The mechanics and energetics of the 100m sprint

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by Elio Locatelli and Laurent Arsac

The authors present an account of a study of the main mechanical and physiological aspects of the 100m sprint, using 4 male and 4 female athletes of the Italian national team competing in the 1994 Italian Championships. A detailed description is given of the methods used to assess the various types of energy expenditure and determine the total energy expenditure and efficiency. The tables included present a complete account of the data obtained from each of the athletes concerned.

They suggest that the results obtained from the study, which intimate that anaerobic glycolysis contributes to about 65-70% of the metabolic energy production during a 100m race, provid new information which should help coaches to plan their training programmes.

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1 Introduction

This study was conducted on 8 sprinters (4 male and 4 female) of the Italian national team. All measurements were taken during the 1994 Italian Championships. Our intention was to study some specific qualities:

- Acceleration phase: measured by video recording the first 60m during competition (see *Tables 1, 2* and *Figures 1, 2*),
- 100m performance and blood lactate concentration $(la)_b$,
- total energy expenditure and running economy at lower velocity,
- metabolic kinetics and instantaneous velocity,
- efficiency: h = w/C (w = mechanical energy expenditure, C = metabolic kinetics).

To calculate the mechanical energy expenditure we utilized the Di Prampero equation (DI PRAMPERO 1986). Metabolic energy was calculated by evolution of blood lactate concentration; the peak values were obtained at 3–5–7 minutes after the race. With this model, it is possible to predict instantaneous power and velocity and determine the critical section of the sprint.

Results obtained from the subjects in the 100m final during the Italian Championships (Naples, 1994)

A.O.:	10.54sec	G.G.:	11.65sec
L.L.:	10.59sec	L.A.:	11.77sec
M.M.:	10.63sec	R.F.:	11.85sec
A.A.:	10.69sec	L.G.:	12.01sec.

Note: for our operations all these fully automatic times must be amended to 'real times'; -0.20s is internationally accepted.

Lactate values after the race (see also *Table 3* and *Figures 3 and 4*):

A.O.:	16.02 mmol/l after 3 min
G.G.:	12.83 mmol/l after 5 min
L.L.:	14.97 mmol/l after 7 min
L.A.:	12.97 mmol/l after 5 min
M.M.:	14.69 mmol/l after 5 min
R.F.:	12.90 mmol/l after 5 min
A.A.:	14.57 mmol/l after 5 min
G.G.:	15.46 mmol/l after 5 min.

Table 1: Times [s] at each marker beginning with the take-off of rear foot from the blocks

100m final men											
Athlete	**10m**	**15m**	**20m**	**25m**	**30m**	**35m**	**40m**	**45m**	**50m**	**55m**	**60m**
Menchi	1.88	2.51	3.04	3.55	4.03	4.50	4.97	5.44	5.92	6.39	6.86
Orlandi	1.86	2.48	3.00	3.49	3.96	4.43	4.88	5.32	5.77	6.22	6.68
Amici	1.86	2.48	3.00	3.51	3.99	4.45	4.92	5.37	5.82	6.28	6.74
Levora	1.84	2.49	3.00	3.49	3.96	4.44	4.91	5.36	5.82	6.27	6.72
100m final women											
Athlete	**10m**	**15m**	**20m**	**25m**	**30m**	**35m**	**40m**	**45m**	**50m**	**55m**	**60m**
Ardisso	1.98	2.69	3.29	3.85	4.39	4.90	5.40	5.92	6.44	6.95	7.46
Gallina	1.92	2.61	3.20	3.75	4.28	4.80	5.31	5.81	6.30	6.79	7.31
Galliga	1.92	2.63	3.22	3.77	4.31	4.84	5.35	5.86	6.36	6.88	7.43
Farina	1.98	2.70	3.29	3.82	4.35	4.87	5.37	5.88	6.37	6.87	7.36

2 Determination of mechanical energy expenditure

The total energy expenditure (E_{tot}) of an athlete running 100m, at a constant speed, at sea level and without wind, can be calculated from the sum of the following components:

- the energy spent against air resistance (Ca),
- the non–aerodynamic expenditure (En.a),
- the energy expended in accelerating the body (Ek)

2.1 Energy spent against air resistance

The energy spent, for each unit of distance, against air resistance (Ca), is proportional to the athlete's surface area and to his v^2 (v = velocity).

The equation used from Di Prampero is:

$Ca = K' \cdot v^2$

K' is a constant ($J \cdot s^2 \cdot m^{-3}$ and per m^2 of body surface [= s]). Referring to the running events K' = 0.40. Following the Du Bois equation (Di Pamprero pp.142-143) we can obtain a very good approximation of the body surface of our subjects.

To show the procedure used to determine E_{tot}, we will examine the athlete A. Orlandi (A.O., cf. *Table 4*). His anthropometric values are 187cm at 77kg. According to Du Bois, this subject has a body surface of $2.0m^2$.

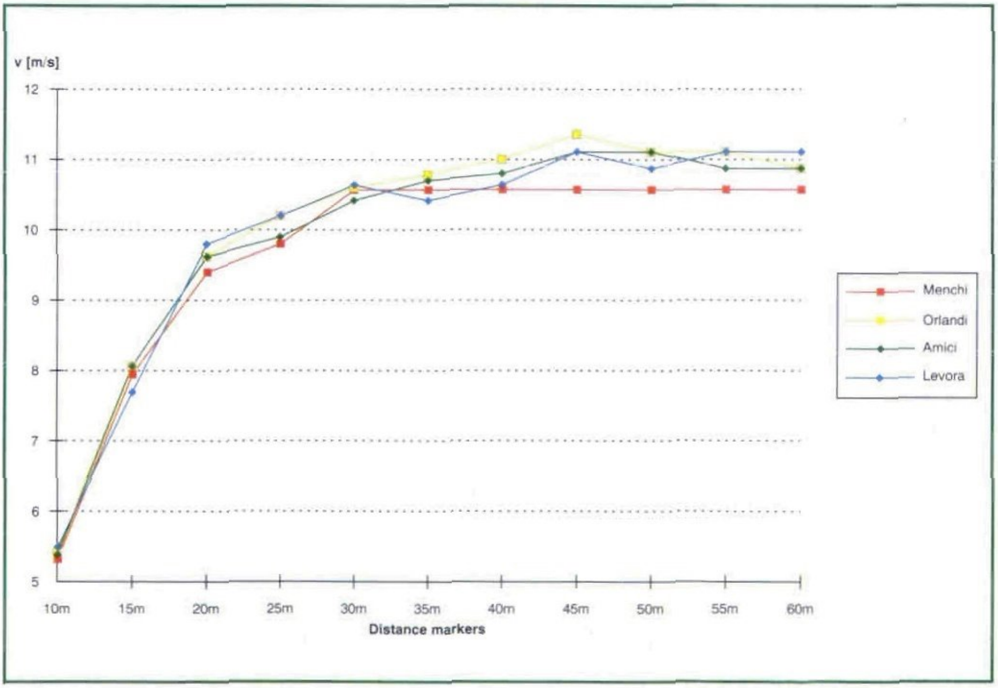

Figure 1: Velocity distribution 100m final men

Table 2: Velocity values [m/s] at each marker

100m final men											
Athlete	**10m**	**15m**	**20m**	**25m**	**30m**	**35m**	**40m**	**45m**	**50m**	**55m**	**60m**
Menchi	5.32	7.94	9.40	9.80	10.57	10.57	10.57	10.57	10.57	10.57	10.57
Orlandi	5.43	8.06	9.62	10.20	10.60	10.78	11.00	11.36	11.11	11.11	10.87
Amici	5.38	8.06	9.62	9.90	10.42	10.70	10.80	11.11	11.11	10.87	10.87
Levora	5.49	7.69	9.80	10.20	10.64	10.42	10.64	11.11	10.87	11.11	11.11
100m final women											
Athlete	**10m**	**15m**	**20m**	**25m**	**30m**	**35m**	**40m**	**45m**	**50m**	**55m**	**60m**
Ardisso	4.95	7.04	8.40	8.93	9.26	9.80	10.00	9.62	9.62	9.80	9.80
Gallina	5.43	7.25	8.47	9.09	9.44	9.62	9.80	10.00	10.20	10.20	9.62
Galliga	5.26	7.04	8.47	9.09	9.30	9.43	9.80	9.80	10.00	9.62	9.09

The speed to be taken into consideration will not be 10.54 (official result), but 10.54 -0.20 = 10.34 (real time). This gives an average speed of 9.67m/s. Now, utilising the above equation, we get:

$Ca = (2 \cdot 0.40) \cdot 9.67^2 = 0.8 \cdot 93.51 = 74{,}8J.$

Since speed is not uniform in a 100m race, the values of energy expenditure per time unit against air resistance cannot be calculated on average speed but must be on instantaneous speed.

During the 1988 Olympic Games and 1991 World Championships, it has been possible to calculate (after video-analysis) the instantaneous speed of the 100m finalists and to determine the needed energy expenditure against air resistance, moment by moment.

Table 3: Lactate concentrations after 100m sprint (mmol/l)

3min	5min	7min	Name
100m final women			
11.86	12.83	12.23	G. Gallina
12.32	12.97	12.54	L. Ardissone
13.60	15.46	14.98	L. Galligani
12.75	12.90	12.25	R. Farina
100m final men			
13.34	14.57	13.36	A. Amici
16.02	15.57	12.14	A. Orlandi
13.83	14.69	–	M. Menchini
12.79	12.53	14.97	L. Levorato

This value is estimated as 6% more than that calculated on the average speed ($\bar{v}$); i.e. 1.06 times this value.

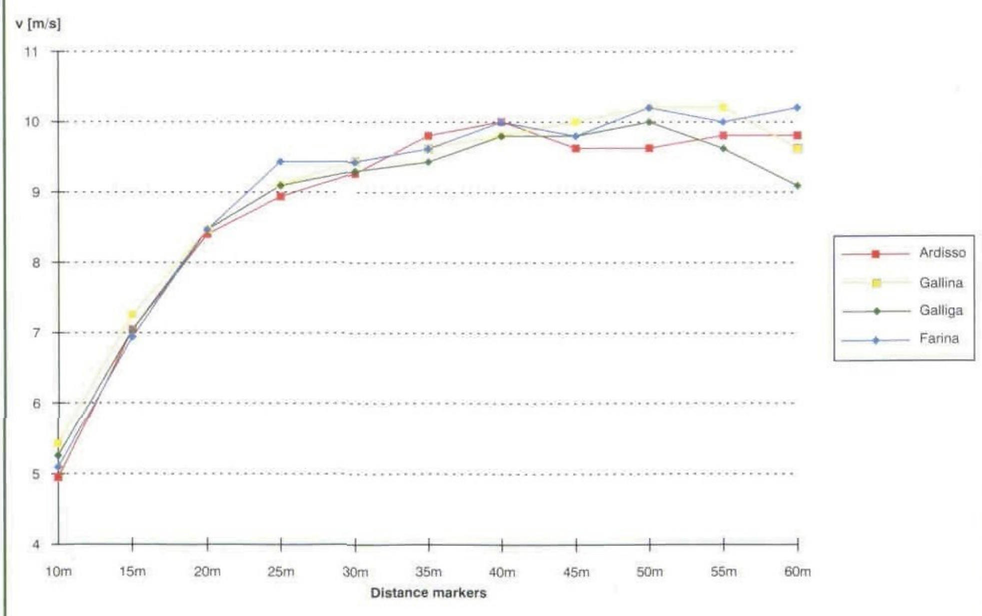

Figure 2: Velocity distribution 100m final women

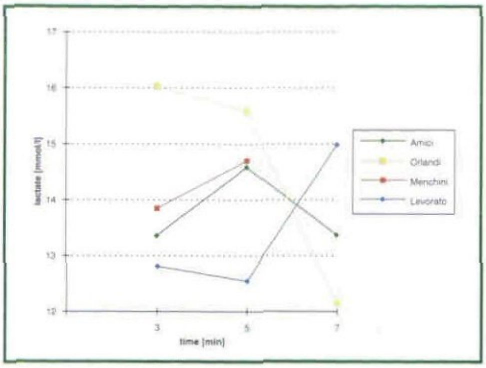

Figure 3: Lactate distribution after 3, 5 and 7min, 100m final men

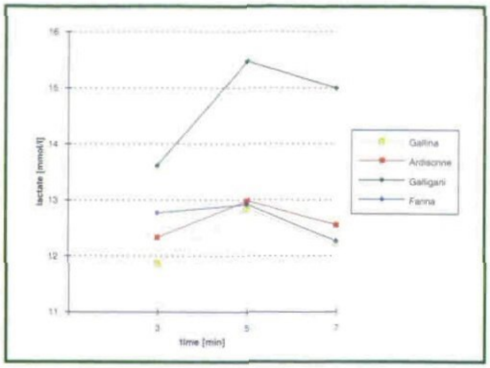

Figure 4: Lactate distribution after 3, 5 and 7min, 100m final women

Table 4: Data from test, Tirrenia 1994

Athlete	Weight (kg)	Speed (m/s)	VO_2 trend (ml.O_2/kg/min)	FC trend (n/min)	EC (kJ/km·kg)
A Orlandi	77	14.29	53.50	187	4.04
M Menchini	80	14.61	52.30	186	4.10
E Madonia	75	14.18	52.24	183	4.05
C Occhiena	72	14.29	53.31	178	4.36
A Amici	70	14.18	49.91	187	4.16
G Gallina	52	13.58	53.78	191	4.32
L Galligani	56	13.58	45.62	183	3.75

A further calculation gives the effective value of energy expenditure against air resistance as:

$Ea = (2 \cdot 0.40) \cdot 10.25^2$
$= 0.80 \cdot 105.06 = 84.05 J/kg.$

Since we are interested in the total expenditure, we will multiply this value by the subject's body mass:

$Ea = 84.05 \cdot 77 = 6472J.$

2.2 The non-aerodynamic expenditure: En.a

To determine this, we calculated the energy cost of the subject at submaximal speed (about 14km/hour). We utilized the direct method, employing K2 apparatus (K2 COSMED, Italy; DAL MONTE et al. 1989) and, as can be seen in *Table 4*, for our subject the EC [KJ/km/kg] is 4.04. Since his body mass is 77kg and the distance is 100m, his expenditure will be:

$4.04 \cdot 77 \cdot 100 = 31{,}108J.$

2.3 Energy expenditure to accelerate the body: Ek

To calculate this value one needs to know the difference between the Kinetic energy at the point of maximum acceleration and that at the start.

From video-analyses made during the race (see *Tables 1, 2* and *Figures 1, 2*), we found that our subject reached the point of maximum acceleration at 45m after the start, when the speed is 11.36 m/s.

The kinetic energy is equal to

$\frac{1}{2} M \cdot (v_{max})^2 - \frac{1}{2} M \cdot v_i$ (v_i = initial speed).

In our case since $v_i = 0$, we have:

$Ek = 38.5 \cdot (11.36)^2 - 0 = 4968J.$

2.4 Total mechanical energy expenditure in running 100m

This final value is obtained from the sum of the Ea, En.a and Ek of each athlete (see *Table 5*).

2.5 Energy spent without wind assistance

According to the DI PRAMPERO equation (1986, p.60), with no wind assistance the energy spent is derived from:

$Ea = K' \cdot v^2 \cdot S$ (S = theoretical calculation of the co-efficient of wind drag).

As the wind speed during this competition was -0.20m/s, we get (for our subject):

$Ew = 0.8 \cdot (10.25 + 0.20)^2 \cdot 10.25$
$= 0.8 \cdot 109.2 \cdot 10.25 = 917J.$

Table 5: Total mechanical energy expenditure in 100m sprint

NAME	RESULT [sec]	Ea [J]	En.a [J]	Ek [J]	Etot [J]	Etot(w) [J]
A.O.	10.34	6472	31108	4968	42548	43465
L.L.	10.39	7393	32548	4876	44817	45809
M.M.	10.43	6613	32800	4469	43881	44754
A.A.	10.49	5429	29120	4320	38869	39683
G.G.	11.45	2741	22464	2705	28463	29016
L.A.	11.57	2312	19750	2375	24763	25269
R.F.	11.65	3914	26780	3381	34075	34697

3 Determination of metabolic energy expenditure

As already mentioned, blood samples were taken within 3 to 7 minutes after the competition, using an enzymatic method (Microzym L., SGI Toulouse, France). The methods of sampling, storage and analysis were validated by GEYSSANT et al. in 1985.

3.1 Estimation of energy expenditure during running

Estimation of metabolic energy production. This method of estimation was based on the same methods as those used to assess the energy cost of running 400 and 800m (LACOUR et al. 1990).

a) The kinetics of O_2 utilization at the beginning of supramaximal exercise could be described as a mono-exponential function, with a time constant of 30sec and an asymptote of 53ml O_2/kg/min. Following this hypothesis, the oxygen consumption over 100m was calculated by PERRONET and THIBAULT (1989).
b) The decrease in the muscle concentration of high energy phosphates during supramaximal exhausting exercise equalled 18mmol/l/kg wet mass. Assuming that the muscle mass involved in sprinting was 25% of the body mass, this corresponded to the utilization of 16ml O_2/kg.
c) Rest $(la)_b$ equalled 1mmol/l.
d) A mmol/l increase in lactate, corresponded to the energy produced by the utilization of 3.30ml O_2/kg.

The energy conversions were made assuming that the consumption of one litre of oxygen is equivalent to the liberation of 20.9 kJ energy.

As an example, in the case of our subject Alessandro Orlandi, the total metabolic expenditure is determined from the sum of the following:

- glycolytic energy,
- phosphagens energy,
- kinetics of O2 utilization.

Glycolitic energy expenditure, arrived at from the lactate production after competition, was 16.02mmol/l. Since 1mmol of $(la)_b$ is equal to 3mmol of O_2/kg we have:

$(16.02 - 1) \cdot 3 = 15.02 \cdot 3 = 45.06$mmol O_2/kg and, for the total,

$45.06 \cdot 77 = 3470$mmol $O_2 \cdot 20.9 = 72523$J.

Phosphagens energy: Assuming that the muscle mass involved in sprinting is 25% of the body mass, corresponding to the utilization of 16ml O_2/kg (HIRVONEN 1987), we have:

$16 \cdot 77 = 1232$ml O_2, which multiplied by 20.9 KJ = 25749J.

Kinetics of O_2 utilization: The equation proposed by PERRONET et THIBAULT was adopted:

$E = VO_2max\ [t + 1/y \cdot e^{(-yt)} - 1/y]$.

Assuming for our sprinters a value of VO_2max of 53ml O_2/kg/min, we get:

$E = (53 \cdot 77) : 60\ (t + 1/0.03 \cdot e^{(-yt)} - 1/0.03)$
$E = 68\ (10.34 + 33.33 \cdot e^{(-0.03 \cdot 10.34)} - 33.33)$
$E = 68\ (10.34 + (33.33 \cdot 0.733) - 33.33)$
$E = 68\ (10.34 + 24.43 - 33.33)$
$E = 68 \cdot 1.44 = 97.92$ml O_2.
$E = 97.92 \cdot 20.9 = 2046$ J

Table 6: Total metabolic energy expenditure in the 100m sprint

Athlete	Glycolitic (la)	Phosphagens (ATP+CP)	Oxygen (kinetic utilisation)	Total
	J	J	J	J
Men				
A Orlandi	72523	25749	2063	100335
A Amici	59559	23408	1924	84891
M Menchini	68669	26752	2142	97563
L Levorato	69198	26418	2596	98212
Women				
G Gallina	38570	17389	2015	57974
L Ardissone	35650	15884	1579	53113
R Farina	48489	21736	2184	72418
L Galligani	50772	18726	2297	71795

4 Discussion

The main purpose of the biomechanics of locomotion is to determine and analyse that part of the expenditure of energy which results in the production of mechanical work, as distinct from that resulting in the production of heat.

The efficiency 'η' is arrived at from the relation between the mechanical energy expenditure 'w' and the metabolic energy expenditure 'C': $\eta = w/C$

For our subject Orlandi it will be:

$n = 43.465 : 100.335 = 0.433$ (i.e. -43%).

For the *efficiency of all athletes* see *Table 7*.

5 Conclusions

The results of this study suggest:

a) that anaerobic glycolysis contributes about 65-70% of the metabolic energy production during a 100m race and that this quite new information should help

Table 7: Total Efficiency for all athletes
(η = w/C)

Athlete	(C) [J]	(w) [J]	Efficiency (η=w/C)
Men			
A Orlandi	100318	43465	0.433
A Amici	84891	39683	0.467
M Menchini	97563	44754	0.459
L Levorato	98212	45809	0.466
Women			
G Gallina	57974	29016	0.500
L Ardissone	53113	25268	0.476
R Farina	72418	34697	0.479
L Galligani	71795	27921	0.389

coaches to improve the planning of a sprinter's training programme and

b) that the efficiency (η) shows that the majority of athletes (7) had values that are in line with the scientific studies published by MARGARIA, CAVAGNA and DI PRAMPERO, who predicted, for sprinters running at a speed of 10m/s, a 45-50% efficiency of running. The only athlete to show a lower value was L.G. (39%).

Our measurements confirm the coach's explanation of her poor results as due to insufficient specific training on speed endurance (note her speed for last 40m and that her best 200m performance is 24.81sec).

Other studies have shown that, in a 100m race, slight variations in (la)b production (e.g. from 14.5 to 16mmol/l) may not necessarily affect performance (HAUTIER et al. 1994); our study seems to confirm this. However, the slight variability in our study may be due to the limited number of subjects measured. All these observations, in my opinion, should need further investigation, to confirm this tendency.

6 Explanations

Mechanical energy expenditure (w)

This was measured following the Di Prampero equation (1986).

Metabolic kinetics (C)

These measurements give a good estimation of energy expenditure during running. The total metabolic expenditure is the sum of:

- Glycolitic energy $(la)_b$ utilisation.
- Phosphagens energy: ATP + PC (HIRVONEN et al. 1987).
- Kinetics of O_2 utilisation: (PERRONET and THIBAUT 1989).

Anaerobic lactic training

This is the classic training method to develop speed endurance. Practically it implies types of training consisting of repetition runs at submaximal speed. The distances recommended are 60 to 300m (circa 6 to 35sec), with a relatively short rest, between the runs and sets, depending on the duration of the runs (intensity 85 to 95%). The lactate production, after a set of 80m runs or a single 300m run at high intensity, will be more than 15mmol/l.

Anaerobic alactic training

This alactic capacity is concerned with muscle power. In practice, it consists of sprints or drills at maximum, or near maximum (over 95%), intensity and with a duration of from 0.3 to 2sec and a short rest interval (2-3min). Lactate production must remain below 6mmol/l. In any case, it appears that a single maximum contraction or a single movement will induce a production of blood lactate that is impossible to measure because the glycolytic part of the energy production in this type of exercise is probably too low.

Mixed alactic and lactic anaerobic training

This occupies a large part of sprint training programmes. In practice, it includes runs of 30 to 80m (circa 3 to 10sec) at submaximum speed (about 85-90%). Lactate production after a set of runs should be between 6 and 15mmol/l. (It seems that, in this type of training, lactic acid is not a limiting factor.)

Efficiency (h)

The different anthropometric details and running techniques of the athletes determine the individual energy cost during performances. Our study made it possible to determine each individual's theoretical total energy expenditure when running the 100m. Athletes with higher energy costs must compensate by achieving a higher production of metabolic energy. In my opinion, in our practical work as coaches, the efficiency index is a very important tool for evaluating the quality of an athlete.

In conclusion, we can say that, in coaching the sprints, it is essential to emphasize running technique with young athletes, in order to build a good base upon which to place the specific training which will eventually lead to top level results.

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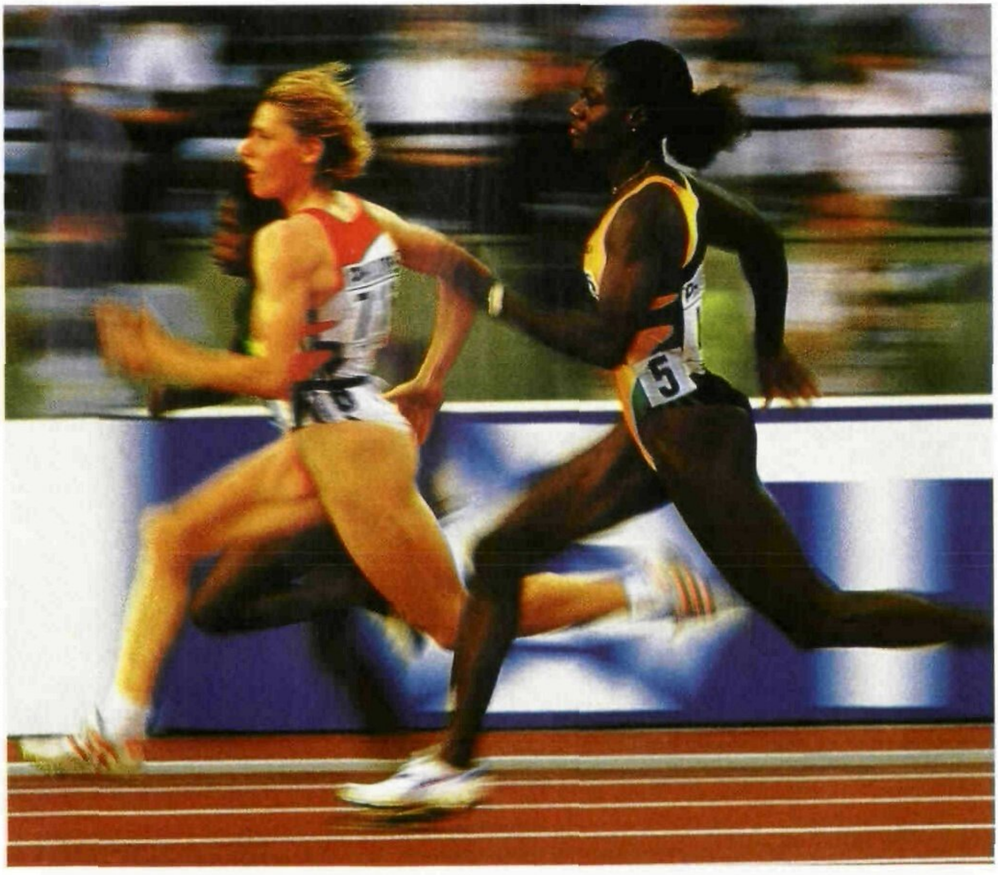

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