Kinematic Analysis of the Women's 400m Hurdles

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ABSTRACT

The women's 400m hurdles is a relatively new discipline and a complex event that cannot be approached as a "simple" 400m "decorated" with ten hurdles. It is, of course, fundamental to develop physical qualities such as speed, strength and endurance, but it is also essential to develop technical and tactical aspects. Literature on the biomechanics of the 400m hurdles, which would guide this development, is relatively sparse. Moreover, the existing studies have analysed only a few kinematic parameters. The aim of this study was to observe different kinematic parameters in women 400m hurdlers of different performance levels in order to describe the management and structure of this discipline. Based on the video observation of 46 female athletes competing at a national meeting in France and the 2011 IAAF World Championships in Athletics, it provides among other things an analysis of stride length, stride frequency, velocity, distribution of effort and the structure of the race. A large range of performance levels was analysed (from 52.47 sec to 71.39 sec) in order to identify the most relevant biomechanical parameters and to isolate the most important ones for world-class performance.

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Introduction

The women's 400m hurdles is a relatively new discipline. Indeed, the first race over this distance was in 1971. It was included in the European Athletics Championships programme only in 1978, then the IAAF World Championships in Athletics in 1983 and finally, the Olympic Games in 1984.

Figure 1 shows the evolution of the yearly world leading performances in the 400m hurdles for both women and men between 1977 and 2011. We can see that the men's performances have been stable since 1977, while women's performances seem to level off only in the last ten years after a significant improvement up until the late 1980's. As the men's event is more than 100 years old, the relative stability of the performances is as would be expected. For women, however, the discipline has only been around for about 40 years and it would not be surprising if the performance level keeps improving in the near future.

Literature on the biomechanics of the 400m hurdles is relatively sparse[1,2,3,4,5,6,7]. Moreover, these studies have analysed only a few kinematic parameters: time per interval, number of strides per interval, distribution of effort (e.g. time difference between first and second 200m, time difference between first and second 200m relatively to the final time, time difference between fastest and slowest interval), location of first change of rhythm (e.g. adding of one stride between hurdles) and finally race's structure.

To calculate the time per interval, one commonly uses the touchdown time after each hurdle[7]. The 200m split time is equal to the time after the fifth hurdle plus 1.7 sec for top-level male athletes and plus 2.3 sec for women[8]. It can also be calculated by adding to the time after the fifth hurdle to 40% of the time in the fifth interval. Based on his observations in major championships (from 1988 to 2006), BEHM reported a difference of 2.4 sec between first and second 200m for men finalists and 3.4 sec for women[2]. In the men's final at the 2000 Olympic Games, a difference of 2.6 sec was observed[4]. For LINDEMAN, the difference between the two 200m splits should not exceed 5% of the final race time (e.g. 2.6 sec for a race in 52 sec, 3 sec for a race in 60 sec...)[7]. BEHM also noted a difference of 0.9 sec between the fastest and the slowest interval for men finalists and more than 1.0 sec for women at the 2000 Olympics[2].

Four typical race structures have been identified in the 400m hurdles[1,7]. The first is named the "n" structure, where the athlete starts in a given number of strides between hurdles and maintains this rhythm to the end. According to BEHM's observations, this structure was used by 12% of the finalists (5% of the women) in the major championships between 1978 and 1999[1]. The second is the "n+1" structure, where one time in the race the athlete adds one stride between the hurdles to the original rhythm and maintains this new number of strides to the end. This structure was used by 33% of finalists (37% of the women) in the major championships between 1978 and 1999[1] For LINDEMAN, this is the most relevant race structure[7]. The third is the "n+1+1" structure, where the athlete adds, twice in the race, one stride between the hurdles. This structure was used by 35% of finalists (45% of the women) in the major championships between 1978 and 1999[1]. The last structure identified is the "n +2", where the athlete adds, one time in the race, two strides between hurdles. This structure was used by 20% of finalists (13% of the women) in the major championships between 1978 and 1999[1]. This structure is com-

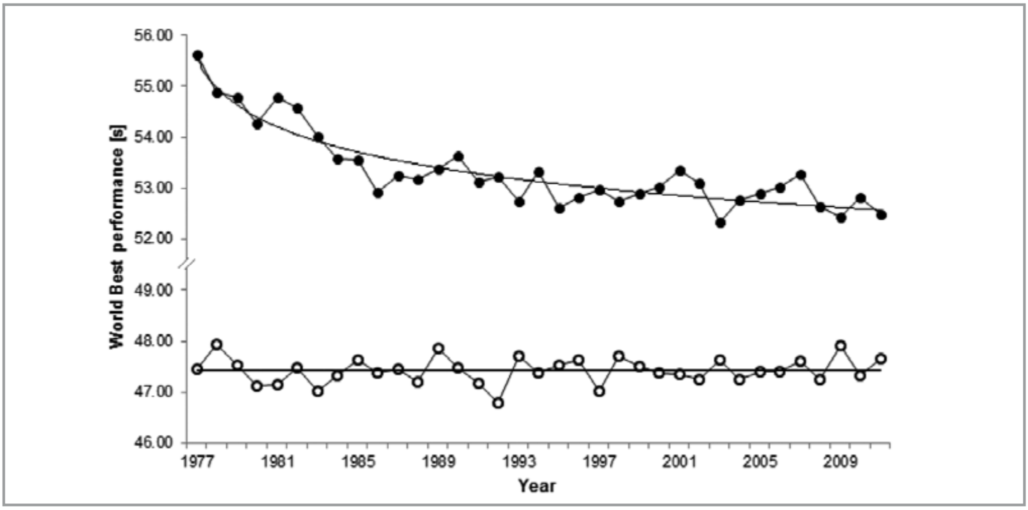

Figure 1: Evolution of the yearly 400m hurdles World leading performance for women (black) and men (white) between 1977 and 2011

monly used by athletes who are unable to hurdle with both lead legs. They run in an odd number of strides between hurdles, this allows them to hurdle always with the same lead leg.

For the athletes who do not use the "n" structure, the location of the first change of rhythm should not take place prior the sixth interval. For LINDEMAN a change too early would indicate a low anaerobic capacity[7]. BEHM observed that 97% of the finalists of the major championships between 1978 and 1999 ran at least until the fourth interval with the same number of strides and 90% of athletes ran until the fifth[1].

The aim of this study was to observe different kinematic parameters among women 400m runners of different performance levels in order to describe the management and structure of this discipline. The 400m hurdles is a complex discipline allowing a wide range of approaches. It is, therefore, important to analyse what is realised by the best athletes in the World and to compare with their lower level counterparts. Given the limited literature on this topic, the purpose of this study was also to determine the most relevant kinematic parameters to achieve world-class performance.

Methods

The races of a national meeting in Tarare (FRA) in July 2011 and the final of the 2011 IAAF World Championships in Athletics in Daegu (KOR) in September 2011 were videoed. An analysis software (Dartfish Software, ProSuite 5.5, Fribourg, Switzerland) was used to identify the touchdown times after the hurdles and to calculate the number of strides per interval.

Several spatial and temporal parameters were analysed:

Temporal parameters

- 400m hurdles time (T_{400})
- First 200m time ($T_{1st\ 200}$)
- Second 200m time ($T_{2nd\ 200}$)
- Time difference between first and second 200 m ($D_{T1st\ -\ 2nd\ 200}$)
- Relative time difference between first and second 200 m ($D\%_{T1st\ -\ 2nd\ 200}$)
- Time difference between first and second 200 m relatively to final time ($D_{T1st\ -\ 2nd\ 200}\%_{T400}$)
- Mean interval time ($T_{int.}$)
- Fastest interval time ($T_{int.\ fast}$)
- Slowest interval time ($T_{int.\ slow}$)
- Time difference between fastest and slowest interval ($D_{Tint.\ fast\ -\ slow}$)
- Relative time difference between fastest and slowest interval ($D\%_{Tint.\ fast\ -\ slow}$)
- Mean loss of time per interval ($L_{int.}$)
- Relative mean loss of time per interval ($L\%_{int.}$)
- Loss of time at the first change of rhythm compared with previous interval ($L_{1st\ +1}$)
- Relative loss of time at the first change of rhythm compared with previous interval ($L\%_{1st\ +1}$)
- Difference between loss of time at the first change of rhythm and mean loss of time per interval ($D_{L1st\ +\ 1\ -\ Lint.}$)
- Relative difference between loss of time at the first change of rhythm and mean loss of time per interval ($D\%_{L1st\ +\ 1\ -\ Lint.}$)

Spatial parameters

- Mean number of strides per interval ($NS_{int.}$)
- Number of strides before the first hurdle (NS_{start})
- Number of strides in first interval ($NS_{1st\ int.}$)
- Number of strides in ninth interval ($NS_{9th\ int.}$)
- Difference between number of strides before first hurdle and in first interval ($D_{NSstart\ -\ 1st\ int.}$)
- Difference between number of strides in ninth and first interval ($D_{NS9th\ -\ 1st\ int.}$)
- Location of first change of rhythm ($Loc_{1st\ +1}$)
- 400m hurdles mean stride length (SL_{400})
- First 200m mean stride length ($SL_{1st\ 200}$)
- Second 200m mean stride length ($SL_{2nd\ 200}$)
- Stride length difference between first and second 200m ($D_{SL1st\ -\ 2nd\ 200}$)
- Relative stride length difference between first and second 200 m ($D\%_{SL1st\ -\ 2nd\ 200}$)
- 400m hurdles mean stride frequency (SF_{400})
- First 200m mean stride frequency ($SF_{1st\ 200}$)
- Second 200m mean stride frequency ($SF_{2nd\ 200}$)

- Stride frequency difference between first and second 200m ($D_{SF1st - 2nd\ 200}$)
- Relative stride frequency difference between first and second 200m ($D\%_{SF1st - 2nd\ 200}$)
- 400 m hurdles stride length to stride frequency ratio (SL/SF_{400})
- First 200 m stride length to stride frequency ratio ($SL/SF_{1st\ 200}$)
- Second 200 m stride length to stride frequency ratio ($SL/SF_{2nd\ 200}$)
- Stride length to stride frequency ratio difference between first and second 200 m ($D_{SL/SF1st - 2nd\ 200}$)
- Relative stride length to stride frequency ratio difference between first and second 200 m ($D\%_{SL/SF1st - 2nd\ 200}$)
- Race's structure: n, n+1, n+1+1, n+1+1+1, ...

Prognostic tools

A proposition of race distribution (for target performances between 52 and 70 sec) was created on the basis of regression curves between interval times and final time of the 46 athletes.

Moreover, interval times with regard to the number of strides per interval were proposed. This was calculated on the basis of the regression curve between the number of strides per interval and the interval time for the 414 analysed intervals.

Statistics

Results are presented as mean ± standard deviation. Analyses of variance (ANOVA) supplemented by Tukey post-hoc tests were performed to compare the differences in various kinematic parameters between the Daegu final group (see below) and the other groups. In addition, Pearson correlations were performed to identify the relationships between the different parameters analysed and the performance. The concordance was considered excellent for r values between 0.81 and 1, good for r values between 0.61 and 0.80, moderate for r values between 0.41 and 0.60, and weak for r values between 0.21 and 0.40. The significance level was set at $p < 0.05$ (SigmaPlot 11.0).

Sample

Forty-six female runners were analysed for this study: 38 competing in Tarare and eight in Daegu. Five groups were defined: The Daegu final group comprised the eight finalists (26.5 ± 2.3 years) of the 2011 IAAF World Championships in Athletics; the Tarare<60 group comprised the 10 athletes (26.1 ± 5.5 years) who ran under 60 sec in Tarare; the Tarare<63 group comprised the nine athletes (21.2 ± 3.6 years) who ran between 60 and 63 sec; the Tarare<66 group comprised the 10 athletes (23.2 ± 4.4 years) who ran between 63 and 66 sec; and finally, the Tarare>66 group comprised nine athletes (22.4 ± 8.2 years) who ran more than 66 sec in Tarare.

Results

Table 1 shows the values obtained for the five groups for the different kinematics parameters. Table 2 displays the correlations between the different kinematics parameters and the final performance.

Temporal parameters

The first and second 200m times were significantly lower in the Daegu final group than in the other groups. First and second 200m times were excellently correlated with the final performance. The time difference (absolute or relative) between first and second 200m was not different between the Daegu final group and the other groups (except between Daegu final and Tarare<63). Time difference between first and second 200m relative to final time was not different between the Deagu final group and the other groups. These parameters of distribution of effort were not correlated with the final performance.

The mean interval time, and the fastest and slowest interval times were significantly lower in the Daegu final group than in the other groups. These three parameters were excellently correlated with the final performance. Mean loss of time (absolute or relative) per interval and the time difference (absolute or relative) between fastest and slowest interval

Table 1: Spatial and temporal analysed parameters (for significant differences with Daegu final group (p<0.05))*

	Parameters	Deagu final (n=8)	Tarare<60 (n=10)	Tarare<63 (n=9)	Tarare<66 (n=10)	Tarare>66 (n=9)
--- Temporal ---	T_{400} [sec]	53.88±0.85	58.84±0.78*	61.66±0.89*	64.54±0.92*	68.60±1.16*
	$T_{1st\ 200}$ [sec]	25.08±0.44	27.82±0.44*	29.44±0.94*	30.23±0.58*	32.08±0.79*
	$T_{2nd\ 200}$ [sec]	28.79±0.56	31.02±0.73*	32.22±0.52*	34.31±0.87*	36.52±0.73*
	$D_{T1st\ -\ 2nd\ 200}$ [sec]	3.71±0.56	3.20±0.92	2.79±1.23	4.08±1.16	4.44±0.98
	$D\%_{T1st\ -\ 2nd\ 200}$ [%]	14.81±2.33	11.53±3.44	9.58±4.42*	13.53±4.02	13.88±3.35
	$D_{T1st\ -\ 2nd\ 200}\%_{T400}$ [%]	6.89±1.01	5.43±1.53	4.53±2.03*	6.31±1.77	6.47±1.45
	$T_{int.}$ [sec]	4.60±0.08	5.08±0.10*	5.35±0.14*	5.64±0.21*	5.88±0.17*
	$T_{int.\ fast}$ [sec]	4.10±0.11	4.55±0.10*	4.70±0.17*	4.99±0.15*	5.15±0.19*
	$T_{int.\ slow}$ [sec]	5.24±0.11	5.61±0.21*	5.99±0.25*	6.21±0.36*	6.48±0.20*
	$D_{Tint.\ fast\ -\ slow}$ [sec]	1.14±0.13	1.06±0.26	1.28±0.24	1.22±0.36	1.34±0.20
	$D\%_{Tint.\ fast\ -\ slow}$ [%]	27.80±3.66	23.43±6.15	27.37±5.21	24.52±7.32	26.04±4.47
	$L_{int.}$ [sec]	0.15±0.02	0.13±0.03	0.13±0.04	0.17±0.03	0.16±0.03
	$L\%_{int.}$ [%]	3.23±0.47	2.57±0.55	2.49±0.79	2.93±0.55	2.80±0.49
	$L_{1st\ +1}$ [sec]	0.15±0.16	0.19±0.08	0.18±0.09	0.27±0.07	0.22±0.13
	$L\%_{1st\ +1}$ [%]	3.27±3.45	3.68±1.58	3.57±1.67	5.04±1.36	3.92±2.25
	$D_{L1st\ +\ 1\ -\ Lint.}$ [s]	0.00±0.17	0.06±0.09	0.04±0.08	0.11±0.07	0.06±0.12
	$D\%_{L1st\ +\ 1\ -\ Lint.}$ [%]	8.40±112.76	50.11±71.95	37.27±73.01	77.50±69.59	39.08±72.53
--- Spatial ---	$NS_{int.}$ [n]	15.43±0.37	16.57±0.43*	16.93±0.22*	17.93±0.32*	18.61±0.89*
	NS_{start} [n]	22.13±0.64	23.40±0.70*	23.56±0.73*	24.10±0.74*	24.56±1.33*
	$NS_{1st\ int.}$ [n]	14.88±0.35	15.80±0.42*	16.00±0.50*	16.60±0.52*	17.33±0.87*
	$NS_{9th\ int.}$ [n]	16.50±0.54	17.70±0.68*	17.89±0.33*	19.20±0.42*	19.67±1.12*
	$D_{NSstart\ -\ 1st\ int.}$ [n]	7.25±0.46	7.60±0.52	7.56±0.53	7.50±0.71	7.22±0.67
	$D_{NS9th\ -\ 1st\ int.}$ [n]	1.63±0.52	1.90±0.57	1.89±0.78	2.60±0.52*	2.33±0.5
	$Loc_{1st\ +1}$ [int. #]	6.38±1.30	4.90±0.74	4.33±2.45*	3.30±1.34*	3.56±1.24*
	SL_{400} [m]	2.09±0.04	1.97±0.05*	1.93±0.03*	1.84±0.03*	1.78±0.08*
	$SL_{1st\ 200}$ [m]	2.16±0.05	2.03±0.06*	1.98±0.04*	1.92±0.04*	1.86±0.08*
	$SL_{2nd\ 200}$ [m]	2.02±0.06	1.91±0.05*	1.88±0.03*	1.76±0.03*	1.71±0.08*
	$D_{SL1st\ -\ 2nd\ 200}$ [m]	-0.14±0.08	-0.12±0.05	-0.10±0.05	-0.15±0.04	-0.15±0.05
	$D\%_{SL1st\ -\ 2nd\ 200}$ [%]	-6.27±2.94	-5.75±2.32	-5.10±2.56	-8.01±1.90	-7.96±2.59
	SF_{400} [Hz]	3.55±0.10	3.46±0.07	3.36±0.09*	3.38±0.07*	3.28±0.14*
	$SF_{1st\ 200}$ [Hz]	3.69±0.09	3.55±0.07	3.43±0.14*	3.45±0.10*	3.36±0.16*
	$SF_{2nd\ 200}$ [Hz]	3.43±0.11	3.38±0.09	3.30±0.07	3.31±0.08	3.21±0.14*
	$D_{SF1st\ -\ 2nd\ 200}$ [Hz]	-0.26±0.07	-0.17±0.08	-0.13±0.13	-0.14±0.12	-0.15±0.11
	$D\%_{SF1st\ -\ 2nd\ 200}$ [%]	-7.00±1.89	4.78±2.12	-3.67±3.69	-4.12±3.38	-4.49±2.93
	SL/SF_{400}	0.59±0.03	0.57±0.03	0.58±0.02	0.55±0.02*	0.54±0.04*
	$SL/SF_{1st\ 200}$	0.59±0.03	0.57±0.03	0.58±0.03	0.56±0.03	0.55±0.05
	$SL/SF_{2nd\ 200}$	0.59±0.03	0.57±0.03	0.57±0.02	0.53±0.02*	0.53±0.05*
	$D_{SL/SF1st\ -\ 2nd\ 200}$	0.00±0.03	-0.01±0.02	-0.01±0.03	-0.02±0.03	-0.02±0.03
	$D\%_{SL/SF1st\ -\ 2nd\ 200}$	0.86±4.95	-0.97±3.58	-1.34±5.12	-3.93±4.30	-3.51±5.02
	n [%]	0.0	0.0	11.1	0.0	0.0
	n+1 [%]	37.5	20.0	0.0	0.0	0.0
	n+1+1 [%]	62.5	70.0	77.8	40.0	66.7
	n+1+1+1 [%]	0.0	10.0	11.1	60.0	33.3

were not significantly different between the Daegu final group and the other groups. Other parameters of distribution of effort were not (or weakly) correlated with the final performance. The loss of time (absolute or relative) at the first change of rhythm compared with the previous interval was not significantly different between the Daegu final group and the other groups. This parameter was not correlated with the final performance. The difference (absolute and relative) between loss of time at the first change of rhythm and mean loss of time per interval

Table 2: Correlations between temporal and spatial parameters and the final performance (The concordance was excellent for r values between 0.81 and 1, good for r values between 0.61 and 0.80, moderate for r values between 0.41 and 0.60, and weak for r values between 0.21 and 0.40.)

	Parameters	Correlation with the final performance (n=46)			
		r	r^2	$p<0.05$	Correlation
--- Temporal ---	$T_{1st\ 200}$ [sec]	0.97	0.94	Yes	Excellent
	$T_{2nd\ 200}$ [sec]	0.98	0.96	Yes	Excellent
	$D_{T1st-2nd\ 200}$ [sec]	0.29	0.08	No	Ø
	$D\%_{T1st-2nd\ 200}$ [%]	0.00	0.00	No	Ø
	$D_{T1st-2nd\ 200}\%_{T400}$ [%]	0.00	0.00	No	Ø
	$T_{int.}$ [sec]	0.96	0.92	Yes	Excellent
	$T_{int.\ fast}$ [sec]	0.94	0.88	Yes	Excellent
	$T_{int.\ slow}$ [sec]	0.90	0.81	Yes	Excellent
	$D_{Tint.\ fast-slow}$ [sec]	0.31	0.10	Yes	Weak
	$D\%_{Tint.\ fast-slow}$ [%]	-0.05	0.00	No	Ø
	$L_{int.}$ [sec]	0.26	0.07	No	Ø
	$L\%_{int.}$ [%]	-0.14	0.02	No	Ø
	L_{1st+1} [sec]	0.25	0.06	No	Ø
	$L\%_{1st+1}$ [%]	0.13	0.02	No	Ø
	$D_{L1st+1-Lint.}$ [sec]	0.17	0.03	No	Ø
	$D\%_{L1st+1-Lint.}$ [%]	0.12	0.01	No	Ø
--- Spatial ---	$NS_{int.}$ [n]	0.91	0.83	Yes	Excellent
	NS_{start} [n]	0.67	0.45	Yes	Good
	$NS_{1st\ int.}$ [n]	0.83	0.69	Yes	Excellent
	$NS_{9th\ int.}$ [n]	0.84	0.71	Yes	Excellent
	$D_{NSstart-1st\ int.}$ [n]	-0.06	0.00	No	Ø
	$D_{NS9th-1st\ int.}$ [n]	0.42	0.18	Yes	Moderate
	Loc_{1st+1} [int. #]	-0.54	0.29	Yes	Moderate
	SL_{400} [m]	-0.91	0.83	Yes	Excellent
	$SL_{1st\ 200}$ [m]	-0.88	0.77	Yes	Excellent
	$SL_{2nd\ 200}$ [m]	-0.89	0.79	Yes	Excellent
	$D_{SL1st-2nd\ 200}$ [m]	-0.14	0.02	No	Ø
	$D\%_{SL1st-2nd\ 200}$ [%]	-0.28	0.08	No	Ø
	SF_{400} [Hz]	-0.72	0.52	Yes	Good
	$SF_{1st\ 200}$ [Hz]	-0.70	0.49	Yes	Good
	$SF_{2nd\ 200}$ [Hz]	-0.64	0.41	Yes	Good
	$D_{SF1st-2nd\ 200}$ [Hz]	0.30	0.09	Yes	Weak
	$D\%_{SF1st-2nd\ 200}$ [%]	0.25	0.06	No	Ø
	SL/SF_{400}	-0.47	0.22	Yes	Moderate
	$SL/SF_{1st\ 200}$	-0.32	0.10	Yes	Weak
	$SL/SF_{2nd\ 200}$	-0.53	0.28	Yes	Moderate
	$D_{SL/SF1st-2nd\ 200}$	-0.32	0.10	Yes	Weak
	$D\%_{SL/SF1st-2nd\ 200}$	-0.33	0.11	Yes	Weak

had a tendency to be lower in the Daegu final group than in the other groups. However this difference was not significant. This parameter was not correlated with the final performance.

The mean number of strides per interval, number of strides before the first hurdle and number of strides in first and ninth intervals were significantly lower in the Daegu final group than in the other groups. These four parameters were excellently (or well) correlated with the final performance. The difference between the number of strides before the first hurdle and in first interval was not significantly different between the Daegu final group and the other groups. This parameter was not correlated with the final performance. The difference between the number of strides in the ninth and first intervals was significantly lower in the Daegu final group than in the Tarare<66 group and tended to be lower than in the Tarare>66 group. This parameter was moderately correlated with the final performance. The location of the first change of rhythm was significantly later in the race in the Daegu final group than in the Tarare<63, <66 and >66 groups and this change tended to take place later in the race than in the Tarare<60 group. This parameter was moderately correlated with the final performance.

The mean stride length and the first and second 200m mean stride lengths were significantly higher in the Daegu final group than in the other groups. These three parameters were excellently correlated with the final performance. The stride length difference (absolute or relative) between the first and second 200m was not significantly different between the Daegu final group and the other groups. This parameter was not correlated with the final performance.

The mean stride frequency and the first 200m mean stride frequency were significantly higher in the Daegu final group than in the Tarare<63, <66 and >66 groups and tended to be higher than in the Tarare<60 group. The second 200m mean stride frequency was significantly lower in the Deagu final group than in the Tarare>66 group and tended to be lower than in the other groups. These three parameters were well correlated with the final performance. The stride frequency difference (absolute or relative) between the first and second 200m was not significantly different between the Daegu final group and the other groups. This parameter was not (or weakly) correlated with the final performance.

The stride length to stride frequency ratio and the second 200m stride length to stride frequency ratio were significantly higher in the Daegu final group than in the Tarare<66 and >66 groups. The first 200m stride length to stride frequency ratio was not significantly different in the Daegu final group than in the other groups. These three parameters were moderately (or weakly) correlated with final performance. The stride length to stride frequency ratio difference (absolute or relative) between the first and second 200m tended to be lower in the Daegu final group than in the Tarare <66 and >66 groups. This parameter was weakly correlated with the final performance.

The most used race structure in the Daegu final, Tarare<60, <63 and >66 groups was n+1+1 while n+1+1+1 was the most used in the Tarare<66 group. The second most used structure was n+1 in Daegu final and Tarare<60 groups while structures with more rhythm changes were preferred in the slower groups.

Prognostic tools

Table 3 shows the race distribution for target performance between 52 and 70 sec. Table 4 proposes interval times with regard to the number of stride in interval. Conversely, it also sets the number of stride per interval in regard to the interval time.

Discussion

Several temporal and spatial parameters were used to compare the performances of the world's best female 400m hurdlers and their lower-level counterparts. Some of these parameters have already been used in kinematic analyses (e.g. the time difference between first and second 200m, the time difference between first and second 200m relative to final time, the time difference between fastest and slowest interval, race's structure, etc.)[1,2,3,4,5,6,7] whereas others have been

Table 3: Time to be achieved at each hurdle in order to run in the desired final time (between 52 and 70 sec)

Final time	Time at each hurdle [sec]									
	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
52.0	6.1	10.0	14.1	18.2	22.5	26.9	31.5	36.1	41.0	46.0
53.0	6.2	10.2	14.3	18.6	23.0	27.4	32.1	36.9	41.8	47.0
54.0	6.3	10.4	14.6	19.0	23.4	28.0	32.8	37.6	42.7	47.9
55.0	6.4	10.6	14.9	19.3	23.9	28.6	33.4	38.4	43.5	48.8
56.0	6.5	10.8	15.2	19.7	24.3	29.1	34.1	39.1	44.4	49.8
57.0	6.6	11.0	15.5	20.1	24.8	29.7	34.7	39.9	45.2	50.7
58.0	6.7	11.2	15.7	20.4	25.3	30.2	35.4	40.6	46.1	51.6
59.0	6.9	11.4	16.0	20.8	25.7	30.8	36.0	41.4	46.9	52.6
60.0	7.0	11.6	16.3	21.2	26.2	31.3	36.7	42.1	47.8	53.5
61.0	7.1	11.7	16.6	21.5	26.6	31.9	37.3	42.9	48.6	54.4
62.0	7.2	11.9	16.9	21.9	27.1	32.5	38.0	43.6	49.5	55.4
63.0	7.3	12.1	17.1	22.3	27.6	33.0	38.6	44.4	50.3	56.3
64.0	7.4	12.3	17.4	22.7	28.0	33.6	39.3	45.1	51.2	57.3
65.0	7.5	12.5	17.7	23.0	28.5	34.1	39.9	45.9	52.0	58.2
66.0	7.7	12.7	18.0	23.4	28.9	34.7	40.6	46.6	52.9	59.1
67.0	7.8	12.9	18.3	23.8	29.4	35.2	41.2	47.4	53.7	60.1
68.0	7.9	13.1	18.5	24.1	29.8	35.8	41.9	48.1	54.6	61.0
69.0	8.0	13.3	18.8	24.5	30.3	36.3	42.5	48.9	55.4	61.9
70.0	8.1	13.5	19.1	24.9	30.8	36.9	43.1	49.6	56.3	62.9

used, to our knowledge, for the first time in this study (e.g. the stride length to stride frequency ratio, the difference between loss of time at the first change of rhythm and mean loss of time per interval, ...). The systematic use of relative values is also a key point of the present study.

Temporal parameters

As expected, performance in the 400m hurdles is strongly linked to the first 200m time, the second 200m time, the mean interval time and the fastest and slowest interval times. However it was surprising to find no relationship between the final performance and various parameters of distribution of effort (i.e. the time difference (absolute or relative) between first and second 200m, the time difference between first and second 200m relative to final time, the mean loss of time (absolute or relative) per interval and the time difference (absolute or relative) between fastest and slowest interval. These parameters are commonly used in kinematic analysis of the 400m hurdles. For example, LINDEMAN suggests that time difference between the first and second 200m should not exceed 5% of the final time[7]. In the present study, for the eight finalists at the IAAF World Championships in Athletics this difference was 7%. Moreover, this parameter was not correlated ($r = 0.00$, $p > 0.05$) with the final performance of the 46 analysed athletes. It is not the first time that such an important difference is reported in a World Championship final. Indeed, a mean difference of 7.1% was noted in the final of the 2009 IAAF World Championships in Athletics[5] and, according to data collected by BEHM, in all women finalists of major Championships (i.e. Olympic Games, European and World Championships) from 1988 to 2006, there is a mean difference of 6.2% between the first and second 200m relative to final time (i.e. mean performance = 54.5 sec, mean time difference between the first and second 200m = 3.4 sec)[2]. Therefore, we can state that this maximum difference of 5% between the first and second 200m relative to final time is not a legitimate criteria for female athletes.

Would they really be faster if they distributed their effort better? To answer this question we can analyse the performances of male

Table 4: Appropriate number of strides with regard to the interval time (between 3.95 and 6.65 sec)

NS per int. [n]	14	14/ 15	15	15/ 16	16	16/ 17	17	17/ 18	18	18/ 19	19	19/ 20	20
Time min [sec]	3.95	4.15	4.35	4.55	4.80	5.00	5.20	5.40	5.65	5.85	6.05	6.25	6.50
Time max [sec]	4.10	4.30	4.50	4.75	4.95	5.15	5.35	5.60	5.80	6.00	6.20	6.45	6.65

athletes. In recent major championships, men finalists have had a difference between the first and second 200m relative to final time close to 5% (even if in Daegu it was more than 7%)[2]. The gap between the 400m and 400m hurdles world records is 3.6 sec in men, whereas it is 4.7 sec in women. Proportionally to race's time, to be comparable to men, this gap should be 4.0 sec in women. This would put the women's 400m hurdles world record at 51.6 (currently it is 52.3). One may, therefore, hypothesise that a way to reduce this gap between 400m flat and hurdles times would be to decrease this difference between first and second 200m.

Despite no correlation with the final performance, the difference between loss of time at the first change of rhythm and mean loss of time per interval seems to be an interesting parameter. Indeed, since speed is defined by stride length multiplied by stride frequency, it is important during the first change of rhythm (i.e. one stride more in the interval, therefore stride length is decreased in the interval) to increase stride frequency in order to minimise the speed loss in this interval. In the present study, only the Daegu final group had no difference between loss of time at the first change of rhythm and mean loss of time per interval. Therefore, it is important to work this transition in training and to emphasise increasing stride frequency.

Spatial parameters

It was expected that stride length and stride frequency in the Daegu final group would be higher than in the other groups and that these two parameters are very well correlated with final performance. However, stride length was better correlated with performance than stride frequency ($r=-0.91$, $p<0.05$ vs. $r=-0.72$, $p<0.05$).

To further analyse these parameters, a stride length to stride frequency ratio was established. It was shown that stride frequency and stride length are negatively correlated in short sprint events ($r=-0.78$, $p<0.05$)[9]. We found the same negative correlation in the Daegu final group ($r=-0.82$, $p<0.05$). The proposed ratio appears as a useful tool in order to assess the relationship between these two parameters. A significantly higher ratio in the Daegu final group than the other groups was noted as well as a moderate correlation between this ratio and the final performance. This means that world-class athletes give more importance to stride length than to stride frequency than their lower-level counterparts. Moreover, the Daegu final group maintained their ratio in the second 200m while slower groups had a 4% loss of ratio during the second half of the race. In future kinematic studies, it would be interesting to use this ratio to establish norms according to the discipline, performance level of the athletes and gender.

Race structure is a frequently used parameter in 400m hurdles analysis. In this study, the n+1+1 structure was largely preferred to the others. In fact, two-thirds of the 46 athletes and five finalists at the IAAF World Championships in Athletics chose this structure. In every group (except Tarare<66) n+1+1 was the most used structure. In the slower groups the second most used structure was n+1+1+1 while n+1 (or n) was the second must used in the faster groups.

These results are consistent with BEHM's observations, except that in the present study, the n+2 structure was not observed while it was used by 13% of female finalists in major championships between 1978 and 1999[1]. As the 400m hurdles for women is a relatively new event, we can then expect some technical or tactical improvements. We can interpret the absence of n+2 structure in our study as a technical improvement in regard to the 1980's and 1990's. In fact, all the 46 analysed women were able to hurdle with both lead legs.

Overall, it seems that n+1 and n+1+1 are the best choices. Unlike the n structure, they allow a quick start without using an overly high stride frequency in the first part of the race. Later in the race, when it becomes difficult to maintain the initial number of strides per interval, adding a stride allows - in theory - to increase frequency or, at least, to stabilise it and thus to limit speed loss.

The location of the first change of rhythm is moderately well correlated with the final performance. This interesting parameter has to be considered when determining the race tactics. It seems that the first change of rhythm should take place between the fifth and seventh intervals if the chosen structure is n+1+1. When the chosen structure is n+1, it should take place between sixth and eighth intervals. This proposal is consistent with observations or recommendations of BEHM and LINDEMAN[1,7].

Prognostic tools

Table 3 allows trainers to predict final time from intermediate times. It also gives an idea of the time to be achieved at each hurdle in order to run the desired final time. Of course, this table does not take into account various distributions of effort scenarios.

As mentioned above, the relationship between stride length and stride frequency is an important parameter in the 400m hurdles. Table 4 is a pertinent tool to control this relationship. Indeed, it allows choosing the appropriate number of strides with regard to the interval time in order to run with the best possible compromise between stride length and stride frequency.

Conclusion

The 400m hurdles is a complex event that cannot be approached as a "simple" 400m "decorated" with ten hurdles. It is, of course, fundamental to develop physical qualities such as speed, strength and endurance, but it is also essential to develop technical and tactical aspects. Like in 4x100m or in other technical events, the 400m hurdles is one of those athletics disciplines where one can successfully compensate some physical limitations by a controlled management of technical and tactical aspects. Knowledge of these aspects is essential if we want athletes to express fully their physical potential.

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