Biomechanical Research Project at the VIth World Championships in Athletics, Athens 1997: Preliminary Report

© by IAAF
12:2-3; 43-73, 1997

by Harald Müller and Helmar Hommel (eds.)

Various data of a biomechanical research project, carried out during the 6th World Championships in Athletics in Athens 1997, are given in this priliminary. The following events finals (male and female) are presented: 100m, 200m, 400m; 110m and 100m hurdles; long jump, triple jump, high jump (men only) and pole vault.

Prof. Dr Gert-Peter Brüggemann is the head of the Institute for Athletics of the German Sport University Cologne and the leader of the Athens' Biomechanics Project.

Adiamantios Arampatzis, Harald Müller, Dr Wolfgang Ritzdorf and Falk Schade are co-workers at the Institute for Athletics of the German Sport University Cologne.

Helmar Hommel is a member of the NSA Executive Editorial Board.

1 Introduction

The International Athletic Foundation appointed the Institute for Athletics of the German Sport University Cologne to carry out a Biomechanical Research Project during the 6th World Championships in Athletics in Athens 1997. This scientific approach was intended to be a follow-up study to that carried out at the 2nd World Championships in Rome 1987, which was the first extensive data-capture of elite athletes under competitive conditions in different track and field events.

The purpose of this project was:
- to update the database of biomechanical parameters of elite athletes
- to provide coaches and athletes with quantitative information on individual techniques
- to improve the general knowledge of the limiting factors of athletic performance
- to generate data on gender-specific techniques
- to help the international media to produce competent, attractive athletics coverage and to present the collected scientific data.

The project comprised three sub-projects:
- An information service for the media, with initial distribution of simple information brochures in three languages (English, French, Spanish) concerning historical aspects and important biomechanical concepts.
- A fast biomechanical information service the day after the finals, when the collected data were presented and discussed with coaches and athletes and representatives of the media.
- A detailed analysis of the collected data and their presentation in a report with an accompanying video in December 1997. This final report will be published as a supplement of "*New Studies*" and will be available from the IAAF Bureau in Monaco at the beginning of 1998.

The project focused on the finals (men and women) of the following events:
- 100m, 200m, 400m, 4x100m
- 100m and 110m hurdles
- 5,000m, 10,000m
- Long, triple, high jump and pole vault
- Discus throw.

Of special interest were different characteristics of female techniques in the jumping, sprinting and throwing events. The long distance events were chosen to study the effects of fatigue on running technique and mechanical efficiency.

The biomechanical data were gathered using High Speed Video Techniques, 3-dimensional motion analysis, speed and time measurements. A new measurement system, the LAVEG-Laser, was used to a greater extent than in previous studies.

The first results were presented and explained daily at a Fast Information Service Meeting of the IAF Biomechanical Research Team at the Championships. Biomechanical information was presented for the following events (men and women):

- 100m, 200m, 400m
- 110m hurdles
- Long, triple, high jump.

During these meetings, the participants received printed results of the previous day's finals, including short comments and interpretations.

Because this was the first time that both men's and women's triple jump had been analysed in a major international competition, extra emphasis was given to the biomechanical analysis of gender-specific differences in this event.

The data of the 100m hurdles final from the very last day of the championships and the preliminary results of the pole vault analysis are also presented.

2 Methods and procedures

2.1 Electronic measurements

2.1.1 Photocells

For the measurement of run-up information, a photocell system was installed 11m, 6m, and 1m from the board for the long jump and triple jump. This was used to measure mean velocities over the distances between the photocells.

2.1.2 Laser

The instantaneous run-up speeds of the athletes in the long jump, triple jump, pole vault, short sprint and hurdle events were measured using a laser system (LAVEG Sport) installed behind the runway and starting blocks of the 100m and hurdle events. The system operators used an optical control device to follow the athlete's lower back during the entire approach run (long jump, triple jump, pole vault), the hop, the step, and the jump (triple jump), the entire 100m, 100m hurdle and 110m hurdle races, as well as the last 80 metres of the 200m sprint. Using the known speed of infrared light, the distance between the laser detector and the reflecting object was measured 50 times per second. From the position time history the object's speed was calculated by the first time derivative. The raw data and the calculated speed curves were registered and stored in a PC on field.

2.2 Video techniques

2.2.1 50 Hz Motus

The jumping events of the World Championships in Athletics 1997 were recorded with multiple synchronised S-VHS video cameras, operating at 50 fields per second. For the long and triple jumps, the cameras were placed perpendicular to the plane of motion. For the triple jump, 4 cameras were used. Camera 1 was positioned to capture the last two steps of the approach, cameras 2, 3, and 4 were focused on the hop, the step and the jump, respectively. For the long jump, 3 cameras were used. Camera 1 was positioned to film the 4th and 3rd to last steps, camera 2 was focused on the penultimate and last step and camera 3 was used to film the flight phase.

For the pole vault, 4 cameras were used. Cameras 1 and 3 recorded from the last two steps until shortly after maximum pole flexion. Cameras 2 and 4 recorded from shortly before maximum pole flexion until bar clearance. Because the pole vault was to be analysed three dimensionally, cameras 1 and 2 were positioned at right angles to cameras 3 and 4.

For data reduction of the relevant video sequences, data were transferred via the video grabber board to the videodata disk of the Motus video motion analysis system (Peak Performance).

2.2.2 Highspeed video

For filming of the triple jump, one high-speed video camera (motionscope, redlake), operating at 250 frames per second, filmed the take-off for the step, and a second high-speed system (Peak Performance) recorded the take-off for the hop at 200 frames per second. Fixed high-speed cameras were also used for filming the long jump take-off, the 100m sprints at 60m, and the hurdles at 60m.

2.2.3 Pan and tilt

The pan and tilt technique was used for data collection in the long jump, high jump, triple jump, pole vault, 100m, 200m (the curve) and the hurdles. For the women's high jump and the pole vault, 50Hz. systems were used. For the other events, the pan and tilt method was used, in conjunction with high-speed cameras.

Tripods with pan tilt angle decoders were used. Using calibration poles as a reference system, the camera positions, the pan and tilt angles and the focal length were calculated for each frame of every pair of cameras. This input information enabled a 2D-DLT technique to be used for camera calibration and co-ordinate reconstruction.

2.2.4 Data analysis and co-ordinate systems

For the long and triple jump, the co-ordinate system had its x-axis along the runway, pointing in the direction of jumping. The y-axis was vertical and perpendicular to the x-axis. The origin was fixed in the middle of the front edge of the take-off board. The co-ordinate system used for the high jump had its x axis parallel to the bar, the y axis was horizontal and perpendicular to the x axis and the z axis was vertical and perpendicular to the other two axes. The origin was fixed on the ground directly under the centre of the bar.

For the pole vault, the co-ordinate system had its x axis along the runway, pointing in the direction of jumping. The y axis was vertical and perpendicular to the x axis. The origin was fixed at ground level directly above the deepest point of the pole vault box.

For the biomechanical analysis of each event, a standard 12 segment model of the human body was used, calculated via 19 landmarks. Both feet, both lower legs, both thighs, the trunk, the upper arms, the forearms with hands, and the head with the neck represented the rigid body model.

3 100 metres

(by Wolfgang Ritzdorf)

3.1 Methods and procedures

Data from the 100m finals were recorded with two different devices: Laveg laser measurement from a rear position and video analysis from a rectangular side position.

While the laser analysis allows a calculation of the instantaneous velocity during the race, the video based time analysis gives the intermediate times for each 10m section. As only six laser devices were available, data are presented for six competitors in the men's and women's final respectively.

3.2 Results and comments

3.2.1 Men's final

Times

Table 1 (cf. next page) shows the interval times for the 10m sections.

The data from the Athens finals confirm some well-known trends. Top sprinters reach their maximum speed between 50 and 70m and show a more or less marked deceleration in the last 20 metres. The fastest 10m section ever measured was registered by Carl Lewis (WCh Tokyo 1991) and Donovan Bailey (OG Atlanta 1996) with 0.83s, both finishing their race in a new world record time. None of the Athens finalists reached such a speed.

Figure 1 illustrates that Bailey lost this race mostly in the first 10m section, with a loss of 0.06s. From 10 to 50m, Bailey made up 0.05s. From 60 to 90m there was no difference between these two athletes, while Greene gained another 0.02 seconds in the last 10m.

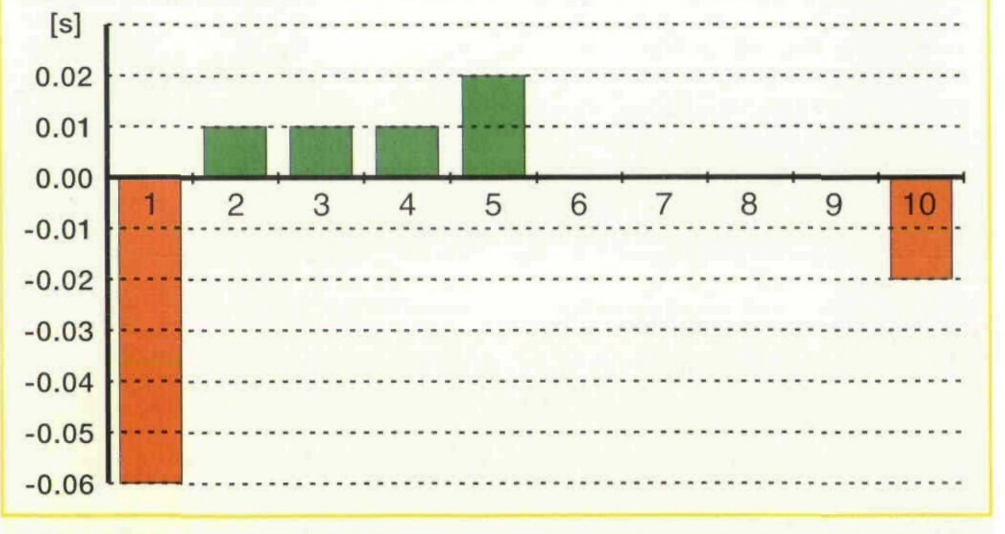

Figure 1: Comparison of individual interval times of Greene and Bailey
(1-10: Intervals; Zero-Line: Reference value Greene; Bars: Actual value of Bailey;
+: faster than reference value; –: slower than reference value)

Table 1: Interval times in the men's 100 metres final [s]

Name	Result	RT [ms]	0-10m	10-20m	20-30m	30-40m	40-50m	50-60m	60-70m	70-80m	80-90m	90-100m
Greene (USA)	9.86	134	1.71	1.04	0.92	0.88	0.87	0.85	0.85	0.86	0.87	0.88
Bailey (CAN)	9.91	145	1.77	1.03	0.91	0.87	0.85	0.85	0.85	0.86	0.87	0.90
Montgomery (USA)	9.94	134	1.73	1.03	0.93	0.88	0.86	0.86	0.86	0.87	0.88	0.90
Fredericks (NAM)	9.95	129	1.73	1.04	0.93	0.89	0.87	0.86	0.86	0.87	0.88	0.89
Boldon (TRI)	10.02	123	1.72	1.05	0.93	0.89	0.87	0.87	0.87	0.88	0.90	0.92
Ezinwa (NGR)	10.10	135	1.77	1.05	0.94	0.89	0.87	0.87	0.87	0.88	0.89	0.93

Table 2: Velocities at the end of intervals in the men's 100 metres final [m/s]

Name	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
Greene (USA)	8.71	10.47	11.14	11.50	11.67	11.80	11.68	11.57	11.51	11.30
Bailey (CAN)	8.90	10.55	11.28	11.63	11.76	11.80	11.70	11.55	11.38	11.00
Montgomery (USA)	8.82	10.34	11.14	11.54	11.62	11.61	11.54	11.42	11.25	10.95
Fredericks (NAM)	8.77	10.35	11.02	11.43	11.60	11.72	11.52	11.43	11.27	10.79
Boldon (TRI)	8.67	10.36	11.03	11.41	11.50	11.54	11.34	11.20	11.05	10.46
Ezinwa (NGR)	8.55	10.21	11.08	11.38	11.52	11.51	11.42	11.30	11.07	10.36

Velocities

Table 2 shows the instantaneous velocities at the end of the indicated interval.

Of course, there is the same overall tendency as in *Table 1*. But a second look provides some interesting information in the comparison between Greene and Bailey. Although Bailey loses 0.06sec in the first 10m, his velocity at the end of the interval is somewhat higher than Greene's. Consequently, the loss must have occurred during the first strides and was then followed by an extraordinary acceleration in the latter half of this section.

All finalists analysed have an actual velocity of more than 11 m/s after 30m. Most of them reach their maximum speed at the end of the 60m section. A more detailed analysis is given in *Table 3*.

Table 3 confirms the above-mentioned results. Maximum velocity was reached at about 60m. The highest actual velocity in this final was measured as 11.87m/s and was shown by both Greene and Bailey.

Other new information was gathered from the laser data. This is the distance covered within certain velocity limits. *Table 4* gives some details.

The results accurately reflect the race characteristics. The longer the top speed area the better the result. The medallists covered more than 70m at a velocity of more than 11.0m/s. Greene ran more than the half of the overall distance with a velocity of more than 11.5m/s and was faster than 11.0m/s even at the finish line. Bailey demonstrated the best acceleration ability and was the first to reach the 11.0 and 11.5m/s barrier – but, unlike Greene, he was also the first to leave this area.

Table 3: Maximum velocity and location of maximum velocity in the men's 100 metres final

Name	V max [m/s]	V max at [m]
Greene (USA)	11.87	58.10
Bailey (CAN)	11.87	62.30
Montgomery (USA)	11.67	60.20
Fredericks (NAM)	11.74	59.20
Boldon (TRI)	11.66	60.80
Ezinwa (NGR)	11.56	61.90

3.2.2 Women's final

Times

Table 5 shows the interval times for the 10-m-sections.

According to these data, maximum velocity was reached between 40 and 60m, and thus earlier than by the men. Deceleration is obvious in the last 20m for the medallists, and even in the last 30m for the other finalist analysed.

Figure 2 gives a comparison of individual interval time of Jones and Pintusevitch. Like Maurice Greene in the men's final, Marion Jones won the final mainly in the first and the last 10m interval. Despite her poor reaction time, her acceleration over the first 10m and her finishing speed were sufficient for victory.

Table 4: Distances covered at more than 11.0m/s and 11.5m/s in the men's 100 metres final

Name	V max > 11m/s			V max > 11.5m/s		
	from [m]	to [m]	difference [m]	from [m]	to [m]	difference [m]
Greene (USA)	28.64	100.00	71.36	40.20	90.36	50.16
Bailey (CAN)	24.26	95.90	71.64	36.24	82.75	46.51
Montgomery (USA)	27.78	97.91	70.13	37.73	76.91	39.18
Fredericks (NAM)	29.62	97.63	68.01	43.15	74.02	30.87
Boldon (TRI)	30.09	92.70	62.61	44.35	68.44	24.09
Ezinwa (NGR)	28.86	93.55	64.69	43.96	63.99	20.03

Table 5: Interval times in the women's 100 metres final [s]

Name	Result	RT [ms]	0-10m	10-20m	20-30m	30-40m	40-50m	50-60m	60-70m	70-80m	80-90m	90-100m
Jones (USA)	10.83	160	1.81	1.11	1.02	0.97	0.95	0.94	0.95	0.95	0.97	0.99
Pintusevich (UKR)	10.85	130	1.86	1.12	1.01	0.97	0.94	0.94	0.94	0.96	0.98	1.00
Arron (FRA)	11.05	165	1.89	1.15	1.02	0.98	0.96	0.95	0.96	0.97	0.99	1.01
Miller (USA)	11.18	117	1.88	1.15	1.05	1.00	0.98	0.97	0.98	1.00	1.01	1.04
Paschke (GER)	11.19	138	1.89	1.14	1.04	1.00	0.98	0.98	0.98	1.00	1.01	1.03
Ottey (JAM)	11.29	139	1.89	1.13	1.01	0.98	0.96	0.97	0.97	1.00	1.04	1.20

Table 6: Velocities at the end of intervals in the women's 100 metres final [m/s]

Name	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m
Jones (USA)	8.22	9.59	10.16	10.58	10.59	10.67	10.63	10.53	10.38	10.10
Pintusevich (UKR)	8.12	9.56	10.26	10.49	10.66	10.65	10.51	10.43	10.23	–
Arron (FRA)	7.92	9.41	10.08	10.44	10.46	10.55	10.36	10.12	10.00	9.52
Miller (USA)	7.95	9.27	9.75	10.14	10.27	10.21	10.11	9.97	9.83	9.50
Paschke (GER)	8.00	9.34	9.84	10.09	10.24	10.22	10.14	9.93	9.86	9.47
Ottey (JAM)	8.10	9.54	10.12	10.30	10.46	10.39	10.09	9.89	9.25	8.24

Table 7: Maximum velocity and location of maximum velocity in the women's 100 metres final

Name	V max [m/s]	V max at [m]
Jones (USA)	10.68	58.80
Pintusevich (UKR)	10.72	54.10
Arron (FRA)	10.65	56.70
Miller (USA)	10.34	52.40
Paschke (GER)	10.29	55.00
Ottey (JAM)	10.47	45.40

Velocities

Table 6 shows the instantaneous velocities at the end of the indicated interval.

The data confirm the findings of the interval times. Only the medallists achieve top speeds of more than 10.5m/s and of more than 10m/s at the finish. Merlene Ottey's extraordinary ability is shown in the acceleration phase. However, knowing she could not win the race, she obviously gave up in the last phase. According to these findings, a top result in the women's 100m requires a velocity of more than 10.0m/s at 30m, a top speed of more than 10.5m/s in the phase between 40 and 80m and still more than 10m/s at the finish.

Table 7 shows the maximal velocity ind its location fore all finalists.

As mentioned above, maximum velocities are reached a little earlier than in the men's competition. Arron's maximum velocity is very close to that of the medallists, whereas the others fail to reach a speed of higher than 10.5m/s.

As well as the absolute top speed, the distance that can be covered at a near maximum speed is of major interest. Data are given in *Table 8*.

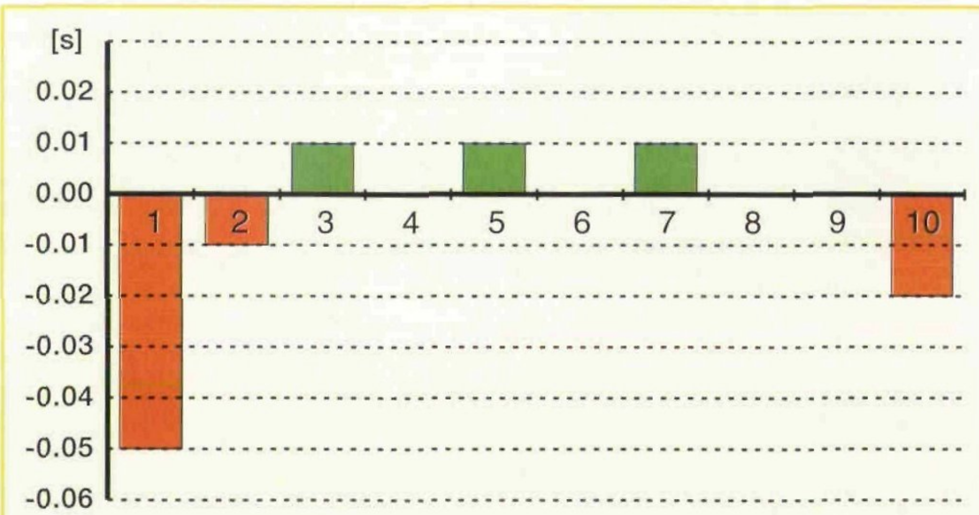

Figure 2: Comparison of individual interval time of Jones and Pintusevitch
(1 – 10: Intervals; Zero-Line: Reference value Jones; Bars: Actual value of Pintusevitch; +: faster than reference value; –: slower than reference value)

Table 8: Distances covered at more than 11.0m/s and 11.5m/s in the women's 100 metres final

Name	V max > 11m/s			V max > 11.5m/s		
	from [m]	to [m]	difference [m]	from [m]	to [m]	difference [m]
Jones (USA)	28.38	100.00	71.62	38.48	84.81	46.33
Pintesuvich (UKR)	26.71	95.81	69.10	40.53	73.23	32.70
Arron (FRA)	27.55	92.73	65.18	51.26	63.88	12.62
Miller (USA)	34.29	78.59	44.30	–	–	–
Paschke (GER)	34.88	76.18	41.30	–	–	–
Ottey (JAM)	25.89	75.97	50.08	–	–	–

The results confirm the men's findings. The longer the distance run at top speed, the better the result. The medallists covered more than 2/3rds of the whole distance at a velocity of more than 10.0m/s. Jones ran almost half the distance at a velocity of more than 10.5m/s and was faster than 10.0m/s even at the finish line.

Table 9: Split times for the 50m intervals in the 200 metres men's final

Name	Result [s]	RT [ms]	0-50m [s]	50-100m [s]	100-150m [s]	150-200m [s]
Boldon (TRI)	20.04	132	5.69	4.54	4.78	4.90
Fredericks (NAM)	20.23	127	5.66	4.62	4.82	5.00
Da Silva (BRA)	20.26	141	5.76	4.66	4.80	4.90
Garcia (CUB)	20.31	131	5.66	4.64	4.76	5.12
Panagiotopoulos (GRE)	20.32	115	5.73	4.64	4.82	5.02
Thompson (BAR)	20.37	184	5.75	4.56	4.80	5.08
Drummond (USA)	20.44	144	5.62	4.58	4.86	5.24
Stevens (BEL)	20.44	183	5.74	4.64	4.80	5.08

Note: Split times do not include reaction times.

4 200 metres

(by Wolfgang Ritzdorf)

4.1 Methods and procedures

Data from the 200m finals were gathered from three video cameras placed at 50, 100 and 150m. Intermediate times were calculated for each finalist. The laser device was used to analyse the top speed in the last 70 metres.

4.2 Results and comments

4.2.1 Men's final

Table 9 shows the split times for the 50m intervals.

The results confirm earlier findings. The reaction times were slightly slower than in the 100 metres. The fastest 50m section for all finalists was between 50 and 100m. The top speeds were slower than in the 100 metres sprint. Only the medallists were able to cover the last 50m in under 5.00 seconds.

Table 10 sums up the split times for the 1st and 2nd 100m interval.

Table 10: 100m split times in the men's 200 metres final [s]

Name	1st 100m	2nd 100m	Difference
Boldon (TRI)	10.23	9.68	0.55
Fredericks (NAM	10.28	9.82	0.46
Da Silva (BRA)	10.42	9.70	0.72
Garcia (CUB)	10.30	9.88	0.42
Panagiotopoulos (GRE)	10.37	9.84	0.53
Thompson (BAR)	10.31	9.88	0.43
Drummond (USA)	10.20	10.10	0.10
Stevens (BEL)	10.38	9.88	0.50

Note: Split times do not include reaction times.

Among the medallists, Gold medallist Boldon was the fastest in both sections, while third placed Da Silva demonstrated a very fast 2nd interval, but was too slow in the 1st 100m. Drummond proved his qualities as a 100m specialist with the fastest 1st section, but showed a quite poor 2nd 100m. Boldon exactly doubled his 100m final result of 10.02s while Fredericks was 0.38s slower than the time obtained by doubling his 100m final result of 9.95 seconds.

Table 11 shows the calculated velocities in the intervals.

As the velocities are calculated by dividing the 50m distance by the time for this interval, they must be identical to the split times.

No finalist except Boldon showed a mean velocity of more than 11.0 m/s in his fastest interval. When calculating the mean velocities for the same intervals in the 100m final, the respective values are:

Table 11: Mean velocities in the 50m sections in the men's 200 metres final [m/s]

Name	0-50m	50-100m	100-150m	150-200m
Boldon (TRI)	8.79	11.01	10.46	10.20
Fredericks (NAM	8.83	10.82	10.37	10.00
Da Silva (BRA)	8.68	10.73	10.42	10.20
Garcia (CUB)	8.84	10.78	10.50	9.77
Panagiotopoulos (GRE)	8.73	10.78	10.37	9.96
Thompson (BAR)	8.70	10.96	10.42	9.84
Drummond (USA)	8.90	10.92	10.29	9.54
Stevens (BEL)	8.72	10.78	10.42	9.84

Table 12: Split times for the 50m intervals in the 200 metres women's final

Name	Result [s]	RT [ms]	0-50m [s]	50-100m [s]	100-150m [s]	150-200m [s]
Pintusevich (UKR)	22.32	124	6.00	5.04	5.32	5.84
Jayasinghe (SRI)	22.39	181	6.05	5.02	5.32	5.82
Ottey (JAM)	22.40	146	5.99	5.00	5.24	6.02
Leshchova (RUS)	22.50	149	6.21	5.10	5.40	5.64
Miller (USA)	22.52	143	6.08	5.04	5.36	5.90
Trandenkova (RUS)	22.65	138	6.25	5.14	5.36	5.76
Gainsford-Taylor (AUS)	22.73	150	6.24	5.06	5.38	5.90
Felix (FRA)	22.81	157	6.37	5.20	5.36	5.72

Note: Split times do not include reaction times.

Table 13: 100m split times in the women's 200 metres final [s]

Name	1st 100m	2nd 100m	Difference
Pintusevich (UKR)	11.04	11.16	-0.12
Jayasinghe (SRI)	11.07	11.14	-0.07
Ottey (JAM)	10.99	11.26	-0.27
Leshchova (RUS)	11.31	11.04	0.27
Miller (USA)	11.12	11.26	-0.14
Trandenkova (RUS)	11.39	11.12	0.27
Gainsford-Taylor (AUS)	11.30	11.28	0.02
Felix (FRA)	11.57	11.08	0.49

Note: Split times do not include reaction times.

Boldon	1st 50m: 9.16 [m/s]	2nd 50m: 11.26 [m/s]
Fredericks	1st 50m: 9.16 [m/s]	2nd 50m: 11.47 [m/s]
Greene	1st 50m: 9.23 [m/s]	2nd 50m: 11.60 [m/s]
Bailey	1st 50m: 9.21 [m/s]	2nd 50m: 11.55 [m/s]

Thus both the 1st and the 2nd 50m are markedly slower than in the 100 metres final.

These findings should be compared with analysis of another, faster 200 metres race, since the winning time in Athens was not outstanding.

4.2.2 Women's final

Table 12 shows the split times for the 50m intervals.

As in the men's findings, the fastest interval is the 2nd 50m. Merlene Ottey had the best split times up to 150m, but had an extremely poor finish. As in the 100 metres final, the women's reaction times are somewhat slower than the men's. Jayasinghe lost 6 of her 7/100s to Pintusevitch due to her poor reaction time.

Table 13 sums up the split times for the 1st and 2nd 100m interval.

The results are quite different from the men's findings. While the men's 2nd 100m was about 0.50s faster than the 1st 100m (except Drummond), there is no clear tendency in the women's data.

The medallists and Miller were very fast in the 1st 100m but markedly slower in the 2nd half. Felix, the extreme opposite, had a very slow start followed by an extraordinary 2nd 100m interval. This is confirmed by the velocities in *Table 14*.

Merlene Ottey shows the fastest 50m interval with a mean velocity of 10.0m/s but is the slowest finalist at the finish. Both Russian sprinters demonstrate good speed endurance with a fast last interval.

Reference values for the 100 metres final are as follows:

Pintusevich	1st 50m: 8.47[m/s]	2nd 50m: 10.40[m/s]
Ottey	1st 50m: 8.18[m/s]	2nd 50m: 9.92[m/s]
Miller	1st 50m: 8.25[m/s]	2nd 50m: 10.00[m/s]
Jones	1st 50m: 8.53[m/s]	2nd 50m: 10.40[m/s]

5 400 metres

(by Wolfgang Ritzdorf)

5.1 Methods and procedures

Data from the 400 metres finals were gathered with three video cameras placed at 100, 200 and 300m. Intermediate times were calculated for each finalist.

5.2 Results and comments

5.2.1 Men's final

Table 15 (next page) shows the split times for the 50m intervals.

Although it is well known that reaction times are slower in longer races, reaction times of markedly slower than 0.20s are inefficient. For example, Richardson lost all of his 8/100ths to Washington in his reaction time. Pettigrew would have placed 4th with a reaction time of 0.16s.

The pace distribution of the race may be better understood by comparing the 50m intervals (*Table 16*, next page).

Johnson showed the best pace judgement in the race, losing only 1.01s in the 2nd half. Pettigrew lost less time, but this result was

Table 14: Mean velocities in the 50m sections in the women's 200 metres final [m/s]

Name	0-50m	50-100m	100-150m	150-200m
Pintusevich (UKR)	8.34	9.92	9.40	8.56
Jayasinghe (SRI)	8.27	9.96	9.40	8.59
Ottey (JAM)	8.34	10.00	9.54	8.31
Leshchova (RUS)	8.05	9.80	9.26	8.87
Miller (USA)	8.23	9.92	9.33	8.47
Trandenkova (RUS)	8.00	9.73	9.33	8.68
Gainsford-Taylor (AUS)	8.01	9.88	9.29	8.47
Felix (FRA)	7.85	9.62	9.33	8.74

Table 15: 50m split times in the 400 metres men's final [s]

Name	Result	RT [ms]	0-50m	50-100m	100-150m	150-200m	200-250m	250-300m	300-350m	350-400m
Johnson (USA)	44.12	167	6.01	4.98	5.20	5.28	5.28	5.40	5.66	6.14
Kamoga (UGA)	44.37	216	6.23	5.04	5.04	5.02	5.24	5.46	5.78	6.34
Washington (USA)	44.39	161	6.07	5.00	5.10	5.30	5.46	5.40	5.80	6.10
Richardson (GBR)	44.47	245	5.91	4.98	5.20	5.24	5.38	5.54	5.72	6.26
Young (USA)	44.51	185	6.16	5.00	5.08	5.08	5.40	5.48	5.86	6.26
Thomas (GBR)	44.52	165	5.72	5.02	4.94	5.16	5.40	5.68	5.98	6.46
Pettigrew (USA)	44.57	275	6.30	4.96	5.18	5.28	5.28	5.50	5.72	6.08
Baulch (GBR)	45.22	158	6.08	4.88	5.00	5.20	5.46	5.84	6.00	6.60

Note: Split times do not include reaction times.

Table 16: 100m and 200m split times in the 400 metres men's final [s]

Name	Result	0-100m	100-200m	200-300m	300-400m	1st 200m	2nd200m	Difference
Johnson (USA)	44.12	10.99	10.48	10.68	11.80	21.47	22.48	-1.01
Kamoga (UGA)	44.37	11.27	10.06	10.70	12.12	21.33	22.82	-1.49
Washington (USA)	44.39	11.07	10.40	10.86	11.90	21.47	22.76	-1.29
Richardson (GBR)	44.47	10.89	10.44	10.92	11.98	21.33	22.90	-1.58
Young (USA)	44.51	11.17	10.16	10.88	12.12	21.33	23.00	-1.68
Thomas (GBR)	44.52	10.74	10.10	11.08	12.44	20.84	23.52	-2.69
Pettigrew (USA)	44.57	11.26	10.46	10.78	11.80	21.72	22.58	-0.86
Baulch (GBR)	45.22	10.96	10.20	11.30	12.60	21.16	23.90	-2.74

Table 17: Mean velocities in the men's 400 m final [m/s]

Name	Result	0-50m	50-100m	100-150m	150-200m	200-250m	250-300m	300-350m	350-400m
Johnson (USA)	44.12	8.32	10.04	9.62	9.47	9.47	9.26	8.83	8.14
Kamoga (UGA)	44.37	8.02	9.92	9.92	9.96	9.54	9.16	8.65	7.89
Washington (USA)	44.39	8.24	10.00	9.80	9.43	9.16	9.26	8.62	8.20
Richardson (GBR)	44.47	8.47	10.04	9.62	9.54	9.29	9.03	8.74	7.99
Young (USA)	44.51	8.11	10.00	9.84	9.84	9.26	9.12	8.53	7.99
Thomas (GBR)	44.52	8.75	9.96	10.12	9.69	9.26	8.80	8.36	7.74
Pettigrew (USA)	44.57	7.94	10.08	9.65	9.47	9.47	9.09	8.74	8.22
Baulch (GBR)	45.22	8.22	10.25	10.00	9.62	9.16	8.56	8.33	7.58

Table 18: 50m split times in the women's 400 metres final [s]

Name	Result	RT [ms]	0-50m	50-100m	100-150m	150-200m	200-250m	250-300m	300-350m	350-400m
Freeman (AUS)	49.77	226	6.54	5.72	5.64	5.80	6.00	6.20	6.60	7.04
Richards (JAM)	49.79	167	6.50	5.56	5.76	5.88	6.08	6.24	6.60	7.00
Miles-Clark (USA)	49.90	143	6.67	5.56	5.56	5.96	6.08	6.24	6.60	7.08
Breuer (GER)	50.06	143	6.44	5.48	5.24	6.36	6.20	6.40	6.64	7.16
Ogunkoya (NGR)	50.27	126	6.58	5.72	5.64	5.76	6.08	6.20	6.76	7.40
Fuchsova (CZE)	50.66	159	6.62	5.56	5.52	5.96	6.24	6.48	6.76	7.36
Davis (BAH)	50.68	127	6.58	5.72	5.88	6.00	6.20	6.41	6.60	7.16
Alekseyeva (RUS)	51.37	167	6.48	5.76	5.40	5.84	6.24	6.56	6.96	7.96

Note: Split times do not include reaction times.

due to a rather slow 1st 200m. Kamoga's decrease of 1.49s must be set against his very fast 1st half, especially the 2nd 100m section. British finalists Thomas and Baulch clearly started too fast and thus lost more than 2.5 seconds in the 2nd part of the race.

As in the 200 metres final, velocities can be calculated from the split times (*Table 17*).

Maximum mean velocities are slightly higher than 10m/s. The mean velocity in the last 50m interval varies by 0.64m/s between the finalists.

The relevance of good pace judgement is illustrated by two other facts. Firstly, despite his winning performance, there is only one section (300-350m), where Johnson is the fastest sprinter in this final. Secondly, Silver medallist Kamoga is the only finalist who did not reach a maximum mean velocity of 10.0m/s in any section.

5.2.2 Women's final

Table 18 shows the split times for the 50m intervals.

Compared to the men's findings, women's reaction times are quite fast, except for gold medallist Freeman. At first sight there is no outstanding result. Only Breuer's 100-150m section is extremely fast, compared with that of the other finalists. The pace judgement of the race may be better understood by comparing the 50m intervals (*Table 19*).

Except for Davis, the rank order is almost identical with the loss in the 2nd 200m. Alekseyeva, with the dramatic loss of 4.24s, clearly went too fast at the beginning with the fastest 1st 200m of all finalists.

The calculated velocities are given in *Table 20.*

Table 19: 100m and 200m split times in the 400 metres women's final [s]

Name	Result	0-100m	100-200m	200-300m	300-400m	1st 200m	2nd 200m	Difference
Freeman (AUS)	49.77	12.26	11.44	12.20	13.64	23.70	25.84	-2.14
Richards (JAM)	49.79	12.06	11.64	12.32	13.60	23.70	25.92	-2.22
Miles-Clark (USA)	49.90	12.23	11.52	12.32	13.68	23.76	26.00	-2.24
Breuer (GER)	50.06	11.92	11.60	12.60	13.80	23.52	26.40	-2.88
Ogunkoya (NGR)	50.27	12.30	11.40	12.28	14.16	23.70	26.44	-2.74
Fuchsova (CZE)	50.66	12.18	11.48	12.72	14.12	23.66	26.84	-3.18
Davis (BAH)	50.68	12.30	11.88	12.61	13.76	24.18	26.37	-2.19
Alekseyeva (RUS)	51.37	12.24	11.24	12.80	14.92	23.48	27.72	-4.24

Table 20: Mean velocities in the women's 400 m final [m/s]

Name	Result [s]	0-50m	50-100m	100-150m	150-200m	200-250m	250-300m	300-350m	350-400m
Freeman (AUS)	49.77	7.64	8.74	8.87	8.62	8.33	8.06	7.58	7.10
Richards (JAM)	49.79	7.69	8.99	8.68	8.50	8.22	8.01	7.58	7.14
Miles-Clark (USA)	49.90	7.49	8.99	8.99	8.39	8.22	8.01	7.58	7.06
Breuer (GER)	50.06	7.77	9.12	9.54	7.86	8.06	7.81	7.53	6.98
Ogunkoya (NGR)	50.27	7.59	8.74	8.87	8.68	8.22	8.06	7.40	6.76
Fuchsova (CZE)	50.66	7.55	8.99	9.06	8.39	8.01	7.72	7.40	6.79
Davis (BAH)	50.68	7.60	8.74	8.50	8.33	8.06	7.80	7.58	6.98
Alekseyeva (RUS)	51.37	7.71	8.68	9.26	8.56	8.01	7.62	7.18	6.28

Maximum mean velocities of more than 9m/s are shown by Breuer between 50 and 150m, followed by quite a slow next 50m section. Fuchsova and Alekseyeva also demonstrated a similar pattern. Only the medallists' velocity in the last 50m section is faster than 7m/s. The importance of balanced pace judgement is illustrated by the following data (the difference between the fastest and the slowest 50m section):

Freeman	1.76s
Richards	1.85s
Miles-Clark	1.93s
Breuer	2.56s
Ogunkoya	2.11s
Fuchsova	2.26s
Davis	1.76s
Alekseyeva	2.98s.

The trend is not perfect, but still quite clear: the smaller the variation, the better the result. Breuer's result in particular indicates inadequate pace judgement.

6 110 and 100 metres hurdles (by Helmar Hommel)

6.1 Methods and procedures

Data from the 110m hurdles final were recorded with two different devices: LAVEG laser measurement from a rear position and video analysis from a rectangular side position. As other finals in the jumping events were taking place simultaneously, only 4 laser devices were available. Data for the 100m hurdles final were calculated from video only.

While the laser analysis allows a calculation of the *instantaneous velocity* during the race, the video-based time analysis gives the *intermediate velocities* for each hurdle section [start to touch-down after the 1st hurdle (1), the hurdle sections from touch-down to touch-down (2 ... 10) and touch down after the 10th hurdle to run-in (11)].

Beside the men's instantaneous velocities (*Table 21*) taken from laser measurement, all other data from the hurdles finals given here in this first information were analyzed from video. The resulting data are given in tables and, according to previous analysis of major competitions, the medallists' data are transferred to standard diagrams.

6.2 Results and comments

A good race distribution is described by a short reaction time (< 0.13s), a high initial velocity increase up to hurdle 2 with a further increase to a high maximum speed level at hurdle 3 (> 9m/s) that is maintained more or less until hurdle 7 to 10, short hurdle clearance times (≈ 0.30s) and a final velocity increase at the run-in, cf. *Figure 4*/Jackson as a good example).

The hurdle clearance times (tHurdle) are not only an indicator of sprinting abilities but especially of the technical level of the athlete, but one must take into consideration that the hurdle

Table 21: Instantaneous velocities in the men's 110 metres hurdles final [m/s]

Name	Result [s]	RT [ms]	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	run-in
Johnson (USA)	12.93	128	8.67	9.11	9.33	9.22	9.10	9.06	8.99	8.90	8.81	8.78	9.04
Jackson (GBR)	13.05	118	8.66	8.93	9.14	9.17	9.16	8.98	8.96	8.83	8.74	8.63	8.97
Kovac (SLO)	13.18	161	8.45	8.78	8.85	8.92	8.96	8.93	8.86	8.82	8.76	8.90	8.97
Schwarthoff (GER)	13.20	141	8.41	8.77	9.03	9.02	8.88	8.95	8.81	8.83	8.67	8.68	–

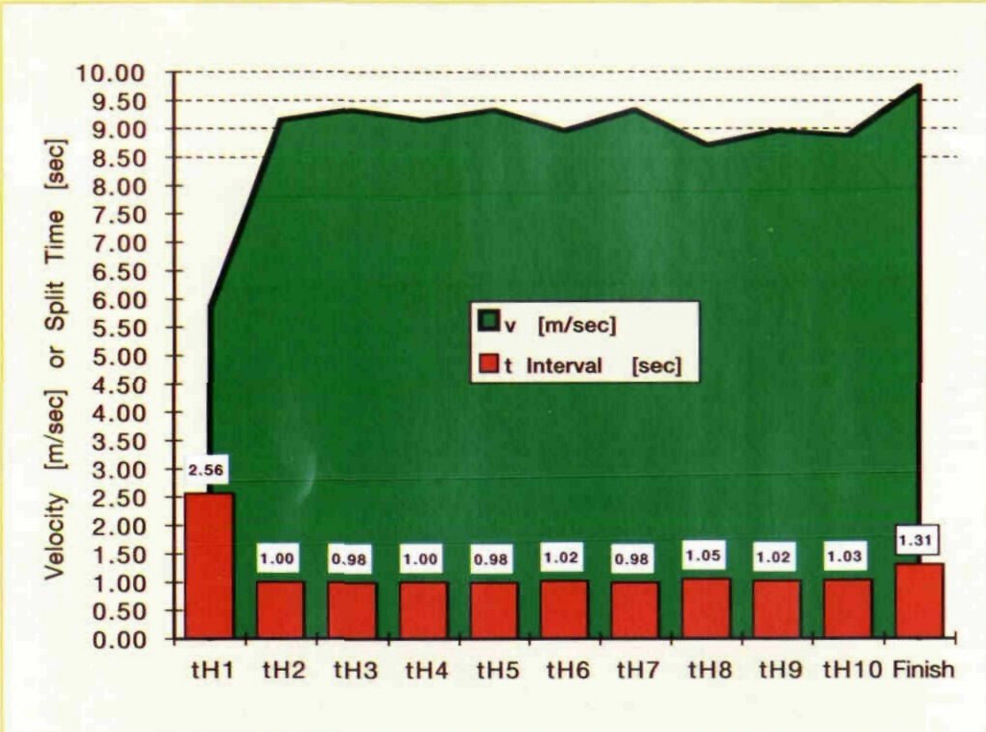

Figure 3: Allen Johnson (USA) – 12.93s, Gold medal

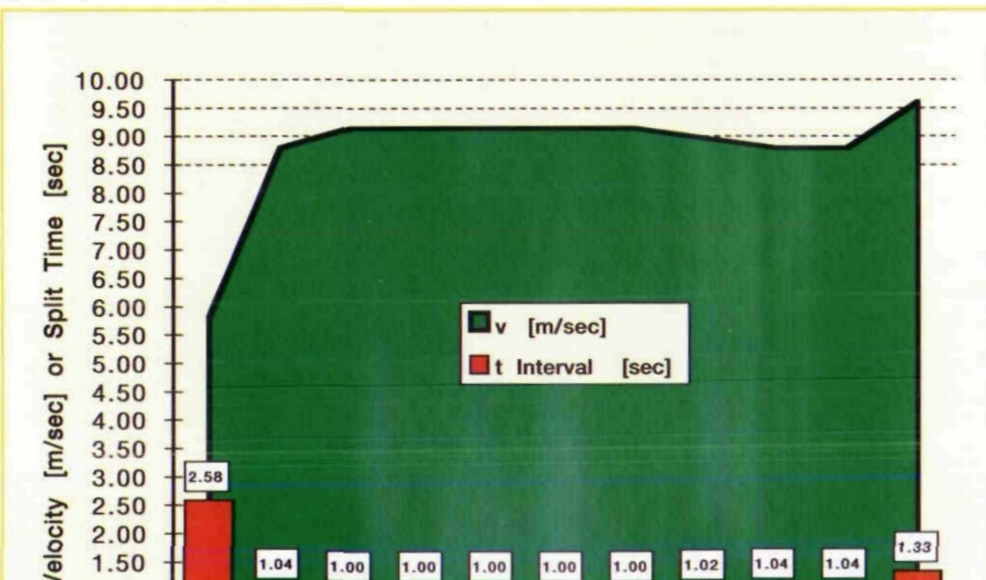

Figure 4: Colin Jackson (GBR) – 13.05s, Silver medal

Table 22: 110 metres hurdles final – interval times [s]

Result	Reaction time	0-tH1	tH1-tH2	tH2-tH3	tH3-tH4	tH4-tH5	tH5-tH6	tH6-tH7	tH7-tH8	tH8-tH9	tH9-tH10	Finish
Johnson, Allen (USA)												
12.93	0.128	2.56	1.00	0.98	1.00	0.98	1.02	0.98	1.05	1.02	1.03	1.31
Jackson, Colin (GBR)												
13.05	0.118	2.58	1.04	1.00	1.00	1.00	1.00	1.00	1.02	1.04	1.04	1.33
Kovac, Igor (SVK)												
13.18	0.161	2.62	1.06	1.02	1.02	1.00	1.02	1.04	1.00	1.04	1.04	1.32
Schwarthoff, Florian (GER)												
13.20	0.141	2.58	1.06	1.00	1.02	1.02	1.02	1.02	1.02	1.04	1.06	1.36
Philibert, Dan (FRA)												
13.26	0.118	2.62	1.08	1.00	1.00	1.00	1.02	1.02	1.02	1.06	1.04	1.40
Reese, Terry (USA)												
13.30	0.117	2.66	1.06	1.02	1.00	1.02	1.02	1.02	1.02	1.08	1.10	1.30
Crear, Mark (USA)												
13.55	0.134	2.60	1.04	1.01	1.01	1.00	1.10	1.02	1.08	1.06	1.14	1.49

Table 23: 110 metres hurdles final – hurdle clearance times [s]

	tH1	tH2	tH3	tH4	tH5	tH6	tH7	tH8	tH9	tH10
Johnson, Allen (USA)	0.35	0.34	0.32	0.32	0.32	0.34	0.32	0.35	0.35	0.34
Jackson, Colin (GBR)	0.34	0.36	0.36	0.34	0.36	0.34	0.36	0.34	0.35	0.34
Kovac, Igor (SVK)	0.34	0.34	0.32	0.34	0.32	0.32	0.32	0.32	0.34	0.34
Schwarthoff, Florian (GER) 0.32	0.34	0.28	0.30	0.30	0.32	0.32	0.32	0.32	0.32	
Philibert, Dan (FRA)	0.32	0.36	0.34	0.34	0.30	0.32	0.34	0.34	0.36	0.36
Reese, Terry (USA)	0.38	0.40	0.36	0.38	0.38	0.38	0.38	0.36	0.40	0.44
Crear, Mark (USA)	0.36	0.36	0.35	0.36	0.34	0.42	0.36	0.36	0.36	0.36

Table 24: 110 metres hurdles final – section velocities [m/s]

	0-tH1	tH1-tH2	tH2-tH3	tH3-tH4	tH4-tH5	tH5-tH6	tH6-tH7	tH7-tH8	tH8-tH9	tH9-tH10	Finish
Johnson (USA)	5.85	9.14	9.33	9.14	9.33	8.96	9.33	8.70	8.96	8.87	9.75
Jackson (GBR)	5.80	8.79	9.14	9.14	9.14	9.14	9.14	8.96	8.79	8.79	9.60
Kovac (SVK)	5.71	8.62	8.96	8.96	9.14	8.96	8.79	9.14	8.79	8.79	9.67
Schwarthoff (GER)	5.80	8.62	9.14	8.96	8.96	8.96	8.96	8.96	8.79	8.62	9.39
Philibert (FRA)	5.71	8.46	9.14	9.14	9.14	8.96	8.96	8.96	8.62	8.79	9.12
Reese (USA)	5.63	8.62	8.96	9.14	8.96	8.96	8.96	8.96	8.46	8.31	9.82
Crear (USA)	5.76	8.79	9.05	9.05	9.14	8.31	8.96	8.46	8.62	8.02	8.57

clearance time depends on antropometric data of the given athlete (leg length, centre of mass) and must be seen in relation to the flight distance (take-off before to touch down after the hurdle). Top athletes tend to have from hurdle 1 to 10 an increase in distance of take-off point while poor performancing athletes run ever closer to the hurdle. But such data could not be retrieved from this video analysis for the first information, it needs a closer analysis with landmarks on the track.

In the women's 100 metres hurdles a similar distribution of the velocity curve – just at a lower level – could be seen, but what is different is a slight decrease of the velocity in the second half of the race. Due to the shorter distance from the last hurdle to the finish line, the final increase of velocity is normally much less, compared to the men's 110m hurdles, cf. *Figure 7*/Dimitrova).

Men's winner Johnson (*Figure 3*) showed an unsteady race distribution, reaching his top speed at tH3, tH5 and tH7 and the highest run-in speed (9.75m/s). Second placed world record holder Jackson (*Figure 4*) ran a good constant race but with a lower level of top speed (9.14m/s from tH3 to tH7). Kovac (rank 3) ran until hurdle 8 behind Schwarthoff but won the bronze medal because of his faster finish.

Schwarthoff, finishing fourth, reached also 9.75m/s at tH3 but decreased then only to a level of 8.94m/s (cf. *Table 24*). His race was constant with the shortest hurdle clearing times (0.28-0.32s) among the finalists (cf. *Table 23*).

Outstanding reaction times (cf. *Table 22*) were achieved by Rees (0.117s) Jackson and Philibert (0.118s).

In the women's final gGold medallist Enquist (*Figure 6*) reached the highest speed between hurdle 4 and 5 (9.04s) whilst second placed Dimitrova (*Figure 7*) realized only 8.85s but having more constant intervals except at tH10 because of touching the hurdle. Bronze medallist Freeman (*Figure 8*) gained her top speed at tH4 (8.85m/s) but then lost speed continuously until tH10. She was leading the race until hurdle 9 but had no chance of accelerating to the finish because she touched hurdle 10 which caused some problems of balance.

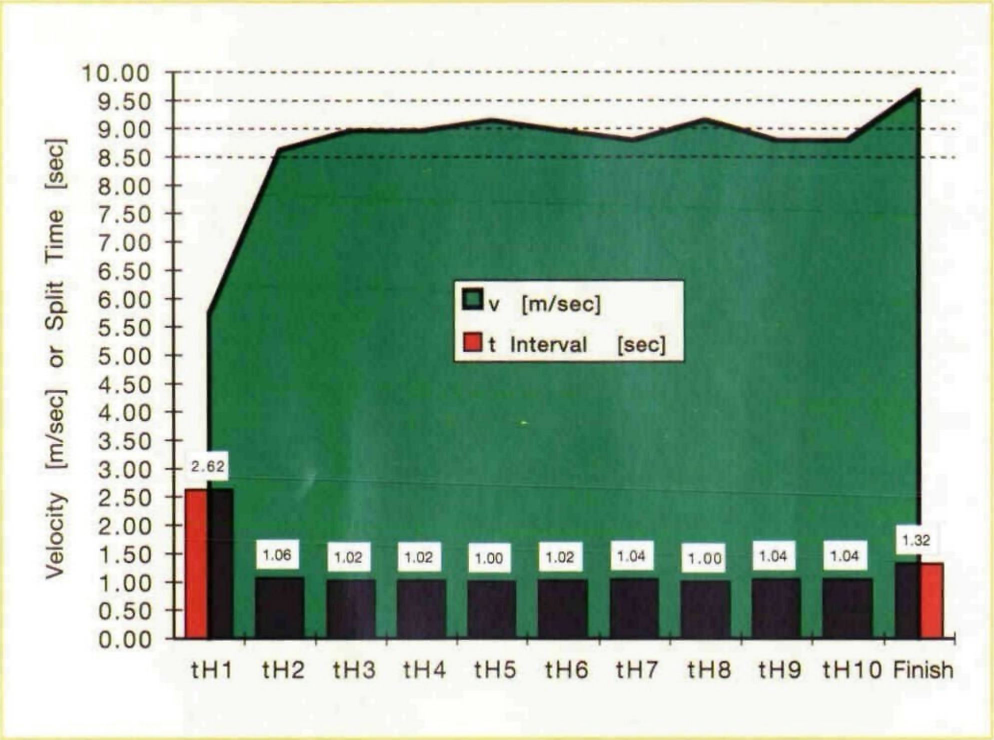

Figure 5: Igor Kovac (SVK) – 13.18s, Bronze medal

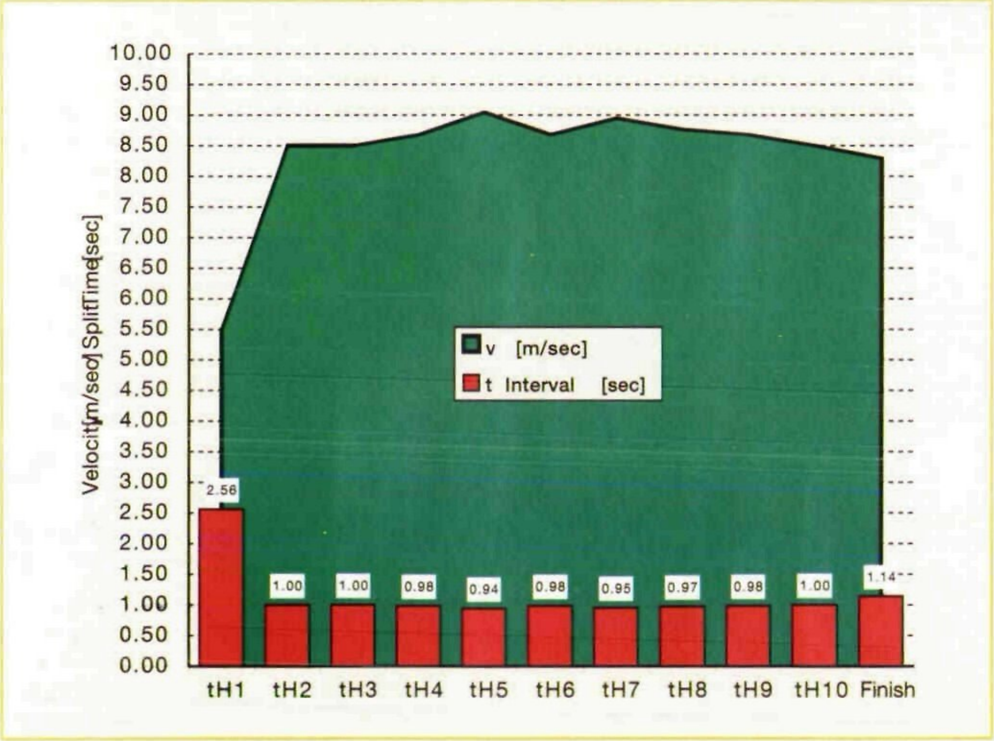

Figure 6: **Ludmila Engquist (SWE) – 12.50s, Gold medal**

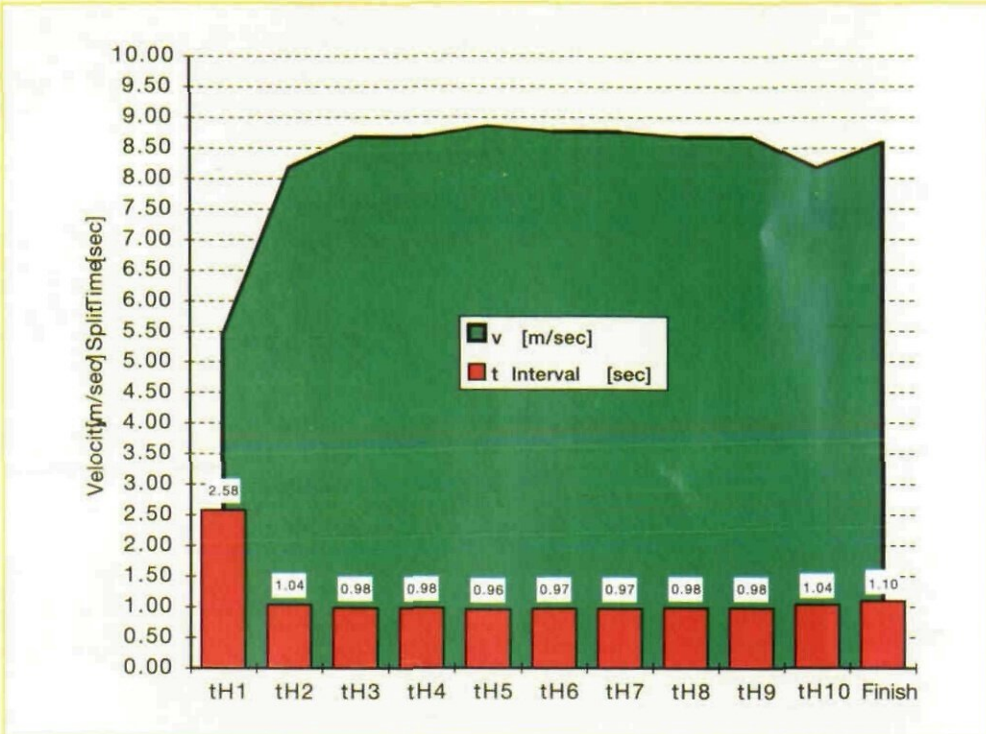

Figure 7: Svetla Dimitrova (BUL) – 12.58s, Silver medal

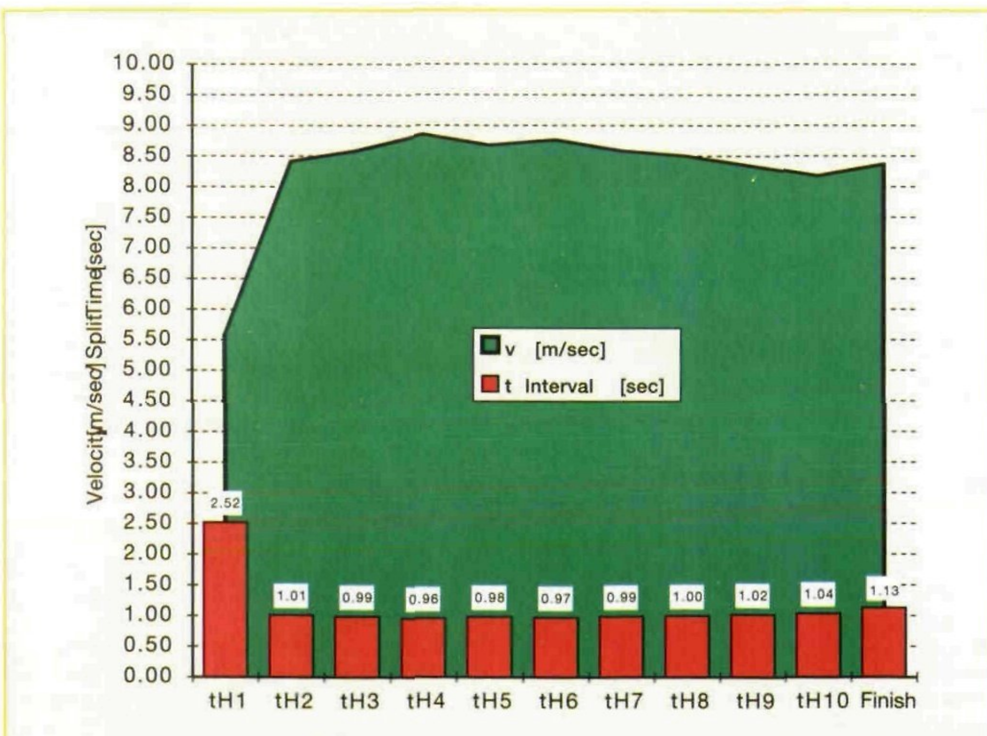

Figure 8: Michelle Freeman (JAM) – 12.61s, Bronze medal

Table 25: 100 metres hurdles final – interval times [s]

Athlete	Result	Reaction time	0-tH1	tH1-tH2	tH2-tH3	tH3-tH4	tH4-tH5	tH5-tH6	tH6-tH7	tH7-tH8	tH8-tH9	tH9-tH10	Finish
			Section										
Engquist, Ludmila (SWE)	12.50	0.126	2.56	1.00	1.00	0.98	0.94	0.98	0.95	0.97	0.98	1.00	1.14
Dimitrova, Svetla (BUL)	12.58	0.136	2.58	1.04	0.98	0.98	0.96	0.97	0.97	0.98	0.98	1.04	1.10
Freeman, Michelle (JAM)	12.61	0.145	2.52	1.01	0.99	0.96	0.98	0.97	0.99	1.00	1.02	1.04	1.13
Bukovec, Brigita (SLO)	12.69	0.146	2.60	0.98	1.00	0.98	0.96	0.97	1.01	1.00	1.00	1.04	1.15
Rose, Dionne (JAM)	12.87	0.118	2.60	0.98	1.00	0.98	1.00	1.00	1.02	1.02	1.04	1.02	1.21
Anderson, Katie (CAN)	12.88	0.127	2.54	1.04	1.00	1.00	0.98	1.00	1.00	1.04	1.04	1.08	1.16
Laukhova, Svetlana (RUS)	12.89	0.135	2.58	1.04	1.02	1.00	1.00	1.00	1.03	1.03	1.02	1.08	1.09

Table 26: 100 metres hurdles final – hurdle clearance times [s]

	tH1	tH2	tH3	tH4	tH5	tH6	tH7	tH8	tH9	tH10
	Hurdle									
Engquist (SWE)	0.30	0.30	0.32	0.32	0.30	0.32	0.29	0.29	0.28	0.28
Dimitrova (BUL)	0.32	0.32	0.32	0.30	0.30	0.31	0.30	0.32	0.30	0.32
Freeman (JAM)	0.32	0.31	0.34	0.30	0.32	0.33	0.32	0.34	0.34	0.34
Bukovec (SLO)	0.30	0.28	0.30	0.28	0.28	0.27	0.30	0.30	0.28	0.30
Rose (JAM)	0.36	0.30	0.28	0.28	0.30	0.30	0.32	0.32	0.32	0.28
Anderson (CAN)	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.32	0.34	0.34
Laukhova (RUS)	0.30	0.34	0.30	0.30	0.30	0.30	0.31	0.31	0.30	0.32

Table 27: 100 metres hurdles final – section velocities [m/s]

	0-tH1	tH1-tH2	tH2-tH3	tH3-tH4	tH4-tH5	tH5-tH6	tH6-tH7	tH7-tH8	tH8-tH9	tH9-tH10	Finish
	Section										
Engquist (SWE)	5.49	8.50	8.50	8.67	9.04	8.67	8.95	8.76	8.67	8.50	8.29
Dimitrova (BUL)	5.45	8.17	8.67	8.67	8.85	8.76	8.76	8.67	8.67	8.17	8.59
Freeman (JAM)	5.58	8.42	8.59	8.85	8.67	8.76	8.59	8.50	8.33	8.17	8.36
Bukovec (SLO)	5.40	8.67	8.50	8.67	8.85	8.76	8.42	8.50	8.50	8.17	8.22
Rose (JAM)	5.40	8.67	8.50	8.67	8.50	8.50	8.33	8.33	8.17	8.33	7.81
Anderson (CAN)	5.53	8.17	8.50	8.50	8.67	8.50	8.50	8.17	8.17	7.87	8.15
Laukhova (RUS)	5.45	8.17	8.33	8.50	8.50	8.50	8.25	8.25	8.33	7.87	8.67

Enquist performed her shortest hurdle clearing times in the last part of the race (0.29 at hurdles 7 and 8, 0.28 at hurdles 9 and 10 – cf. *Table 26*).

The best reaction time (cf. *Table 25*) was 0.118s by Rose (fifth place).

7 Long jump

(by Harald Müller and Gert-Peter Brüggemann)

7.1 Introduction and purpose

The purpose of this study is to update the current biomechanical data on the centre of mass (CM) and segmental parameters of the long jump at elite level. The data collected during the World Championships allows comparisons to be made between male and female athletes and techniques, as well as between recent data and data from the literature and previous projects. In order to get a wide range of information, data was obtained from the finals and qualification rounds of male and female competitors.

7.2 Methods and procedures

The finals of the long jump at the World Championships 1997 were recorded with three synchronised S-VHS videocameras operating at 50 fields per second. The cameras were placed perpendicular to the plane of motion. Camera one filmed the 3rd and 2nd last step. Camera two recorded the 2nd last step to take-off and camera three was focused on the jump. In addition to this set-up, one high-speed camera (Motionscope, Redlake), operating at 250 frames per second, filmed the take-off.

All trials of the women's and men's finals were recorded. For data reduction, the relevant video sequences were transferred via a video grabber board to the videodata disk of the Motus video motion analysis system (Peak Performance). Using a calibration cube as reference system, the camera positions, the pan and tilt angle and the focal length were calculated for each of the cameras. Thus, a so-called 3D-DLT was used for camera calibration and co-ordinate reconstruction.

The x-axis of the co-ordinate system pointed in the direction of jumping along the runway. The y-axis was vertical and perpendicular to the x-axis. The origin was fixed in the middle of the front edge of the take-off board. The best valid jumps of the eight finalists in the men's and women's competition were selected for further analysis. In order to get more run-up information, a photocell system was installed 11m, 6m and 1m from the board. The instantaneous run-up speed of the athletes was measured by a laser system installed behind the runway.

7.3 Results

Distances

The distances within the long jump are defined as follows:

The *official distance* is, according to the rules, the horizontal distance from the front edge of the board to the nearest mark made in the sand by the athlete.

The *effective distance* is the horizontal distance from the toe of the athlete's take-off foot to the nearest point of the feet when hitting the sand at landing.

The distances lost due to poor landing in the sand, lateral deviation in the jump or toe-to-board space are added together to make the *total lost distance (TLD)*.

The distance lost at take-off is called *toe-to-board distance (TTB)*, which describes the distance from the tip of the take-off foot to the pit edge of the board.

Data for all the absolute distances are given in *Table 28* for the men and *Table 33* for the women. The tables include data for the best valid jump of each competitor.

7.3.1 Men's final

The standard of the competition was high but not outstanding, which is illustrated by the mean of 8.12m (±0.20m) and a best result of 8.42m. The run-up precision was quite good, with an average loss of 0.12m (±0.10m) on the take-off board. This, together with the loss of distance in the sand made a total loss of distance of, on average, 0.31m (±0.22m), with individual trends. Glavatskis' run-up accuracy and his total lost distance (total 0.08m) gave him a better competition result than, for example, Dilworth, who lost dramatically in the sand and on the take-off board (total 0.80m). Pedroso's data are close to the average values, but they still show just average run-up accuracy (0.14m) and a total lost distance of 0.25m. Walder and Susunov followed this trend (cf. *Table 28*).

The speed of the centre of mass (CM) at the instant of touchdown (TD) is of major importance for a good result (VxTD). The initial velocity provides the jumper with mechanical energy for the take-off (TO). In homogenous groups a high horizontal velocity is necessary, but not enough in itself for a good performance.

Much more important seems to be the vertical velocity of the CM at the moment of take-off (VyTO), without any great loss of horizontal velocity.

This trend is confirmed by the data from Athens. Pedroso could produce the highest VyTO of all finalists with 3.86m/s (second placed Walder VyTO 3.31m/s), although his horizontal velocity at touchdown (VxTD 10.82m/s) and at take-off (VxTO 8.72m/s) was lower than, for example Walder's (VxTD 11.12m/s and VxTO 9.29m/s).

Data of the angle of projection confirm the different behaviour of Pedroso during take-off compared to all other jumpers. Due to his high vertical velocity at take-off, he produced the greatest angle of projection (24°, see *Table 29*).

An analysis of the stride length of the last three strides reveals a general behaviour with a ratio "long-short" for the last two strides. This adjustment of the stride length allows the jumper to lower his CM in the 2nd to last stride. As soon as he transmits the CM position into the last stride, he is able to extend the vertical acceleration path during take-off. *Tables 30 and 31* confirm this trend for the majority of the jumpers. While the average stride length in the 2nd to last

Table 28: Official, effective, total lost and toe-to-board distances – men's final

Name	Result [m]	Effective distance [m]	Total lost distance [m]	Toe-to-board distance [m]
Pedroso (CUB)	8.42	8.67	0.25	0.14
Walder (USA)	8.38	8.58	0.20	0.11
Susunov (RUS)	8.18	8.46	0.28	0.19
Beckford (JAM)	8.07	8.44	0.37	0.07
Ferreira Jr. (BRA)	8.04	8.36	0.32	0.01
Glavatski (BLR)	7.98	8.06	0.08	0.00
Toure (FRA)	7.98	8.17	0.19	0.11
Dilworth (USA)	7.88	8.68	0.80	0.29
mean	*8.12*	*8.43*	*0.31*	*0.12*
std. dev.	*±0.20*	*±0.22*	*±0.22*	*±0.10*

Table 29: Velocities of the centre of mass [m/s] and angle of projection [°] during take-off – men's final

Name	Result [m]	VxTD	VxTO	VyTO	AngPr
Pedroso	8.42	10.82	8.72	3.86	24
Walder	8.38	11.12	9.29	3.31	20
Susunov	8.18	10.81	8.65	3.55	22
Beckford	8.07	10.75	8.53	3.48	22
Ferreira Jr.	8.04	10.47	8.87	3.10	19
Glavatski	7.98	10.19	8.22	3.38	22
Toure	7.98	10.62	9.15	3.15	19
Dilworth	7.88	10.52	9.24	3.45	20
mean	*8.12*	*10.66*	*8.83*	*3.41*	*21*
std. dev.	*±0.20*	*±0.28*	*±0.38*	*±0.24*	*±1.77*

Table 30: Stride lengths of the last three strides [m] – men's final

Name	Result [m]	3LS	2LS	1LS
Pedroso	8.42	2.28	2.43	2.16
Walder	8.38	2.34	2.43	2.27
Susunov	8.18	–	2.50	2.40
Beckford	8.07	2.49	2.45	2.13
Ferreira Jr.	8.04	2.21	2.24	2.27
Glavatski	7.98	2.44	2.28	2.10
Toure	7.98	–	2.46	2.33
Dilworth	7.88	–	2.45	2.21
mean	*8.12*	*2.35*	*2.41*	*2.23*
std. dev.	*±0.20*	*±0.11*	*±0.09*	*±0.10*

stride is 2.41m (±0.09m), the mean in the last step is 2.23m (±0.10m). Nearly all finalists shorten their stride length in the last step (except Ferreira Jr.), on average by 0.18m.

As already mentioned, most of the finalists lowered their CM in the 2nd last stride by extending their stride length. This corresponds to the data of the height of the CM in *Table 4* (average decrease of 8cm ±2.4cm). All jumpers (one exception: Walder) transmitted their lowered CM into the take-off. From the 2nd last step to the take-off, the CM was shifted into a vertical direction by approx. 4-6cm.

Concerning the change of mechanical energy during take-off, one can observe that the jumpers on average lost 14.19% (std. ±3.95%) of their total mechanical energy in the take-off. A trend whereby the better jumpers are losing less energy was not discernible.

Table 31: Change of height of centre of mass during the last strides [cm] – men's final

Name	Result [m]	2LS to last	last to TO
Pedroso	8.42	-8	-4
Walder	8.38	-10	4
Susunov	8.18	-8	-2
Beckford	8.07	-9	-7
Ferreira Jr.	8.04	-11	-5
Glavatski	7.98	-7	0
Toure	7.98	-8	-3
Dilworth	7.88	-3	-5
mean	*8.12*	*-8*	*-2.75*
std. dev.	*±0.20*	*±2.39*	*±3.45*

Table 32: Change of mechanical energy during support phases [in % of touch down energy] – men's final

Name	Result [m]	2LS	L	TO
Pedroso	8.42	-5.4	6.4	-16.6
Walder	8.38	-6.2	3.4	-15.1
Susunov	8.18	–	1.6	-17.9
Beckford	8.07	-5.6	3.9	-18.4
Ferreira Jr.	8.04	2.4	-5.0	-12.9
Glavatski	7.98	-3.5	1.0	-15.0
Toure	7.98	–	3.7	-11.1
Dilworth	7.88	–	-2.7	-6.50
mean	*8.12*	*-3.66*	*1.54*	*-14.19*
std. dev.	*±0.20*	*±3.54*	*±3.75*	*±3.95*

7.3.2 Women's final

Because Johanson and Khristova had the same official distance, the Research Team decided to include nine instead of eight jumpers into the study.

The competition level was relatively high. With an average of 6.81m (std. dev. ±0.14m) and the best (and only) jump over 7.00m (Galkina 7.05m), this competition follows the pattern of similar recent competitions (cf. *Table 33*). It is interesting that the majority of the jumpers had an accurate run-up (average 0.08 ±0.05m). While, in terms of the total lost distance, the champion Galkina, showed optimal results (TTB 0.06m, TLD 0.12m), it seems that Xanthou and May lost first place due to a considerable loss, both on the board and in the sand (Xanthou's TLD 0.34m and May's 0.40m).

The absolute values of the horizontal run-up speed (*Table 34)* are within the average for other

Table 33: Official, effective, total lost and toe-to-board distances – women's final

Name	Result [m]	Effective distance [m]	Total lost distance [m]	Toe-to-board distance [m]
Galkina (RUS)	7.05	7.17	0.12	0.06
Xanthou (GRE)	6.93	7.27	0.34	0.15
May (ITA)	6.91	7.31	0.40	0.13
Drechsler (GER)	6.89	6.99	0.10	0.01
Joyner-Kersee (USA)	6.79	7.02	0.23	0.08
Tiedke-Greene (GER)	6.75	6.98	0.23	0.09
Vershinina (UKR)	6.71	6.83	0.12	0.10
Johanson (SWE)	6.64	6.74	0.10	0.00
Khristova (BUL)	6.64	6.85	0.21	0.06
mean	*6.81*	*7.02*	*0.21*	*0.08*
std. dev.	*±0.14*	*±0.20*	*±0.11*	*±0.05*

Table 34: Velocities of the centre of mass [m/s] and angle of projection [°] during take-off – women's final

Name	Result [m]	VxTD	VxTO	VyTO	AngPr
Galkina	7.05	9.72	8.32	2.95	20
Xanthou	6.93	9.66	7.84	3.48	24
May	6.91	9.77	7.98	3.32	23
Drechsler	6.89	9.54	8.43	2.88	19
Joyner-Kersee	6.79	9.94	8.28	2.88	19
Tiedke-Greene	6.75	9.38	8.07	3.09	21
Vershinina	6.71	9.33	7.79	3.17	22
Khristova	6.64	9.20	7.98	2.99	21
Johanson	6.64	9.13	7.55	3.27	23
mean	*6.81*	*9.52*	*8.03*	*3.11*	*21.33*
std. dev.	*±0.14*	*±0.28*	*±0.28*	*±0.21*	*±1.80*

Table 35: Stride lengths of the last three strides [m] – women's final

Name	Result [m]	3LS	2LS	1LS
Galkina	7.05	2.18	2.41	2.07
Xanthou	6.93	2.61	2.12	2.27
May	6.91	2.30	2.29	2.25
Drechsler	6.89	2.24	2.48	2.43
Joyner-Kersee	6.79	2.33	2.16	2.16
Tiedke-Greene	6.75	2.23	2.48	2.37
Vershinina	6.71	–	2.68	2.54
Johanson	6.64	1.92	2.21	2.07
Khristova	6.64	1.90	2.04	2.01
mean	*6.81*	*2.21*	*2.32*	*2.24*
std. dev.	*±0.14*	*±0.23*	*±0.21*	*±0.18*

Table 36: Change of height of centre of mass during the last strides [cm] – women's final

Name	Result [m]	2LS to last	last to TO
Galkina	7.05	-4	-6
Xanthou	6.93	-5	-10
May	6.91	-2	-7
Drechsler	6.89	-7	-4
Joyner-Kersee	6.79	-4	-6
Tiedke-Greene	6.75	-2	-4
Vershinina	6.71	-1	-7
Johanson	6.64	-3	-4
Khristova	6.64	-6	-3
mean	*6.81*	*-3.78*	*-5.67*
std. dev.	*±0.14*	*±1.99*	*±2.18*

Table 37: Change of mechanical energy during support phases [in % of touch down energy] – women's final

Name	Result [m]	2LS	L	TO
Galkina	7.05	4.5	-2.3	-10.5
Xanthou	6.93	-4.2	5.1	-13.8
May	6.91	-0.6	0.4	-14.0
Drechsler	6.89	2.0	-5.3	-6.60
Joyner-Kersee	6.79	-0.1	-3.9	-15.1
Tiedke-Greene	6.75	1.4	-3.1	-8.90
Vershinina	6.71	–	-0.1	-11.4
Johanson	6.64	0.9	-1.7	-10.7
Khristova	6.64	-1.6	-0.3	-7.80
mean	*6.81*	*0.29*	*-1.24*	*11.38*
std. dev.	*±0.14*	*±2.59*	*±3.03*	*±2.58*

studies (9.52m/s ±0.28m/s) and approx. 1m/s slower than for the men. Generally, we find the same behaviour for women in the use of kinetic energy during the take-off movement (see above). The data of the champion, Galkina, are exceptional, in that she was able to win the competition with a lower VyTO (2.95m/s) than the second or third-placed athletes. Both Xanthou and May jumped with a strong bracing action during ground support and, therefore, had a greater loss of horizontal velocity (Xanthou from 9.66m/s to 7.84m/s and May from 9.77m/s to 7.98m/s). Higher VyTO's (3.48m/s and 3.32m/s) and bigger angles of projection (24 and 23°) could not compensate for the loss of VxTO.

It is interesting that Joyner-Kersee, with 9.94m/s, had the highest run-up speed and, therefore, the greatest amount of kinetic energy at touchdown. But she was not able to transfer this energy sufficiently into the vertical direction, as evidenced by a relatively low VyTO of 2.88m/s and a small angle of projection (19°).

Data of the stride lengths during the last three strides (*Table 35*) generally confirm the ratio: "long-short" for the last two steps. The absolute amount of length-reduction is different from that of the men (men's average difference approx. 0.18m; women's approx. 0.08m). Especially among the first four finalists, we can identify just one jumper (Galkina) who shows similar behaviour to the men (difference: 0.34m). The others have a nearly balanced ratio or an increase of stride length from the second last to last stride. This corresponds with data of the CM height in *Table 36*. The absolute length of the strides are close to the men's data, which means that the women's strides are relatively long. Particularly the last stride is slightly longer than the men's strides (women 2.24m / ±0.18m men 2.23m / ±0.10m).

Comparing data of men and women, there is obviously different behaviour in the change of the CM height during the run-up. In general the women lower the CM more within the last stride (-5.67cm, ±2.18cm), the men within the second to last stride (-8cm, ±2,39cm).

Concerning the change of mechanical energy during take-off (*Table 37*), one can observe that the female jumpers lost 11.38% (±2.58%) mechanical energy in the take-off. This loss is less than for the men (men 14,19% ±3.95%). A trend whereby the better jumpers lose less energy was not discernible.

8 Triple jump

(by Gert-Peter Brüggemann and Adiamatios Arampatzis)

8.1 Introduction

Multiple jumps were popular events at ancient town festivals in many cultures. A form of triple jump was a well-known exercise with GUTS MUTHS and JAHN. In the 19th century, German gymnastic pioneers practised a so-called "German triple jump" (left-right-left or vice versa). The Irish technique (hop-hop-jump) was dominant when athletics began to become established in its present form. In 1887, the Irish athlete John Purcell jumped 15.11m with this technique. The present technique (hop-step-jump) was already dominant by the end of the 19th century. J.B. Connolly (USA) was the first Olympic champion in 1896, with a jump of 13.71m.

The first IAAF world record was registered in 1911 with a jump of 15.12m by Daniel Ahearn (USA). The triple jump scene in the 1930's was dominated by several Japanese athletes, one of whom, Naoto Tajima, jumped 16.00m to win the gold medal at the 1936 Olympics in Berlin. The Brazilian Ferreira da Silva attracted a lot of attention after 1955. He set five world records (1955: 16.56m) and was Olympic champion in 1952 and 1956. In 1960, Józef Schmidt (POL) was the first to break the 17m barrier with a jump of 17.03m. Willie Banks (USA) was the first to approach the 18m mark with 17.97m in 1995. Michael Conley, the Olympic gold medallist in 1992 could not officially break the barrier either, despite jumping 18.17m to win in Barcelona. This distance could not be validated because it was wind-assisted. Jonathan Edwards improved the world record considerably and became world champion in 1995 with 18.29m. The second person to jump further than 18.00m was Kenny Harrison (USA), who jumped 18.09m in Atlanta in 1996.

Although the IAAF hesitated for a long time over the introduction of the triple jump for women, as the injury risk to the ankles due to extreme forces at take-off was regarded as too high, there are many women's triple jump distances on record. The first known distance is 8.805m, jumped by Catherine Hand (USA) in 1909. In the 1980's more and more countries introduced the triple jump into their national competition programme. The IAAF has maintained a world record list since 1 January 1990. In 1990 Li Huirong (CHN) jumped 14.54m. The event was first included in the World Championships programme in Stuttgart in 1993, when Ana Birykova (RUS) became the first woman to jump further than 15.00m with 15.09m. Inessa Kravets (UKR) improved the record to 15.57m at the World Championships in Göteburg 1995.

Recently, top female triple jumpers have been able to reach approximately 84% of the distance achieved by male athletes. The increase or change of percentage from the World Championships 1993 to 1997 is negligible (see *Table 38*).

It is noticeable that the mean of the official distances in the men's and women's final did not differ significantly ($p<0.05$) from 1993 to 1997. In other words, the average performance in the triple jump did not improve significantly in the last three World Championships, at least as far as the eight finalists of each event were concerned.

In the short sprint events, the relative difference between men's and women's performances is smaller, at approximately 10%. When one considers that female athletes can come so close to male athletes in their capacity to reach a high running speed and to produce a high amount of kinetic energy in the sprints, and that the difference in performance in the triple jump (and in other horizontal and vertical jumps) between men and women is greater than in sprint events, the question arises as to the biomechanical reason for female athletes failure to use their energetic potential in multiple jumps. Deficient technique or training may play a significant role in this phenomenon.

The purpose of this study is to present the first analysis of biomechanical data from the women's triple jump final of an international competition and to begin to explain the utilisation of mechanical energy during multiple jumping. In order to create a basis for comparison, data of the men's final will also be presented.

8.2 Methods and procedures

The triple jump finals of the World Championships in Athletics 1997 were filmed with four synchronised S-VHS video cameras operating at 50 fields per second. The cameras were placed perpendicular to the plane of motion. Camera 1 filmed the last two strides of the approach, while cameras 2, 3, and 4 were focused on the hop, the step, and the jump, respectively. In addition to the described set-up, one high-speed video camera (motionscope, redlake), operating at 250

Table 38: Results of the men's and women's triple jump finals at the World Championships 1993,1995, and 1997

	Men			*Women*		
Year	1993	1995	1997	1993	1995	1997
mean (n=8)	17.26m	17.41m	17.42m	14.32m (82.96%)*	14.77m (84.8 %)*	14.57m (83.6%)*
std. dev.	±0.34m	±0.46m	±0.30m	±0.39m	±0.50m	±0.44m
maximum	17.86m	18.29m	17.85m	15.09m (84.5%)*	15.50m (84.7%)*	15.20m (85.1%)*
minimum	16.65m	16.93m	17.11m	13.80m	14.18m	14.02m

* percentage of the men's values

frames per second, filmed the take-off for the step, and a second high-speed system (Peak Performance) recorded the take-off for the hop at 200 frames per second.

All trials of the women's and men's finals were recorded. For data reduction, the relevant video sequences were transferred via the video grabber board to the videodata disk of the Motus video motion analysis system (Peak Performance). Using a calibration cube as reference system, the camera positions – the pan and tilt angle and the focal length – were calculated for each of the cameras. Thus a so-called 2D-DLT was used for camera calibration and co-ordinate reconstruction.

The co-ordinate system used had its x-axis along the runway, pointed in the direction of jumping. The y-axis was vertical and perpendicular to the x-axis. The origin was fixed in the centre of the top of the take-off board.

For the biomechanical analysis, a 12-segment model of the human body was used, calculated via 19 landmarks. Both feet, both lower legs, both thighs, the trunk, the upper arms, the forearms including the hands, and the head with the neck represented the rigid body model.

The best valid jump from each of the eight finalists of the men's and women's competitions were selected for further analysis.

In order to obtain more run-up information, photocell systems were installed at 11m, 6m and 1m before the board.

The instantaneous run-up speeds of the athletes were measured by a laser system installed behind the runway. The operator of the system used an optical control device to follow the athlete's lower back during the entire approach run, the hop, the step and the jump. Using the known speed of infrared light, the distance between the laser detector and the reflecting object was measured 50 times per second.

From the position time history, the object's speed was calculated by the first time derivative. The raw data and the calculated speed curves were registered and stored on a PC on the infield.

8.3 Results

8.3.1 Distances

In the triple jump, the outcome or the total distance of the jump depends on the distribution of effort of the jumper over the three phases: the hop, the step and the jump. The major emphasis of coaches and scientists has, therefore, been on the understanding of an optimal distribution of the phase ratios in the men's triple jump. No scientific data are available for the women's triple jump in competition. Effort distribution is usually analysed by the absolute and relative distances achieved in each of the phases. The distances are usually measured perpendicular to the pit edge of the take-off board. The partial distances are defined so that:

- the hop distance is the horizontal distance from the tip of the take-off foot at the take-off for the hop to the tip of the same foot at the take-off for the step,
- the step distance is the horizontal distance from the tip of the take-off foot at the take-off for the step to the tip of the other foot at take-off for the jump, and
- the jump distance is the horizontal distance from the tip of the take-off foot at the take-off for the jump to the nearest mark made in the sand by the heels at the instant of touching the ground.

The effective distance is the horizontal distance from the toe of the athlete's take-off foot at take-off to the nearest point of the feet when hitting the sand at landing. The phase ratios or distance percentages of hop, step and jump are calculated as a percentage of the effective distance.

The official distance is – according to the rules – the horizontal distance from the front edge of the board to the nearest mark made in the sand by the athlete. The distance lost at take-off is called toe-to-board distance (the distance from the tip of the take-off foot to the pit edge of the board). The distance lost due to poor landing in the sand, lateral deviation in the jumps and toe-to-board space are summarised as the total lost distance.

The data for all the absolute distances are given in *Table 39* for the women's final and in *Table 40* for the men's final. The tables include the data for the best valid jump of each competitor.

On average, the women reached 83.64% of the men's official distance, the percentage for the effective distance is 83.30%. The female jumpers hit the board more accurately than the men. The women demonstrated a mean toe-to-board distance of 0.11 (±0.03)m; the mean for the male finalists is 0.19 (±0.09)m. Similar results were seen in the total lost distance. The female finalists lost an average of 0.20 (±0.06)m, the men 0.31 (±0.11)m. Both differences are statistically significant ($p<0.05$). One reason for the higher precision and the smaller loss of distance of the female triple jumpers could be the lower speed of the run-up.

The phase ratios are listed in *Tables 41 and 42.* The men's data give an average effort distribution

Table 39: Official, effective, total lost and toe-to-board distances [m] – women's final

Name	Official distance	Effective distance	Total lost distance	Toe-to-board distance
Kasparkova (CZE)	15.20	15.46	0.26	0.07
Mateescu (ROM)	15.16	15.44	0.28	0.08
Govorova (UKR)	14.67	14.82	0.15	0.12
Vasdeki (GRE)	14.62	14.72	0.10	0.08
Hansen (GBR)	14.49	14.69	0.20	0.09
Marinova (BUL)	14.34	14.54	0.20	0.11
Blazevica (LAT)	14.06	14.29	0.23	0.15
Lise (FRA)	14.02	14.23	0.21	0.16
mean	*14.57*	*14.77*	*0.20*	*0.11*
std. dev.	*±0.44*	*±0.46*	*±0.06*	*±0.03*

Table 40: Official, effective, total lost and toe-to-board distances [m] – men's final

Name	Official distance	Effective distance	Total lost distance	Toe-to-board distance
Quesada (CUB)	17.85	18.08	0.23	0.12
Edwards (GBR)	17.69	17.91	0.22	0.14
Urrutia (CUB)	17.64	17.77	0.13	0.10
Kapustin (RUS)	17.59	17.86	0.27	0.14
Wellman (BER)	17.22	17.66	0.44	0.13
Romain (DMN)	17.14	17.57	0.43	0.37
Meletoglou (GRE)	17.12	17.50	0.38	0.24
Owusu (GHA)	17.11	17.49	0.38	0.26
mean	*17.42*	*17.73*	*0.31*	*0.19*
std. dev.	*±0.30*	*±0.21*	*±0.11*	*±0.09*

of 36.14 (±0.88)% - 29.39 (±1.20)% - 34.46 (±1.15)%, while the mean ratio of the women's is 36.63 (±1.22)% - 27.70 (±1.71)% - 35.67 (±1.05)%. The analysis of variance indicates a significant ($p<0.05$) difference in the relative step and jump lengths between male and female triple jumpers.

To simplify the discussion of different phase ratios. HAY (1990) defined three techniques based upon hop and jump percentages. A hop-dominated technique is one in which the hop percentage is at least 2% greater than the jump percentage. A jump-dominated technique is one in which the jump percentage is at least 2% greater than the hop percentage and a balanced technique is one in which neither the hop nor the jump percentage is at as much as 2% greater than the other. Based on this definition, the means of both groups indicate a preponderance of the balanced technique. However, this general trend does not hold when considering the individual phase ratios. Two women and four men used the hop-dominated technique, six female and four male jumpers chose a more balanced technique. No jump-dominated attempt was identified. The subgroups with the hop-dominated technique

Table 41: Absolute and relative phase ratios – women's final

Name	Hop	Step	Jump	Technique
Kasparkova	5.61m (36.3%)	4.20m (27.2%)	5.64m (36.5%)	balanced
Mateescu	5.70m (36.9%)	4.19m (27.1%)	5.54m (36.0%)	balanced
Govorova	5.57m (37.6%)	4.09m (27.6%)	5.16m (34.8%)	hop-dominated
Vasdeki	5.42m (36.8%)	3.92m (26.6%)	5.38m (36.6%)	balanced
Hansen	5.00m (34.0%)	4.50m (30.6%)	5.19m (35.4%)	balanced
Marinova	5.27m (36.2%)	4.09m (28.1%)	5.18m (36.7%)	balanced
Blazevica	5.45m (38.1%)	3.57m (25.0%)	5.28m (36.9%)	balanced
Lise	5.27m (37.0%)	4.17m (29.3%)	4.80m (33.7%)	hop-dominated
mean	*5.41m (36.63%)*	*4.09m (27.70%)*	*5.27m (35.67%)*	
std. dev.	*±0.23m (1.22%)*	*±0.27m (1.71%)*	*±0.26m (1.05%)*	

Table 42: Absolute and relative phase ratios – men's final

Name	Hop	Step	Jump	Technique
Quesada	6.68m (37.0%)	5.21m (28.8%)	6.19m (34.2%)	hop-dominated
Edwards	6.34m (35.4%)	5.21m (29.1%)	6.35m (35.5%)	balanced
Urrutia	6.54m (36.8%)	5.47m (30.8%)	5.76m (32.3%)	hop-dominated
Kapustin	6.26m (35.1%)	5.20m (29.1%)	6.40m (35.8%)	balanced
Wellman	6.33m (35.8%)	5.44m (30.8%)	5.90m (33.4%)	hop-dominated
Romain	6.57m (37.4%)	4.88m (27.8%)	6.12m (34.8%)	hop-dominated
Meletoglou	6.16m (35.2%)	5.36m (30.6%)	5.98m (34.2%)	balanced
Owusu	6.38m (36.5%)	4.92m (28.2%)	6.18m (35.3%)	balanced
mean	*6.41m (36.14%)*	*5.21m (29.39%)*	*6.11m (34.46%)*	
std. dev.	*±0.17m (0.88%)*	*±0.22 m (1.20 %)*	*±0.22m (1.15%)*	

reached average effective distances of 17.76m (men) and 14.53m (women). For the groups using the balanced technique, 17.69m (men) and 14.86m (women) were measured as the effective distances. For the women, the balanced technique occurred more frequently and tended to produce longer effective distances, while for the men the distribution of the two techniques was even, and the hop-dominated technique showed slightly better results.

No statistically significant ($p<0.05$) correlation could be found between the phase ratios and the effective distance with the exception of the significant correlation of jump and effective distance for the women's competition. The highly significant ($p<0.01$) correlation coefficients between the toe-board distance in the men's and women's competition indicate the importance of run-up accuracy in high-level level triple jumping.

Considering the multiple regression between the effective distance and the hop, step and jump distances for the female jumpers. The stepwise approach initially used the jump distance as input for the equation. This is followed by entering the step distance in the multiple equation with a multiple R of 0.93. This result supports the previous finding on the preponderance of the balanced technique in female triple jumpers.

8.3.2 Approach

In the horizontal jumps, the run-up velocity is of major importance for a successful performance. A high horizontal velocity of the centre of mass (CM) at the instant of touchdown for the take-off into the hop is the necessary prerequisite for an optimum result. The initial velocity or – to be more precise – the initial total mechanical energy of the jumper at the beginning of the jumping activity must be of major importance from a purely mechanical standpoint. From a more biomechanical point of view, it is necessary to analyse if the individual jumper is able to manage and use the maximum energy available or produced during the approach run. In addition to the production of sufficient kinetic energy for the jump, the run-up has to be as accurate as possible, in order to minimise the loss of distance on the board. Therefore the speed of the CM during the last strides and the stride lengths have been analysed for male and female finalists.

The means of the stride lengths of both, women and the men, were longer than the reported stride lengths during the long jump finals in Rome 1987. While all the men demonstrated the strategy of long-short for the last two strides – a strategy generally observed in the long jump (HAY/MILLER 1985) – three out of the eight women did not. The variation in the lengths of the last two strides is not as extreme as was found for elite long jumpers – e.g. Lewis (Rome 1987) in his five valid jumps: 2nd last – 2.47 (±0.05)m, last – 1.82 (±0.04)m.

The horizontal CM velocities at the take-off into the last stride, the initial horizontal velocity for the hop were 9.31 (±0.30)m/s for the female and 10.47 (±0.15)m/s for the male finalists. The women's initial velocity was calculated to be 89% of the men's. This data supports the hypothesis that, in sprinting, female athletes are able to produce about 90% of the amount of kinetic energy produced by men (see above). The men's data, on average, are as high as reported from top jumpers by MILLER/HAY (1986). The mean is higher than ever described in the literature. All men accelerated in the last two strides, whereas two of the women maintained a constant CM velocity and two of them even decelerated in the very last phase of the run-up. This could possibly be caused by the motor control or the stabilised technique of former long jumpers who transferred to the triple jump. The acceleration into the last stride and the take-off into the hop seems to be an important factor in the minimising of speed reduction and energy loss during the hop.

The correlation analysis indicates a significant ($p<0.05$) linear correlation between the CM velocity prior to the touch-down for the take-off into the hop and the performance for the female jumpers, but no significant correlation for the male competitors. This underlines that a high

Table 43: Lengths of the last strides of the run-up and horizontal CM velocity at take-off into the 2nd last and last strides

	Stride length [m]		CM velocity [m/s]			Stride length [m]		CM velocity [m/s]	
Name (women)	2nd last	last	2nd last	last	Name (men)	2nd last	last	2nd last	last
Kasparkova	2.37	2.42	9.4	9.2	Quesada	2.44	2.28	10.1	10.3
Mateescu	2.41	2.38	9.9	9.6	Edwards	2.34	2.33	10.5	10.7
Govorova	2.28	2.05	9.2	9.2	Urrutia	2.50	2.35	10.1	10.6
Vasdeki	2.49	2.39	9.5	9.5	Kapustin	2.71	2.59	10.1	10.4
Hansen	2.19	2.03	9.2	9.4	Wellman	2.41	2.11	10.1	10.5
Marinova	1.85	2.02	8.9	9.2	Romain	2.07	1.99	10.0	10.5
Blazevica	2.15	2.26	9.2	9.3	Meletoglou	2.47	2.17	10.1	10.2
Lise	2.42	2.40	9.0	9.1	Owusu	2.17	2.00	10.0	10.5
mean	*2.27*	*2.24*	*9.29*	*9.31*	*mean*	*2.39*	*2.23*	*10.12*	*10.47*
std. dev.	*±0.21*	*±0.18*	*±0.30*	*±0.18*	*std. dev.*	*±0.20*	*±0.20*	*±0.14*	*±0.15*

run-up speed or a high initial velocity prior to the take-off for the hop is a necessary precondition, but is not sufficient in itself for an optimum result. The higher the performance level and the stronger the homogeneity of the group under study, the lower the correlation between run-up speed and total performance.

The correlation coefficients between the CM horizontal velocity prior to take-off into the hop and the horizontal CM speed at take-off for the hop are highly significant ($p<0.01$) for the women and significant ($p<0.05$) for the men. The data and results underline the great importance of run-up speed for women, while the male triple jumpers require a speed of more than 10.0m/s. However, additional parameters during the three take-off actions are of major influence on total performance.

8.3.4 Hop, step and jump

During the take-off for the hop, the horizontal CM velocity decreases and vertical velocity is gained. The horizontal velocities at the take-off for the hop were 8.40 (±0.23)m/s for the women and 9.77 (±0.15)m/s for the men. The decreases in the horizontal velocity were 0.92 (±0.08)m/s and 0.71 (±0.10)m/s for women and men respectively. The difference of the means is highly significant ($p<0.01$). The vertical CM velocity data at take-off for the hop indicate no statistically significant differences between the two groups of competitors. The mean vertical velocity of the men was measured as 2.40 (±0.16)m/s and the speed of the female jumpers as 2.34 (±0.25)m/s. The means of the angles of projection show a significant ($p<0.05$) difference between men and women. The men's take-off angle of projection for the hop is flatter than the women's. This is caused by the higher horizontal CM velocity and a similar vertical speed at take-off.

The kinetic energy achieved in the approach and available at the touchdown for the take-off into the hop decreased in all measured subjects. Expressed as a percentage of the initial total mechanical energy. the losses are 7.72 (±1.82)% and 3.97 (±1.59)% for the female and male competitors respectively. The difference between the means is highly significant ($p<0.001$). The elite male triple jumpers demonstrated a capacity to take-off with very little energy loss. Such an extremely low amount of energy loss implies an excellent capacity to reutilize elastic energy in the muscle-tendon complex. The elastic energy is stored during the short eccentric phase of the early support at take-off for the hop. The use of an optimal muscle stiffness, in combination with an optimal kinematic positioning of the body segments, seems to play the important role in minimising energy loss. No difference between the male and female jumpers could be identified in the knee lift or hip angle of the lead leg at the take-off for the hop. The support leg angle data indicate differences between the groups, although these differences are not statistically significant. The maximum knee flexion during the take-off for the hop is an average of 3° more in the female group than in the male group. The range of maximum knee flexion during the take-off support in the women finalists was recorded as 34 to 55° and in the men's group as 31 to 51°. With some reservations, it can be concluded that the male jumpers are able to perform the take-off with a stiffer support leg and thus the men are able to take-off with less energy dissipation than the female triple jumpers. Further research, using high speed recordings will allow deeper insight into the optimum take-off strategy with minimum loss of mechanical energy.

As described for the hop, the horizontal CM velocity also decreased during the take-off for the step. The horizontal velocities at take-off for the step were 7.58 (±0.27)m/s for the women and 8.61 (±0.27)m/s for the men. The losses were 1.15 (±0.19)m/s and 0.81 (±0.21)m/s for women and men respectively. The difference of these means is highly significant ($p<0.01$). The vertical velocity data of the CM at take-off for the step indicate a statistically significant difference ($p<0.01$) be-

Table 44: Horizontal (vx) and vertical (vy) CM velocities at take-off for the hop, the step and the jump [m/s] – women's final

Name	Hop		Step		Jump	
	vx	vy	vx	vy	vx	vy
Kasparkova	8.3	2.6	7.7	1.7	6.8	2.4
Mateescu	8.8	2.4	7.9	1.6	6.7	2.5
Govorova	8.3	2.5	7.5	1.3	6.2	2.8
Vasdeki	8.6	2.5	7.8	1.1	6.7	2.4
Hansen	8.6	1.9	7.7	1.8	6.5	2.5
Marinova	8.2	2.4	7.5	1.7	6.3	2.6
Blazevica	8.2	2.5	7.6	1.3	6.6	2.5
Lise	8.2	2.0	7.0	1.8	6.0	2.4
mean	*8.40*	*2.34*	*7.58*	*1.52*	*6.46*	*2.53*
std. dev.	*±0.23*	*±0.25*	*±0.27*	*±0.27*	*±0.29*	*±0.13*

Table 45: Horizontal (vx) and vertical (vy) CM velocities at take-off for the hop, the step and the jump [m/s] – men's final

Name	Hop		Step		Jump	
	vx	vy	vx	vy	vx	vy
Quesada	9.7	2.6	8.5	2.1	7.3	2.6
Edwards	10.1	2.2	9.0	2.0	7.6	2.6
Urrutia	9.8	2.6	9.5	2.2	6.8	2.9
Kapustin	9.8	2.3	9.0	1.6	7.3	2.9
Wellman	9.6	2.6	8.2	2.2	6.7	2.7
Romain	9.8	2.4	8.5	1.7	7.0	2.7
Meletoglou	9.6	2.4	8.5	1.9	7.0	2.6
Owusu	9.8	2.3	8.8	1.8	6.6	3.3
mean	*9.77*	*2.40*	*8.61*	*1.95*	*7.02*	*2.79*
std. dev.	*±0.15*	*±0.16*	*±0.27*	*±0.22*	*±0.33*	*±0.26*

tween both groups of competitors. The mean men's vertical velocity was measured higher - 1.94 (±0.22)m/s - than that of the female jumpers - 1.52 (±0.27)m/s. The men's take-off angle of projection for the hop is a little steeper than the women's, but the means of the angles of projection show no significant ($p<0.05$) difference. The steeper men's take-off was due to higher vertical CM velocities.

The kinetic energy achieved during the approach and available at the touchdown for the take-off into the hop decreases during the take-off. During the take-off for the step, additional energy reduction could be identified for all measured subjects. The losses in total mechanical energy prior to touch-down for the take-off into the step expressed as percentages are 17.49 (±2.05)% and 20.15 (±2.42)% for the female and male competitors respectively. The difference between the means is significant ($p<0.05$). The elite

Table 46: Changes of horizontal CM velocities at take-off for the hop, the step and the jump [m/s] – men's and women's final

	Hop		Step		Jump	
Rank	Women	Men	Women	Men	Women	Men
1	-.91	-.63	-.58	-1.11	-.92	-1.28
2	-.82	-.62	-.92	-1.06	-1.20	-1.42
3	-1.0	-.74	-.72	-1.38	-1.35	-1.66
4	-.89	-.63	-.75	-.85	-1.11	-1.70
5	-.86	-.91	-.94	-1.40	-1.22	-1.49
6	-.98	-.75	-.73	-1.29	-1.12	-1.50
7	-1.04	-.62	-.64	-1.10	-1.03	-1.52
8	-.84	-.76	-1.22	-1.04	-1.05	-2.17
mean	*-.92***	*-.71*	*-.81***	*-1.15*	*-1.13***	*-1.59*
std. dev.	*± 0.08*	*± 0.10*	*±0.21*	*±0.19*	*±0.13*	*±0.27*

* Indicates significant ($p<0.05$) differences between the means.
** Indicates highly significant ($p<0.01$) differences between the means of the male and female competitors.

Table 47: Relative changes of total mechanical energy during the take-off for the hop, the step and the jump – men's and women's final [all data are given in percentage to mechanical energy at touch-down for the take-off into hop, step and jump respectively]

	Hop		Step		Jump	
Rank	Women	Men	Women	Men	Women	Men
1	-5.5	-1.7	-15.0	-20.4	-11.2	-17.5
2	-5.4	-3.1	-19.3	-18.2	-14.5	-18.5
3	-10.3	-4.5	-16.7	-22.7	-16.0	-21.6
4	-7.0	-3.5	-17.1	-16.4	-13.4	-19.3
5	-7.8	-6.8	-16.5	-22.3	-16.5	-21.6
6	-9.0	-4.7	-16.8	-23.2	-14.4	-17.7
7	-9.7	-2.6	-17.0	-18.7	-10.8	-21.6
8	-7.0	-5.0	-21.7	-19.4	-14.6	-24.4
mean	*-7.72***	*-3.97*	*-17.49**	*-20.15*	*-13.92***	*-20.27*
std. dev.	*±1.82*	*±1.59*	*±2.05*	*±2.43*	*±2.04*	*±2.41*

* Indicates significant ($p<0.05$) differences between the means.
** Indicates highly significant ($p<0.01$) differences between the means of the male and female competitors.

male triple jumpers show much less energy loss than the female finalists. Regarding the loss of mechanical energy from the initial condition prior to the hop, both groups have an almost equal energy loss throughout the first two take-offs. The remaining total mechanical energy at touchdown for the jump is 74.78 (±2.45)% for the women and 75.88 (±3.52)% for the men, relative to their initial energy from the run-up.

No major segmental kinematic differences could be detected between the two analysed groups. Therefore, the longer distance in the step shown in the male subjects is related more to the increase of vertical take-off velocity than to minimisation of energy loss during the support phase. This leads to the assumption that the step performance should be more strength-related.

At take-off into the jump, the horizontal velocities were 6.46 (±0.29)m/s for the women and 7.01 (±0.33)m/s for the men. The decreases were measured as 1.13 (±0.13)m/s and 1.59 (±0.27)m/s for women and men respectively.

The difference between the means of horizontal take-off velocity and changes of horizontal velocities are both highly significant ($p<0.01$). The vertical velocity data of the CM at the take-off for the jump indicate a statistically significant difference ($p<0.05$) between both groups of competitors. The mean men's vertical velocity was higher 2.79 (±0.26)m/s than that of the female jumpers 2.52 (±0.13)m/s. The means of the angle of projection of the take-off for the jump were similar for men and women.

During the take-off for the jump, an additional energy reduction could be identified for all measured subjects. Expressed as a percentage of the total mechanical energy prior to touch-down at the take-off into the jump, the means and standard deviation of the losses were 13.92 (±2.04)% and 20.27 (±2.41)% for the female and male competitors respectively.

The difference between the means is highly significant ($p<0.001$). The elite male triple jumpers showed a considerably higher energy loss during the take-off for the jump than the female finalists. The remaining total mechanical energy after the take-off for the jump was 60.87 (±3.71)% for the women and 55.61 (±4.70)% for the men, relative to their initial energy from the run-up.

The total mechanical energy achieved in the run-up by the male finalists decreased more during the hop, the step and the take-off for the jump than that of the female athletes. A possible interpretation could be that male jumpers distribute their initial mechanical energy more effectively than women.

8.4 Summary and conclusion

The best attempts of the eight male and female finalists in Athens were recorded and analysed using video-based motion analysis techniques. The data extracted give detailed information on the effort distribution during the jumps and on biomechanical parameters of the approach run, the hop, the step and the jump.

The phase ratios of the women are different from those of the men. While, in the male group, 50% of the subjects used the hop-dominated technique and the other 50% the balanced technique, in the female subjects only two of eight competitors performed the hop-dominated technique. The other women used the balanced technique. In the men's group the better performers used the hop technique, while the more successful women used the balanced technique.

The means of the sample of the approach runs analysed show the fastest run-ups ever recorded and published from an international meeting. For the female group, no comparable data are available in the international literature. The means of the male and female finalists show that women are able to reach approximately 90% of the men's run-up speed in the triple jump.

All subjects decrease the horizontal CM speed during the take-off for the hop. The male subjects' speed losses are significantly lower than those of the women. The loss of the men's total mechanical energy during the take-off into the hop is approximately half that of the women. This phenomenon may be related to an optimal stiffness control of the take-off leg musculature prior to and during the take-off.

In the step and the jump, both groups decrease their horizontal CM speed. The loss of energy is higher in the men's take-off than in the women's. This could be due to more strength-related activity by the men during the take-off for the step and the jump.

Further research will use high-speed recordings of the individual take-offs and will thus provide a deeper insight into the take-off techniques, and especially into the use of the elastic properties of the skeletal muscle system in jumping with high initial mechanical energy.

8.5 References

AE, M.; FUKASHIRO, S.; YAMAMOTO, E.; ITO, N; SAITO, N.:
Biomechanical analysis of the take-off techniques of men's triple jump. In: SASAKI, H.; KOBAYASHI, K.; AE, M. (eds.): Techniques of the World's Best Track and Field Athletes [Japanese]. Tokyo: Baseball Magazine Co. Ltd., 1994, pp. 152-166

BRÜGGEMANN, G.-P.:
Biomechanical analysis of the triple jump: an approach towards a biomechanical profile of the world's best triple jumpers. In: BRÜGGEMANN, G.-P.; GLAD, B. (eds.): International Athletic Foundation/International Amateur Athletic Federation Scientific Research Project at the Games of the XXIV Olympiad – Seoul 1988: Final Report, 1990, pp. 306-362

HAY, J.G.:
The biomechanics of sports techniques, 4th ed.. Englewood Cliffs, NJ: Prentice-Hall, 1993a

HAY, J.G.:
Citius, altius, longius [faster, higher, longer]: the biomechanics of jumping for distance. In: Journal of Biomechanics 26 (1993b), pp. 7-21

HAY, J.G.:
The biomechanics of the triple jump: a review. In: Journal of Sport Sciences 10 (1992), pp. 343-378

HAY, J.G.:
The biomechanics of triple jump techniques. In: BRÜGGEMANN, G.-P.; RÜHL, J.K. (eds.): Techniques in Athletics, 1st International Conference, Cologne 7-9 June 1990, vol. 1, 1990, pp. 296-308

HAY, J.G.; MILLER, J.A.:
Techniques used in the triple jump. In: International Journal of Sports Biomechanics 1 (1985), pp. 185-196

MILLER, J.A.; HAY, J.G.:
Kinematics of a world record and other world-class performances in the triple jump. In: International Journal of Sports Biomechanics 2 (1986), pp. 272-288

9 Men's high jump

(by Gert-Peter Brüggemann and Adiamantios Arampatzis)

9.1 Introduction and purpose

Biomechanical data of the high jump for both men and women were taken during the finals at the World Championships in Athletics in Athens 1997. This first report focuses on the men's final because the results of the competition were close to the results of the Championships in Tokyo 1991, where the last biomechanical study during a World Championships had been performed. In Tokyo, Charles Austin won with 2.38m and the three next (Sotomayor, Conway, Grant) cleared 2.37m. The Athens competition was dominated by Sotomayor with 2.37m followed by two athletes (Forsyth and Partyka) with a height of 2.35m. The methods used in both meeting were similar. This makes a comparison of data from both meetings possible, even from a methodological point of view.

It is notable that the means of the achieved heights of the best six jumpers in the men's final decreased by approximately 2cm from 1991 to 1997.

The purpose of this study is to present a first description of biomechanical data from the men's high jump final and to advance general understanding of the high jump event. In order to provide a basis for data comparison, the data of the men's final of the World Championship Tokyo 1991 will be taken into account.

9.2 Methods and procedures

The men's high jump final of the World Championships 1997 was recorded with two sets of two synchronised S-VHS video cameras operating at 50 frames per second. The cameras of each set were placed perpendicular to each other. One pair of cameras filmed the right footed jumpers, the other pair the left footed jumpers. The last step of the approach the take-off and the flight were recorded. In addition to the described set-up, one pair of panned and tilted high-speed video cameras (Peak Performance) operating at 200 frames per second followed the athlete throughout the run-up and the jump.

All trials of the women's and men's finals were recorded. For data reduction of the relevant video sequences, data were transferred via the video grabber board to the videodata disk of the Motus video motion analysis system (Peak Performance). Using a calibration cube as reference system the DLT was used for camera calibration and co-ordinate reconstruction.

The co-ordinate system used had its x-axis perpendicular to the bar. The y-axis was parallel with the bar. The z-axis was the vertical. The origin was fixed in the middle of the poles at ground level.

For the biomechanical analysis, a 12 segment model of the human body was used calculated via 19 landmarks. Both feet, both lower legs, both thighs, the trunk, the upper arms, the forearms with hands, and the head with the neck represented the rigid body model.

The best valid jumps from each of the top six finalists were selected for further analysis.

9.3 Results

9.3.1 Partial heights

Table 48 presents the basic performance characteristics of the jumps analysed with regard to the partial heights. The table includes:

- the take-off height, the vertical distance of the centre of mass (CM) from the ground at the instant the take-off foot leaves the ground (last frame of ground contact),
- the height of flight, the vertical distance the CM travels during the flight from the instant of the take-off to its highest position in flight,
- the height of bar clearance, the vertical distance between the highest position of CM during the flight and the bar, and
- the maximum height, the vertical distance between the highest position of the CM during the flight and the ground.

The partial heights are very close to the data reported from the World Championships 1991 where IIBOSHI et al. (1993) found a mean for maximum height of 2.40m, a take-off height of 1.35m and a height of flight of 1.05m for the eight finalists. The maximum height of Sotomayor (2.50m) is one of the highest flights ever reported in the literature. The take-off height of this jump was 73.3% of the athlete's standing height. The take-off height percentage of total height is 57.2%. The significant correlation coefficient ($p<0.05$) between the take-off height and the performance underlines the importance of this parameter, which is closely related to body height.

9.3.2 Path of CM prior to and during take-off

The vertical trajectory of the CM during take-off was calculated to be 0.45m on average. The longest path of acceleration was measured in the winning jump of Sotomayor, who had the highest vertical take-off velocity. To increase the path of acceleration, athletes lower the CM prior to the touch-down for the take-off. This is often combined with an extremely long last stride. In the analysed sample Sotomayor and Partyka used this technique. Forsyth and Grant did not lower their CM from the last support to the support for the take-off. These athletes increased the height of CM. The height of CM at the touch-down for

Table 48: Height of bar, take-off height, height of bar clearance and maximum height [m] – men's final

Name	Height of bar	Take-off height	Height of flight	Height of bar clearance	Maximum height
Sotomajor	2.37	1.43	1.07	-0.13	2.50
Forsyth	2.35	1.41	1.01	-0.07	2.42
Partyka	2.35	1.32	1.06	-0.03	2.38
Hoen	2.32	1.29	1.10	-0.07	2.39
Grant	2.32	1.33	1.00	-0.01	2.33
Papakostas	2.32	1.30	1.08	-0.06	2.38
mean	*2.34*	*1.35*	*1.06*	*-0.06*	*2.40*
std. dev.	*±0.02*	*±0.06*	*±0.04*	*±0.04*	*±0.06*

the last stride and the take-off was constant for Hoen and Papakostas.

A high horizontal centre of mass (CM) velocity at the instant of touchdown for the take-off is the necessary prerequisite for a successful high jump. The initial velocity or – to be more precise – the initial total mechanical energy of the jumper at the beginning of the jumping activity is of major importance from a purely mechanical standpoint.

Table 49: Take-off height, height of flight and height of bar clearance as percentage of total height [%] – men's final

Name	Take-off height	Height of flight	Height of bar clearance
Sotomajor	57.2	42.8	5.2
Forsyth	58.3	41.7	2.9
Partyka	55.5	44.5	1.3
Hoen	54.0	46.0	2.9
Grant	56.7	43.4	0.4
Papakostas	54.6	45.4	2.5
mean	*56.03*	*43.97*	*2.54*
std. dev.	*±1.63*	*±1.62*	*±1.64*

The average run-up speed was higher than the reported velocity of the 1991 final. The highest value was calculated for the jump of Sotomayor. It is of major interest that the second best jumper achieved the lowest velocity of the whole group. For all the analysed jumps an increase of horizontal CM velocity was observed. Sotomayor reduced his run-up speed by more than 50% during the take-off. Forsyth, on the other hand, is the athlete with the lowest increase of horizontal CM velocity. The steepest flight resulting from a high vertical take-off velocity was found in Sotomayor's jump. The flattest angle of projection was found for Forsyth's jump.

The total mechanical energy achieved during the approach and available at the touchdown for the take-off decreases during the take-off. During the take-off, energy reduction could be identified for all measured subjects. The highest loss of the total mechanical energy was 24.6% for Sotomayor's best jump. Remarkably little increase could be analysed for Forsyth's technique. His take-off is characterised by a stiff support leg.

Table 50: Height of centre of mass (CM) at touch-down for the last stride and the take-off, vertical path of acceleration during take-off and the length of the last stride [m] – men's final

Name	Height of CM – last stride	Height of CM – take-off	CM lowering	CM path of acceleration	Stride length
Sotomajor	.91	.86	.05	.57	2.16
Forsyth	.96	.99	-.03	.42	2.00
Partyka	.98	.93	.05	.39	1.93
Hoen	.85	.85	.00	.44	1.99
Grant	.83	.88	-.05	.44	2.00
Papakostas	.89	.89	.00	.41	1.98
mean	*0.90*	*0.90*	*0.00*	*0.45*	*2.01*
std. dev.	*±0.06*	*±0.05*	*±0.04*	*±0.06*	*±0.08*

Table 51: Velocities of centre of mass (CM) at touch-down for the take-off and at take-off [m/s], angle of projection [°], the changes of horizontal velocity and total mechanical energy [as percentage of mechanical energy at touch-down] during the take-off – men's final

Name	Horizontal velocity at touch-down	Horizontal velocity at take-off	Vertical velocity at take-off	Angle of projection	Change of horizontal velocity	Change of mechanical energy
Sotomajor	8.04	3.58	4.80	53	-4.46	-24.6
Forsyth	6.94	4.08	4.45	47	-2.86	-5.2
Partyka	7.39	4.20	4.56	47	-3.19	-12.1
Hoen	7.32	3.71	4.63	51	-3.61	-14.3
Grant	7.32	4.07	4.52	48	-3.25	-12.1
Papakostas	7.36	3.87	4.60	50	-3.49	-14.0
mean	*7.40*	*3.92*	*4.59*	*49.3*	*-3.48*	*-13.7*
std. dev.	*±0.36*	*±0.24*	*±0.12*	*±2.40*	*±0.55*	*±6.30*

Table 52: Horizontal run-up angles at last stride and take-off, inward lean angles at last stride and take-off [°] – men's final

Name	Run-up angle last stride	Run-up angle take-off	Inward lean last stride		Inward lean take-off	
			touch-down	take-off	touch-down	take-off
Sotomajor	38	49	10	26	2	-3
Forsyth	55	57	22	24	2	-2
Partyka	44	53	8	17	4	-4
Hoen	55	61	6	27	3	0
Grant	57	61	6	30	0	-1
Papakostas	49	47	8	24	4	-3
mean	*49.7*	*56.3*	*10*	*24.7*	*2.5*	*-2.2*
std. dev.	*±7.5*	*±4.7*	*±6.1*	*±4.4*	*±1.5*	*±1.5*

9.3.4 Preparation for take-off

The curve of the run-up was described by the parameters run-up angles and inward lean. The run-up angle is the deviation from a perpendicular approach to the bar. The positive angle of the horizontal CM velocity vector to the x-axis was calculated for the flight of the last stride and of the jump. The average run-up angles were 49.7° and 56.3° respectively.

Inward lean was measured as the angle of the line from the CM to the tip of the support leg, to the vertical. Inward lean data are given for the instants of touchdown and take-off of the last stride and the take-off. Positive values indicate a lean to the inside of the curve. Two strategies could be identified. Forsyth started the support phase of the last stride with a far greater inward lean than all other evaluated competitors. This lean was continued through to the take-off of the last stride. The others had considerable increases in lean angle during the support of the last stride.

9.4 Summary and conclusion

The best trials of the 6 male finalists in Athens 1997 were recorded and analysed using video-based motion analysis techniques. The data extracted give detailed information on the effort distribution and on biomechanical parameters of the approach run and the jump.

The results of the analysis of the approach run indicate the fastest run-ups ever recorded and published in an international meeting, for the mean of the sample.

All subjects decrease horizontal CM speed during take-off. The loss of total mechanical energy during take-off is considerable. The minimum energy decrease was demonstrated by the unconventional technique of the Australian Forsyth. His technique maybe related to an optimal stiffness of the lead-leg musculature during the take-off.

Further research will use the high-speed recordings and will be focused on segmental interactions during last stride, take-off and flight.

9.5 References

IIBOSHI, A.; AE, M.; TAKAMATSU, J.; NAGASAWA, M.; TANG, H.P.; YUUKI, M.: Techniques of elite high jumpers at the 3rd IAAF World Championships in Athletics. In: Abstracts of the International Society of Biomechanics, XIVth Congress, Paris, 4-8 July, 1993, vol. I, Paris, 1993, pp. 608-609

10 Pole vault

(by Adiamantios Arampatzis, Falk Schade, Gert-Peter Brüggemann)

10.1 Methods and procedures

The pole vault final was recorded by four genlocked video cameras synchronized using LEDs. For the purpose of this two dimensional analysis, video footage from two of the above-mentioned cameras was used. The video cameras were operated at 50 fields per second. Camera 1 (S-VHS) filmed the athlete from the penultimate step until shortly after the position of 'maximum pole bend' (MPB). Camera 2 filmed the athlete from the MPB position up to bar clearance. The cameras recorded the vault in the direction of jumping from an angle of approx. 60° in relation to the plane of movement. For the purpose of a three dimensional analysis, the other two cameras were positioned at right angles to cameras one and two and recorded the same field of view. For the calculation of the 2D co-ordinates of an 18 segment model of the human body, the DLT method was used. The origin of the initial co-ordinate system was located directly over the deepest point of the pole vault box at ground level. The total energy of the pole vaulter was calculated as the sum of the kinetic and potential energy of the athlete's centre of mass (CM). The flex numbers, length and maximum bend of the pole were used to calculate the flex energy of the pole.

The highest successful jump from each finalist (n=11) was used in the analysis. The variables for the analysis were chosen on the basis of energy calculations. The parameters in this study are not used with the classic partial height model, but rather for the purpose of calculating energy production, exchange and transfer. For these calculations the following phase definitions were constructed:

- I Main phase of energy production: this phase is from the start of the approach to the moment the pole tip contacts the back of the box (PP).
- II Main phase of energy exchange: this phase begins at the PP and ends when the pole vaulter releases the pole.

The second main phase can be broken down into two sub-phases. The first is the energy transfer phase, from PP until the point where the pole reaches maximum flexion (MPB). During this phase, energy is transferred to the pole. The second is the energy return phase, which starts at MPB and continues until the vaulter releases the pole. Because the methods used do not allow the detection of the exact moment when the pole contacts the back of the box, the main phase of energy exchange in this study was measured from the moment the jump foot made contact with the ground before take-off. Other authors (GROS/KUNKEL 1990) have used the take-off as the start of the energy transfer phase, but this is not appropriate for energy calculations, because at take-off the poles of most vaulters already show a definite bend.

10.2 Results

By the end of the main energy production phase, the vaulters had reached a horizontal velocity of approximately 9.72m/s and an energy of 57.03J/kg (see *Table 53*). At this moment, as they released the pole, the vaulters had already produced about 95% of the total energy generated. Neither of these factors show a significant correlation with jumping performance.

Table 53: Jump height, horizontal velocity of the CM at touchdown of the jump foot (VCMxTD) and initial energy (IntEng) as energy of the CM at the touchdown of the jump foot

Name	Jump height [m]	VCMxTD [m/s]	IntEng ([/Kg]
Bubka, Sergey (UKR)	6.01	9.92	59.23
Tarasov, Maksim (RUS)	5.96	10.04	60.85
Starkey, Dean (USA)	5.91	9.55	55.68
Lobinger, Tim (GER)	5.80	9.72	56.57
Buckfield, Nicholas (GBR)	5.70	9.60	55.90
Manson, Pat (USA)	5.70	9.61	55.78
Smiryagin, Yevgeniy (RUS)	5.70	9.60	55.73
Strogalyov, Vadim (RUS)	5.70	9.68	56.40
Barthel, Trond (NOR)	5.50	9.67	57.13
Eriksson, Martin (SWE)	5.50	9.89	58.31
Krasnov, Danny (ISR)	5.50	9.63	55.80
mean	*5.73*	*9.72*	*57.03*
std. dev.	*±0.18*	*±0.16*	*±1.72*

Table 54: Parameters of the main phase of energy production – height of the CM at touchdown of the penultimate step (HLSTD) and of the last step (HabTD), stride length (LSD), height of the top hand at touchdown of the take-off step (HObHTD), horizontal distance from the top hand to the tip of the foot at take-off (WObHTD)

Parameter	mean	s	min	max
HLSTD [m]	0.98	0.03	0.92	1.05
HabTD [m]	0.99	0.04	0.94	1.05
LSD [m]	2.10	0.14	1.96	2.37
HObHTD [m]	1.97	0.06	1.84	2.06
WObHTD [m]	0.76	0.11	0.53	0.87

Table 55: Parameters of the energy transfer phase: energy of the CM (MPBEng) and pole energy (PoleEng) at moment of the maximum pole flexion (MPB) and the amount of flexion (FL) measured as the distance from the pole chord to the maximum flexion point of the pole

Name	MPBEng [J/Kg]	PoleEng [J/Kg]	FL [m]
Bubka, Sergey	32.40	31.56	1.63
Tarasov, Maksim	36.33	26.35	1.45
Starkey, Dean	33.17	26.22	1.55
Lobinger, Tim	32.05	27.25	1.54
Buckfield, Nicholas	31.90	23.58	1.52
Manson, Pat	30.17	24.48	1.64
Smiryagin, Yevgeniy	31.78	25.33	1.60
Strogalyov, Vadim	33.35	25.58	1.50
Barthel, Trond	32.31	26.07	1.48
Eriksson, Martin	31.45	25.36	1.60
Krasnov, Danny	32.26	24.72	1.52
mean	*32.47*	*26.04*	*1.55*
std. dev.	*±1.53*	*±2.08*	*±0.06*

Table 54 presents further parameters from the end of the main energy production phase. Unlike the other jumping events, it is characteristic that pole vaulters do not show a significant lowering of the centre of mass during the penultimate stride. The length of the last stride of 2.10 ±0.14 m, as measured in this study, is longer ($p<0.01$) than that reported by GROS/KUNKEL (1990) of 1.99 ±0.06 m (from the Olympic Games in Seoul 1988).

During the energy transfer phase, the energy of the pole vaulter is reduced to about 43% of the initial energy (see *Table 55*). At the end of this phase (MPB), the flex energy of the pole reaches its highest value. This value shows a significant correlation with both the official jump height ($r=0.62$, $p<0.05$) and the effective jump height ($r=0.80$, $p<0.01$). The maximum amount of pole flexion (defined as the distance between the pole cord and the point of maximum flexion of the pole) is approximately 1.55m; this shows no significant correlation with the flex energy of the pole.

Various parameters for the energy transfer phase are displayed in *Table 56*. No significant correlation could be found between these parameters and jump height. During the energy return phase the total energy of the pole vaulters was increased by about 27.13J/kg (*Table 57*). The final energy showed significant correlation with both the official jump height ($r=0.92$, $p<0.01$) and the effective jump height ($r=0.99$, $p<0.01$). Significant correlations were also found between jump height and height of CM at pole release ($r=0.71$, $p<0.05$), as well as between jump height and the difference between initial and final energy ($r=0.66$, $p<0.05$). The mean vertical take-off

Table 56: Parameters of the energy transfer phase: height of the CM at take-off (HabTO), height of the top hand at take-off (HObHTO), horizontal distance from top hand to tip of take-off foot at take-off (WObHTO), horizontal velocity of the CM (MPBVx) and vertical velocity of the CM (MPBVy) at the MPB, and the rock-back angle at MPB (MPBWin), as the angle CM-right shoulder-vertical axis (for left-footed jumpers)

Parameter	mean	s	min	max
HAbTO [m]	1.16	0.05	1.08	1.23
HObHTO [m]	2.18	0.09	2.06	2.38
WObHTO [m]	0.18	0.13	0.00	0.37
MPBVx [m/s]	2.97	0.26	2.67	3.54
MPBVy [m/s]	3.08	0.24	2.73	3.50
MPBWin [°]	66	7	51	74

Table 57: Parameters of the main phase of energy exchange: effective jump height as maximum height of flight of the CM (EJH), height of the CM at pole release (AbH), energy of the CM (FinEng) and the energy difference (EngDif) as difference between initial and final energy

Name	EJH [m]	AbH [m]	FinEng [J/Kg]	EngDif [J/Kg]
Bubka, Sergey	6.50	6.05	64.23	5.00
Tarasov, Maksim	6.23	5.97	61.96	1.11
Starkey, Dean	6.12	5.94	60.69	5.00
Lobinger, Tim	6.00	5.94	59.63	3.06
Buckfield, Nicholas	5.85	5.63	57.98	2.08
Manson, Pat	5.97	5.56	59.22	3.44
Smiryagin, Yevgeniy	5.96	5.32	59.17	3.44
Strogalyov, Vadim	6.03	5.55	60.10	3.70
Barthel, Trond	5.80	5.71	57.56	0.43
Eriksson, Martin	5.73	5.54	57.50	-0.80
Krasnov, Danny	5.79	5.60	57.57	1.78
mean	*6.00*	*5.71*	*59.60*	*2.57*
std. dev.	*±0.22*	*±0.23*	*±2.10*	*±1.84*

velocity of the vaulters was 2.26m/s (*Table 58*) – enough for a standing jump height of 26cm.

10.3 Discussion

At the end of the main phase of energy production, the athletes had an initial energy of about 95% of the final energy. The fact that there was no significant correlation between the initial energy and the jump height does not mean that initial energy is unimportant, but rather that, among elite athletes, the initial energy does not explain the different jump heights. The main phase of energy exchange seems to be very important. During this phase, the athletes can use the elasticity of the pole while, at the same time, performing muscular work. The energy difference in this phase is an expression of the muscular work performed. The average value for the trials analyzed was 2.57J/kg, but there were large individual differences (cf. *Table 57*). A comparison of Bubka with Tarasov shows that both have a very high initial energy (cf. *Table 53*), but that, during the energy exchange phase, Bubka produced a value of 5J/kg muscular work while Tarasov produced a value of only 1.11J/kg. This difference could be considered the definitive factor of Bubka's technique.

The most important factor for a high vault clearance is the amount of total energy the athlete has at the end of the main energy exchange phase. This factor showed a high correlation with both official jump height and effective jump height. The amount of final energy of the athlete is the algebraic sum of the initial energy and the energy produced through muscular work during the energy exchange phase. The initial energy is produced by the athlete during the approach, in the main phase of energy production. A high approach velocity is predominantly influenced by sprinting ability.

The athlete can produce muscular work during the main phase of energy exchange in both the energy transfer and the energy return phase. During the first phase of energy exchange, there is a decrease in the total energy of the athlete. At the same time, energy is transferred to the pole and stored as elastic energy. When the stored energy in the pole is greater than the decrease of the total energy of the athlete, the athlete has put energy into the system through muscular work. If the energy stored in the pole is less than the decrease in the athlete's energy, then the athlete has absorbed energy.

The bigger the difference between the stored energy and the energy reduction of the body, the better the elasticity of the pole is being used during this phase. With respect to this factor, which seems to be critical for performance, the athletes analysed in this study differed greatly (*Figure 9*). This criterion shows whether the athletes worked during the rock back phase or whether they were too passive. It has significant correlation with both official jump height ($r=0.68$, $p<0.05$) and effective jump height ($r=0.76$, $p<0.01$).

In the next phase, the energy in the pole is returned to the athlete, thereby increasing again the energy possessed by the athlete. If the increase in the athlete's energy is greater than that returned by the pole, then the athlete has again added energy into the system via muscular work. If the increase is less, the athlete has absorbed energy. The more energy the athlete can produce during this phase the better. On further analysis of this second criterion, substantial differences were found between the athletes (*Figure 10*).

Both criteria are displayed in *Figure 11*. Upon observation of these criteria, specific deficits of the individual athletes can be identified. For example, Bubka produces a lot of energy during the energy transfer phase and less during the second phase. This indicates that the possibility exists for Bubka to improve further. Other athletes, such as Buckfield, Manson, and Eriksson, demonstrate negative values for the first criterion, which

Table 58: Parameters at the end of the energy return phase: horizontal (PRVx) and vertical velocity (PRVy) of the CM and the angle of projection of the CM (PA) at pole release

Parameter	mean	s	min	max
PRVx [m/s]	1.22	0.16	1.01	1.60
PRVy [m/s]	2.26	0.76	1.09	3.55
PA [°]	60	9	42	72

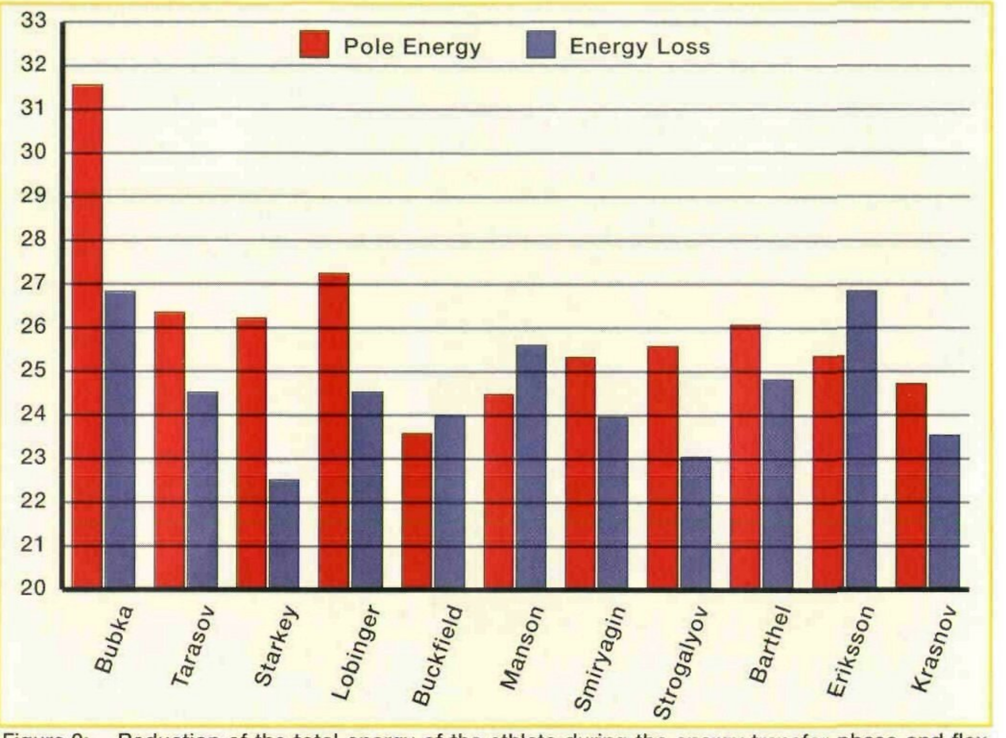

Figure 9: Reduction of the total energy of the athlete during the energy transfer phase and flex energy of the pole at MPB

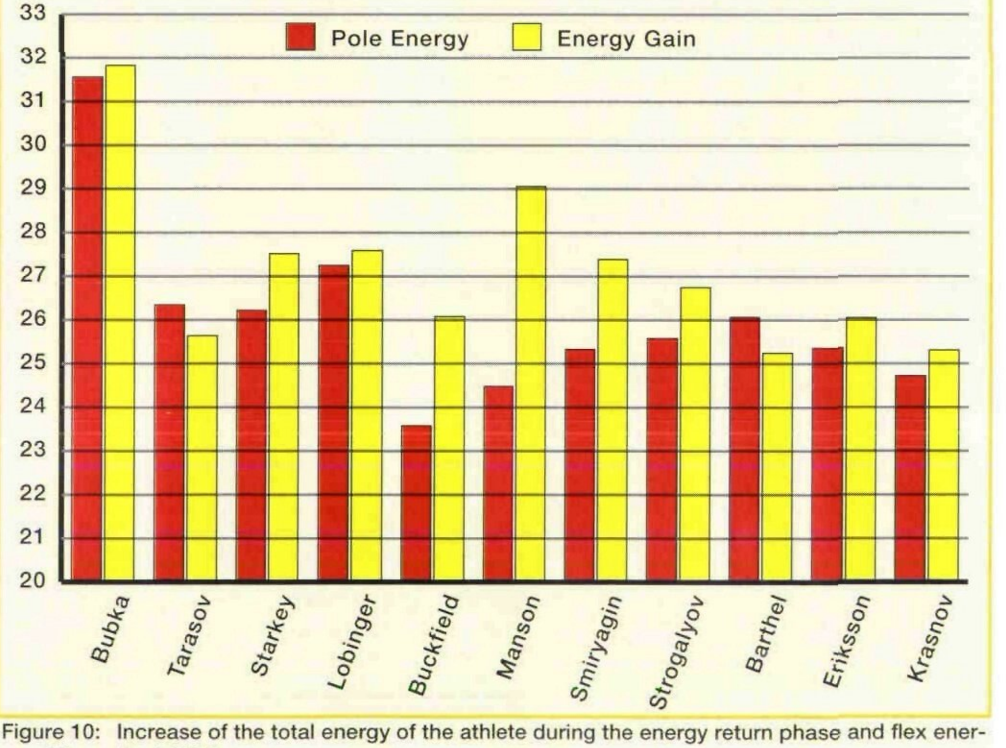

Figure 10: Increase of the total energy of the athlete during the energy return phase and flex energy of the pole at MPB

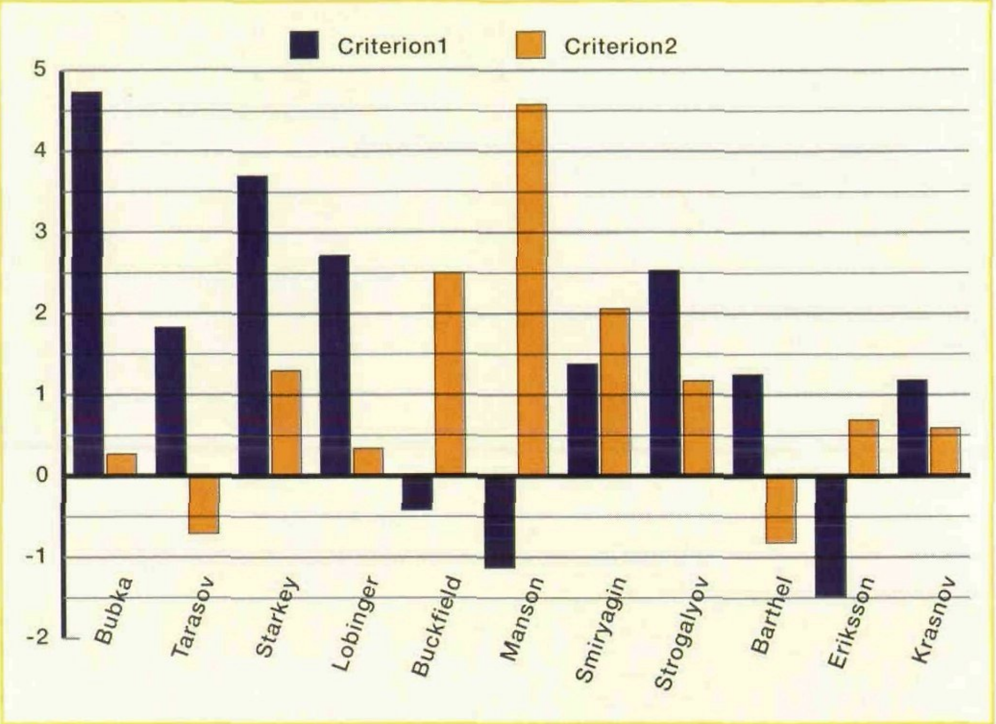

Figure 11: Energy gain during the energy transfer phase (criterion 1) and energy return phase (criterion 2)

means that they are losing energy in that phase. This could be explained by a passive rock back phase. Tarasov and Barthel show negative values for the second criterion, which indicates technical problems during the energy return phase. Starkey shows good values for both criteria but is limited by low initial energy.