their personal best 200m time[36].

The choice of initial race velocity will determine the pace at which energy is delivered and, thus, the ability to sustain velocity for a longer period of time[43]. The optimal distribution of energy throughout the 400m will favour the use of a larger amount of high-energy phosphates, increased activity of glucolytic enzymes (PFK and LDH), and acceleration of VO_2 kinetics. Pyruvate is transformed into lactate by the action of LDH, so glucolysis contributes much more in the second half of the race, and after 300m athletes tend to delay or limit the loss of useful force in each stride. Consequently, the stride length does not drastically decrease, as shown by MORIN et al.[44] When fatigue occurs, the loss of frequency is related to stiffness due to increased activity of the femoral biceps and external gastrocnemius[45]. NUMMELA et al. recorded an increase in EMG activity in the last phase of 400m runs, probably to compensate for the negative influence of biochemical and metabolic factors on muscle contractibility. In addition, they recorded a 39% performance loss in a drop jump post-400m run at maximum intensity[23].

Methodology

To begin, this is an *ex post facto* investigation that cannot establish causal relationships. In practice, a model consisting of three tests was explored together with 400m observations during competition. We suggest that the variables recorded and observed in each test provide useful information on the estimation of individual pacing strategies for suitable intermediate times or speeds, and for optimisation of stride lenght and frequency in the final 100m. The measurements and observations also made it possible to identify some basic parameters on which to design the ideal pace over the 400m and to optimise competition results.

Data were analysed for the eight female athletes in the Spanish 400m and 4x400m relay teams who participated in official international competitions and used the model

	Age (y)	Weight (kg)	t 30m (sec)	t 60m (sec)	SJ (cm)	CMJ (cm)	CMJA (cm)	1RJ (cm)
Mean	24.88	55.33	4.19	7.57	39.16	43.44	49.71	47.51
SD	3.60	5.47	0.11	0.22	3.27	3.90	4.69	2.82
Range	20-30	50-63	4.03-4.30	7.27-7.82	35.7-44.7	38.6-49.4	41.9-56.1	43.55-51.8

Table 2: Anthropometry, sprinting performance (30 and 60m from standing position), and performance in a battery of vertical jumps (Squat, Countermouvement with/without Arms swing, and Rebound) for the 1991 Spanish women's 400m team

	200m Indoor (sec)	400m Indoor (sec)	200m Outdoor (sec)	400m Outdoor (sec)
Mean (SD)	24.20 (0.66)	53.69 (1.43)	23.83 (0.74)	52.78 (1.53)
Range	22.81–24.92	50.99–54.98	22.38–24.72	49.67–54.29

Table 3: Performance in 200 and 400m for the 1991 Spanish women's 400m team

National Records (1986-2018)				
Outdoor			**Indoor**	
400m	**49.67**	**1991** (Myers)	**50.99**	**1991** (Myers)
4x400m	**3:27.57**	**1991: SPAIN** (Merino, Lacambra, Myers, Ferrer)	**3:31.86**	**1991: SPAIN** (Myers, Merino, Ferrer, Lahoz)
Top-3 Averages (1986-1992 / 1993-2016)				
Outdoor			**Indoor**	
400m	**51.00**	**1986-1992** (Myers, Lacambra, Merino)	**51.94**	**1986-1992** (Myers, Merino, Pérez)
400m	**51.60**	**1993-2016** (Terrero, Bokesa, Carabali)	**53.01**	**1993-2016** (Terrero, Bokesa, Reyes)
Outdoor				
4x400m	**3:28.69**	**1986-1992** (Myers, Merino, Lacambra, Ferrer, Lahoz, Pérez, Pujol)		
4x400m	**3:31.66**	**1993-2016** (Myers, Lahoz, Alba, Recio, Olivero, Martínez, Bravo Reyes, Antonio, Carabali)		

Table 4: Spanish women's national 400m and 4x400m records in 2016, and average best of the top-three athletes/relay teams 1986-1992 and 1993-2016 Spanish women's 400m team

presented during preparation for the 1992 Olympic Games in Barcelona. Their performances at 30 and 60m and on a battery of vertical jumping tests (Table 2), as well as in official 200m and 400m races (Table 3) help calibrate the international level of this sample.

During the training cycles and competitions analysed, some of the international results were very positive. For example, some of the women were on the Spanish teams that reached the final of the 4x400m relay at the world championshops (indoor and outdoor) for the first times. In the 400m, one athlete was a finalist at the IAAF World U20 Championship and placed 4th at the European Athletics Indoor Championships. The best performing athlete won a gold medal (1992 European Athletics Indoor Championships), a silver medal (1991 IAAF World Indoor Championships), and a bronze medal (1991 IAAF World Championships in Athletics). The Spanish national records current in 2016 are from that Olympic cycle, and the average of the three best Spanish times between 1986 and 1992 is better than the same average from 1993 to 2016 (Table 4).

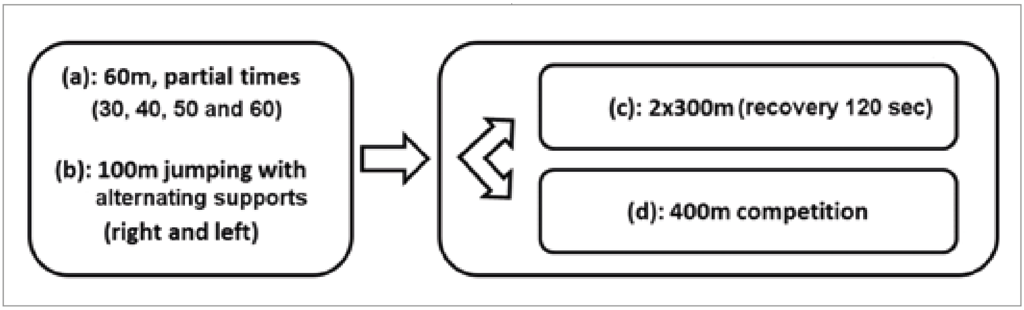


Figure 2: A model for individual pacing strategy and training control ((a) sprint tests over 30 to 60m; (b) 100m jumping test (b); and (c) 2x300m with 120 sec recovery (Data are compared to 400m in competition (d))

Procedure

Tests were performed every 4-6 weeks during the specific preparation and precompetitive cycle (Figure 2). On the first day, the atheltes did three repetitions of 60m, and times were recorded at the 30, 40, 50 and 60m marks, as shown in Figure 2 –a-, followed by three repetitions of 100m jumping with alternative supports at a speed that allowed the participant to make maximum length jumps (Figure 2 –b-).

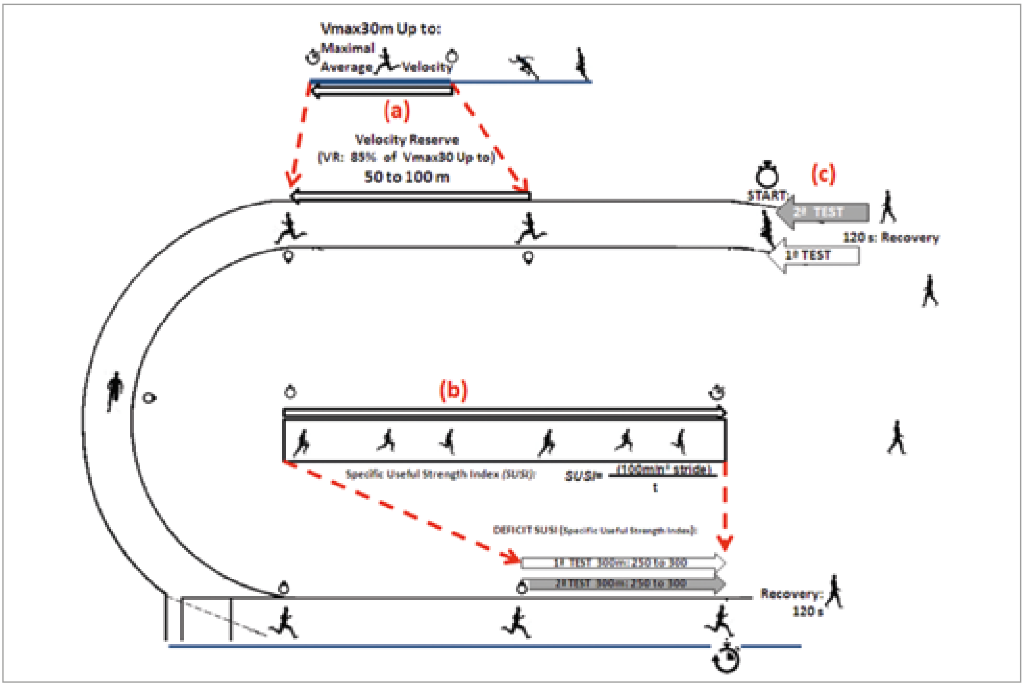


Figure 3: Model for 400m race strategy and training control (The average maximum velocity at 30m (a), and after accelerating for a another 30m, and the difference in the peak velocity (PKV) in the 50m section of the 2x300m test (c) are related. The Specific Useful Strength Index (SUSI) obtained in the 100m jumping run (b), and the same index obtained in the last sections of each of the 2x300m with 120 sec recovery (c) are compared. The average maximum velocities, velocity losses and stride length and frequency were analysed and compared with the different 50m sections of each 2x300m run (c).)

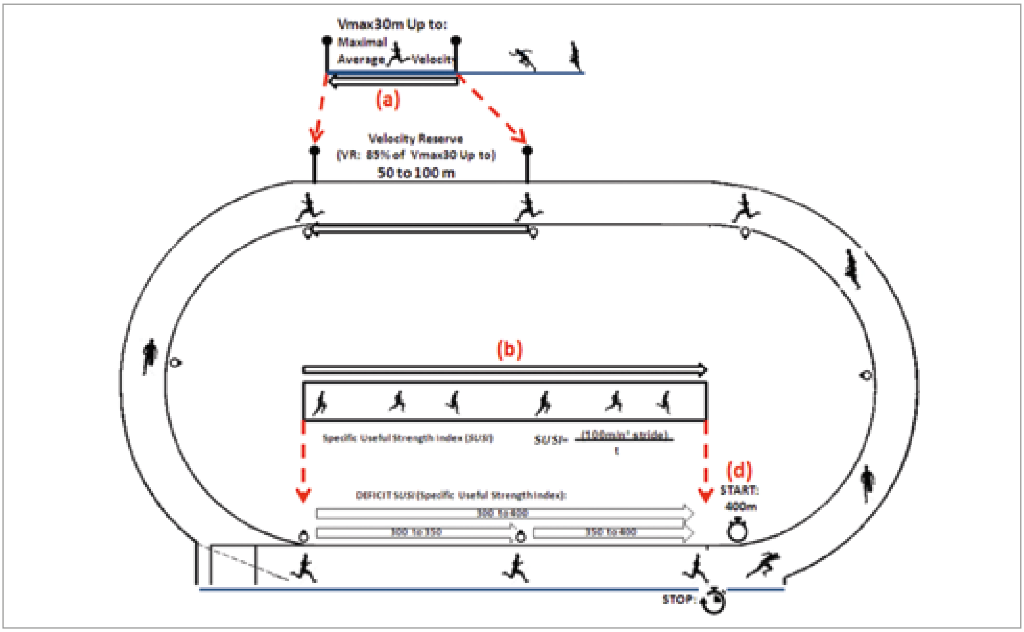


Figure 4: Model for the individualised 400m race strategy (The average maximum velocity at 30m (Vmax30m) and after accelerating for another 30m (a), the Specific Useful Strength Index (SUSI) obtained in the 100m jumping (b), and the average maximum velocities, velocity losses and stride length in a number of 400m competitions (d) were related and compared.)

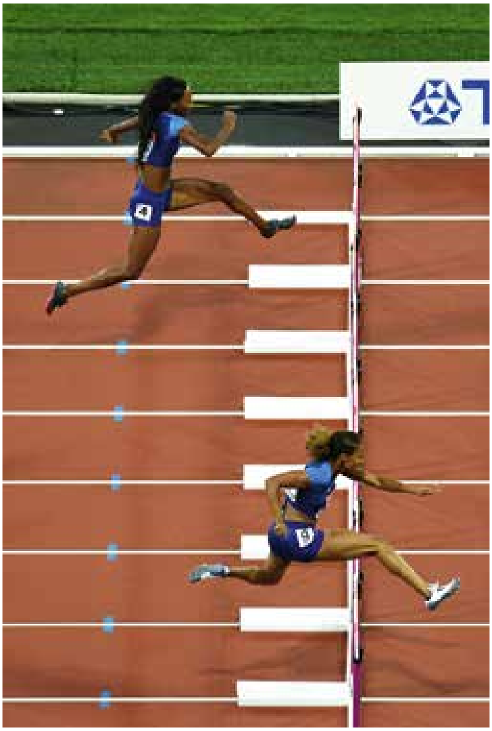
In all runs, the total time was recorded and the total number of strides was counted. This test and the derived Specific Useful Strength Index (SUSI) were suggested by VITTORI as [SUSI = (100 / # strides) / t]^2.

On the second day, a 2x300m test was performed (Figure 3) with 120 sec recovery pause (c). The strides were timed and counted for each partial distance.

During the competition cycle, tests (a) and (b) were carried out to monitor the training effects (Figure 4) and the energy distribution strategy (partial race velocities) in the 400m competition (d).

Equipment

All tests were conducted on the certified 400m athletics track (synthetic surface) at the High-Performance Centre (CAR Sant Cugat, Barcelona). Timing was done using Heuer-TAG photoelectric cells and videotape recording.



Results

The group of women athletes from the Spanish 400m team achieved a Vmax30m of up to 8.88 m/sec in test (a) (Figure 2), and a Specific Useful Strength Index (SUSI) of 16.84 in test (b). Test (c) (2x300m) produced a maximum blood lactate of 18.3 mmol/l, with a velocity loss of 4.3% between repetitions (Table 5).

In the 2x300m test, for both repetitions (Table 6), the maximum group values for each 50m section (mean time, velocity, stride frequency and stride lengths) occurred in the sector between 50 and 100m. For the stride kinematic parameters of length and frequency, there was a 12% loss with respect to this maximum value in the final sector from 250 to 300m. Comparing these parameters between the first and second repetition, there was an average velocity loss of 3.7% and 5% of PKV in the sector from 50 to 100m in the second 300m test.

With respect to the average stride length in the second 300m test, there was only a 1% loss compared to the first, but there were losses of 3.2% in the sector from 50 to 100m, and 3.1% for the last sector (250-300m). Average stride frequency was not a limiting factor for speed loss at the end of the 2x300m test, since the frequency decrease never reached 1%.

	a)	b)	c)	c)	c)
	Vmax 30m (m/sec)	**SUSI*** (length average /sec)	**Mean V** 1st 300m (m/sec)	**Mean V** 2nd 300m (m/sec)	**Lactate** max (mmol/l)
Mean	8.88	16.84	7.02	6.76	18.30
SD	0.29	1.39	0.20	0.30	2.60
Range	8.52–9.26	15.08–18.47	6.82–7.27	6.49–7.32	14.7–22.1

*__SUSI=__ (100/strides)/seconds

Table 5: Results of the training control tests for 400m race strategy in the Spanish women's 400m team: (a) Vmax30m; (b) SUSI (Specific Useful Strength Index); (c) 2x300m test with 120 sec recovery

Distance mark	**First 300m**				**Second 300m**			
	T (s)	**V (m/s)**	**f (hz)**	**l (m)**	**T (s)**	**v (m/s)**	**f (hz)**	**l (m)**
0 to 300m	42.77	7.02	3.51	1.96	44.42	6.76	3.46	1.94
50 to 100m	6.38	7.84	3.59	2.19	6.74	7.42	3.50	2.12
250 to 300m	7.29	6.86	3.55	1.93	7.59	6.59	3.52	1.87

Table 6: Mean parameters in the 2x300m tests (with 120 sec recovery) for the Spanish women's team (T = time, V = velocity, f = stride frequency, l = stride length)

Considering Vmax Up to (Vmax30m) (test a) with respect to the maximum peak velocity (PKV), 88.3% was used in the first repetition (Table 7), leaving a velocity reserve (RV) in the first repetition of 11.7%. In this first repetition, it was found that the Specific Useful Strength Index (SUSI) was at maximum (100%) in the 50-100m segment, and decreased by 21.2% in the final sector from 250 to 300m. In the second repetition, a lower percentage of the Vmax Up to PKV was recorded and the SUSI also had a lower value (94.2%). In the two repetitions, the loss of specific useful force was very high in the final sector from 250 to 300m, and highest in the second repetition (Table 7).

The average values for stride length (Figure 5, left) and stride frequency in each 50m section (Figure 5, right) showed similar trends in the 2x300m repetitions. The stride length profile decreased (100-150m) after reaching its maximum value (50-100m), increased again (more in the first repetition) to 200-250m, and dropped drastically in the last section. The stride frequency in the second repetition increased again from the middle of the run (150m) and reached its maximum in the last section, while in the first repetition it increased somewhat later (200m) and reached the second highest frequency in the last section (250-300m).

Distance mark	**First 300m**		**Second 300m**	
	(a)	**(b)**	**(a)**	**(b)**
	% Vmax30m	**% SUSI**	**% Vmax30m**	**% SUSI**
(c) 50 to 100m	88.3%	100%	83.6%	94.2%
(c) 250 to 300m	77.3%	78.8%	74.2%	73.2%

Table 7: Average results of the 2x300m tests (recovery 120 sec) for the Spanish women's team (Comparisons are % of peak velocity (50-100m, test c) with maximum velocity (Vmax30m Up to, test a), and % of Specific Useful Strength Index (SUSI) in the 100m jumping (test b) with and in the 250-300m section of each repetition (test c).)

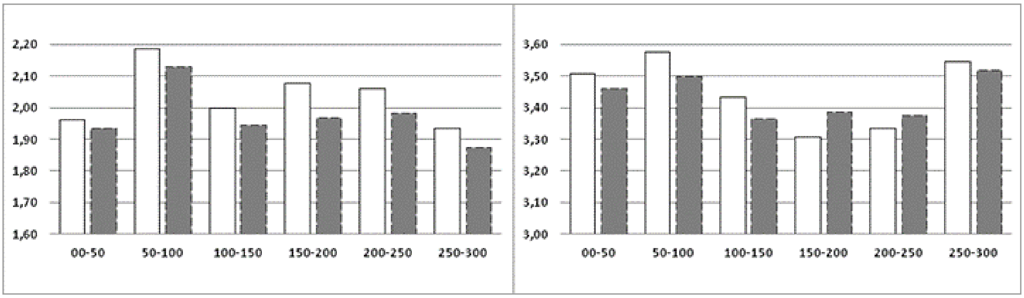


Figure 5: Stride length (left) and stride frequency (right) averages every 50m in the first (white) and second (grey) repetitions of the 2x300m test (recovery 120 sec) by the 1991 Spanish women's 400m team

Discussion

The most common reference for establishing pacing or energy consumption strategies for 400m races is the personal best time over 200m in competition. By using only this reference, training decisions to develop optimal individual strategies cannot be started until the athlete has almost reached his/her best physical condition. The model presented in this study was designed and applied to deal with this information deficit. It allows the evaluation of an athlete in any conditioning level using the Vmax Up to (Vmax30m) and the reserve velocity (VR) for the fastest section in specific race-pace workouts, as well as estimating the anaerobic capacity and the specific useful strength. The model also makes it possible to assess the impact of fatigue on kinematic variables (speed, stride length and stride frequency) in each of the 50m sections, and enables monitoring specific training at the end of each mesocycle. Using the 100m alternating support jumping test, it is possible to estimate a reference index of useful strength (SUSI) and to compare it with the different 2x300m sections where fatigue will damage neuromuscular activation to a greater extent, and with the last sections a 400m race.

The model also allows us to evaluate training for special endurance, since we will be able to check, for example, the dynamics of velocity loss in each section of the first 300m to asess the effects of anaerobic training in short, maximum intensity races that, organised in series (VITTORI et al.), would increase the reserves of ATP-PCr, enzymatic activity and peripheral aerobic energy consumption[46]. We can also observe the impact of anaerobic lactic training by comparing the velocity loss in each 50m section of the second 300m repetition with the first one. Finally, we can obtain the velocity percentage change in the last 200m of each 300m test, with respect to the athlete's personal best time over 200m. For example, in the data presented for one of the tests of the women's Spanish team, the group average was 85% in the first 300m repetition and 82% in the second one. With this last comparison, it is possible to evaluate the direction of training in races with greater glycolytic requirements, which increase the glycogen reserves, and glucolytic and oxidative enzyme activity, as well as the power of the aerobic system[48].

We recorded an average top velocity of 8.88 m/sec for the female Spanish specialists (52.78 sec), which is consistent with data reported by NUMMELA et al. (8.78 m/sec in female 400m specialists (51.89 sec)[49]. In both cases, these are maximum velocities (Vmax30m) which, when managing the necessary speed reserve for the 400m competition (see PKV) means both samples are below the velocity development required for placing finalist in World Championships or Olympic races. For example, in the 1997 IAAF World Championships in Athletics, the average velocity in the 100-150m section was 8.97 m/sec, which suggests that these runners would have a Vmax30m value approaching 10 m/sec.

In several studies[19,50,51] the velocity difference in the last sector from the peak value in 400m races ranges from 13 to 25%. The average difference for the 400m finalists in the 1997 IAAF World Championships in Athletics was 23.2%. Johnson, in his 1999 world record run, showed a difference of 12.5%; in his 2016 World record Van Niekrek had a difference of 18.5%. The results presented here for the female Spanish athletes in the 2x300m test showed a speed loss of 12.4% in the first 300m repetition and 11.4% in the second one.

HANNON et al. recorded a maximum blood lactate value of 16.8 mmol/l in a single 300m test, and maximum of 22.0 mmol/l in a 400m test[11]. In the 2x300m test for female Spanish athletes the average was 18.7 mmol/l, which was in line with the literature for 400m tests[5,12,16,17,18]. In an official 400m competition for the Spanish team, values of 16 to 23 mmol/l were recorded.

HANON & GAJER observed that the maximum velocity in females was obtained with a stride frequency of 3.74 Hz and a stride length of 1.98m when to completing 400m in 53.8 sec[31]. In the sector of maximum speed in the 2x300m test, the Spanish team recorded 3.59

Hz and 2.12m in the first repetition, and 3.50 Hz and 2.12m in the second one. Nevertheless, the averages in each repetition were 3.52 Hz and 1.96m and 3.46 Hz and 1.94m, respectively. HANON & GAJER also reported a stride length loss of 11.5% between the peak and the final sector in the 400m race. The Spanish athletes in the 2x300m tests presented here lost 11.5% of stride length in the first repetition, and 12% in the second one. However, the stride frequency increased in the last section of each 300m test, returning almost to its peak value for the 50-100m section in the first 300m (99.1%) and slightly exceeding it in the second (100.6%).

HOBARA et al. studied vertical stiffness and its relationship with the parameters of velocity, frequency, and stride length performance in a 400m race. The vertical stiffness and race velocity reached their maximum values in the range of 50-100m, and decreased systematically from the middle to the end of the race. Comparing the maximum values of vertical stiffness and race speed with those of the last 50m, there was a decrease of 40% and 25% respectively[51].

When calculating the SUSI index in the World records of Johnson and Van Niekerk, in addition to the silver and bronze medallists – Kirani James (GRN) and LaShawn Merrit (USA) – in the 2016 Olympic Games, values between 17.7 and 19.8% of specific useful strength loss were found. In our study, the athletes in the 2x300m test lost 21-26.5% in the last 50m section (first and second repetition, respectively).

In the two repetitions of the 2x300m test, after having reached the PKV (50-100m), the Spanish team athletes' average shows an attempt to maintain velocity at the expense of stride length (100 to 250m), although it never reaches the highest average (50-100m). When it falls again (250-300m), it is the stride frequency that "holds" the velocity drop, reaching an average value very close to the maximum in the first 300m test, and even higher in the second one. This data reinforces the hypothesis that, at least in the case of women, a "stiffness reserve" may exist.

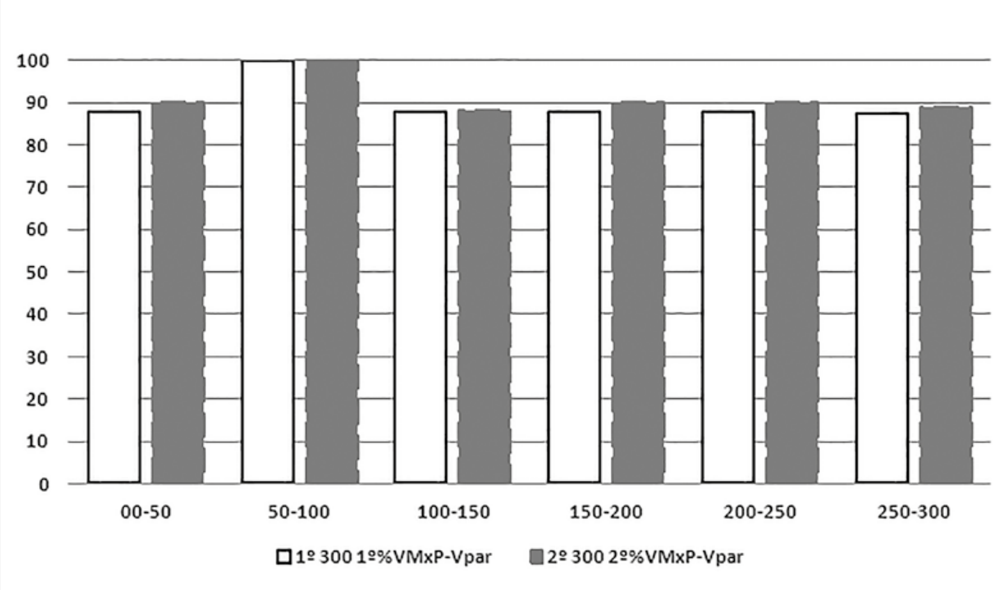


Figure 6: Percentage (%) of average velocity every 50m compared to the peak velocity (PKV, 100%) in the 2x300m tests (120 sec recovery), for the 1991 Spanish women's 400m team

In the sample presented here, the highest rate of velocity loss in the two repetitions of the 2x300m test occurred from 100 to 150m (21-22 sec of high-intensity effort). In 400m races, the highest rate of velocity loss was found around 30 sec into the race[10]. It is possible that in order to reach PKV, in both 300m tests, there is a rapid decrease in PCr, which could cause an increase in the speed of the VO$_2$ kinetics response (VO$_2$)[47]. Also, a more accentuated "crossover point" (around 30 sec of intense exercise) has been observed, especially in the second part of the second 300m[6,9].

Considering the average values for the Spanish team, estimating the PKV as 100% of the average intra-repetition velocity (Figure 6), we can see that in all sections for the second 300m test, the athletes maintained a velocity slightly closer to the PKV than in the first 300m repetition. One explanation is that the RV in the first 300m was 11.8%, whereas in the second it was higher (16.4%).

The present results support the idea that the 2x300m test causes metabolic, mechanical and neurophysiological conditions very close to the competition demands of the 400m without requiring athletes to be in their best anaerobic condition. The 2x300m test can be used at various times and training periods. The athlete has to run the 300m twice with a short recovery time (120 sec), so the psychological conditions to deal with the control of energy consumption strategy, pace times and speeds, are more easily under volitional control.

By observing the average stride length for different groups and athletes in each 50m section in the 2x300m test, we confirm the need to

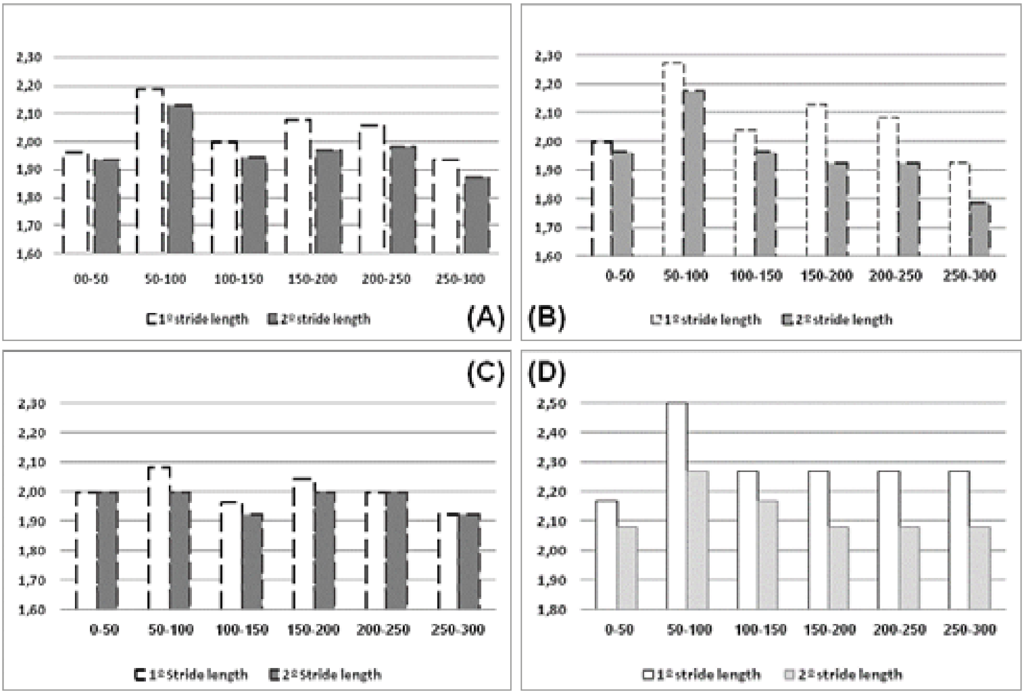


Figure 7: Evolution of the average stride length every 50m in the 2x300m test (120 sec recovery) ((A) average for the 400m Spanish women´s team (mean PB = 52.78 sec); (B) results for a female athlete (PB: 52.67 sec) with a high loss of stride length in the last section of the 300m tests, especially in the second one; (C) results for a female athlete with a high segment time stability (53.21 sec) between the first and second 300m tests; and (D) results for a male athlete (PB: 45.98 sec).)

individualise energy expenditure and VR strategies, and the optimal relationship between stride amplitude and frequency, especially in the final sections (Figure 7).

Practical Applications

In addition to training the athlete's biomechanical and metabolic capacities, reaching maximum performance in the 400m may be optimised by using a new model for specific training closely linked to individual metabolic energy expenditure strategies (pace time and/or velocity) and volitional psychological responses.

Models of energy distribution strategy throughout the 400m race are based on determining the personal best speed an athlete achieves in a 200m competition, estimating the "reserve speed" of the pacing time in the middle of a 400m race, and determining the difference between that time and the second half of the 400m. The new model considers, as a basic reference, the maximum velicty attainable (Vmax30m) by the athlete, incorporating the percentage relative to the maximum peak speed (PKV) in a specific section (50-100m, and/or 100-150m) of a 400m race for assessment and monitoring of individual training and competition strategies. This new model also includes a test of 2x300m (120 sec recovery), analysing the percentage of relative velocity (50-100m) with respect to Vmax30m, and the partial velocity profiles, stride amplitude and frequency in each 300m test repetition, along with measurement of post-exercise maximum blood lactate.

In published studies on stride amplitude and frequency, a clear tendency is to try to reduce velocity loss in the last stages of the reace by voluntarily maintaining the longest possible stride. The new model incorporates as a reference the Specific Useful Strength Index (SUSI) in the 100m alternate limb jumping test, to analyse the force loss due to fatigue in the final sections of 300m tests and 400m races. This additional information allows investigation of the best individual orientation in either of the two stride components (length or frequency), since it is feasible that in some cases velocity maintenance may be favored by a voluntary increase in stride frequency. This may be linked to obtaining performance from stiffness[44,51], and therefore involve lower energy costs and greater efficiency.

It seems advisable to use a training programme that, along with metabolic objectives, also pays attention to neuromuscular technical goals. This can be done by training at high intensity intervals (HIT), allowing the athlete to increase his/her endurance for working at a higher intensity before experiencing lactic acid accumulation, also improving maximum oxygen consumption[52]. MACDOUGALL et al., used 30 sec sprints (Wingate test) with 2-4 min of recovery, carried out three times a week, over several weeks and with progressive loads, recording $\dot{V}O_2$max before and after the entire programme and performing biopsies of the vastus lateralis before and after the training programme. The results showed a significant increase in peak power output, $\dot{V}O_2$max, and aerobic and anaerobic enzyme activity.

In order to develop increased endurance, it is also necessary to define the direction and control of training, when using short and intense runs with little recovery time[53]. VITTORI wrote that in the phase of velocity loss at the end of a sprint "the involvement of the central nervous system (CNS) is decisive and, if required at maximum, it may not be in a position to maintain its full effectiveness in long runs" (6 sec sprints). This hypothesis is currently being verified by advances in neurophysiology[21,22,24–29], which seek to determine the role of the CNS in recovery between sprint repetitions[55]. Thus, the effects of the athlete's perceived fatigue on strategic behaviour and kinematic parameters must be controlled in training sessions close to racing level using 2x300m tests (120 sec recovery), and 400m races.

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