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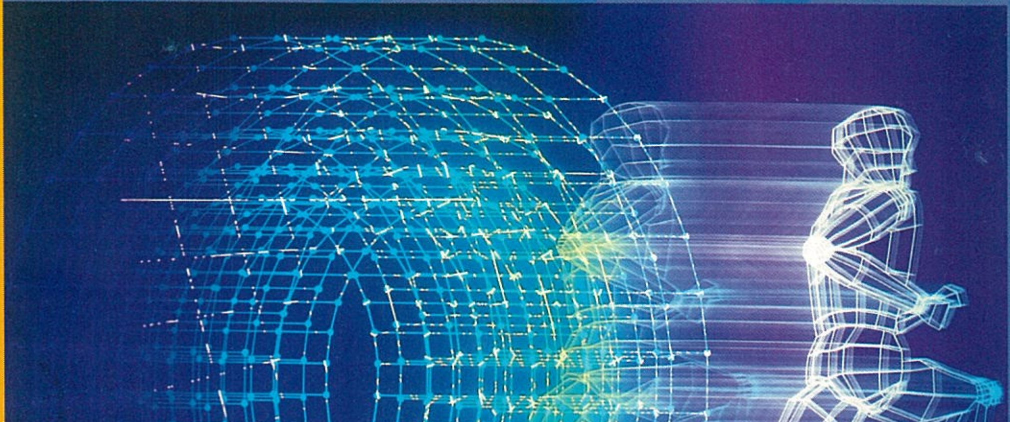

BIOMECHANICAL RESEARCH PROJECT ATHENS 1997

Final Report

Edited by:
G.-P. Brüggemann/ D. Koszewski,
H. Müller

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Biomechanical Research Project
Athens 1997

Final Report

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Biomechanical Research Project Athens 1997

Final Report

Edited by
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Report on the Biomechanical Research Project at the 6th World Championships in Athletics, Athens 1997, sponsored by the International Athletic Foundation

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Preface

The International Athletic Foundation appointed the Institute for Athletics of the German Sport University Cologne to carry out the Biomechanics Research Project during the 6th World Championships in Athletics in Athens 1997.

This project was intented to update the knowledge on current trends in technique and performance since the last project of that kind was completed in 1991. By means of an explicit analysis and interpretation of the data gathered from the world championships 1997, the main aim was to draw new conclusions to give access to new approaches and ideas.

The final report consists of various contributions each of which provides an abstract, nomenclatures, methods, a list of the literature analysed and a summary of the results.

The editors would welcome any comments on this report, or any other aspect of the project, as well as suggestions that will help to improve future projects. These comments should be addressed to:

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50933 Köln
Germany

The Editors
December 1998

Foreword by Dr. Primo Nebiolo

President – International Athletic Foundation
President – International Amateur Athletic Federation

On behalf of the International Athletic Foundation, I am delighted to introduce to the Athletic World this scientific report: "Biomechanical Research Project: Athens 1997" that continues the IAAF series in this field.

This report will be another contribution to the advanced coaches by analysing the athletes' performances and will improve the general knowledge of the limiting factors of athletic performance.

In Athens, the Biomechanical Team conducted by Prof. G.-P. Brüggemann introduced a stunning new technique of measurement using a Laser System that enabled us to detect the "fastest" man and woman at the World Championships.

This project, following previous research carried out in Rome, 1987 and Seoul 1988, will also update the database of biomechanical parameters of elite athletes at the end of the second millennium.

This book will be distributed to all the IAAF Member Ferderations and I sincerely hope its publication will help Coaches and Athletes to improve their performances through the application of scientific methods in training.

We strongly believe that the continued scientific study and analysis of the fundamentals of the training process are an important part of helping each individual develop honestly and avoid the temptation of dangerous shortcuts that are not only unacceptable from an ethical point of view, but also post a risk to the athletes' health.

Dr. Primo Nebiolo

1. Introduction

1.1 Description and purpose

In co-operation with the IAF the Project Team defined different purposes of this study:

- to update the database of biomechanical parameters of elite athletes.
- to support 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 support the international media in producing competent, attractive athletics coverage and presentation of the collected scientific data.

The project comprises three sub-projects:

- information-service for the media with initial distribution of simple information brochures in three languages (English, Spanish, French), concerning historical aspects and important biomechanical concepts.
- fast biomechanical information service on the day after the finals, when the collected data were presented and discussed with coaches, athletes and representatives of the media.
- detailed analysis of the collected data and their presentation in a report with a corresponding Biomechanics-Video.

The project focussed on the finals (men and women) of the following events:

- 100m, 200m, 400m
- 100m and 110m hurdles
- Long-, Triple-, High Jump and Pole Vault
- Discus Throw

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, has been used to a greater extend than in previous studies.

The first results were presented and explained daily at a Fast Information Service Meeting of the IAF-Biomechanics Research Team at the Championships. Biomechanical information were 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.

Two months after the competition a preliminary report was published in the magazine "New Studies in Athletics" (No. 2-3/1997, pg. 43-74). It contains a further analysis of the men's and women's sprinting and jumping events. Because this was the first time that both men's and women's Triple Jump were analysed in a major international competition, extra emphasis were given to the biomechanical analysis of gender specific differences.

The final report is not primarily focussed on the merely descriptive data of the events. The objective is to lead to a more detailed understanding of athletics techniques than to add further data to already existing investigations. Additionally descriptive data are listed in the appendix.

The general scientific and technical methods and procedures used in Athens are described in more detail in the above mentioned article in "New Studies in Athletics". The interested reader may refer to that article. If a more specific description was indicated it is covered within the different articles of the final report.

1.2 Project Team and authors

The Project Team consisted of 20 members from six nations:

Project Leader	Prof. Dr. Gert-Peter Brüggemann (GER).
Project Co-ordinator	Harald Müller (GER)
Co-workers	Frank Andrä (GER)
	Dr. Adiamantios Arampatzis (GRE)
	Dr. Tony Arndt (AUS)
	Oliver Bloch (GER)
	Dean Gathercole (AUS)
	Helmar Hommel (GER)
	Juha Isoletho (FIN)
	Dr. Uwe Kersting (GER)
	Dr. Axel Knicker (GER)
	Iraklis Kollias (GRE)
	Dietmar Koszewski (GER)
	Gaspar Morey (ESP)
	Dr. Eberhard Nixdorf (GER)
	Dr. Wolfgang Ritzdorf (GER)
	Falk Schade (GER)
	Gary Scheirman (USA)
	Marc Walsh (USA)

The articles in this final report are indicated with the individual names of the responsible authors. Harald Müller was the responsible editor and Dietmar Koszewski managed the layout.

1.3 Acknowledgements

The Project Team would like to express their acknowledgement to Dr. Karl Lennartz and Dr. Jochen Rühl, both from the German Sport University Cologne, Germany, for the authorship of the historical introductions in the event-specific press-releases.

We like to thank Mr. Elio Locatelli for his tremendous support in the preparation and organization of the project.

Additionally the Project Team would like to express their acknowledgement to the sponsors of the project:

- Peak Performance Technologies Inc. (Denver, USA) for technical support
- Dedo Weigert (Munich, GER) for High Speed Video System (Motion Scope, Redlake Inc.)
- ISL (Lausanne, SUI) for co-ordination of the sponsors
- Adidas (Herzogenaurach, GER) for provision with clothes
- TDK (Luxembourg) for provision with video tapes
- Mita Copiers

The Project Team would like to thank the IAF for their confidence and patience in the different stages of the project.

2. Results

2.1 Biomechanical Analysis of the Sprinting Events

Uwe G. Kersting

Abstract

In this chapter results of measurements of the instantaneous speed and further kinematic analyses of the 100, 200 and 400 m events are presented. Split times for defined intervals and basic kinematic parameters such as average step length and step rate were calculated from video recordings. Running speed was directly estimated by a laser speed measuring system. For the men's 100 m and women's 200 m semi-finals the body kinematics of selected sprinters were determined by high speed video positioned at 30 m and 70 m, respectively. A total of 17 runs from the semi-finals were digitised and were used to identify kinematics of top level athletes.

The analysis of speeds clearly shows that most competitors in the finals and semi-finals were able to maintain a speed of over 11.5 m/s between 30 to 90 m in men. The women reach their maximum speed earlier but also show an earlier decrease in speed as opposed to the men. Differences between single athletes were greatest during the starting phase and towards the end of the race, but reaction times (RT) appeared to have a minor influence on the result. The analysis of body movement clearly reflects that even in the narrow world class field specific differences are discernible. The kinematic data suggest that muscle stiffness is a crucial factor in sprint performance.

Introduction

History

100 m men: Strictly speaking there was no ancient equivalent of today's 100 m sprint. In those times the shortest sprint distance was between 155 and 210 m based upon the ancient distance measurement of one stadium (600 foot) and the shape of the sports arenas named thereafter which consisted of a 600 foot straight. Early physical exercise teachers at the beginning of the 18th century based the sprinting distance upon this measurement, e.g. Friedrich Ludwig Jahn whose distance of 192 m corresponded to the length of the stadium in Olympia. When round tracks originated during the onset of amateur athletics in England the maximum length of the straights was 100 or 110 yds ($^1/_{16}$ of an English mile). The 100 m distance on the European continent was the equivalent. Thomas Burke (USA) was the first Olympic champion in 12.0 s. At present the 100 m is dominated by black runners. The first black sprinter to win the Olympic 100 m was „Eddie“ Tolan (CAN) in Los Angeles, 1932. He also held the world record of 10.3 s. Significant time advantages were achieved after the invention of starting blocks and the development of the first synthetic tracks in the 60's then facilitated times under 10.0 s. The „brush shoe“ with many small „spike nails“ was invented to fully utilise the advantages of the synthetic tracks but was banned soon after. The first additional electronic times were kept at the 1912 Olympic Games. The ever increasing density of top performances necessitated times measured in $^1/_{100}$ s. James Hines (USA) was therefore, the first runner to legitimately break the 10 second barrier with his 9.95 s (9.9 s with bonus) at the Mexico City Olympic Games in 1968.

The world champion Donovan Bailey (CAN) before the Athens championships still held the world record with his 9.84 s Olympic victory in Atlanta, 1996. Carl Lewis (USA) is, however, the most popular sprinter of the 80's. His victory in Seoul was not achieved until Ben Johnson (CAN) was found guilty of doping after running 9.79 s.

100 m women: During the expansion of women's athletics after the first world war it seemed natural that the shortest sprint distance for women was also set at 100 m. The first 100 yds world record of the Fédération Sportive Féminine Internationale (FSFI) was 11$^4/_5$ s set by Mary Lines (GBR) on the 30.10.1921. Elizabeth Robinson (USA) was the first Olympic champion in 12.2 s when women were first „allowed into the Olympic stadium“ as competitors in 1928.

As with the corresponding men's event, black female sprinters became more and more dominant. The first black star was Wilma Rudolph (USA) who won Olympic gold in Rome in the world record time of 11.3 s. The present world record of 10.49 s was set on the 16.7.1988 by Florence Griffith Joyner (USA) who in the years 1987 and 1988 attracted a lot of attention because of quite obvious changes in her muscle profile. Gwen Torrence (USA) is the present world champion with 10.85 s. She was third at the Olympic Games in

Atlanta 1996 behind Gail Devers (USA) with 10.94 s and Merlene Ottey (JAM) with 10.94 s.

200 m men: The ancient distances were, however, not used during the development of modern athletics in England during the second half of the 18th century. The „longer sprint" was either based upon $^1/_8$th of an English mile, 220 yds or half the track or 440 yds. The first recorded best time of 24.0 s over 220 yds was achieved by Percy Thornton (GBR) on the 24.4.1866. It first appeared on the Olympic programme in Paris, 1900 where Walter Tewkesbury (USA) won in 22.2 s. The dream of all great sprinters is to win the double over the 100 and 200 m distances. This was first achieved by „Archie" Hahn (USA) in the USA in 1904 and latest by Carl Lewis (USA) in 1984.

The first time under 21.0 s acknowledged by the IAAF, was run by Jesse Owens (USA) who ran the final of the Olympic Games in Berlin in 20.7 s on the 5.8.1936. Pietro Mennea (ITA), later Olympic champion in Moscow in 1980, also benefited from the advantages of altitude when he set a new world record of 19.72 s at the Universiade in Mexico City on the 12.9.79. This record remained for a long time until Michael Johnson (USA) reduced it to 19.66 s on the 23.6.1996 in Atlanta before all but pulverising it with the time of 19.32 s at the same location in the final of the Olympic Games. Johnson is also the present world champion with a time of 19.79 s.

200 m women: Marie Mejzliková (TCH) ran $28^3/_5$ s in Paris on the 21.5.1922 during a competition between France and Czechoslovakia. The women's 200 m sprint was initially not included in the Olympic programme and made its premiere appearance in London, 1948. The multi-talented Fanny Blankers Koen (HOL) won the first Olympic title in 24.4 s. Similar to in the 100 m Florence Griffith Joyner (USA) improved considerably upon this time at the end of the 80's. At the Seoul Olympic Games she ran 21.56 s in the semi-final and subsequently broke this record with a time of 21.34 s in the final.

400 m men: The 400 m run presumably corresponds to the antique Diaulos, a double run of two stadiums which was started at the finish and included a turn at the halfway mark. The 400 m run already had its premiere at the first Olympic Games in Athens, 1896.

The 400 m distance has been and still is dominated by athletes from the USA. The first time that the 45.0 s barrier was broken was at the Olympic Games in Rome, 1960, where Otis Davis (USA) and Karl Kaufmann (GER) both ran 44.9 s. The next barrier was already broken eight years later at the Olympic Games in Mexico City when Lee Evans (USA) won in a time of 43.8 s (electronically 43.86). This record held for 20 years until Butch Reynolds (USA) lowered it to 43.29 s in Zurich on the 17.8.88. A Jamaican, not an American, was the first world champion in Helsinki, 1983, where Bert Cameron won in 45.05 s. The present world champion is Michael Johnson (USA) who got close to the world record in Göteborg in 1995 with 43.39 s.

400 m women: The first available time for this distance was reported from Stockholm where Berit Hjulhammar (SWE) ran 72.5 s on the 12.9.1914. Not until 1964 could women participate in this event at the Olympic Games. Marita Koch (GDR) set seven new world records, the last one being 47.6 s in Canberra on the 6.10.1985.

Biomechanics – A Summarising Review

The goal of a competitive sprinter is simply to cover a given distance in the shortest possible time. In more mathematical terms: starting from point A (start line) moving as fast as possible to point B (finish line) from a still standing position, starting the run at a given signal. This implies a short reaction time (RT), accelerating the body as hard as possible thus attaining the maximum speed in a very short time and then maintaining this speed up to the finishing line. During the acceleration phase the sprinter must produce maximal forces to push the body into a forward direction. At the very first level of kinematic analysis speed is simply the product of step length and step frequency (Dillman, 1975; Mero, Komi & Gregor, 1992; Sinning & Forsyth, 1970; Hoshikawa, Matsui & Miyashita 1973). Therefore, to maximise running velocity the sprinter must maximise both step frequency and step length. According to Cavanagh (1990) in the following text the term 'step' will be defined as the instant of one foot contact to the following contralateral contact in contrast to 'step', which marks the time between two ipsilateral ground contacts. It was formerly emphasised that it has to be differentiated between velocity and speed (Hay, 1978) in biomechanical research. Since in the current study only level running is considered both terms will be used synonymously.

Sprint running related research focussing on the mechanical background and physiological limitations of human sprinting performance indicates that step length and rate can not be increased without limits. The research agrees that changes in step rate are more crucial at the higher velocities, though at what point this becomes more important than step length is not known (Vaughan, 1984; Wood, 1987). Regardless of when step rate becomes the more important determinant it is an inability to increase step rate which limits the sprinter to a certain velocity. Apart from these more descriptive factors which are directly influenced by the time spent with the foot in contact with the ground (support or contact time) and the time spent in the air (flight time), the mechanical properties affecting the body movement are of importance.

A decrease in contact time allows the sprinter less time in which to generate the necessary impulse during the propulsive ground contact phase to overcome the retarding forces and to drive the body forward. The runner must produce larger impulses to be able to further increase velocity when the contact time is reduced. Impulse is simply defined as the integral of force and time. Thus those individuals that can produce the greatest forces in the shortest time are the ones most likely to reach the highest velocities in sprint running (Radford, 1978). Analysis of active forces produced by the body system determine how acceleration can be produced and speed can be maintained. Energy transfer calculations between body segments and electromyographical studies (Chapman and Caldwell, 1983a, b) indicate that a crucial factor is the eccentric contraction of the hamstring muscles during the airborne phase. This allows to store elastic energy which can be utilised during ground contact to produce greater forces into the forward direction. To minimise the retarding forces and to maximise the propulsive forces for each step during a sprint the mechanical analysis of sprint running has shown that several kinematic factors are connected with sprinting qualities e.g. the leg angle at touch down, which is directly connected with the horizontal distance of the centre of mass to the position of the foot at ground contact and the horizontal velocity of the foot prior to touch-down. During the swing phase the leg lift angle defined as the angle of the thigh in relation to a horizontal axis is strongly connected with running speed (Kunz & Kaufmann, 1980).

The purpose of this study was to analyse speeds and interval times during the important phases in sprint races at the WC in Athens, 1997). The comparison with data from former competitions (WC Rome, 1987; Olympic Games (OG) Seoul, 1988 and WC Tokyo, 1991) focussed on the development in performance during the last ten years. Kinematic analysis has to be implemented for identification of important technical factors and interpretation of observed variations.

Methods

Video cameras operating at 50 Hz were placed perpendicular to the running direction on the upper stands at the 30, 50 and 60 m line in the 100 m events. Markers were placed at each 10 m interval of the 100 m running track which allowed interval times for each 10 m interval to be calculated by counting the frames in the video. For the other races the same procedure was used. For the 200 and 400 m runs the interval borders were 50/100/150 m and 50/100/150/200/250/300/350 m respectively.

The number of steps over the whole race and three subsections was counted to calculate the average step length and frequency. Two 200 Hz video cameras were positioned on the lower stands approximately 7 m above the track level at 30 m and 79 m distance from the start line. The field of view covered a distance of approximately 8 m of the runway. Two dimensional kinematic analysis was performed by use of Peak 5.0 (Peak Performance, Englewood, CO). To compensate for projection errors the 2D data was transformed via DLT technique according to the oblique projection angle, which was performed on each lane of the track (software developed by Adamantios Arampatzis, Cologne). A modified body model out of fifteen landmarks was used, representing 11 body segments. The parameters determined were: knee angle (γ),hip angle (β) trunk angle (τ) and the horizontal velocity of the foot tip (v_{xTip}) at touch down, the thigh angle with respect to the horizontal (δ).

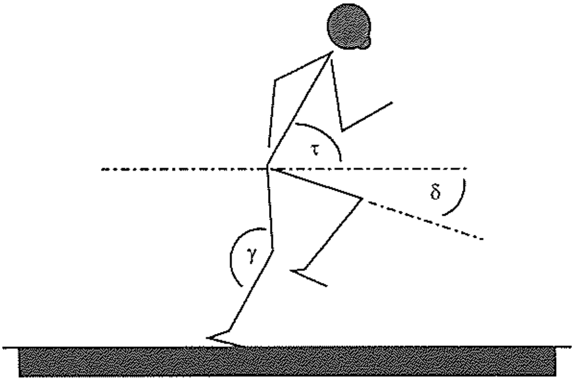

Figure 1: Definition of joint angles for kinematic analysis; $\beta = \tau + \delta$.

From the video analyses the following parameters were determined. All values were calculated for two steps in each particular camera view and averaged for further analysis. The following listing contains a description of the denotations used:

γ_TD [°]	knee angle at touch-down (TD)
$\Delta\gamma$_TD [°]	knee flexion during stance
$d\gamma/dt_{mean}$ [°/s]	mean velocity of knee flexion
$d\gamma/dt_{max}$ [°/s]	maximum instantaneous knee flexion velocity
$d\beta/dt$_TD [°/s]	hip extension velocity at TD
v_x Tip [m/s]	horizontal velocity of the foot tip prior to TD
τ_TD [°]	trunk angle at TD
δ_{min} [°]	maximum knee lift during swing

The instantaneous running speeds were measured by a laser system (LAVEG Sport, Jenoptik, Jena, Germany) as described in the general methods section. The raw data was filtered by a FFT filter using a cut-off frequency of 3 Hz. During the sprinting competitions in Athens six of the described systems were used and placed 15 m behind the start line fixed on a tripod. Due to commercial and broadcasting reasons the systems had to be set up behind the advertising wall at a height of approximately 1.7 m (figure 1). The laser beams were directed to the lower back of the athletes which made it possible to determine speed values from that time instant where the athletes began to raise their trunks after leaving the starting block until they had crossed the finish line. This could be realised in most runs during the first 10 m. The error due to the difference in height of the systems in relation to the height of the lower back could be neglected.

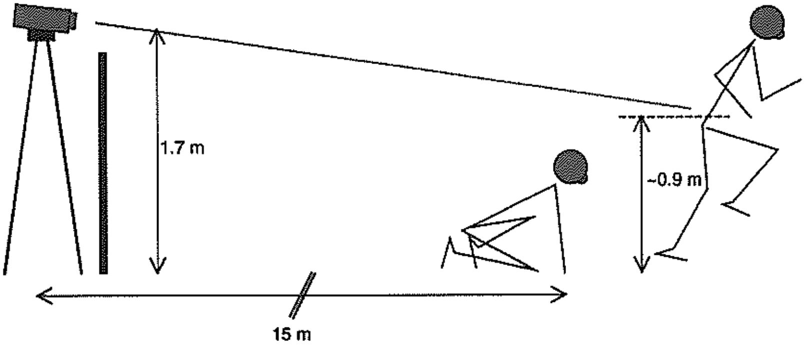

Figure 2: Schematic of the setup of the speed measurement system.

In the analyses mainly descriptive statistics were applied. For the analysis of relationships between variables Pearson's correlation coefficients were calculated after testing for normal distribution. Differences between groups were determined by ANOVA using a Newman-Keuls procedure as post-hoc test.

2.1.1 100 m

Men's 100 m

The interval times for the 10 m sections of the men's final are listed in table 1. Using the constant interval length the average velocity is inversely proportional to the section times. It is evident that all finalists exceed the 10 m/s (1.0 s) mark between 20 and 30 m and reaching an average interval time of 0.883 s, which corresponds to a speed of 11.23 m/s, during the next 10 m interval. The table clearly demonstrates the narrowness in performance on the world elite level in men's 100 m sprinting since the variation over all finalists is very small.

Table 1: Interval and reaction times [s] of the men's 100 m final (Intervals: 1 = 0 – 10 m, …, 10 = 90 – 100 m).

Interval	Greene	Bailey	Montgomery	Fredericks	Boldon	Ezinwa	Mean	SD
Result	9.86	9.91	9.94	9.95	10.02	10.10	9.963	0.085
RT	0.134	0.145	0.134	0.129	0.123	0.135	0.133	0.007
1	1.71	1.77	1.73	1.73	1.72	1.77	1.738	0.026
2	1.04	1.03	1.03	1.04	1.05	1.05	1.040	0.009
3	0.92	0.91	0.93	0.93	0.93	0.94	0.927	0.010
4	0.88	0.87	0.88	0.89	0.89	0.89	0.883	0.008
5	0.87	0.85	0.86	0.87	0.87	0.87	0.865	0.008
6	0.85	0.85	0.86	0.86	0.87	0.87	0.860	0.009
7	0.85	0.85	0.86	0.86	0.87	0.87	0.860	0.009
8	0.86	0.86	0.87	0.87	0.88	0.88	0.870	0.009
9	0.87	0.87	0.88	0.88	0.90	0.89	0.882	0.012
10	0.88	0.90	0.90	0.89	0.92	0.93	0.903	0.019

Note: Lanes one and eight were not considered; SD = Standard Deviation.

The data from the Athens' final confirms some well known trends. Top sprinters reach their maximum speed between 50 and 70 m and show a more or less marked deceleration in the last 20 m (Brüggemann & Glad, 1990, Sušanka, 1989). Though the maximum speed area, 40 – 70 m, of this final corresponds well to the analysis at the Olympic Games, Seoul 1988, (Brüggemann & Glad, 1990), it can be seen that the decrease towards the end of the run shows an earlier onset. The fastest 10 m section ever measured was performed by Lewis (WC Tokyo 1991, Ae et al., 1992) and Bailey (OG Atlanta 1996) with 0.83 s, both finishing their race in a new world record time. This value was not attained by the finalists in Athens.

Figure 3 gives an individual comparison of the interval times of Greene, Montgomery and Bailey. Negative values indicate a longer time compared to Greene which in turn means a slower speed. The figure illustrates that Bailey lost this race mostly in the first 10 m section with a loss of 0.06 s and a slight loss due to his longer RT. From 10 to 50 meters Bailey made up 0.05 s. From 50 to 90 metres there was no difference in these two athletes while Greene gained another 0.02 s in the last 10 metres. Montgomery on the other hand did not lose that much during the early acceleration but did reach such a high velocity only for a markedly shorter period of time, therefore, lost continuously from 50 to 90 m, also showing a loss of 0.02 s during the last 10 m.

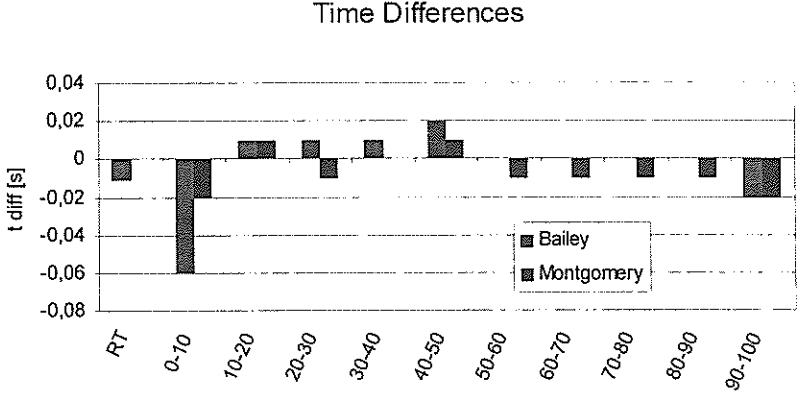

Figure 3: Individual comparison of interval times (Zero line: Reference value of Greene; Bars: Actual differences of Bailey and Montgomery; > 0: faster than reference value; < 0: slower than reference value).

As mentioned above the average interval speeds can be directly calculated from the split times given in table 1. In the following the speeds measured instantaneously will be used. The measurements conducted with the laser system allowed for the determination of instantaneous horizontal running velocities over the whole run: Figure 4 gives a plot of the running velocity versus distance run as derived from the laser measurements, demonstrating the necessity of smoothing the raw data.

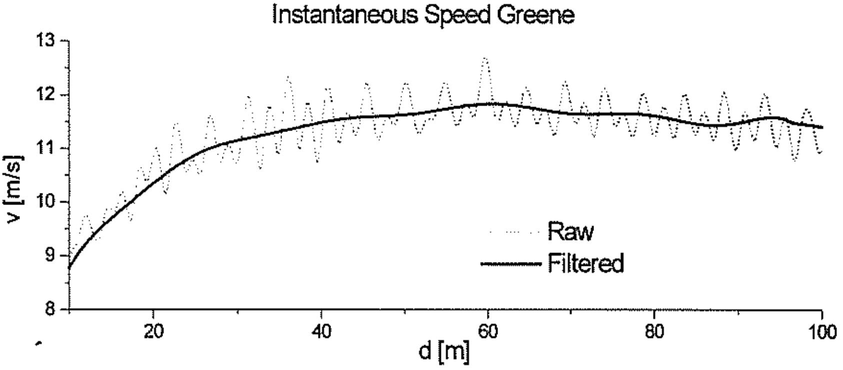

Figure 4: Example of velocity measurement; final run of Greene.

Based on the laser measurements the actual speeds at the end of each interval were determined. This allowed for a direct comparison of the finalists. The data is listed in table 2, which gives the velocity profile of each runner and the means and standard deviations.

Table 2: Instantaneous speeds at the end of each interval in the men's 100 m final.

	Greene (USA)	**Bailey** (CAN)	**Montgomery** (USA)	**Fredericks** (NAM)	**Boldon** (TRI)	**Ezinwa** (NGR)	**Mean**	**SD**
10m	8.71	8.90	8.82	8.77	8.67	8.55	8.737	0.122
20m	10.47	10.55	10.34	10.35	10.36	10.21	10.38	0.117
30m	11.14	11.28	11.14	11.02	11.03	11.08	11.11	0.096
40m	11.50	11.63	11.54	11.43	11.41	11.38	11.482	0.094
50m	11.67	11.76	11.62	11.60	11.50	11.52	11.612	0.096
60m	11.80	11.80	11.61	11.72	11.54	11.51	11.663	0.128
70m	11.68	11.70	11.54	11.52	11.34	11.42	11.533	0.141
80m	11.57	11.55	11.42	11.43	11.20	11.30	11.412	0.143
90m	11.51	11.38	11.25	11.27	11.05	11.07	11.255	0.177
100m	11.30	11.00	10.95	10.97	10.46	10.36	10.810	0.352

There is the same overall tendency as in table 1, though some obvious discrepancies in comparison to Greene, Montgomery and Bailey are created. Although Bailey loses 0.06 s in the first 10 m his velocity at the end of the interval is slightly higher. Consequently the loss must have happened during the first steps combined with an extraordinary acceleration in the latter half of this section. The situation is again graphically presented in figure 5. It becomes clear that Bailey could maintain his higher speed gained during the acceleration for an additional 30 m reaching the same velocity as Greene. However, Greene was able to continue at this higher speed for a longer duration. The data in table 2 and figure 5 demonstrates that on the men’s top level the performance niveau differences are very small.

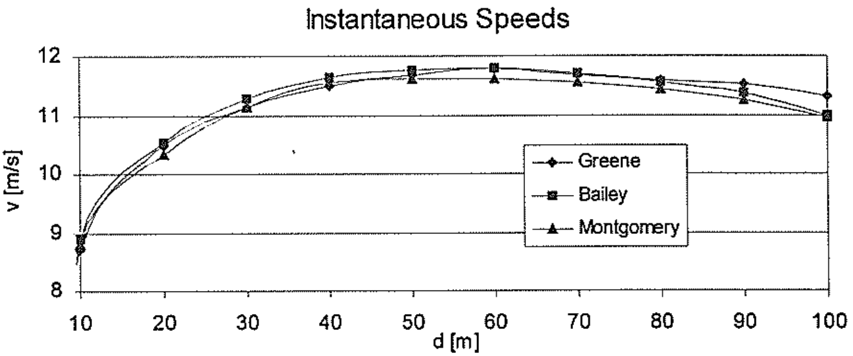

Figure 5: Comparison of velocities during the race for the three medallists.

Interestingly all of the six measured finalists reach a speed of over 10 m/s prior to the 20 m mark, all finalists analysed have an actual velocity of more than 11 m/s after 30 metres. Most of them reach their maximum speed at the end of the 60 m section. A more detailed analysis is given in table 3.

Table 3: Maximum speed and location of maximum speed.

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
Mean	11.728	60.417
SD	0.113	1.460

The table confirms the above mentioned results. The maximum velocity is reached at approximately 60 m by all athletes, which agrees with the results reported from the Seoul Games and the World Championships (WC) in Rome, 1987, and the Olympic Games (OG) in Seoul, 1988, (Brüggemann & Glad, 1990; Sušanka, 1989a). The highest actual velocity in this final was measured as 11.87 m/s and was shown by both Greene and Bailey. The distances covered within certain velocity limits which are given in table 4 in greater detail.

Table 4: Distances covered with more than 11.0 m/s and 11.5 m/s.

Name	v > 11 m/s			v > 11.5 m/s		
	from [m]	Till [m]	diff. [m]	from [m]	till [m]	diff. [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
Mean	28.208	96.282	68.073	40.938	76.078	35.140
SD	1.911	2.541	3.392	3.124	8.736	11.104

The data mirrors the race results. The longer the top speed area the better the result. The medallists covered more than 70 m with a velocity of more than 11.0 m/s. Greene realised more than the half of the overall distance with a velocity of more than 11.5 m/s and was faster than 11.0 m/s even at the finish line. Bailey demonstrated the best acceleration abilities and was the first to reach the 11.0 and 11.5 m/s barrier. But compared to Greene he was also the first to leave this area.

During the men's semi-finals and finals and several measurements during the qualifications a total of 31 athletes' runs could be quantified with the LAVEG system. The system allows for the definition of marker positions at the end of each 10 m section. Aided by these the split times, velocities and mean accelerations for each interval were calculated. This data was statistically compared by a correlation analysis. Table 5 gives the Pearson correlation coefficients (r) of velocities, split times and accelerations.

Table 5: Correlation coefficients (r) of the resulting time and measured maximum speed with split times, momentary velocity and mean accelerations for 31 runs (S – 10 m = split time excluding RT; $r > |0.35|$ are significant at $p < 0.05$: *; $r > |0.45|$ are significant at $p < 0.05$: **).

Location	r_{Speed}	Interval	$r_{Split\ time}$	$r_{Acceleration}$
10 m	-0.58 **	S – 10 m	0. 37 *	
20 m	-0.62 **	0 – 10 m	0.53 **	-0.69 **
30 m	-0.86 **	10 – 20 m	0.80 **	-0.21
40 m	-0.87 **	20 – 30 m	0.86 **	-0.19
50 m	-0.90 **	30 – 40 m	0.86 **	-0.13
60 m	-0.94 **	40 – 50 m	0.87 **	-0.05
70 m	-0.94 **	50 – 60 m	0.93 **	-0.43 *
80 m	-0.93 **	60 – 70 m	0.91 **	-0.16
90 m	-0.91 **	70 – 80 m	0.94 **	0.13
100 m	-0.76 **	80 – 90 m	0.92 **	-0.33
(v_{max})	-0.94 **	90 – 100 m	0.84 **	-0.43 *

Table 5 demonstrates the greater connection between the velocities at 60 and 70 m and with the resulting time. This reflects the trends given by the data of the finals, where the runners reached their maximum velocity at around 60 m. Assuming that all sprinters show a comparable speed development during the race it has to be expected that the maximum velocity correlates in such a way. The fact that reaction times show no relationship ($r = 0.01$) with the race result appears somewhat amazing but stands in good accordance with former results (Brüggemann & Glad, 1990). These calculations are of greater statistical power than the mentioned investigation since many more runs were included. Looking at the correlation coefficients of the split times similar trends can be discerned but the highest correlation is found for the interval from 70 to 80 m. This reflects the importance of maintaining the high average speed for as long as possible. Comparing the correlation coefficients of the mean accelerations it becomes obvious that the acceleration during the first 10 m shows the closest relationships to the result. This was already illustrated by the comparison between Greene, Montgomery and Bailey (figure 3) above.

In the following part the kinematics of the men's sprint competitions will be analysed. First of all the average step length (SL) and step frequency (SF) for the whole run and three subsections will be presented. The values are summarised in table 6, where data from Lewis, Burell and Johnson is included for comparison.

Table 6: Step frequency and step length for the men's 100 m final; lower part: Values for the 1st and 2nd at the WC, 1987, the OG, 1988, and the WC 1991, (Johnson, Lewis and Burell).

	Step Frequency [1/s]				Step Length [m]			
Interval [m]	0–30	30–60	60–100	0–100	0–30	30–60	60–100	0–100
Greene	4.29	5.00	4.73	4.65	2.00	2.22	2.31	2.18
Bailey	4.29	4.64	4.57	4.49	2.00	2.31	2.42	2.25
Montgomery	4.72	4.81	4.89	4.81	1.76	2.31	2.25	2.09
Fredericks	4.43	5.00	4.67	4.67	1.94	2.22	2.29	2.15
Boldon	4.17	4.81	4.30	4.39	2.00	2.31	2.50	2.27
Ezinwa	4.44	4.64	4.65	4.57	1.88	2.31	2.33	2.16
Surin	4.31	4.81	4.37	4.47	1.94	2.31	2.40	2.21
Marsh	4.10	4.63	4.15	4.26	1.88	2.40	2.61	2.28
Johnson (1987, 9.83)	4.50	4.96	4.73	4.72	1.79	2.34	2.45	2.22
Johnson (1988, 9.79)	4.26	5.02	4.74	4.76	1.80	2.36	2.44	2.22
Lewis (1987, 9.93)	4.12	4.71	4.49	4.40	1.94	2.46	2.60	2.36
Lewis (1988, 9.92)	4.15	4.73	4.42	4.40	1.93	2.46	2.60	2.36
Lewis (1991, 9.86)	4.36	4.64	4.52	4.51	1.92	2.51	2.61	2.37
Burell (1991, 9.88)	4.34	4.45	4.41	4.40	1.95	2.59	2.62	2.41

Neither the frequency nor the step length values show an ordered relationship to the race results. Figures 6 and 7 display the changes between the selected intervals during the final in Athens.

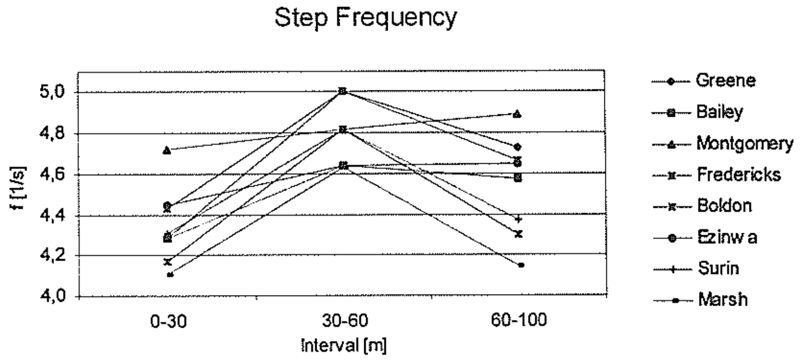

Figure 6: Average step frequency in three intervals.

Certain differences in the temporal development of SL and SF are evident for all runners in the final. The step frequency is characterised in most cases by a maximum during the maximum speed phase while towards the end of the run the step frequency has a tendency to decrease again. It is obvious that the general decrease in running velocity towards the end of the race (table 2) can be attributed mainly to a lowered step frequency since SL increases for most runners. A subgroup of three athletes demonstrates a diverse trend (Montgomery, Bailey and Ezinwa). Their step frequency remains on the same level which was attained during the middle section. The average step length steadily increases (figure 7). Of the mentioned subgroup Montgomery shows a decrease in step length from the 30 - 60 m to the 60 - 100 m section; Ezinwa shows the smallest increase while Bailey demonstrates an increase comparable to the rest of the runners. As a general observation from figure 5 it can be concluded that the athletes who reach the highest maximum step frequency are the three medallists.

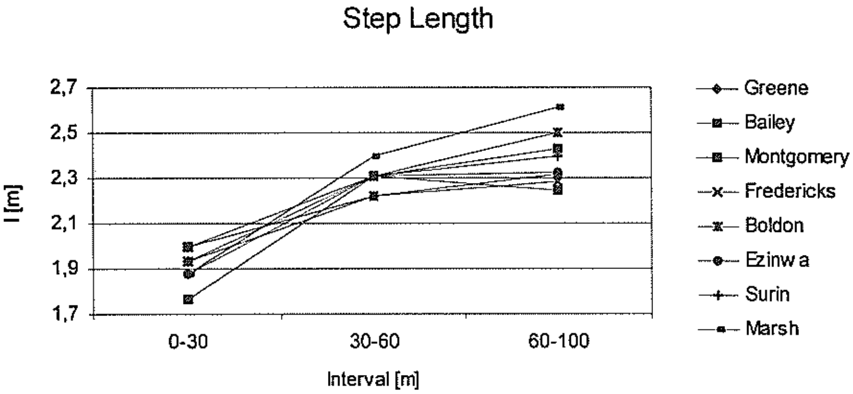

Figure 7: Average step length in three intervals.

Values from data gathered at the WC, 1987, the OG, 1988, and the WC, 1991, from Johnson, Lewis and Burell (Sušanka, 1989; Ae et al., 1992) were calculated for comparison (table 6). Johnson and Lewis show a nearly perfect resemblance of their SF and SL values even though a time span of one year lies between both races. Comparison with values for Greene indicates the importance of a high step frequency especially during the mid section of the race. Johnson was able to run the best time ever measured with the highest frequency of all competitors. However, it should be mentioned that he was disqualified after that race, thus this extraordinarily high value only seems to be possible when leaving the given physiological bounds. Only Fredericks was able to attain such high step frequency from the finalists in Athens. He is a 200 m specialist, and it may be argued that he was not able to reach optimum balance between SF and SL over the shorter 100 m distance. On the other hand Lewis never displayed such high step frequencies although he is set apart from his counterparts by a greater step length. Burell in the Tokyo final achieves almost the same values for SL produced by Lewis though being unable to reach appropriate step frequencies. It can be summarised that the middle section of a 100 m dash can be described as being step frequency weighted while the last third is more step length dependent. It appears that interindividual differences probably given by anthropometrical factors have a great effect. The development of the SF during the race appears different for each elite athlete in this comparison. Looking at the rest of the field it becomes difficult to identify a general trend. Marsh for example shows the greatest step length but the slowest resulting time.

Summarising the results it can be concluded that the maximum velocity is the most important factor to win a race. During the short time of a 100 m sprint there is not room to develop a certain speed profile. Simply the capacity to accelerate and to maintain the high velocity level are crucial for succeeding in sprinting. Regarding the SF and SL different patterns can be observed. To identify the factors, influencing the kinematic patterns further investigations are necessary.

Kinematic data was obtained for six athletes out of the semi-finals. Four of them could be analysed at both, the 30 and 70 m mark which allowed for a comparison of the late acceleration and high speed phase. Six could only be analysed at the 70 m mark.

Table 7: Kinematic parameters of four semi-finalists at d = 30 m from the start.

Parameter	Ezinwa 10.15	Boldon 10.00	Greene 9.90	Fredericks 9.93	Mean 9.995	SD 0.099
γ_TD [°]	157.1	152.5	146.8	137.4	148.48	8.49
$\Delta\gamma$_TD [°]	6.4	10.8	7.7	0.2	6.26	4.45
$d\gamma/dt_{mean}$ [°/s]	108.7	235.7	202.8	14.7	140.47	99.63
$d\gamma/dt_{max}$ [°/s]	50.5	382.8	266.7	393.5	273.37	159.28
$d\beta/dt$_TD [°/s]	1138.1	238.7	554.4	311.4	560.26	408.22
v_x Tip [m/s]	0.75	2.56	1.81	1.25	1.592	0.774
τ_TD [°]	78.9	78.9	75.3	75.4	77.11	2.05
δ_{min} [°]	17.7	12.6	10.1	9.9	12.57	3.61

Prior to discussing the results it has to be emphasised that kinematics were only analysed for a few athletes. Video data could only be gathered for the semi-finals. Therefore, the resulting times of the coinciding runs are given in the headers of tables 7 and 8.

According to the speed development data the 30 m line can be characterised as the late acceleration phase as the runners have almost reached their top speed values. Two groups could be differentiated with their resulting times of over 10.0 s and less than 10.0 s. At this instance it can be seen that the faster runners lift their thigh higher while their trunk is leaned forward to a greater extent. This allows for a better positioning of the foot in relation to the centre of mass and is therefore, beneficial for a continued acceleration. The angular velocity of knee flexion during stance is slower for the faster runners indicating a stiffer knee joint. This factor in the past has been associated with the capabilities of faster runners (Mero & Komi, 1985). The hip extension velocity at touch-down is higher for Greene, compared to Boldon and Fredericks. The highest value is shown by Ezinwa, who also demonstrates the lowest horizontal speed of the foot tip at TD. As was pointed out in the biomechanical overview the minimisation of this value would be beneficial for attaining a high sprinting velocity.

It can be summarised that Greene shows stiffer adjustments of his leg at touch-down which might contribute to his better performance (Mero et al., 1992). Fredericks shows an obviously different technique which was clearly demonstrated by his SL and SF values. This could perhaps be attributed to the fact that he is a 200 m specialist.

Table 8: Kinematic parameters of six semi-finalists determined at d = 70 m from the start.

Parameter	**Ezinwa 10.15**	**Boldon 10.00**	**Greene 9.90**	**Fredericks 9.93**	**Bailey 9.91**	**Montgomery 10.08**	**Mean 9.995**	**SD 0.010**
γ_TD [°]	155.5	155.3	153.0	140.9	155.2	145.5	150.89	6.18
$\Delta\gamma$_TD [°]	20.6	22.3	11.4	5.3	14.4	9.8	13.98	6.52
$d\gamma/dt_{mean}$ [°/s]	415.0	371.3	324.0	235.3	189.3	351.5	314.40	85.69
$d\gamma/dt_{max}$ [°/s]	597.0	542.7	439.4	346.8	326.6	211.5	410.70	144.06
$d\beta/dt$_TD [°/s]	491.3	362.0	170.9	519.5	558.0	695.0	465.59	180.56
v_x Tip [m/s]	2.58	2.70	2.43	1.48	2.18	1.40	2.13	0.56
τ_TD [°]	78.8	87.1	77.0	84.1	85.6	80.2	82.16	4.04
δ_{min} [°]	19.9	13.7	17.1	9.3	20.5	17.4	16.25	4.14

The analysis at the 70 m mark again emphasises that Fredericks differs from the rest of the athletes in almost every parameter (table 8). Apart from him it is still Greene who demonstrates the slowest knee flexion during stance. His trunk is leant forward to a greater extent than the other athletes. The hip extension velocity is again slower at touch-down and does not reach such a high as those of the other athletes. The ranking changes for the maximum knee lift, where Greene shows an average value. This might support the opinion that a higher knee lift during acceleration could be of advantage rather than during the top speed region (Chapman & Caldwell, 1983b).

Due to the fact that Fredericks shows a completely different pattern his values were excluded for the following comparison. Only Greene, Boldon and Ezinwa were regarded for the graphical representation in figures 8 and 9. There a comparison is presented of the mean values of these three runners at the 30 m and the 70 m mark.

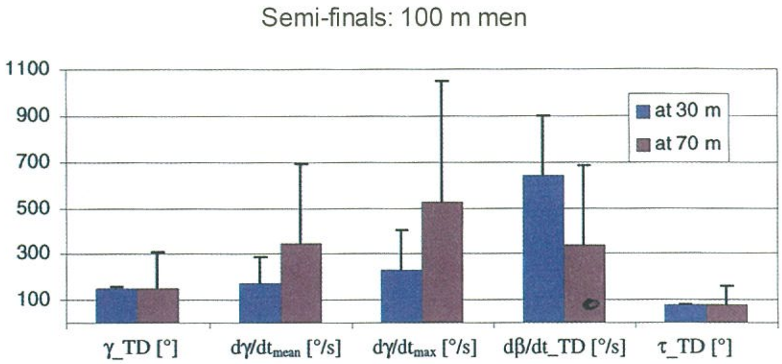

Figure 8: Angles and angular velocities for the men's 100 m semi-finals (Average of Greene, Boldon, Ezinwa).

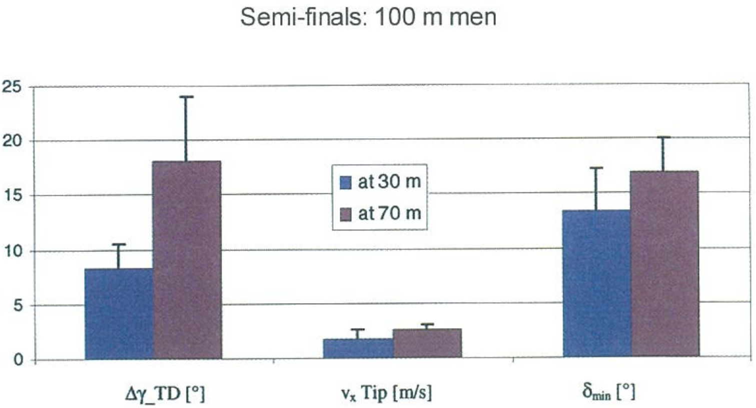

Figure 9: Angles and horizontal velocities for the men's 100 m semi-finals (Average of Greene, Boldon, Ezinwa)

Although only three athletes were considered for the graphical comparison it is obvious that the knee angle at TD does not alter throughout the race. The amount of knee flexion is doubled from 30 to 70 m while the angular velocity of flexion also. The hip extension velocity decreases during the race. Keeping in mind that the capacities of the hamstrings were attributed to be performance limiting, training strategies might help to stabilise or further increase performance. It can be assumed that a decrease in horizontal velocity of the foot tip at TD will be influenced by changes in hip kinematics in the desired way.

As a general observation it becomes obvious that most kinematic parameters show a greater variability at the 70 m mark. Concentrating on the individual values it seems likely that Greene's greater joint stiffness and hip extension velocity allow him to produce the best performance in this particular race.

Apart from the support of earlier findings demonstrating the importance of the capability to accelerate maximally and maintain a top speed level for as long as possible it was shown that even on the world elite level considerable variations in technique exist. It is suggested that joint stiffness and therefore, muscular characteristics are important. Future training strategies should focus on these areas.

Women's 100 m

The data obtained for the women are presented in the following section. Table 15 shows the interval times for the 10 m sections. According to the overall results, which show that women need approximately one second longer to cover the 100 m distance, the time intervals are longer than for the men.

Table 15: Interval times and reaction times [s] in the women's 100 m final.

	Jones (USA)	**Pintussevich** (UKR)	**Arron** (FRA)	**Miller** (USA)	**Paschke** (GER)	**Ottey** (JAM)	**Mean**	**SD**
Result	10.83	10.85	11.05	11.18	11.19	11.29	11.065	0.190
RT	0.160	0.130	0.165	0.117	0.138	0.139	0.142	0.018
1	1.81	1.86	1.89	1.88	1.89	1.89	1.870	0.032
2	1.11	1.112	1.15	1.15	1.14	1.13	1.133	0.016
3	1.02	1.01	1.02	1.05	1.04	1.01	1.025	0.016
4	0.97	0.97	0.98	1.00	1.00	0.98	0.983	0.014
5	0.95	0.94	0.96	0.98	0.98	0.96	0.962	0.016
6	0.94	0.94	0.95	0.97	0.98	0.97	0.958	0.017
7	0.95	0.94	0.96	0.98	0.98	0.97	0.963	0.016
8	0.95	0.96	0.97	1.00	1.00	1.00	0.980	0.023
9	0.97	0.98	0.99	1.01	1.01	1.04	1.000	0.025
10	0.99	1.00	1.01	1.04	1.03	1.20	1.045	0.078

According to the data women reach their maximum velocity earlier than the men, between 40 and 60 m, with the medallists decelerating during the last 20 m; the others during the last 30 m. Therefore, it can be stated that the top female athletes reach their maximum speed area earlier and also leave this area earlier than the men. Data presented by Brüggemann and Glad (1990) is in good accordance with these findings. Taking into account that women need approximately 1 s more to cover the distance it can be concluded that the velocity development by time follows a similar pattern as for the men.

Figure 10 gives an individual comparison of velocities attained in 10 m intervals for Jones, Arron and Pintussevich. It can be seen that the medallists are very close in speed during the middle part of the race and that the differences are greater during the first 20 and the last 30 m of the run.

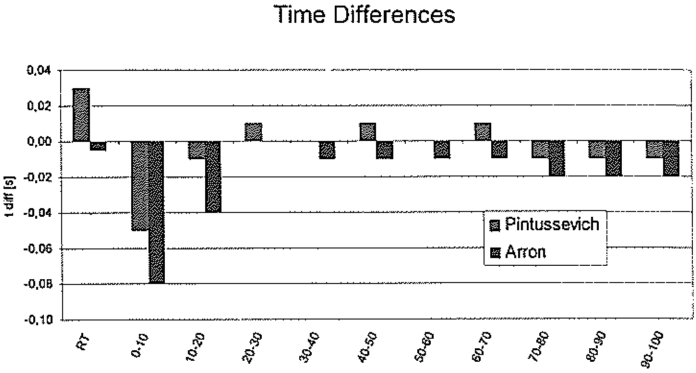

Figure 10: Individual comparison of interval times (Reference value: Jones; Bars: Actual differences of Pintussevitch and Arron; > 0: faster than reference value; < 0: slower than reference value).

Table 16: Velocities [m/s] at the end of intervals in the women's 100 m final.

	Jones	**Pintussevich**	**Arron**	**Miller**	**Paschke**	**Ottey**	**Mean**	**SD**
10m	8.22	8.12	7.92	7.95	8.00	8.10	8.052	0.115
20m	9.59	9.56	9.41	9.27	9.34	9.54	9.452	0.131
30m	10.16	10.26	10.08	9.75	9.84	10.12	10.035	0.197
40m	10.58	10.49	10.44	10.14	10.09	10.30	10.340	0.197
50m	10.59	10.66	10.46	10.27	10.24	10.46	10.447	0.168
60m	10.67	10.65	10.55	10.21	10.22	10.39	10.448	0.206
70m	10.63	10.51	10.36	10.11	10.14	10.09	10.307	0.229
80m	10.53	10.43	10.12	9.97	9.93	9.89	10.145	0.273
90m	10.38	10.23	10.00	9.83	9.86	9.25	9.925	0.394
100m	10.10	---	9.52	9.50	9.47	8.24	9.366	0.682

Note: Lanes 1 and 8 were excluded.

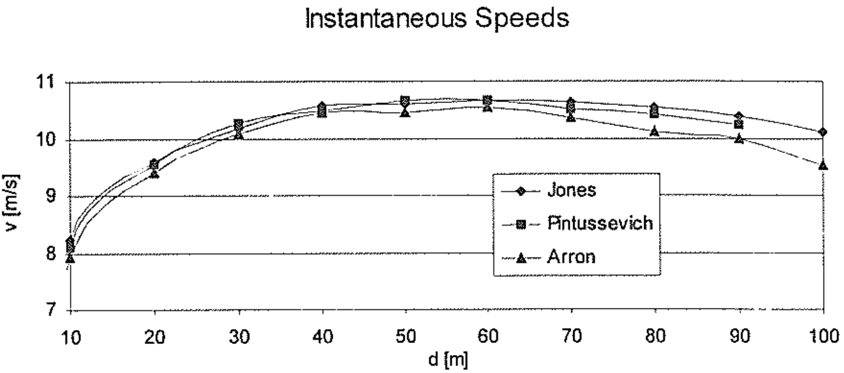

Figure 11: Comparison of velocities during the women's final for the three medallists.

Only the medallists achieve top speeds of more than 10.5 m/s and of more than 10 m/s in the finish. Ottey's extraordinary abilities are proved in the acceleration phase. But knowing she could not win the race she obviously gave in to defeat in the last phase. According to these findings a top result in the women's 100 m requires a velocity of more than 10.0 m/s at 30 m, a top speed of more than 10.5 m/s in the phase between 40 and 80 m and still more than 10 m/s in remaining 20 m. Compared to the men's final greater differences appear. These show an additional effect due to the longer running time. On the background of a relative stagnation in performance over the last 10 years it can be followed that a further increase in top speed of female top athletes is questionable. In the development of training concepts more stress has to be placed on the capacity to maintain the velocity on that high level. This might give some room to increase performance at the world class level.

Table 17 shows the maximum velocity and its location for the women's finalists. It was previously mentioned that maximum velocities are reached earlier than in the men's competition.

Table 17: Maximum speed and location of maximum speed.

Name	**v_{max} [m/s]**	**V_{max} at [m]**
Jones (USA)	10.68	58.8
Pintussevich (UKR)	10.72	54.1
Arron (FRA)	10.65	56.7
Miller (USA)	10.34	52.4
Paschke (GER)	10.29	55.0
Ottey (JAM)	10.47	45.4
Mean	10.525	53.73
SD	0.184	4.64

Arron's maximum velocity is very close to the medallists whilst the others fail to run faster than 10.5 m/s.

As demonstrated for the men's competition not only the absolute top speed but also the distance that can be covered at near maximum speed is of major interest. Results are given in table 18. The table demonstrates more clearly that the maximum speed area is reached earlier than in the male competition and that the interindividual differences are greater.

Table 18: Distances covered with more than 10.0 m/s and 10.5 m/s

	v > 10.0 m/s			**v > 10.5 m/s**		
Name	from [m]	till [m]	diff. [m]	from [m]	till [m]	diff. [m]
Jones (USA)	28.38	100.00	71.62	38.48	84.81	46.33
Pintussevich (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	---	---	---
Mean	29.617	86.547	56.930	43.423	73.973	30.550
SD	3.942	10.841	13.287	6.864	10.485	16.958

The results confirm the general findings from the men's competition. The longer the top speed area the better the result. It can again be seen that Ottey is the first to reach a speed over 10 m/s but obviously she already slowed down before half of the distance of the run was completed and therefore, didn't reach the 10.5 m/s mark. The medallists covered more than two thirds of the whole distance with a velocity of more than 10.0 m/s. Jones realised almost half of the distance with a velocity of more than 10.5 m/s and was faster than 10.0 m/s even at the finish line.

The data of 24 subjects from the whole competition was used to look at dependencies between values gathered for each interval and the race result. Table 19 summarises the calculated correlation coefficients.

Table 19: Correlation coefficients of the resulting times and maximum velocity with split times, instantaneous velocities and mean accelerations for N = 24 runs (S – 10 m = split time excluding RT; $r > |0.36|$ are significant at $p < 0.05$: *; $r > |0.50|$ are significant at $p < 0.01$: **).

Location	r_{speed}	Interval	$r_{Split\ time}$	$r_{Acceleration}$
10 m	-0.53 **	S – 10 m	-0.10	
20 m	-0.76 **	0 – 10 m	0.45 *	-0.56 **
30 m	-0.87 **	10 – 20 m	0.65 **	-0.50 **
40 m	-0.92 **	20 – 30 m	0.83 **	-0.22
50 m	-0.95 **	30 – 40 m	0.92 **	-0.23
60 m	-0.95 **	40 – 50 m	0.93 **	-0.45 *
70 m	-0.93 **	50 – 60 m	0.95 **	-0.12
80 m	-0.93 **	60 – 70 m	0.92 **	-0.36 *
90 m	-0.90 **	70 – 80 m	0.92 **	0.29
100 m	-0.74 **	80 – 90 m	0.91 **	0.27
(v_{max})	-0.94 **	90 – 100 m	0.85 **	0.34

The results resemble the findings found for the men. The RT does not show a correlation to the resulting time (r = -0.02). The fact that the maximum velocity area is entered earlier and also left earlier becomes obvious again. These observations are also represented by the correlation values showing the highest values at 40 to 60 m. This supports the notion that some potentials for increasing performance can be seen in the speed endurance. The stride length and frequency calculations from the video recordings are given in table 20.

Table 20: Average step length and frequency for the women's 100 m final, Athens, 1997 and Seoul, 1988.

	Step Frequency [1/s]				Step Length [m]			
Interval [m]	**0-30**	**30-60**	**60-100***	**0-100**	**0-30**	**30-60**	**60-100***	**0-100**
Jones	4.05	4.68	4.44	4.38	2.00	2.07	2.23	2.11
Pintussevich	4.47	4.68	4.63	4.59	1.76	2.07	2.19	2.01
Fynes	4.19	4.52	4.49	4.40	1.94	2.14	2.11	2.06
Arron	3.85	4.35	4.12	4.09	2.00	2.22	2.40	2.21
Miller	4.38	4.67	4.47	4.49	1.71	2.14	2.14	1.99
Paschke	4.49	4.52	4.70	4.58	1.71	2.14	2.03	1.95
Ottey	4.13	4.48	3.94	4.15	1.82	2.31	2.31	2.14
Gaines	4.39	4.83	4.38	4.51	1.67	2.07	2.16	1.96
Joyner (10.54)	4.35	4.68	4.58	4.52	1.69	2.29	2.40	2.10
Ashford (10.83)	4.48	4.93	4.79	4.69	1.61	2.13	2.19	1.97
Drechsler (10.85)	4.08	4.51	4.37	4.28	1.78	2.31	2.40	2.16

* Values for the competition in Seoul were determined for an interval reaching from 60 – 90 m.

The race in Seoul was extraordinarily fast. Regarding the maximum value for SF no difference can be discerned while in the first section it can be clearly seen that the medallists of 1988 demonstrate a higher frequency during the accelerations phase. This conforms with the shorter SL during the first 30 m. During the middle section Joyner, Ashford and Drechsler show a much longer SL which results in a greater speed. This might be influenced by the fact that these athletes show a greater body height. The figures 12 and 13 show a representation of SL and SF for the final women's 100 m run in Athens.

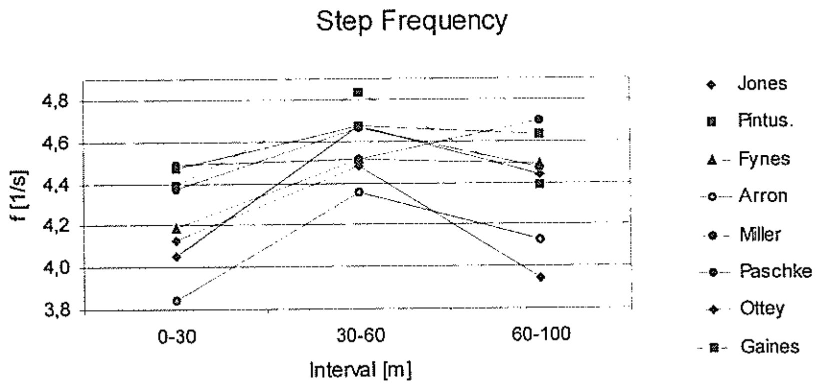

Figure 12: Average step frequency in the women's 100 m final.

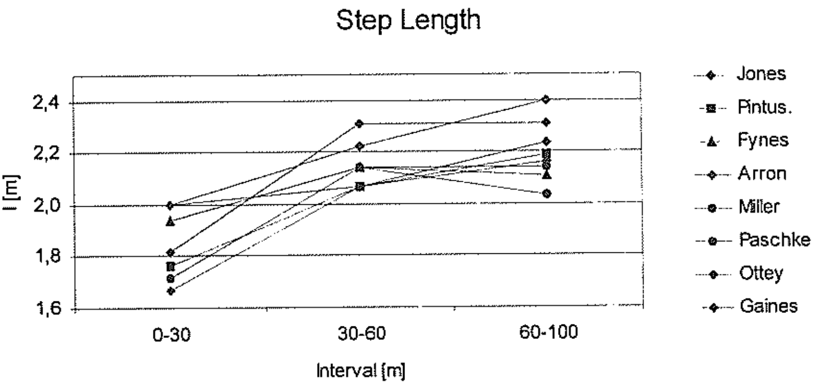

Figure 13: Average step length in the women's 100 m final.

The figures demonstrate a more uneven pattern for step frequency than for the men. Jones, Arron, Miller, Ottey and Gaines show a clear maximum in SF during the middle section while the remaining athletes keep on that level for the last interval. Ottey shows a dramatic decrease in step frequency while her step length remains unchanged from the second to the third section. Therefore, her decrease in velocity is a direct result of her changes in step frequency. As for the men, most runners increase or at least hold the level of their step length towards the finish. The only exception is Paschke who shows a decrease in stride length but an exceptional increase in step frequency.

Table 21: Kinematic parameters of three semi-finalists at 70 m from the start.

Parameter	**Pintussevich**	**Jones**	**Fynes**	**Mean**	**SD**
	11.10	**10.94**	**11.11**	**11.05**	**0.03**
γ_TD [°]	155.5	147.4	136.8	146.56	9.42
$\Delta\gamma$_TD [°]	7.6	12.6	4.7	8.31	3.98
$d\gamma/dt_{mean}$ [°/s]	201.6	253.3	117.2	190.67	68.68
$d\gamma/dt_{max}$ [°/s]	282.4	329.4	272.1	294.65	30.51
$d\beta/dt$_TD [°/s]	740.1	317.4	383.5	480.23	227.81
v_x Tip [m/s]	1.76	2.14	2.99	2.300	0.629
τ_TD [°]	83.6	76.3	75.7	78.51	4.40
δ_{min} [°]	14.1	16.0	17.0	15.72	1.46

Most of the kinematic values show a clear ranking according to the resulting time in the semi-final. Pintussevich shows the greatest knee angle but an average amount of knee bending during the stance phase. Although Fynes' parameters regarding the knee flexion lie in the same range Pintussevich demonstrates the by far fastest hip extension prior to TD. She shows the lowest forward velocity of the foot at TD while her trunk is more upright than for the other competitors. This could be due to the situation in the semi-final; at this point she already knew that she was qualified for the final and therefore, might have left the forward position that early.

Since the kinematic data is only available for three finalists at the 70 m mark in figures 14 and 15 the values from table 8 are used and compared to the mean values for the men at the 70 m mark.

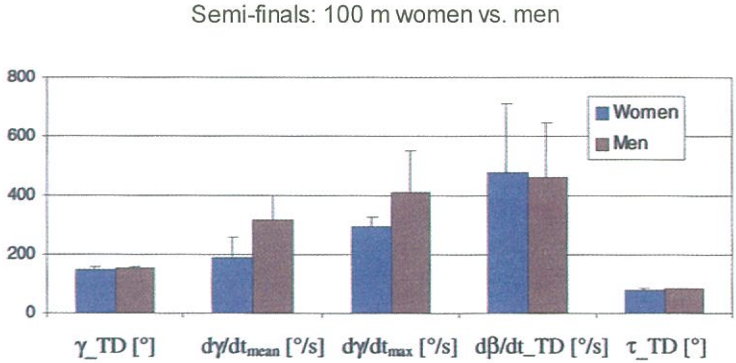

Figure 14: Comparison of kinematic parameters for men and women at the 70 m mark.

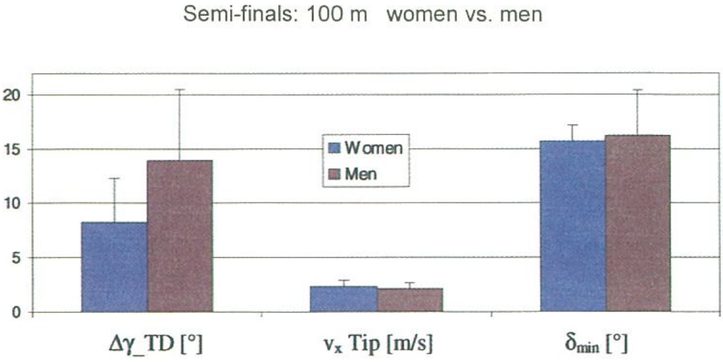

Figure 15: Comparison of kinematic parameters for men and women at the 70 m mark.

It becomes obvious that women and men show comparable knee angles at TD. Knee flexion appears considerably faster for the men while the women's data show a slightly more forward trunk position and a slightly faster hip extension velocity at touch-down. Figure 15 shows a greater knee bending for the men during ground contact which coincides with the greater flexion velocity during the stance phase. The SF data shows lower values (approximately 8 %) for the women in comparison to the men. Therefore, the higher knee flexion velocity is produced by a combination of increased step frequency and increased amount of knee flexion (tables 6 and 14). The forward velocities of the foot tip are similar, which means that the men due to their higher running speed are able to move their foot relatively faster backwards than the women. This can not be attributed to a difference in hip extension velocity.

It can be summarised that for elite female sprinters it is again the maintenance of maximum running speed over a long duration which is imperative to success in competitions. For the women it was shown that more room is given for performance increase due to improvements in speed endurance. This result stands in good accordance to Brüggemann and Glad (1990). Another hint at the possibility of improvement of sprinting performance in women is the fact that differences between athletes are greater than in the men's competitions. Training strategies should focus on the speed endurance capacities of female world class sprinters.

2.1.2 200 m

Men's 200 m

During the 200 m competitions the data collection via the laser system was possible only for some athletes since the view at the transition from the curve to the straight was covered by other runners. For the velocity analysis only the split times were used, therefore, average speeds were calculated. Table 22 shows the split times for the 50 m intervals.

Table 22: Split times [s] for the men's 200 m final.

Name	Result	RT	0-50 m	50-100 m	100-150 m	150-200 m
Boldon (TRI)	20.04	0.132	5.69	4.54	4.78	4.90
Fredericks (NAM)	20.23	0.127	5.66	4.62	4.82	5.00
Da Silva (BRA)	20.26	0.141	5.76	4.66	4.80	4.90
Garcia (CUB)	20.31	0.131	5.66	4.64	4.76	5.12
Panagiotopoulos (GRE)	20.32	0.115	5.73	4.64	4.82	5.02
Thompson (BAR)	20.37	0.184	5.75	4.56	4.80	5.08
Drummond (USA)	20.44	0.144	5.62	4.58	4.86	5.24
Stevens (BEL)	20.44	0.183	5.74	4.64	4.80	5.08
Mean	20.301	0.145	5.701	4.610	4.805	5.043
SD	0.130	0.026	0.051	0.044	0.030	0.114

Note: All split times are calculated without reaction time.

The results conform with earlier findings (Sušanka, 1989). The reaction times are slightly longer than in the 100 m runs. The fastest 50 m section for all finalists is the distance between 50 and 100 m. The top speeds are slower than in the 100 m sprint. Only the medallists are able to cover the last 50 m in less than 5.00 s. Table 23 sums up the split times for the 1st and 2nd 100 m interval.

Table 23: 100 m split times in the men's 200 m final.

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
Mean	10.311	9.848	-0.464
SD	0.076	0.130	0.175

Among the medallists gold winner 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 100 m. All medallists and some of the other finalists required less time to cover the 2nd half than the actual 100 m winning time. Bearing in mind that the 200 m runners already are at high speed when entering the straight, it is obvious that they are not running faster than in the 100 m sprint. Calculating the fastest average velocity from table 22 (Boldon, 2nd 50 m: 11.01 m/s) it can be concluded that the maximum velocity during a men's 200 m run is approximately 7 % slower than in a 100 m sprint. Drummond proved his qualities as a 100 m specialist with the fastest 1st section but showed a quite poor 2nd 100 m. Boldon precisely doubled his 100 m final result of 10.02 s while Fredericks lost 0.38 s compared with his double 100 m final result of 9.95 s. Although the calculation of velocities provides no new information the speeds are given in table 24 to allow for an overview of the velocities reached.

Table 24: Mean velocities [m/s] in the 50 m sections in the men's 200 m final. Difference of 4th and 2nd 50 m interval.

Name	0-50m	50-100m	100-150m	150-200m	Diff.
Boldon (TRI)	8.79	11.01	10.46	10.20	-0.81
Fredericks (NAM	8.83	10.82	10.37	10.00	-0.82
Da Silva (BRA)	8.68	10.73	10.42	10.20	-0.53
Garcia (CUB)	8.84	10.78	10.50	9.77	-1.01
Panagiotopoulos (GRE)	8.73	10.78	10.37	9.96	-0.82
Thompson (BAR)	8.70	10.96	10.42	9.84	-1.12
Drummond (USA)	8.90	10.92	10.29	9.54	-1.38
Stevens (BEL)	8.72	10.78	10.42	9.84	-0.94

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 100 m final the respective values are:

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

Both the 1st and the 2nd 50 m are markedly slower than in the 100 m final. For the 200 m dashes the average step frequency and step length were determined in the same manner as for the 100 m analysis. The same intervals were used for the last 100 m while for the first 100 m only the total averages was calculated.

The differences between the fastest and the last section shows a clear trend of the medallists being able to maintain a higher speed towards the end.

Table 25: Step length and step frequency for the 200 m men's final.

	Step Frequency [1/s]					Step Length [m]				
Interval [m]	**0-100**	**100-130**	**130-160**	**160-200**	**0-200**	**0-100**	**100-130**	**130-160**	**160-200**	**0-200**
Boldon	4.45	4.46	4.50	4.17	4.40	2.20	2.59	2.22	2.26	2.27
Fredericks	4.62	4.42	4.67	4.18	4.51	2.08	2.61	2.14	2.26	2.19
Da Silva	4.33	4.23	4.33	3.97	4.24	2.20	2.73	2.31	2.42	2.33
Garcia	4.57	4.80	4.52	4.28	4.53	2.08	2.50	2.14	2.22	2.17
Panagi.	4.57	4.62	4.50	4.19	4.49	2.08	2.50	2.22	2.26	2.19
Thomp.	4.24	4.40	4.00	3.96	4.16	2.25	2.73	2.50	2.31	2.36
Drumm.	4.66	4.62	4.50	4.18	4.52	2.11	2.50	2.22	2.06	2.16
Stevens	4.48	4.46	4.31	4.08	4.37	2.11	2.40	2.40	2.37	2.24
Mean	4.490	4.501	4.416	4.126	4.403	2.139	2.570	2.269	2.270	2.239
SD	0.146	0.174	0.203	0.113	0.139	0.067	0.118	0.127	0.108	0.075

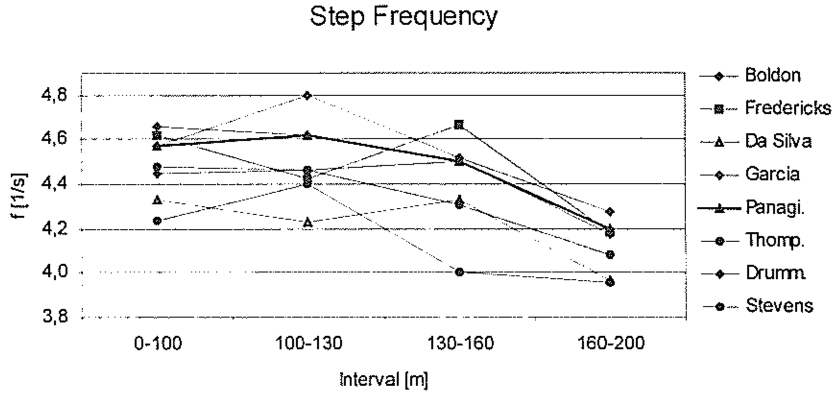

Figure 16: Step frequency of the men's 200 m final.

Three different patterns can be derived from the graphical representation of SF. Garcia and Thompson increase their SF during the 100-130 m section and show a more or less pronounced decrease during the last two sections. Fredericks and Da Silva demonstrate an opposite trend. Their SF reaches a maximum during the 130-160 m section and increases more pronouncedly than for Garcia and Thompson. The rest of the field can be characterised by more evenly distributed values. The highest values are produced and maintained during the first 130 m followed by a moderate decrease during the last two sections.

Regarding the SL development two distinct patterns can be seen. All finalists show a clear maximum during the 100-130 m section. From there on Thompson, Drummond and Stevens demonstrate a continuous decrease while all other runners increase their SL again during the final section. It can be discerned that the groupings according to SL or SF do not correspond to each other.

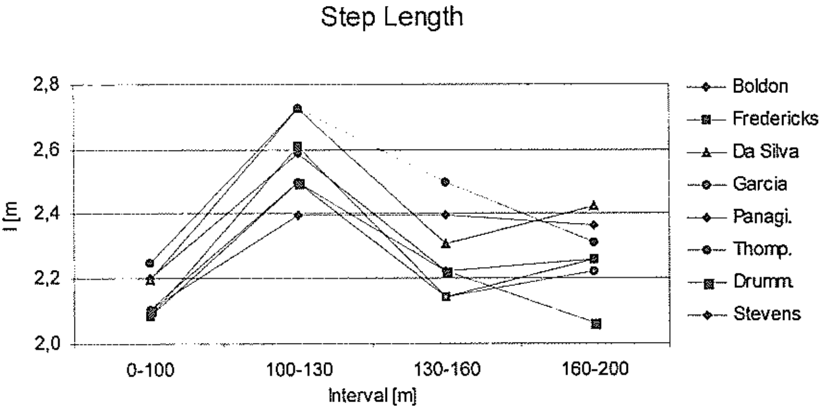

Figure 17: Step length of the men's 200 m final.

Figures 16 and 17 show that the medallists on the one hand belong to the group which produces the highest step frequencies and length while the third placed runner and Thompson demonstrate the absolute greatest step length. Therefore, no general pattern can be described.

Since the data from the finals in 1988 (Brüggemann & Glad, 1990) do not relate to the same intervals which were analysed here only the number of steps is compared in table 26 (which represents the inverse of SL). It can be seen that the medallists from 1988 demonstrate longer steps. Their average step frequency shows only a few slight differences to first three of the Athens' final and remains remarkably constant throughout the race. Since the race in Seoul was quite faster it can be assumed that to reach an extraordinary performance in the 200 m sprint a large step length might provide some advantage as long as the step frequency can be maintained. When comparing the rest of the field it can be observed that e.g. Thompson shows a comparable step length to the 1988 medallists though his step frequency is not sufficient to reach a comparable result.

Table 26: Number of steps in 200 m finals at WC Rome, 1987 and 1997, and at OG Seoul, 1988.

	No. of Steps [-]			**Step Frequency [1/s**		
Name	**0-100m**	**100-200m**	**0-200m**	**0-100m**	**100-200m**	**0-200m**
Boldon	45.4	42.8	88.2	4.45	4.35	4.40
Fredericks	48.0	43.2	91.2	4.62	4.39	4.51
Da Silva	45.5	40.5	86.0	4.33	4.15	4.24
Garcia	48.0	44.0	92.0	4.57	4.49	4.53
Panagiotopoulos	48.0	43.2	91.2	4.57	4.40	4.49
Thompson	44.5	40.3	84.8	4.24	4.08	4.16
Drummond	47.5	44.9	92.4	4.66	4.38	4.52
Stevens	47.5	41.9	89.4	4.48	4.26	4.37
Deloach (1988, 19.75)	44.9	40.7	85.6	4.34	4.33	4.33
Lewis (1988, 19.79)	44.1	40.3	84.4	4.28	4.25	4.26
Silva (1988, 20.04)	45.0	41.8	86.8	4.32	4.34	4.33

The data for the step frequency demonstrate a very diverse pattern of development throughout the race. This could be due to the fact that the longer run time compared to the 100 m final permits more tactical adjustments in speed. Summarising the SL and SF data, both parameters are markedly lower than for the 100 m sprint. It can generally be concluded that the data indicates a greater importance of step length and maintaining a sufficient step frequency for the 200 m run than in the 100 m sprint.

Womens's 200 m

In the following section the data from the women's 200 m final will be presented. Table 27 shows the split times for the 50 m intervals.

Table 27: Split times in the 200 m women's final.

Name	Result	RT	0-50m	50-100m	100-150m	150-200m
Pintussevich (UKR)	22.32	0.124	6.00	5.04	5.32	5.84
Jayasinghe (SRI)	22.39	0.181	6.05	5.02	5.32	5.82
Ottey (JAM)	22.40	0.146	5.99	5.00	5.24	6.02
Leshchova (RUS)	22.50	0.149	6.21	5.10	5.40	5.64
Miller (USA)	22.52	0.143	6.08	5.04	5.36	5.90
Trandenkova (RUS)	22.65	0.138	6.25	5.14	5.36	5.76
Gainsford-Taylor (AUS)	22.73	0.150	6.24	5.06	5.38	5.90
Felix (FRA)	22.81	0.157	6.37	5.20	5.36	5.72
Mean	22.540	0.149	6.149	5.075	5.343	5.825
SD	0.175	0.016	0.138	0.067	0.049	0.119

Note: All split times are calculated without reaction time.

Confirming the men's findings the fastest interval is the 2nd 50 m, Ottey showed the best split times till 150 m but had an extremely poor finish. As in the 100 m final women's reaction times are somewhat longer than men's results. Jayasinghe lost 6 of her 7/100 s to Pintussevich in her weak reaction time. Table 28 sums up the split times for the 1st and 2nd 100 m interval.

Table 28: 100 m split times [s] in the women's 200 m final.

Name	1st 100m	2nd 100m	Difference
Pintussevich (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
Mean	11.224	11.168	-0.056
SD	0.201	0.090	0.260

The results presented in this table are quite different from the men's. While the men's 2nd 100 m were about 0.50 s faster than the 1st 100m (except for Drummond) there is no obvious tendency in the women's data. The medallists and Miller are very fast in the 1st 100 m but markedly slower in the 2nd half. Felix at the extreme opposite end starts very slow with an extraordinary 2nd 100 m interval. These trends can be verified by the calculated velocities which are given in table 29.

Table 29: Mean velocities [m/s] in the 50 m sections in the women's 200 m final; as calculated for the men.

Name	0-50m	50-100m	100-150m	150-200m	Difference
Pintussevich (UKR)	8.34	9.92	9.40	8.56	-1.36
Jayasinghe (SRI)	8.27	9.96	9.40	8.59	-1.37
Ottey (JAM)	8.34	10.00	9.54	8.31	-1.69
Leshchova (RUS)	8.05	9.80	9.26	8.87	-0.93
Miller (USA)	8.23	9.92	9.33	8.47	-1.45
Trandenkova (RUS)	8.00	9.73	9.33	8.68	-1.05
Gainsford-Taylor (AUS)	8.01	9.88	9.29	8.47	-1.41
Felix (FRA)	7.85	9.62	9.33	8.74	-0.88

Ottey showed the fastest 50 m interval with a mean velocity of 10.0 m/s but is the slowest finalist in the finish. Both Russian sprinters demonstrate good speed endurance abilities with a fast last interval. Reference values for comparison with the 100 m final are given below:

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

In the following speed endurance will be factorised by the relation between the fastest (2nd) 50 m interval and the final interval. There is not such a clear dependency as the men's data suggested. Looking at the average over each final run, from the men's data (section 3.3) a decrease in speed of 8.5 % in time can be calculated. For the women the velocity during the ultimate interval is 13 % lower demonstrating clearly the poorer speed endurance capabilities of the female 200 m sprinters. This trend was already indicated by the 100 m data. There may be a considerable potential for mobilising these capacities by varied training strategies.

As shown for the men's final the step frequencies and step lengths were calculated for the women. The results are listed in table 30 and graphically presented in figures 18 and 19.

Table 30: Step frequency and step length in the women's 200 m final.

	Step Frequency [1/s]					Step Length [m]				
Interval [m]	**0-100**	**100-130**	**130-160**	**160-200**	**0-200**	**0-100**	**100-130**	**130-160**	**160-200**	**0-200**
Pintussevich	4.59	4.48	4.09	3.98	4.37	1.96	2.31	2.22	2.00	2.05
Jayasinghe	4.34	4.46	4.24	3.91	4.24	2.04	2.40	2.14	2.05	2.11
Ottey	4.37	4.64	4.09	3.85	4.24	2.06	2.31	2.22	2.00	2.11
Leshchova	4.26	4.31	4.22	3.92	4.19	2.04	2.40	2.22	2.08	2.12
Miller	4.39	4.46	4.39	4.02	4.32	2.00	2.40	2.07	1.98	2.06
Trandenkova	4.48	4.81	4.39	4.17	4.44	1.94	2.31	2.07	1.86	1.99
Gainsford	4.30	4.26	4.09	3.77	4.14	2.02	2.61	2.22	2.03	2.12
Felix	-	-	-	-	-	-	-	-	-	-
Mean	4.390	4.489	4.216	3.946	4.277	2.009	2.391	2.166	2.000	2.080
SD	0.113	0.188	0.135	0.128	0.105	0.045	0.106	0.072	0.070	0.049

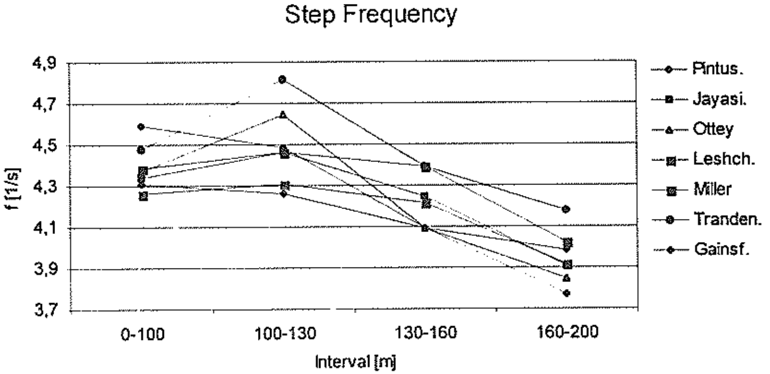

Figure 18: Step Frequency during the women's 200 m final.

It becomes obvious that these parameters develop in a different way to those of the men. A general and significant decrease during the last two sections takes place for all athletes. On average there is a slight increase of the SF during the 100-130 m section. When looking at the step length a similar pattern becomes discernible, showing a pronounced maximum for this section. This indicates an overall gain in SL after leaving the curve. Taking into account the data presented before it can be followed that the men show a comparable decrease in stride frequency but many of them are able to increase the step length during the finish to compensate in some way for the frequency decrease and, therefore, demonstrate better speed endurance.

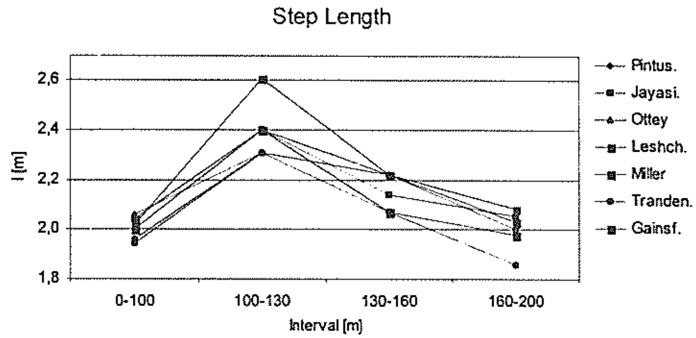

Figure 19: Step length during the women's 200 m final.

The number of steps and the according step frequencies were calculated and compared to the data presented by Sušanka et al. (1989). The values are presented below in table 31.

Table 31: Number of steps and step frequency at the WC Rome, 1997, and OG Seoul, 1988, 200 m women's final.

	No. of Steps [-]			**Step Frequency [1/s]**		
Name	**0-100m**	**100-200m**	**0-200m**	**0-100m**	**100-200m**	**0-200m**
Pintussevich (UKR)	51.0	46.5	97.5	4.59	4.14	4.37
Jayasinghe (SRI)	49.0	46.0	95.0	4.34	4.15	4.24
Ottey (JAM)	48.5	46.5	95.0	4.37	4.12	4.24
Leshchova (RUS)	49.0	45.2	94.2	4.26	4.11	4.19
Miller (USA)	50.0	47.2	97.2	4.39	4.24	4.32
Trandenkova (RUS)	51.5	49.0	100.5	4.48	4.39	4.44
Gainsford-Taylor (AUS)	49.5	44.7	94.2	4.30	3.98	4.14
Joyner (1988, 21.34)	49.0	42.8	91.8	4.38	4.21	4.30
Jackson (1988, 21.72)	43.5	39.8	83.3	3.84	3.83	3.84
Drechsler (1988, 21.95)	46.9	42.6	89.5	4.13	4.02	4.08

The conjecture that the step length might be a crucial factor in the 200 m event receives additional support by the numbers given in table 31. Again the Seoul race is much faster than the Athens' final. Comparing the three medallists a great difference during the 2nd 100 m is obvious. While the step frequency is comparable a clear difference can be seen for the step length which was much greater for the Seoul medallists. It can be speculated that this was a direct effect of the greater body height of the medallists of Seoul.

It has to be kept in mind that a definite reason for those variations could not be given by the presented data. The joint kinematics were examined to identify possible mechanisms which might lead to the differences in performance.

The kinematics of the women's semi-finals are presented in table 32. Pintussevich is the only female athlete participating in the 100 m and 200 m sprint. An individual comparison of kinematic parameters from both disciplines is presented in figures 20 and 21.

Table 32: Kinematic parameters of four semi-finalists at 170 m.

Parameter	**Miller**	**Pintus.**	**Ottey**	**Jayasi.**	**Mean**	**SD**
	22.59	**22.65**	**22.26**	**22.33**	**22.458**	**0.111**
γ_TD [°]	146.8	164.3	155.7	158.5	156.32	7.30
$\Delta\gamma$_TD [°]	2.4	14.0	9.3	8.7	8.60	4.77
$d\gamma/dt_{mean}$ [°/s]	73.9	224.8	173.9	132.6	151.33	63.92
$d\gamma/dt_{max}$ [°/s]	104.9	353.8	267.8	352.6	269.77	117.07
$d\beta/dt$_TD [°/s]	974.4	512.0	289.1	461.9	559.25	292.72
v_x Tip [m/s]	1.03	1.09	1.18	1.56	1.218	0.239
τ_TD [°]	82.0	90.1	92.2	86.8	87.77	4.48
δ_{min} [°]	19.6	19.8	19.3	24.8	20.90	2.63

Pintussevich who shows a slower time in this table is the one with the straightest knee at TD. It can be speculated that this is a technical factor which in the final enabled her to win. The fact that her knee flexion angle is greatest also leads to high values for the flexion velocity. The highest value for hip extension velocity is demonstrated by Miller. For the TD velocity of the foot tip and trunk angle no clear connection with the resulting time becomes obvious. The maximum knee lift also does not show any particular trends.

Compared to the other kinematic results it becomes very difficult to identify any general relationship.

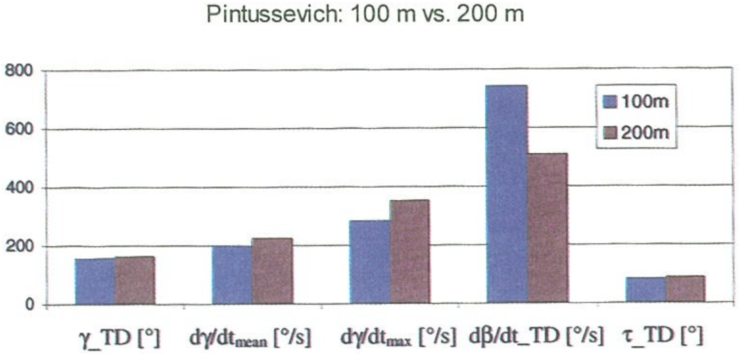

Figure 20: Individual Comparison of kinematic data for Pintussevich.

As for Pintussevich who participated in both, the 100 m and 200 m final, video data for these events were obtained. It can be clearly seen that only minimum differences occur for the knee angle at TD. Flexion of the knee during ground contact is reduced for the 100 m run which shows also an effect for the flexion velocity. A much greater value is demonstrated for the hip extension prior to TD which reflects the higher step frequency for the 100 m. The trunk angle at touch-down is slightly greater during the 200 m run indicating a more upright body position.

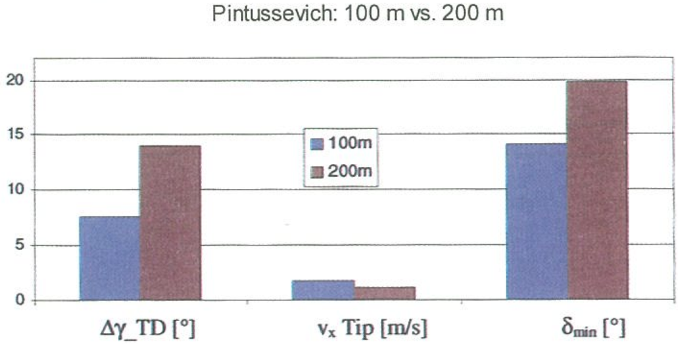

Figure 21: Individual Comparison for Pintussevich.

The horizontal velocity of the foot at TD is slightly lower for the 200 m sprint. Maximum knee lift and the amount of knee flexion during ground contact are greater for the longer race.

It can be summarised that for the women it seems important to maintain a sufficient step length for succeeding in 200 m sprinting competitions. No new information could be derived from the kinematic data. The individual comparison of Pintussevich for the 100 and 200 m provides us with some interesting findings. But no general results can be identified which enlarges our understanding of sprinting mechanics.

2.1.3 400 m

Men's 400 m

Table 33 shows the split times for the 50 m intervals for the men's 400 m final.

Table 33: Results, RT and 50 m split times [s] in the men's 400 m final.

Interval [m]	**Result**	**RT**	**0-50**	**50-100**	**100-150**	**150-200**	**200-250**	**250-300**	**300-350**	**350-400**
Johnson (USA)	44.12	0.167	6.01	4.98	5.20	5.28	5.28	5.40	5.66	6.14
Kamoga (UGA)	44.37	0.216	6.23	5.04	5.04	5.02	5.24	5.46	5.78	6.34
Washington (USA)	44.39	0.161	6.07	5.00	5.10	5.30	5.46	5.40	5.80	6.10
Richardson (GBR)	44.47	0.245	5.91	4.98	5.20	5.24	5.38	5.54	5.72	6.26
Young (USA)	44.51	0.185	6.16	5.00	5.08	5.08	5.40	5.48	5.86	6.26
Thomas (GBR)	44.52	0.165	5.72	5.02	4.94	5.16	5.40	5.68	5.98	6.46
Pettigrew (USA)	44.57	0.275	6.30	4.96	5.18	5.28	5.28	5.50	5.72	6.08
Baulch (GBR)	45.22	0.158	6.08	4.88	5.00	5.20	5.46	5.84	6.00	6.60
Mean	44.521	0.197	6.060	4.983	5.093	5.195	5.363	5.538	5.815	6.280
SD	0.315	0.044	0.184	0.048	0.097	0.102	0.085	0.151	0.124	0.182

Note: All split times are calculated without reaction time.

Although the prolongation of reaction times with increasing distance is well known, reaction times of markedly more than 200 ms are insufficient. Richardson for example lost all his 8/100 s to Washington in the reaction time. Pettigrew would have placed 4th with a reaction time of 160 ms. The adjustment of the race may be better described by summing up the 50 m intervals to four quarters of 100 m each. Table 34 gives the summed times and also the results from the 1987 and 1988 medallists.

Table 34: 100 m and 200 m split times in the 400 m men's final.

Name	**0-100**	**100-200**	**200-300**	**300-400**	**1st 200**	**2nd 200**	**Diff.**
Johnson (USA)	10.99	10.48	10.68	11.80	21.47	22.48	1.01
Kamoga (UGA)	11.27	10.06	10.70	12.12	21.33	22.82	1.49
Washington (USA)	11.07	10.40	10.86	11.90	21.47	22.76	1.29
Richardson (GBR)	10.89	10.44	10.92	11.98	21.33	22.90	1.58
Young (USA)	11.17	10.16	10.88	12.12	21.33	23.00	1.68
Thomas (GBR)	10.74	10.10	11.08	12.44	20.84	23.52	2.69
Pettigrew (USA)	11.26	10.46	10.78	11.80	21.72	22.58	0.86
Baulch (GBR)	10.96	10.20	11.30	12.60	21.16	23.90	2.74
Mean	11.044	10.288	10.900	12.095	21.331	22.995	1.668
SD	0.185	0.175	0.206	0.293	0.256	0.482	0.703
Schönlebe (87, 44.33)	11.11	10.29	11.04	11.89	21.4	22.93	1.53
Egbunike (87, 44.56)	10.91	10.23	11.18	11.89	21.14	23.42	2.28
Reynolds (87, 44.9)	11.22	10.49	11.03	12.06	21.71	23.009	1.30
Lewis (88, 43.87)	11.26	10.15	10.72	11.74	21.41	22.46	1.05
Reynolds (88, 43.93)	11.29	10.39	10.9	11.35	21.68	22.25	0.57
Everett (88, 44.09)	11.03	10.34	10.81	11.91	21.37	22.72	1.35

Johnson demonstrated the best adjustment of the race losing only 1.01 s in the 2nd half. Pettigrew's loss is, however, less but this result is due to a rather slow 1st 200 m. Kamoga's decrease of 1.49 s must be judged by his very fast 1st half, especially the 2nd 100 m section. The British finalists Thomas and Baulch obviously started too fast and thus lost more than 2.5 s in the 2nd part.

As in the 200 m final velocities can be calculated from the split times and are given in table 35.

Table 35: Average speeds [m/s] in the 400 m men's final.

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

The greatest average speeds are slightly higher than 10 m/s. The mean velocity in the last 50 m interval varies by 0.64 m/s between the finalists. The relevance of a balanced race adjustment is also illustrated by the following:

Despite his winning performance there is only one section (300 – 350 m) where Johnson was the fastest sprinter in this final. Silver medallist Kamoga is the only finalist who in no section reached a maximum mean velocity of 10.0 m/s.

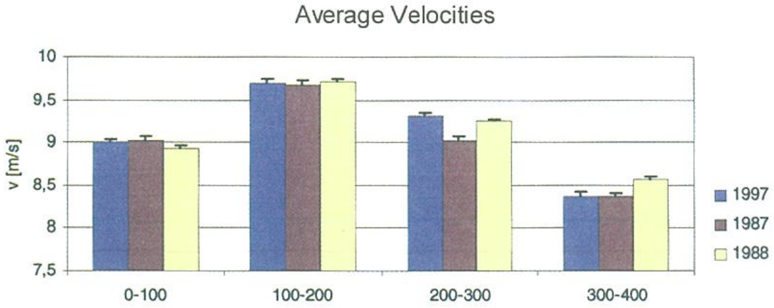

Figure 22: Average velocity of the three medallists in the 400 m men's final (1997: WC Athens, 1987: WC Rome, 1988: OG Seoul).

Figure 22 compares the average velocities of the medallists in the 100 m sections to former competitions. It can be clearly seen that the Seoul final was mainly the fastest heat because of the better speed endurance shown by the first three runners. The velocities for the first three intervals are very similar when comparing 1988 and 1997. For all three finals the first two sections show only minimal variations. It can be said that in the 1987 the wilting takes place already in the third section while in the Athens final it happens on the final straight. A possible training implication can be seen in concentrating on speed endurance on the elite level. The balance of the race was quantified by calculating the time difference between slowest an fastest section:

Johnson	1.90 s	Young	2.01 s
Kamoga	2.03 s	Thomas	2.38 s
Washington	1.80 s	Pettigrew	1.86 s
Richardson	2.05 s	Baulch	2.67 s

The average value is 2.09; the table shows a slight tendency that a small difference meaning a well balanced race might be of advantage.

Women's 400 m

Table 36 shows the split times for the 50 m intervals.

Table 36: Results, RT, 50 m split times in the women's 400 m final.

Name	Result	RT	0-50	50-100	100-150	150-200	200-250	250-300	300-350	350-400
Freeman	49.77	0.226	6.54	5.72	5.64	5.80	6.00	6.20	6.60	7.04
Richard	49.79	0.167	6.50	5.56	5.76	5.88	6.08	6.24	6.60	7.00
Miles-Clark	49.90	0.143	6.67	5.56	5.56	5.96	6.08	6.24	6.60	7.08
Breuer	50.06	0.143	6.44	5.48	5.24	6.36	6.20	6.40	6.64	7.16
Ogunkoya	50.27	0.126	6.58	5.72	5.64	5.76	6.08	6.20	6.76	7.40
Fuchsova	50.66	0.159	6.62	5.56	5.52	5.96	6.24	6.48	6.76	7.36
Davis	50.68	0.127	6.58	5.72	5.88	6.00	6.20	6.41	6.60	7.16
Alekseyeva	51.37	0.167	6.48	5.76	5.40	5.84	6.24	6.56	6.96	7.96
Mean	50.313	0.157	6.551	5.635	5.580	5.945	6.140	6.341	6.690	7.270
SD	0.558	0.032	0.076	0.106	0.201	0.188	0.091	0.139	0.130	0.313

Note: All split times are calculated without reaction time.

In contrast to the men's findings reaction times are quite fast in the women except gold medallist Freeman. At first glance there is no outstanding result, only Breuer's 100-150 m section is extremely fast compared with the other finalists.

The adjustment of the race may be better described by summing up the 50 m intervals.

Table 37: 100 m and 200 m split times in the 400 m women's final at the WC Athens, 1997, Rome, 1987, and the OG Seoul, 1988.

Name	Result	0-100	100-200	200-300	300-400	1st 200	2nd 200	Diff.
Freeman (AUS)	49.77	12.26	11.44	12.20	13.64	23.70	25.84	2.14
Richard (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
Mean	50.313	12.186	11.525	12.481	13.960	23.713	26.441	2.729
SD	0.558	0.133	0.189	0.227	0.441	0.212	0.613	0.722
Bryzgina (87)	49.38	12.34	11.48	12.33	13.23	23.82	25.56	1.74
Müller (87)	49.94	12.2	11.44	12.43	13.87	23.64	26.3	2.66
Emmelmann (87)	50.2	12.21	11.54	12.6	13.35	23.75	25.95	2.2
Bryzgina (88)	48.65	11.94	11.47	12.06	13.18	23.41	25.24	1.83
Müller (88)	49.45	12.33	11.77	12.24	13.11	24.1	25.35	1.25
Nazarova (88)	49.9	12.15	11.44	12.19	14.12	23.59	26.31	2.72

Except for Davis the rank order is almost identical with the loss in the 2nd 200 metres. Alekseyeva with the dramatic loss of 4.24 s undoubtedly was too fast in the beginning with the fastest 1st 200 metres of all finalists. The calculated velocities are given in Table 38.

Table 38: Average speeds [m/s] in the women's 400 m final.

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

Maximum average speeds of more than 9 m/s are shown by Breuer between 50 and 150 metres, followed by a quite slow next 50 m section. Fuchsova and Alekseyeva also demonstrated a similar pattern. Only the medallists' velocity in the last 50 m section is faster than 7 m/s. The relevance of a balanced race adjustment is illustrated by the following data:

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

The values are calculated as the difference, measured in seconds, between the fastest and the slowest 50 m section; the overall average is given with 2.15 s. The trend is not perfect but obvious. A smaller variation of the speeds indicates a better result. Especially Breuer's result indicates an insufficient race adjustment. Compared to the men's data the women show a greater difference between the first and second half of the race in absolute terms but relating the calculated mean to the different speed of the particular race the values are:

Men: 10.3% Women: 9.6%

Therefore, it can be followed that the women show a slightly better balance in their speed development in the 400 m final.

The comparison of the average velocities from the medallists of WC 1987, OG Seoul 1988 and the WC 1997 is plotted in figure 23. It can be seen that the race in Seoul was faster mainly due to the higher speed in the second curve. The race of the current WC was the worst regarding speed endurance.

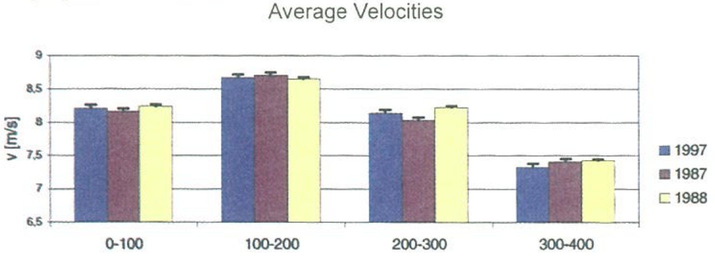

Figure 23: Average velocity of the three medallists in the 400 m women's final (1997: WC Athens, 1987: WC Rome, 1988: OG Seoul).

Figure 24 shows average velocities for the 50 m intervals for the first three athletes of the men's and the women's final in Athens in comparison. It can be depicted that the pronounced decrease during the last section is the reason for the lower endurance value in men. Without changing the maximum speed there should be some room for performance enhancements by a better speed adjustment. On the other hand mental factors may play a role so that changes cannot be invented without respect to tactical considerations.

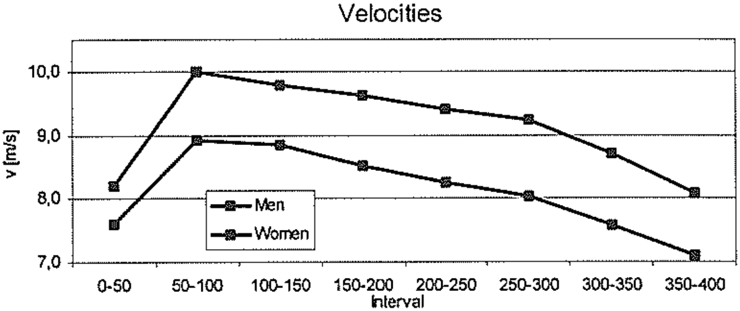

Figure 24: Average velocity of the three male and female medallists in the 400 m finals of the WC Athens, 1997.

Summary

The comparison of the resulting times of the sprint events in Athens with former competitions clearly demonstrates that a relative stagnation in performance during the last 10 years can be depicted. The investigation of speed development and basic kinematic factors i.e. step length or step frequency does not show any particular development throughout the recent years. Moreover these parameters seem to be influenced by individual anthropometrical dimensions to a great extent. Mechanical adjustments like joint stiffness seem to provide possible explanations for differences in performance. Research should be focussed on these factors and their role in newly designed training concepts. Mechanically it seems to be likely that for all disciplines except the men's 100 m sprint a further improvement by changes in race adjustment or speed endurance are possible. The question to what extent physiological limitations i.e. the central nervous must be considered cannot be answered based on the presented data.

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2.1.4 110 and 100m Hurdles

H. Hommel, D. Koszewski

History

The 120 y hurdles was part of the Olympic program from the beginning in Athens 1896 because this discipline had been a championship event of the English Amateur Athletic Association (AAA) since 1880. It is, however, still unclear whether the corresponding event in Athens was a 110 m or 100 m hurdles run. Apparently there were only eight hurdles on the track although 10 hurdles were actually standard and are still standard today.

The first reported time was recorded in 1859 when Philip Norman (GBR) covered the 120 y hurdle distance at Eton in 18.0 s. Since the mid 1860's the hurdles in England were 3.5 foot (approximately 106 cm) high - the standard height of an English sheep fence. This height was standardized for hurdle events in 1860. These hurdles which consisted of planks were solidly anchored in the ground in the same manner as the obstacles in equestrian cross country events. Originally they therefore, had to be cleared rather than run through in order to avoid dangerous falls. The first Olympic champion in Athens, 1896 was Thomas Curtis (USA) in 17.6 s. Four years later Alvin Kraenzlein (USA) already ran 15.4 s. Over the corresponding yard distance he held the world record of 15.2 s. Forest Smithson (USA) who won at the 1908 London Olympic Games in the record time of 15.0 s was known for his improvement of the hurdle technique. He had the unusual technique of running with a book in one hand and was convinced this improved his technique. Subsequently transportable hurdles with perpendicular stands on **either** side were used; a sort of upside down T-model. Improvements of the world record often failed because athletes tore one hurdle. Olympic titles were awarded for this but world records were only valid if **all** hurdles were left standing. Times under 15.0 s did not appear until after the first world war; Earl Thomson (CAN) was Olympic champion in Antwerp in 1920 with a time of 14.8 s.

In the early 30's the American coach Harry Hillman developed the L-model for hurdles with an adjustable weight and height hurdle foot which did not permit the hurdle to fall until a force of eight pounds energy was applied. Anyone who tore more than two hurdles was disqualified until 1935. In that year the IAAF made these hurdles compulsory and modified the rules correspondingly so that hurdles could be torn in records as well. It had been recognized that tearing a hurdle did not improve the time. The 110 m hurdle event was dominated by US-Americans with a few exceptions and these still constitute many Olympic champions today. Forrest Towns, the Olympic champion of Berlin in 1936 was the first to break 14.0 s when he achieved 13.7 s in Oslo on the 27.8.1936. The last world record stopped by hand was 13.0 s by Guy Drut (FRA) in Berlin on the 22.8.1975 who was also Olympic champion in Montreal a year later. The records became a bit „slower“ again with the advent of electronic timing. With 12.93 s Renaldo Nehemiah (USA) finally broke the 13.0 s barrier in Zurich on the 19.8.1981. The present world record is held by Colin Jackson (GBR) who became world champion in 12.91 s in Stuttgart on the 20.8.1993.

Women started running hurdles over 80 m after the Fédération Sportive Féminine Internationale (FSFI) had been founded. The FSFI acknowledged the first world record after Eva von Bredow (GER) ran $12^4/_5$ s in Berlin on the 12.6.1927. This short hurdle event was included in the 1932 Olympic program as a substitute for the 800 m run which was regarded as too unfeminine. The multi-talented „Babe“ Didriksen (USA) was the first Olympic champion in a world record time of 11.7 s. The 10.9 s run by Shirley Strickland-de la Hunty (AUS) at the Olympic Games in Helsinki in 1952 was the first time a woman ran under 11.0 s. The world record was improved in $^1/_{10}$ s intervals over the next 16 years until Vera Korsakova (URS) ran 10.2 s on the 10.6.1968. This record can no longer be broken. Time improvements could hardly be achieved because physical acceleration also led to women becoming larger and the distances between hurdles became too small.

The discipline stagnated despite the small hurdle height of 76 cm. After numerous trials the IAAF therefore, removed this problem by officially introducing the 100 m hurdles with 84 cm hurdles for women in 1969. The first world record over the new distance was set be Karin Balzer (GDR) who ran a time of 13.3 s in Warsaw on the 20.6.1969. A year later she already broke the 13 second barrier with a time of 12.9 s in Berlin on the 5.9.1970. The last hand stopped world record of 12.3 s was set by Annelie Ehrhardt (GDR) in 1973. Yordanka Donkova (BUL) possesses the present world record of 12.21 s set on the 20.8.1988 in the same year she won the Olympic title in Seoul. Increased controls have led to a performance decrease since then. Ludmilla Engquvist (SWE) therefore, won the Olympic title in Atlanta, 1996 in a time of 12.58 s.

Methods and procedures

Data from the 110m hurdles final was 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 was 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 to 10) and touch down after the 10th hurdle to run-in (11)]. Apart from the men's instantaneous velocities (Table 39) 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 is transferred to standard diagrams.

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 (φ 0.30s) and a final velocity increase at the run-in, cf. Figure 25/ 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 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 27/Dimitrova).

Men's winner Johnson (Figure 25) 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 25) ran a good constant race but with a lower level of top speed (9.14m/s from tH3 to tH7). Kovac (rank 3) (cf. Figure 25) ran until hurdle 8 behind Schwarthoff (cf. Figure 26) 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 42). His race was constant with the shortest hurdle clearing times (0.28-0.32s) among the finalists (cf. Table 41). Outstanding reaction times (cf. Table 40) were achieved by Rees (0.117s) Jackson and Philibert (0.118s).

In the women's final Gold medallist Engquist (Figure 27) reached the highest speed between hurdle 4 and 5 (9.04s) whilst second placed Dimitrova (Figure 27) realized only 8.85s but had more constant intervals except at tH10 because of touching the hurdle. Bronze medallist Freeman (Figure 27) 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.

Engquist 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 44).

The best reaction time (cf. Table 43) was 0.118s by Rose (fifth place).

Summary

The determining factors in hurdle sprinting are the hurdle technique, the rhythm in which the athletes are sprinting over the hurdles, the specific sprint endurance and the ability to reach a maximum level of velocity in sprint performance. In the following section the results of the world championships will be set into relation to this determining factors.

In 100 m women's hurdles competition as well as in 110 m hurdles in the men's sprint, the best athletes unite within themselves the most efficient technique sprinting over the hurdles (only very minor loss of velocity while clearing the hurdle, straight movement orientating towards the main direction of movement and if possible a constant crossing of the section in between the hurdles with the maximum individual velocity) and as a presupposition a high specific sprinting velocity as well as special standard of flexibility of the individual athlete.

It must be acknowledged that the hurdle clearance time is not the major determining factor, much more significant is the fact that the two winner, in women and men competition, show the most constant results as to the sprints in the sections between the hurdles (ENGQUIST 0.94 sec. / JOHNSON 0.98 sec.). Further more they both also show a high constancy in their sprinting performance (cf. Table 40 and Table 43).

There is no recognizable connection between the reaction time and time achieved after crossing the 1st hurdle (*men*: REESE 0.117 sec., tH_1 2.60 sec. / JOHNSON 0.128 sec., tH_1 2.56 sec. ; *women*: ROSE 0.118 sec., tH_1 2.60 sec. / ENGQUIST 0.126 sec., tH_1 2.56 sec.). (cf. Table 40 and 43).

The run - in after the last hurdle presents, especially looking at the male hurdle sprinters, an significant increase in velocity, meaning a similar acceleration as can be noticed in the 100 m flat sprints (cf. Table 42 and Table 45).

Conclusions

In connection with the World Championships in Athens no further development can be noticed.

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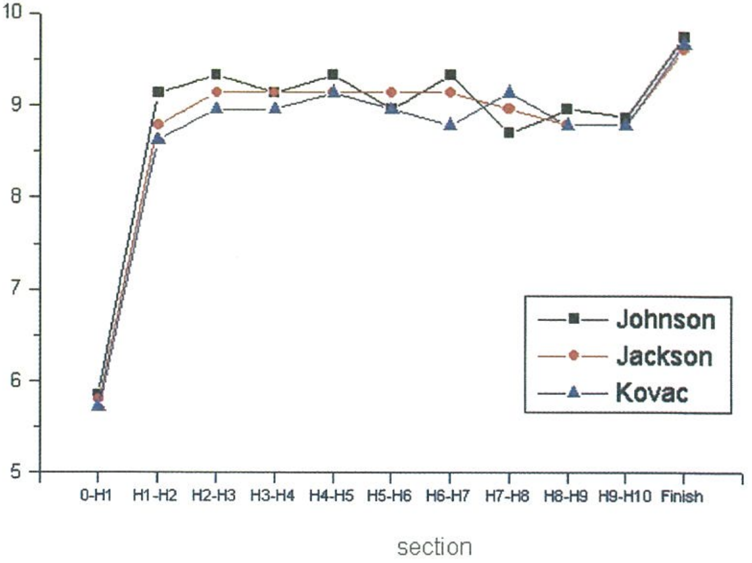

Figure 25: Section velocities in the 110 m hurdles - final (Place 1 - 3)

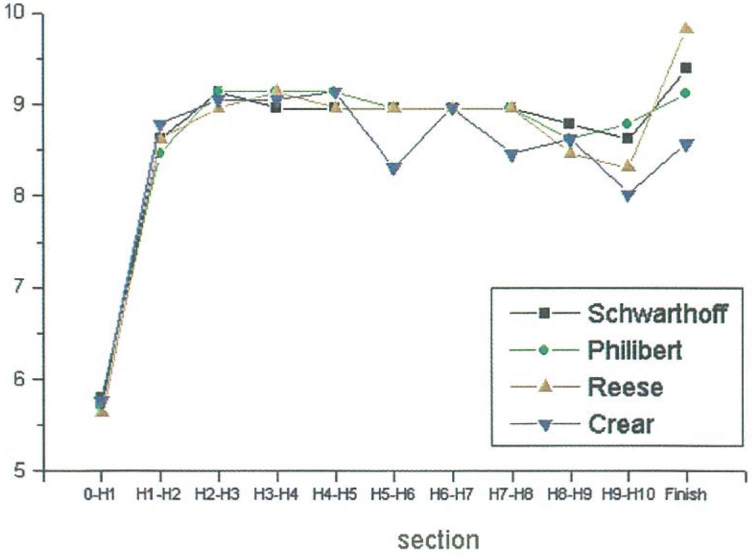

Figure 26: Section velocities in the 110 m hurdles - final (Place 4 - 7)

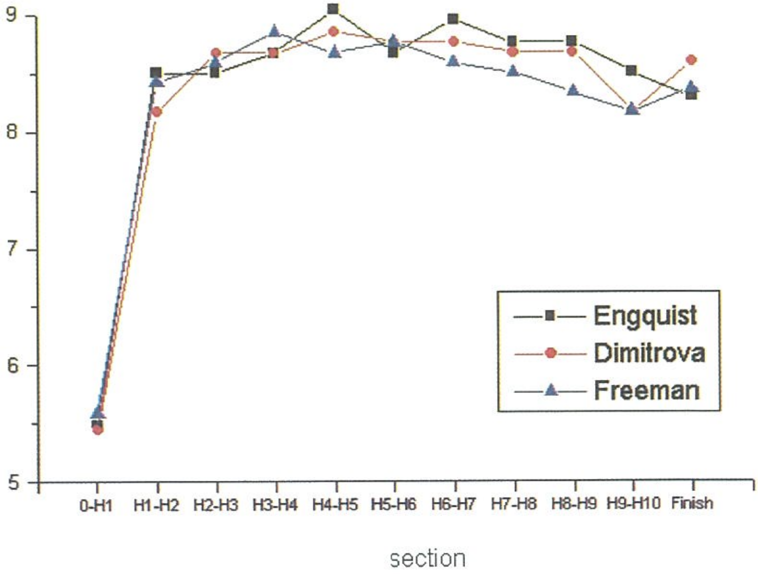

Figure 27: Section velocities in the 100 m hurdles - final (Place 1 - 3)

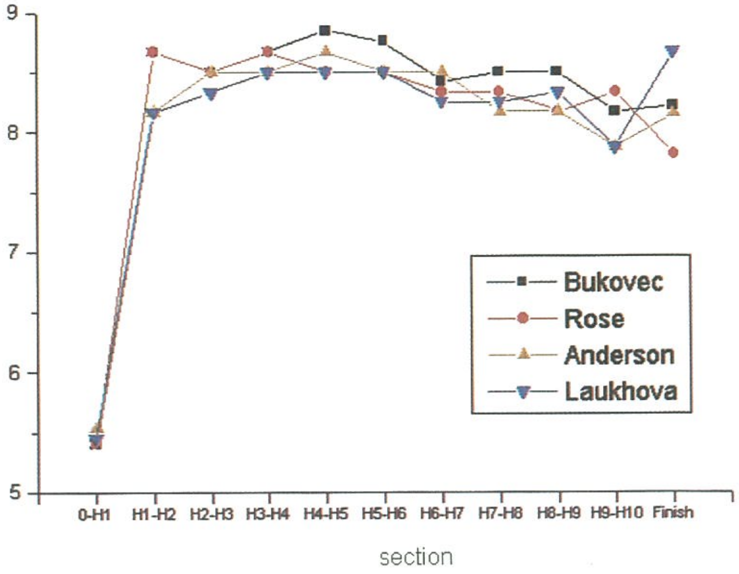

Figure 28: Section velocities in the 100 m hurdles - final (Place 4 - 7)

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Table 39: Instantaneous velocities in the men's 110 metres hurdles final [m/s]

Name	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	run - in
Johnson	8.67	9.11	9.33	9.22	9.10	9.06	8.99	8.90	8.81	8.78	9.04
Jackson	8.66	8.93	9.14	9.17	9.16	8.98	8.96	8.83	8.74	8.63	8.97
Kovac	8.45	8.78	8.85	8.92	8.96	8.93	8.86	8.82	8.76	8.90	8.97
Schwarthoff	8.41	8.77	9.03	9.02	8.88	8.95	8.81	8.83	8.67	8.68	–

Table 40: 110 metres hurdles final – interval times [s]

		Section										
Result	RT	0-tH1	tH1-tH2	tH2-tH3	tH3-tH4	tH4-tH5	tH5-tH6	tH6-tH7	tH7-tH8	tH8-tH9	tH9-tH10	Run-in
Johnson (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 (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 (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 (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 (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 (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 (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 41: 110 metres hurdles final – hurdle clearance times [s]

	Hurdle									
	tH1	tH2	tH3	tH4	tH5	tH6	tH7	tH8	tH9	tH10
Johnson	0.35	0.34	0.32	0.32	0.32	0.34	0.32	0.35	0.35	0.34
Jackson	0.34	0.36	0.36	0.34	0.36	0.34	0.36	0.34	0.35	0.34
Kovac	0.34	0.34	0.32	0.34	0.32	0.32	0.32	0.32	0.34	0.34
Schwarthoff	0.34	0.28	0.30	0.30	0.32	0.32	0.32	0.32	0.32	-
Philibert	0.32	0.36	0.34	0.34	0.30	0.32	0.34	0.34	0.36	0.36
Reese	0.38	0.40	0.36	0.38	0.38	0.38	0.38	0.36	0.40	0.44
Crear	0.36	0.36	0.35	0.36	0.34	0.42	0.36	0.36	0.36	0.36

Table 42: 110 metres hurdles final – section velocities [m/s]

	Section										
	0-tH1	tH1-tH2	tH2-tH3	tH3-tH4	tH4-tH5	tH5-tH6	tH6-tH7	tH7-tH8	tH8-tH9	tH9-tH10	run-in
Johnson	5.85	9.14	9.33	9.14	9.33	8.96	9.33	8.70	8.96	8.87	9.75
Jackson	5.80	8.79	9.14	9.14	9.14	9.14	9.14	8.96	8.79	8.79	9.60
Kovac	5.71	8.62	8.96	8.96	9.14	8.96	8.79	9.14	8.79	8.79	9.67
Schwarthoff	5.80	8.62	9.14	8.96	8.96	8.96	8.96	8.96	8.79	8.62	9.39
Philibert	5.71	8.46	9.14	9.14	9.14	8.96	8.96	8.96	8.62	8.79	9.12
Reese	5.63	8.62	8.96	9.14	8.96	8.96	8.96	8.96	8.46	8.31	9.82
Crear	5.76	8.79	9.05	9.05	9.14	8.31	8.96	8.46	8.62	8.02	8.57

Table 43: 100 metres hurdles final – interval times [s]

		Section										
Result	RT	0-tH1	tH1-tH2	tH2-tH3	tH3-tH4	tH4-tH5	tH5-tH6	tH6-tH7	tH7-tH8	tH8-tH9	tH9-tH10	run-in
Engquist (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 (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 (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 (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 (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 (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 (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 44: 100 metres hurdles final – hurdle clearance times [s]

	Hurdle									
	tH1	tH2	tH3	tH4	tH5	tH6	TH7	tH8	tH9	tH10
Engquist	0.30	0.30	0.32	0.32	0.30	0.32	0.29	0.29	0.28	0.28
Dimitrova	0.32	0.32	0.32	0.30	0.30	0.31	0.30	0.32	0.30	0.32
Freeman	0.32	0.31	0.34	0.30	0.32	0.33	0.32	0.34	0.34	0.34
Bukovec	0.30	0.28	0.30	0.28	0.28	0.27	0.30	0.30	0.28	0.30
Rose	0.36	0.30	0.28	0.28	0.30	0.30	0.32	0.32	0.32	0.28
Anderson	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.32	0.34	0.34
Laukhova	0.30	0.34	0.30	0.30	0.30	0.30	0.31	0.31	0.30	0.32

Table 45: 100 metres hurdles final – section velocities [m/s]

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

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2.1.5 400 m Hurdles

H. Hommel, D. Koszewski

History

The hurdle race was a classic discipline in English athletics. At first the athletes still jumped over cottage ridges preferring a special technique referred to as "sliding style". Practicing this technique they cleared the hurdle with their torso being upright and their leading leg in a right angle.

As early as in 1864 hurdle races took place in England. They were carried out on the occasion of the 1st Oxford - Cambridge - Meeting and a distance of 440 yards was covered. From 1875 onwards race were also run in the USA. But the distance run as well as the distance between the hurdles and their height varied considerably thrughout the next years. So F. Copeland ran the distance of 300 yards with 10 hurdles in 1876, their height being 76,4 cm. He ran a time of $37.^3/_5$ sec. Three years later J. E. Haight ran the 300 yards with 20 hurdles at the height of 91,4 cm in 45,0 sec. and H. H. Mautz ran the 440 yards with 16 hurdles at the height of 76,4 cm in 64,0 sec.

The 1st country to introduce the 400 m hurdle sprint was France, which organized a national championship (10 hurdles, 91,4 cm height). The 1st French champion was Blanchett in exactly 60 sec. From then onwards the 440 yards were run with certain variation in the amount of hurdles (10 - 20) as well as in their height (76,4 cm - 1,06 m).

At the Olympic Games in 1896 in Athens once again the 400 m distance with 10 hurdles was run, but they were only 76,4 cm high. The American athlete J. Tewkesbury won in 55,6 sec. At the next Olympic Games in 1900 in Paris it was decided that the height of the hurdles was to be 91,4 cm and J. Tewkesbury won the final again in $57.^3/_5$ sec. At the Olympic Games in St. Louis in 1904 the height was once again reduced to 76,4 cm and the competition was won by H. Hillman (USA) in 53,6 sec. After that the height of the hurdles of 91,4 cm was generally accepted and hasn't varied in international competitions ever since.

After the basic structure of the distance had been agreed upon the next aspect that was being focused on was the approach to the 1st hurdle and the rhythm in - between the hurdles. A stride rhythm of 22 strides up to the 1st hurdle and of 15 strides in between established itself. This hasn't clayed significantly except for an improvement in the sprinting performance which make an approach of 20 strides towards the 1st hurdle (even 18!) as well as 13 strides in between (K. Young ran 12 strides at the Olympic Games in 1992) possible.

History of women's 400 m hurdles

At the coaches EAA - conference in Brescia in 1970 it was considered to take up a second hurdle distance for women into the competition program. Alternatives being discussed were the 200, 300 or 400 m distances.

• 200 m hurdles	contra arguments: no real alternative to the 100 m distance;
• 300 m hurdles	contra arguments: space in between the hurdles make an efficient race impossible, additional signs would have to be printed on the tracks.

They then decided on the 400 m hurdles with the same distances in between as was common for the men's distance and the height of the women's hurdle was set at 76,4 cm. Since 1974 women's 400 m hurdle competitions are being run - the world record over this distance was 84,3% of the men's world record at this time. At the European championship 1978 seven female athletes already remained under the 56 sec. - barrier and the WR was improved to 54,89 sec. by T. Selentsowa in the same year. At the European championship in 1989 Stepanova ran under 53 sec. for the 1st time which implies an increase in performance of no less than 6% in 12 years.

Summary

Remarkable is the fact that male as well as female 400 metres hurdle sprinters have a high efficiency in hurdle technique (ability to cross the hurdles with both legs) and strong rhythmic capabilities. As to the number of steps in between the hurdles a rather the change in the number of steps and the question of when the change in step number will be performed there are no new results observable.

Another obvious fact is the difference in race tactic of the winners in the finals; DIAGANA chose a very high acceleration starting off and at the 5th hurdle he already was 0.35 sec. in the lead. He was also able to keep this time advantage right to the 10th hurdle as well as way into the finish – line (cf. Table 46).

Table 46: Men's 400 metres hurdles final – interval times [s]

time	Diagana (FRA)	Herbert (RSA)	Bronson (USA)
tH1	05.87	05.96	06.03
tH5	20.60	21.48	20.95
tH10	42.27	42.87	42.62
Finish	47.70	47.86	47.88

In contrast the winner in the women's race BIDOUANE, chose a more careful race tactic. Crossing the 5th hurdle she ranked in 7th position, at hurdle number 7 she had advanced to position number 4 - in the end she won the race at the run - in between the last hurdle and the finish – line (cf. Table 47).

Table 47: Women's 400 metres hurdles final – interval times [s]

time	Bidouane (MAR)	Hemmings (JAM)	Batten (USA)
tH1	6.50	6.46	6,57
tH5	23.92	23.36	23.46
tH7	32.98	32.36	32.46
tH10	47.46	47.31	47.46
Finish	52.97	53.09	53.52

In both finals it could be observed that the main acceleration was finished when reaching the 2nd hurdle (there was one exception in each race (m) MORI, (w) PARRIS, they both shared their highest velocity after crossing the 3rd hurdle) (cf. Table 48 and 49).

Table 48: Men's 400 metres hurdles final – section velocities [m/s]

section velocities	Diagana (FRA)	Herbert (RSA)	Bronson (USA)	Mori (ITA)
0 - H1	7.87	7.75	7.66	7.52
H1 - H2	9.64	9.56	9.64	9.02
H2 - H3	9.62	9.11	9.56	9.31

Table 49: Women's 400 metres hurdles final – section velocities [m/s]

section velocities	Bidouane (MAR)	Hemmings (JAM)	Batten (USA)	Parris (JAM)
0 - H1	7.08	7.12	7.00	7.14
H1 - H2	8.22	8.50	8.56	7.97
H2 - H3	8.10	8.45	8.33	8.86

The determining factor in the end turned out to be the high quality of sprinting endurance all of the 400 metres finalists have in common. The difference between the hurdle clearance times and the section times in the between the hurdles are not as important in connection with the finish results as was presupposed.

Conclusions

In connection with the World Championships in Athens no further development can be noticed.

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List of tables

Women's final

Table 50 – 56: Interval times and section velocities of the finalists in the women's 400 metres hurdles (World Championships 1997)

Bidouane, Nezha		**Reaction Time:** 0.138 sec			
Time Sections	**Split Times [sec]**	**t Interval [sec]**	**t Hurdle [sec]**	v [m/sec]	**Remarks**
tH1	6,50	6,50	0,30	7,08	
tH2	10,76	4,26	0,28	8,22	
tH3	15,08	4,32	0,30	8,10	
tH4	19,50	4,42	0,32	7,92	
tH5	23,92	4,42	0,28	7,92	
tH6	28,44	4,52	0,34	7,74	
tH7	32,98	4,54	0,28	7,71	
tH8	37,74	4,76	0,32	7,35	
tH9	42,62	4,88	0,32	7,17	
tH10	47,46	4,84	0,32	7,23	
Finish	**52,97**	5,51		7,08	
		øtInt. = 4,55	**øtH = 0,31**	**vø = 7,59**	

Hemmings, Deaon		**Reaction Time:** 0.187 sec			
Time Sections	**Split Times [sec]**	**t Interval [sec]**	**t Hurdle [sec]**	v [m/sec]	**Remarks**
tH1	6,46	6,46	0,46	7,12	
tH2	10,58	4,12	0,38	8,50	
tH3	14,72	4,14	0,38	8,45	
tH4	19,00	4,28	0,42	8,18	
tH5	23,36	4,36	0,40	8,03	
tH6	27,76	4,40	0,40	7,95	
tH7	32,36	4,60	0,48	7,61	
tH8	37,22	4,86	0,40	7,20	
tH9	42,20	4,98	0,41	7,03	
tH10	47,31	5,11	0,41	6,85	
Finish	**53,09**	5,78		6,75	
		øtInt. = 4,54	**øtH = 0,41**	**vø = 7,61**	

Batten, Kim **Reaction Time:** 0,170 sec

Time Sections	Split Times [sec]	t Interval [sec]	t Hurdle [sec]	v [m/sec]	Remarks
tH1	6,57	6,57	0,35	7,00	
tH2	10,66	4,09	0,40	8,56	
tH3	14,86	4,20	0,32	8,33	
tH4	19,10	4,24	0,34	8,25	
tH5	23,46	4,36	0,36	8,03	
tH6	27,88	4,42	0,34	7,92	
tH7	32,46	4,58	0,38	7,64	
tH8	37,34	4,88	0,40	7,17	
tH9	42,36	5,02	0,35	6,97	
tH10	47,46	5,10	0,38	6,86	
Finish	**53,52**	6,06		6,44	
		øtInt. = 4,54	**øtH = 0,36**	**vø = 7,56**	

Tereshchuk, Tatyana **Reaction Time:** 0,156 sec

Time Sections	Split Times [sec]	t Interval [sec]	t Hurdle [sec]	v [m/sec]	Remarks
tH1	6,44	6,44	0,32	7,14	
tH2	10,58	4,14	0,32	8,45	
tH3	14,80	4,22	0,32	8,29	
tH4	19,14	4,34	0,32	8,06	
tH5	23,56	4,42	0,32	7,92	
tH6	28,08	4,52	0,32	7,74	
tH7	32,72	4,64	0,28	7,54	
tH8	37,54	4,82	0,32	7,26	
tH9	42,60	5,06	0,36	6,92	
tH10	47,78	5,18	0,35	6,76	
Finish	**53,81**	6,03		6,47	
		øtInt. = 4,59	**øtH = 0,32**	**vø = 7,51**	

Parris, Debbie **Reaction Time:** 0,206 sec

Time Sections	Split Times [sec]	t Interval [sec]	t Hurdle [sec]	v [m/sec]	Remarks
tH1	6,44	6,44	0,32	7,14	
tH2	10,83	4,39	0,35	7,97	
tH3	14,78	3,95	0,06	8,86	
tH4	19,38	4,60	0,36	7,61	
tH5	23,52	4,14	0,36	8,45	
tH6	28,46	4,94	0,32	7,09	
tH7	33,20	4,74	0,38	7,38	
tH8	38,00	4,80	0,36	7,29	
tH9	43,04	5,04	0,38	6,94	
tH10	48,24	5,20	0,36	6,73	
Finish	**54,19**	5,95		6,55	
		øtInt. = 4,64	**øtH = 0,32**	**vø = 7,46**	

Buford-Bailey, Tonja **Reaction Time:** 0,238 sec

Time Sections	Split Times [sec]	t Interval [sec]	t Hurdle [sec]	v [m/sec]	Remarks
tH1	6,60	6,60	0,32	6,97	
tH2	10,72	4,12	0,36	8,50	
tH3	14,92	4,20	0,36	8,33	
tH4	19,21	4,29	0,33	8,16	
tH5	23,60	4,39	0,38	7,97	
tH6	28,22	4,62	0,36	7,58	
tH7	32,92	4,70	0,34	7,45	
tH8	37,92	5,00	0,36	7,00	
tH9	43,14	5,22	0,36	6,70	
tH10	48,54	5,40	0,34	6,48	
Finish	**54,77**	6,23		6,26	
		øtInt. = 4,66	**øtH = 0,35**	**vø = 7,40**	

Smith, Susan **Reaction Time:** 0,135 sec

Time Sections	Split Times [sec]	t Interval [sec]	t Hurdle [sec]	v [m/sec]	Remarks
tH1	6,43	6,43	0,33	7,15	
tH2	10,58	4,15	0,36	8,43	
tH3	14,78	4,20	0,34	8,33	
tH4	19,06	4,28	0,30	8,18	
tH5	23,88	4,82	0,36	7,26	
tH6	28,06	4,18	0,38	8,37	
tH7	32,84	4,78	0,40	7,32	
tH8	37,92	5,08	0,36	6,89	
tH9	43,18	5,26	0,35	6,65	
tH10	48,74	5,56	0,39	6,29	
Finish	**55,25**	6,51		5,99	
		øtInt. = 4,70	**øtH = 0,36**	**vø = 7,35**	

Note: Andrea BLACKETT (Barbados), ranking 8th was most of the time out of the videoframe and therefore could not get analysed.

Men's final

Table 57 – 64: Interval times and section velocities of the finalists in the men's 400 metres hurdles (World Championships 1997)

Diagana, Stephane		**Reaction Time:** 0,157 sec			
Time Sections	**Split Times** [sec]	**t Interval** [sec]	**t Hurdle** [sec]	v [m/sec]	**Remarks**
tH1	05,87	5,87	0,31	7,87	
tH2	09,50	3,63	0,30	9,64	
tH3	13,14	3,64	0,34	9,62	
tH4	16,85	3,71	0,37	9,43	
tH5	20,60	3,75	0,36	9,33	
tH6	24,68	4,08	0,52	8,58	
tH7	28,68	4,00	0,36	8,75	
tH8	32,98	4,30	0,38	8,14	
tH9	37,56	4,58	0,37	7,64	
tH10	42,27	4,71	0,40	7,43	
Finish	**47,70**	5,43		7,15	
		øtInt. = 4,04	**øtH = 0,37**	**vø = 8,51**	

Herbert, Llewellyn		**Reaction Time:** 0,147 sec			
Time Sections	**Split Times** [sec]	**t Interval** [sec]	**t Hurdle** [sec]	v [m/sec]	**Remarks**
tH1	05,96	5,96	0,30	7,75	
tH2	09,62	3,66	0,32	9,56	
tH3	13,46	3,84	0,32	9,11	
tH4	17,32	3,86	0,36	9,07	
tH5	21,48	4,16	0,38	8,41	
tH6	25,64	4,16	0,42	8,41	
tH7	29,86	4,22	0,36	8,29	
tH8	34,14	4,28	0,38	8,18	
tH9	38,48	4,34	0,38	8,06	
tH10	42,87	4,39	0,40	7,97	
Finish	**47,86**	4,99		7,78	
		øtInt. = 4,10	**øtH = 0,36**	**vø = 8,42**	

Bronson, Bryan **Reaction Time:** 0,247 sec

Time Sections	Split Times [sec]	t Interval [sec]	t Hurdle [sec]	v [m/sec]	Remarks
tH1	06,03	6,03	0,37	7,66	
tH2	09,66	3,63	0,36	9,64	
tH3	13,32	3,66	0,34	9,56	
tH4	17,08	3,76	0,38	9,31	
tH5	20,95	3,87	0,41	9,04	
tH6	25,08	4,13	0,36	8,47	
tH7	29,28	4,20	0,38	8,33	
tH8	33,62	4,34	0,38	8,06	
tH9	38,08	4,46	0,38	7,85	
tH10	42,62	4,54	0,38	7,71	
Finish	**47,88**	5,26		7,38	
		øtInt. = 4,07	**øtH = 0,37**	**vø = 8,46**	

Mori, Fabrizio **Reaction Time:** 0,156 sec

Time Sections	Split Times [sec]	t Interval [sec]	t Hurdle [sec]	v [m/sec]	Remarks
tH1	06,14	6,14	0,34	7,52	
tH2	10,02	3,88	0,36	9,02	
tH3	13,78	3,76	0,28	9,31	
tH4	17,72	3,94	0,36	8,88	
tH5	21,72	4,00	0,38	8,75	
tH6	25,85	4,13	0,39	8,47	
tH7	30,04	4,19	0,38	8,35	
tH8	34,40	4,36	0,35	8,03	
tH9	38,78	4,38	0,36	7,99	
tH10	43,18	4,40	0,40	7,95	
Finish	**48,05**	4,87		7,97	
		øtInt. = 4,12	**øtH = 0,36**	**vø = 8,39**	

Matete, Samuel **Reaction Time:** 0,237 sec

Time Sections	Split Times [sec]	t Interval [sec]	t Hurdle [sec]	v [m/sec]	Remarks
tH1	05,98	5,98	0,32	7,73	
tH2	09,66	3,68	0,31	9,51	
tH3	13,41	3,75	0,31	9,33	
tH4	17,24	3,83	0,33	9,14	
tH5	21,16	3,92	0,34	8,93	
tH6	25,18	4,02	0,36	8,71	
tH7	29,20	4,02	0,34	8,71	
tH8	33,62	4,42	0,38	7,92	
tH9	38,10	4,48	0,38	7,81	
tH10	42,70	4,60	0,41	7,61	hit hurdle hard
Finish	**48,11**	5,41		7,17	
		øtInt. = 4,08	**øtH = 0,35**	**vø = 8,41**	

Mashchenko, Russlan **Reaction Time:** 0,166 sec

Time Sections	**Split Times [sec]**	**t Interval [sec]**	**t Hurdle [sec]**	**v [m/sec]**	**Remarks**
tH1	05,88	5,88	0,35	7,86	
tH2	09,60	3,72	0,32	9,41	
tH3	13,36	3,76	0,36	9,31	
tH4	17,16	3,80	0,36	9,21	
tH5	21,02	3,86	0,34	9,07	
tH6	25,02	4,00	0,38	8,75	
tH7	29,30	4,28	0,38	8,18	
tH8	33,61	4,31	0,37	8,12	
tH9	38,26	4,65	0,46	7,53	
tH10	43,06	4,80	0,44	7,29	
Finish	**48,62**	5,56		6,98	
		øtInt. = 4,13	**øtH = 0,38**	**vø = 8,34**	

Morgan, Dinsdale **Reaction Time:** 0,152 sec

Time Sections	**Split Times [sec]**	**t Interval [sec]**	**t Hurdle [sec]**	**v [m/sec]**	**Remarks**
tH1	05,96	5,96	0,36	7,75	
tH2	09,68	3,72	0,34	9,41	
tH3	13,52	3,84	0,36	9,11	
tH4	17,45	3,93	0,39	8,91	
tH5	21,48	4,03	0,36	8,68	
tH6	25,56	4,08	0,38	8,58	
tH7	29,86	4,30	0,40	8,14	
tH8	34,32	4,46	0,40	7,85	
tH9	38,96	4,64	0,43	7,54	
tH10	43,70	4,74	0,44	7,38	
Finish	**49,06**	5,36		7,24	
		øtInt. = 4,19	**øtH = 0,39**	**vø = 8,24**	

Muzik, Jiri **Reaction Time:** 0,179 sec

Time Sections	**Split Times [sec]**	**t Interval [sec]**	**t Hurdle [sec]**	**v [m/sec]**	**Remarks**
tH1	06,02	6,02	0,40	7,67	
tH2	09,78	3,76	0,38	9,31	
tH3	13,62	3,84	0,40	9,11	
tH4	17,58	3,96	0,42	8,84	
tH5	21,80	4,22	0,48	8,29	
tH6	26,12	4,32	0,48	8,10	
tH7	30,42	4,30	0,48	8,14	estimated values for tH7 athlete was partly covered
tH8	34,92	4,50	0,42	7,78	
tH9	39,52	4,60	0,44	7,61	
tH10	44,14	4,62	0,42	7,58	
Finish	**49,51**	5,37		7,23	
		øtInt. = 4,24	**øtH = 0,43**	**vø = 8,15**	

2.2 Biomechanical Analysis of the Jumping Events

2.2.1 Long Jump

A. Arampatzis, G.-P. Brüggemann, M. Walsch

Abstract

In this study the performance of world class long jumpers was analyzed to determine whether the jumpers can be divided into groups which show the same take-off parameters and different jumping styles but nevertheless attain the same jump distance. The jumps will also be examined to determine if there are ideal jump strategies for various given take-off parameters for both men and women at the world class level of competition. The data for this study was recorded at the 1997 Track and Field World Championships in Athens, Greece. The data was collected using three stationary video cameras (50 Hz). A total of 31 jumps performed by 12 athletes were analyzed from both the men's and women's competitions.

It can be seen in both the men's and women's groups that athletes demonstrating different take-off parameters and different combinations of vertical and horizontal velocities attain the same jump distance. The total energy at touch down determines the maximum jumping distance but most athletes fail to use this energy optimally. The take-off parameters which are determined by the loss of the centre of mass (CM) energy during take-off and from the transformation of the approach energy to jump energy (transformation index) are very important for determining the jump distance. The transformation index shows a high correlation with both the start energy at touch down and energy decrease during the take-off phase. The transformation index was estimated with a high corelation coefficient (r=0.91 for the men and r=0.94 for the women) using a multiple regression equation dependent on the start energy and energy loss. The optimum energy loss at take-off for the athletes analyzed was determined to be 5.5- 6.0 J/kg for the women and 7.5-8.4 J/kg for the men. For a few athletes the measured values and the theoretical values varied considerably. These instances may indicate that the transformation index is dependent on individual physical differences. This would mean that the transformation index, the optimal amount of energy decrease and energy at take-off vary individually and can be individually determined for training purposes.

Introduction

In 1935 Jesse Owens performed the first long jump over 8 m. His 8.13 m remained the world record for 25 years until Ralph Boston (USA) jumped 8.21 m on 12.8.1960. Boston increased the world record six times the last being in 1969 when he jumped 8.35 m. In a similar fashion to the flop technique in the high jump in the 1970s athletes experimented with a somersault long jump („flip"). This technique was, however, prohibited because 1. mats were required, 2. there was no clear foot print and 3. neck injuries could not be excluded. In Mexico City Bob Beamon performed 1968 a similarly spectacular feat to that of Jesse Owens with a jump of 8.90 m. As expected this record remained for a long time. The best long jumper in the 70s and 80s was Carl Lewis (USA) who won this event at the Olympic Games in Los Angeles in 1984 (8.54 m), in Seoul in 1988 (8.72 m), in Barcelona in 1992 (8.67 m) and in Atlanta in 1996 (8.50 m). The closest long jump competition took place at the world championships in Tokyo in 1991 when Mike Powell (USA) won the championships with 8.95 m and Carl Lewis came second with 8.91 m (wind assisted). Carl Lewis who had won 65 consecutive competitions since 1981 was beaten for the first time but had the best series of jumps ever completed: 8.68 m, -, 8.83 m, 8.91 m (wind assisted), 8.87 m, 8.84 m.

The 6.12 m jumped by Christel Schulz (GER) in 1939 was the first jump over 6 m acknowledged by the IAAF. Athletes from the eastern block countries dominated the women's long jump for decades after the second world war. Vilma Bardauskiene (URS) jumped 7.07 m in 1978 and Heike Drechsler approached the 7.50 m mark when she broke the world record with 7.45 m in 1986. The 7.50 m barrier was first cleared by Galina Chistyakova (URS) in 1987 with 7.52 m. The performance level of women's long jump has also slowed down strongly since the relevant controls have been introduced. Only few jumps over the 7 m mark have been registered in recent years. Fiona May (ITA) is reigning world champion with 6.98 m. Chioma Ajunwa (NGA) won the Olympic event in Atlanta with 7.12 m.

A great number of biomechanical studies dealt with the description of run-up speed, partial distances, take-off and flight kinematics as well as landing strategies. The long jump seems to be one of the best or most studied disciplines in athletics in terms of kinematics and statistical relations between performance limiting factors. It can be stated that in the period of time when the majority of knowledge in the long jump was accumulated the performance in men and especially in women remained nearly constant or decreased. Most of the research was focussed on total body kinematics and only few discussed the segmental or muscular role neither during take-off nor in flight. Therefore the former research was mainly result orientated and was not able to contribute to a more detailed understanding of the role of the muscular drives during the fast take-off, the limiting phase in the long jump.

Purpose

The goals of this study were to describe the run-in, the take-off, and the flight kinematics and to estimate changes of kinetic energy properties during take-off of the finalists of the 1997 World Championships, representing the best athletes in the world at this time. Strategies for an efficient use of run-up velocity or initial energy used by world class athletes should be identified. Therefore the general task is to contribute to a better understanding of energy transfer or transmission phase from the run-in into the take-off. This has to be discussed together with the question of limits of performance in the discipline under study.

Basic model

Distances in the long jump: Long jump performance is determined by the so-called "official distance". This is obtained by measuring the length of an imaginary perpendicular line from the front edge of the take-off board to the nearest mark that the athlete leaves in the sand. For purpose of analysis Hay (1973) stated that the official distance in the long jump is the sum of three distances for which the athlete is credited:

D_{TO}: The take-off distance – the horizontal distance between the front edge of the take-off board and the athlete's centre of mass (CM) at the instant of take-off.

D_{FL}: The flight distance – the horizontal distance covered by the CM while the athlete is in the air.

D_{LD}: The landing distance – the horizontal distance between the CM at the instant the heel hits the sand and the mark in the sand from which the distance is ultimately measured.

This division of the official distance has been extensively used in discussions and research concerned with techniques in the long jump. One must note that two measures of athlete's performance are commonly used when analyzing the long jump. They must be carefully differentiated one from the other:

D_{OFF}: The official distànce – the horizontal distance, measured according to the rules, and

D_{EFF}: The effective distance – the horizontal distance the athlete jumped, measured from the toe of the take-off foot at the instant of take-off to the nearest point of the feet when hitting the sand at landing.

The effective (D_{EFF}) distance is the sum of the so-called toe-to-board distance (D_{TB}), the official distance (D_{OFF}) and the distance lost while landing (fall-back distance). The distances lost due to poor landing in the sand, lateral deviation in the jump or toe-to-board space are added to make the total lost distance (D_{TLO}). D_{TLO} can be a measure for the efficient use of jump capacity and/or precision.

The flight distance: The most important influence on the effective distance is the flight distance of the CM (Hay 1986; Quade & Sahre 1989; Lees et al. 1994). This distance is determined by the CM's take-off velocity (v), the take-off angle (the angle of projection) (a), and the relative height of the CM from take-off to landing. The relative height of the CM depends on the CM heights at the instants of take-off and landing. The precise identification of the instant of landing and therefore the measuring of the exact landing height is somewhat difficult and deficient. Therefore for further considerations and calculations will enclosed : the "theoretical flight distance" D_{TFL} - CM's horizontal flight distance from take-off until the CM theoretically hits the ground. The distance (D_{TFL}) can be calculated using the following formula:

$$D_{TFL} = \frac{v^2 \sin 2a}{2g} + v \cos a \sqrt{\frac{2}{g}\left(h + \frac{v^2 \sin^2 a}{2g}\right)} \qquad (1)$$

From the formula it is evident that the distance (D_{TFL}) depends on the height of the CM, and the horizontal and vertical take-off velocities at the take-off. From this causal dependency various researchers over the past decades (Ballreich 1970, 1979; Kollath 1980, 1982; Hay et al. 1986; Ballreich & Brüggemann 1986; Koh & Hay 1990; Hay & Nohara 1990; Lees et al. 1993, 1994) have tried to identify which components (horizontal or vertical) of the take-off velocity plays a larger role concerning the jump and flight distances. The results are often controversial and dependant on the performance level of the analyzed jumpers.

Transmission of run-up speed into flight distance: Koh and Hay (1990) reported that the goal of the take-off is not to minimize the loss of the horizontal CM velocity. This result was supported by the observation that a loss in horizontal velocity often leads to an increase in vertical take-off velocity (Hay et al. 1986; Hay & Nohara 1990; Koh & Hay 1990; Lees et al. 1993, 1994). Quade and Sahre (1989) concluded that the loss of horizontal velocity during the take-off should be kept to a minimum while producing as high as possible of a vertical take-off velocity. For both men and women a loss of total mechanical energy during the take-off has been reported by different researchers (Witters et al. 1992; Lees et al. 1993, 1994; Müller & Brüggemann 1997). This means that during the transmission of approach energy (or initial energy) to jump energy a loss in athlete's total mechanical energy is to be expected. This also means that a decrease in horizontal CM velocity does not imperatively lead to an increase in vertical CM's take-off velocity. Witters et al. (1992) found that the conversion efficiency was dependant on the horizontal CM touchdown velocity. The conversion factor varied among athletes. It is commonly believed (Ballreich & Brüggemann 1986; Möser 1990; Dieß & Pfeifer 1991) and has been proven by the scientific community (Hay et al. 1985; Hay et al. 1986; Prause 1990; Nixdorf & Brüggemann 1990; Hay and Nohara 1990) that the horizontal CM's touchdown velocity (the run-up velocity) has a strong relation to the various long jump performance. The correlation coefficient becomes smaller at higher levels of performances (Hay et al. 1985; Nixdorf & Brüggemann 1990).

Purpose and hypothesis: All of these observations lead to the hypothesis that (a) an optimum combination of jump and/or take-off parameters exists which allows a maximum jump (flight) distance, and (b) jump distance and optimal take-off parameters are dependant on the physical capacities of the individual athlete. The purpose of this study was to examine performances of world class long jumpers under competitive conditions in order to determine if the athletes can be divided into groups with similar initial conditions and different take-off characteristics while achieving similar flight distances. Furthermore optimal take-off parameters should be calculated for given initial conditions for both men and women jumpers on recent world class level.

Methods

Data collection

Kinematic data were recorded from 31 jumps completed by male jumpers and 31 jumps by female jumpers. The jumps were performed by the 12 finalists in both the men's and women's long jump finals of the World Championships in Athens. Only legal jumps were analyzed. For data acquisition three fixed video cameras (Pal, 50 fields/s) were used installed perpendicular to the runway and the pit. The shutter speed was set at 1/1000s. Camera 1 was positioned to capture the last three strides of the run-up prior to take-off. Camera 2 recorded the last step and take-off. The third camera filmed the take-off and flight phase until landing. All three cameras were calibrated using the same calibration frame. The front edge of the calibration frame was positioned on the front edge of the take-off board. The X axis is positive to the direction of motion and the Z axis is oriented positive to the vertical axis. Direct linear transformation technique was applied to calculate the spatial coordinates (x, y) from the raw data.

During each of the support phases of take-off and the two previous steps five frames were digitized using 19 landmarks representing a 15-segment-model of the athlete's body.

Frame 1:	the last frame prior to ground contact,
Frame 2:	the first visible contact with the ground,
Frame 3:	minimum knee angle,
Frame 4:	last frame the foot is on the ground,
Frame 5:	first frame after the last contact to the ground.

In addition to these frames additional pictures in the flight phase close to the highest point of the flight were analyzed. The Peak-Motus system was used to grab and digitize the video data. From the discrete video frames various parameters (CM's positions, joint and body position angles, CM's touchdown and take-off velocities and total CM's energy) were calculated using a fast information system developed by the Institute of Track and Field of the German Sport University in Cologne, Germany.

Data analysis

Equation 1 can be written in the following form:

$$D_{TFL} = \frac{E_{k2}\sin 2a}{g} + \frac{2\cos a}{g}\sqrt{E_{k2}(E_{p2} + E_{k2}\sin^{2} a)} \tag{2}$$

$$E_{k2} = \frac{E_{kin2}}{m}, E_{p2} = \frac{E_{pot2}}{m}, E_{kin2} = \frac{1}{2}mv^{2}, E_{pot2} = mgh$$

where: E_{kin2} and E_{pot2} are the athlete's potential and kinetic energy at take-off into the flight, a is the angle of projection, h the CM's height and v the CM's velocity at take-off, m indicates the athlete's body mass.

The distance (D_{TFL}) can be calculated as a function of the total CM's mechanical energy at take-off and take-off angle. The distance D_{TFL}, which can be calculated using equation 2, shows positive correlation coefficients with the jump distance ($r=0.70$, $p<0.000$ for the men and $r=0.71$, $p<0.000$ for the women) and also with the effective distance ($r=0.80$, $p<0.000$ for the men and $r=0.75$, $p<0.000$ for the women). During the take-off phase a decrease in the CM's total mechanical energy was calculated. To quantify the transmission or transformation of the initial kinetic energy produced during the run-up (E_{T1}) into the flight a transformation index (T_{Index}) was defined. T_{Index} shows the relationship between the change of the direction of CM's path and the energy loss during the take-off ($E_{decrease}$). The transformation index is defined as the quotient of the take-off angle (angle of projection) and the energy loss during take-off.

$$T_{Index} = \frac{a}{E_{decrease}} \tag{3}$$

The total CM's mechanical energy at the end of take-off (E_{T2}) can be described by the following equation (4):

$$E_{T2} = E_{T1} - E_{decrease} \Rightarrow$$

$$E_{p2} + E_{k2} = E_{T1} - E_{decrease} \Rightarrow E_{k2} = E_{T1} - E_{decrease} - E_{p2} \tag{4}$$

$$E_{T1} = \frac{E_{tot1}}{m}, \quad E_{T2} = \frac{E_{tot2}}{m}$$

The differences of the athletes potential energy at the end of the take-off phase are very small and can therefore be represented by a constant value E_{P2}. We can convert equation 3 to:

$$a = T_{Index}.E_{decrease} \tag{5}$$

From equations (2), (4) and (5) the distance (D_{TFL}) can be calculated as a function of the initial energy, energy loss, and the transformation index.

$$\begin{gathered} D_{TFL} = \frac{(E_{T1} - E_{decrease} - E_{p2})\sin(2T_{Index}E_{decrease})}{g} + \frac{2\cos(T_{Index}E_{decrease})}{g} \cdot \\ \sqrt{E_{p2}(E_{T1} - E_{decrease} - E_{p2}) + (E_{T1} - E_{decrease} - E_{p2})^2 \sin^2(T_{Index}E_{decrease})} \end{gathered} \tag{6}$$

The initial energy represents the initial conditions for the take-off. The energy loss and the transformation index describe the take-off characteristics.

Data reduction

For data reduction and grouping a cluster analysis was performed to create groups of subjects on the basis of initial or run-up energy, energy loss during take-off and the transformation index. An independent groups T-test was used to measure the differences among the groups.

Results

The standard of the men's and women's finals was high but not outstanding. The mean of the official distance of the best 10 participants of the men's final was 8.04m ±0.23 and of the 11 best in the women's competition 6.78m ±0.15. The best jumps were performed by Pedroso (CUB) and Galkina (RUS) with 8.42m and 7.05m, respectively. Tables 65 and 66 summarizes the results of commonly used parameters in long jump research. The tables present the individual data of the best jumps of the 10 and 11 subjects under study, respectively.

Table 65 : Official,effective,toe-to-board and total lost distances
(a) men's final , (b) women's final

	D_{off} [m]	D_{eff} [m]	D_{TB} [m]	D_{TLO} [m]
Pedroso	8,42	8,67	-,077	-,25
Walder	8,30	8,53	-,137	-,23
Sosunov	8,18	8,46	-,193	-,28
Dilworth	7,88	8,68	-,286	-,80
Beckford	8,07	8,44	-,067	-,37
Ferreira Jr.	8,04	8,36	-,010	-,32
Toure	7,98	8,25	-,002	-,27
Jianfeng	7,76	8,24	-,063	-,48
Glavatski	8,03	8,08	-,014	-,05
Morigana	7,70	8,02	-,160	-,32
mean	8,04	8,37	-,100	-,34
std. dev.	±0,23	±0,23	±0,08	±0,20

	D_{off} [m]	D_{eff} [m]	D_{TB} [m]	D_{TLO} [m]
Galkina	7,05	7,17	-,060	-,12
Xanthou	6,93	7,27	-,150	-,34
May	6,91	7,31	-,130	-,40
Drechsler	6,89	6,99	-,010	-,10
Joyner-Kersee	6,79	7,02	-,080	-,23
Tiedtke-Greene	6,77	6,90	-,080	-,13
Vershinina	6,71	6,83	-,100	-,12
Johanson	6,64	6,74	±,000	-,10
Khristova	6,64	6,85	-,060	-,21
Jones	6,63	6,89	-,140	-,26
Jasklofsky	6,61	6,81	-,180	-,20
mean	6,78	6,98	-,090	-,20
std. dev.	±0,15	±0,19	±0,06	±0,10

Table 66: Velocities of CM (m/s) and angle of projection (°) at take-off.
[v_{xTD}– horizontal velocity at touch-down, v_{xTO}– horizontal velocity at take-off; v_{yTO}- vertical velocity at take-off; *a* - angle of projection]
(a) Women's final ; (b) Men's final

name	**D_{off}**	**v_{xTD}**	**v_{xTO}**	**v_{yTO}**	**a**
Galkina	7,05	9,72	8,32	2,95	19,50
Xanthou	6,93	9,66	7,84	3,48	22,40
May	6,91	9,77	7,98	3,32	22,60
Drechsler	6,89	9,54	8,43	2,88	18,90
Joyner-Kersee	6,78	9,94	8,28	2,88	19,20
Tiedtke-Greene	6,77	9,36	7,93	3,05	21,10
Vershinina	6,71	9,33	7,79	3,17	22,60
Johanson	6,64	9,13	7,55	3,27	28,50
Khristova	6,64	9,20	7,98	2,99	19,90
Jones	6,63	9,24	8,01	3,12	19,10
Jaklofsky	6,61	9,45	7,82	2,88	21,30
mean	6,78	9,49	7,99	3,09	21,37
std. dev.	±0,15	±0,26	±0,26	±0,20	±2,34

name	**D_{off}**	**v_{xTD}**	**v_{xTO}**	**v_{yTO}**	**a**
Pedroso	8,42	10,82	8,72	3,86	23,90
Walder	8,30	10,78	8,76	3,41	21,30
Sosunov	8,18	10,81	8,65	3,66	22,30
Dilworth	7,88	10,52	9,24	3,45	20,50
Beckford	8,07	10,75	8,53	3,48	22,20
Ferreira Jr.	8,04	10,47	8,87	3,10	19,30
Toure	7,98	10,73	8,79	3,09	19,40
Jianfeng	7,76	10,71	9,04	3,13	19,10
Glavatski	8,03	10,32	8,59	3,35	21,30
Morigana	7,70	10,51	8,88	3,19	19,70
mean	8,04	10,64	8,81	3,36	20,90
std. dev.	±0,23	±0,17	±0,21	±0,24	±1,58

Table 67: Stride lengths of the last three strides [m]
(a) women's final ; **(b)** men's final

name	D_{off}	3rd last stride	2nd last stride	1st last stride
Galkina	7,05	2,18	2,41	2,07
Xanthou	6,93	2,16	2,12	2,27
May	6,91	2,30	2,29	2,25
Drechsler	6,89	2,24	2,48	2,03
Joyner-Kersee	6,78	2,33	2,16	2,16
Tiedtke-Greene	6,77	2,28	2,49	2,30
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
Jones	6,63	1,52	1,89	2,06
Jaklofsky	6,61	2,23	2,19	2,35
mean	6,78	2,15	2,26	2,19
std. dev.	±0,15	±0,14	±0,15	±0,13

name	D_{off}	3rd last stride	2nd last stride	1st last stride
Pedroso	8,42	2,28	2,43	2,16
Walder	8,30	-	2,61	2,22
Sosunov	8,18	-	2,50	2,40
Dilworth	7,88	-	2,45	2,21
Beckford	8,07	2,49	2,45	2,13
Ferreira Jr.	8,04	2,31	2,24	2,27
Toure	7,98	2,54	2,05	2,34
Jianfeng	7,76	2,17	2,32	2,35
Glavatski	8,03	2,52	2,33	2,10
Morigana	7,70	2,40	2,31	2,11
mean	8,04	2,37	2,37	2,23
std. dev.	±0,23	±0,15	±0,16	±0,11

Men's final: The run-up precision was quite good, with an average loss of 0.09m ±0.05 at the take-off board. This together with the loss of distance of, on average, 0.20m (±0.10m), with individual trends. Glavatskis' run-up accuracy and his total lost distance (0,05 m) gave him a better competition result than, for example, Dilworth, who lost distance dramatically in the sand and on the take-off board (total: 0.80 m). Pedroso's data was close to the average values, but it still show just average run-up accuracy and a total loss of 0.25 cm. Walder and Sosunov followed the trend.

The speed of the CM at the instant of touch-down into the take-off is of major importance for a good result. The initial velocity provides the jumper with mechanical energy for the take-off. In elite groups a high run-up velocity is present, but not sufficient for a good performance.

Much more important seems to be the generation of vertical velocity of the CM at the instant of take-off, without any great loss of horizontal velocity. This trend is confirmed by the data from Athens. Pedroso could produce the highest CM vertical take-off velocity of all finalists with 3.86m/s (second place Walder: 3.31m/s), although his horizontal velocity at touchdown (10.82 m/s) and at take-off (8.72m/s) was lower than, for example Walder's (11.12 m/s and 9.29 m/s). For comparison: Powell's vertical take-off velocity was measured 3.7 m/s in Tokyo (1991) when he jumped 8.95m, his horizontal CM's velocity at touch-down was 11.0 m/s and at take-off 9.09 m/s. The equivalent data for Lewis in his wind supported 9.91 m jump were: 3.22 m/s, 11.06 m/s and 9.72 m/s.

The angle of projection data confirm the different behavior of Pedroso during the 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 66). The analysis of stride length of the last three strides reveals a general behavior with a "long-short" for the last two strides. This adjustment of stride length allows the jumper to lower his CM in the 2nd last to last stride. This allows the jumper to extend the vertical acceleration path during take-off. The data confirm this trend for the majority of the jumpers.

While the average stride length in the 2nd to last stride is 2.37 m (± 0.06 m), the mean in the last step is 2.23 m (± 0.10 m). Nearly all finalists shorten their stride length in the last step (except Ferreira, Jr.), on average by 0,14 m. As already mentioned, most of the finalists lowered their CM during the 2nd last stride by extending their stride length. This corresponds to the CM data (average decrease of 8 cm ± 2.4 cm). All jumpers (one exception: Walder) showed a lowered CM entering the take-off. From the 2nd last step to the take-off, the CM was raised vertically by approx. 4-6 cm.

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 of better jumpers losing less energy was not discernible.

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 6.81 m (std. dev. ± 0.14 m)· and the best (and only) jump over 7.00 m (Galkina 7.05 m), this competition follows the pattern of similar recent competitions (cf. table 66). It is interesting that the majority of the jumpers had an accurate run-up (average 0.08 ± 0.05 m). While, in terms of the total lost distance, the champion Galkina, showed optimal results (D_{TB} 0,06 m, D_{TL} 0,12 m), it seems that Xanthou and May lost first place due to a considerable loss of distance, both on the board and in the sand (Xanthou's D_{TL} 0,34 m and May's 0,40 m).

The absolute values of the horizontal run-up speed (table 66) are within the average for other studies (9,49 m/s ± 0,26 m/s) and approx. 1 m/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 Vy_{TO} (2.95 m/s) than the second or third-placed athletes. Both Xanthou and May jumped with a strong braking action during ground support and, therefore, had a greater loss of horizontal velocity (Xanthou from 9,66 m/s to 7,84 m/s and May from 9,77 m/s to 7,98 m/s). Higher Vy_{TO} (3,48 m/s and 3,32 m/s) and bigger angles of projection (24 and 23°) could not compensate for the loss of Vx_{TO}.

It is interesting that Joyner-Kersee, with 9,94 m/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 vertical velocity (Vy_{TO} of 2,88 m/s) and a small angle of projection (19°).

Data of the stride lengths during the last three strides (table 67) generally confirm the "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. 0,18 m; women's average difference approx. 0.18 m; women's approx. 0.08 m). Among the first four finalists, we can identify just one jumper (Galkina) who shows similar behaviour to the men (difference: 0.34 m). 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. 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 2,24 m./ ± 0,18 m men 2.23 m/± 0,10 m).

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 (-5.67 cm, ± 2.18 m), the men within the second to last stride (-8 cm, ± 2,39 cm).

Concerning the change of mechanical energy during take-off, one can observe that the female jumpers lost 11.38 % (± 2,58 %) of their 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.

Statistical Analysis

For both the men and the women 3 relatively homogeneous groups could be identified by the cluster analysis.

Women: Groups 1 and 2 didn't show a significant difference in the initial energy of the body, while group 2 had the lowest value (table 68). During the take-off the energy decrease from group 3 was the highest (table 69). For the other two groups no significant difference ($p<0.05$) was found. Because of the large energy loss of group 3 the end energy was the highest in group 1 (table 68 and figure 29). Although the transformations index in group 3 was the smallest the take-off angle of this group was significantly ($p<0.05$) larger than group 1 (table 69 and figure 29). The take-off angle of groups 2 and 3 showed no clear difference (table 68). The largest values for the jump distance and the effective distance were measured in groups 1 and 3 (table 68 and figure 30). For these two values group 2 had the smallest results (table 68). For loss at take-off and loss of distance all groups showed similar values (table 68).

The knee angle at take-off varied between group 3 and the other two groups (table 69). The minimum knee angle from group 3 is significantly ($p<0.05$) smaller compared to groups 1 and 2 (table 69). For the angle of projection at touchdown and angle of·projection at take-off no significant difference could be found among the groups (table 69).

The horizontal CM touchdown velocity was the lowest in group 2 (table 70). The horizontal and vertical CM take-off velocities from groups 2 and 3 showed no significant ($p<0.05$) differences (table 70).

Group 1 produced the highest horizontal CM take-off velocity and the lowest vertical CM take-off velocity of the three groups (table 70).

Between groups 1 and 3 over the last three steps no difference was found for total energy or horizontal CM velocity (table 71). Group 2 had again the lowest value for this parameter (table 71). The length of the last step was the same for all three groups (table 72). The length of the second and third to last steps were the longest in group 1 (table 72). No significant ($p<0.05$) differences among the three groups could be found in the sinking of the CM over the last three steps (table 72).

Men: From the men's competition groups 1 and 2 had the same beginning energy and group 3 showed the most beginning energy going into the take-off (table 73). Group 3 also had the largest energy loss and the lowest transformation index (table 73 and figure 31). Group 2 on the other hand had the lowest energy loss and the largest transformation index (table 73). Group 1 had the lowest take-off energy and the other two groups showed no significant difference (table 73). The take-off angles of groups 1 and 3 showed no significant ($p<0.05$) difference while group 2 had the lowest value (table 73 and figure 32). The largest values for jump distance and effective distance are found in group 1 (table 73 and figure 31). Statistically significant ($p<0.05$) differences of loss at the take-off and loss of distance could only be identified between groups 1 and 3 (table 73) where group 3 had the lower value. Differences among the groups could not be found for angle of projection at touchdown, angle of projection at take-off, hip or knee angles (table 74).

Group three also demonstrated the highest horizontal CM touch down velocity as well as the highest vertical CM take off velocity (table 75). A significant ($p<0.05$) difference between groups 1 and 2 was found only with the horizontal cm take off velocity (table 75). Over the last three steps before take off group 3 demonstrated the highest values for both total energy and horizontal CM velocity (table 76). There was no apparent differences among the three groups in stride length or lowering of the CM (table 77).

Discussion

From the results it is clear that both the men's and women's groups can be divided into two primary jumping styles which demonstrate the same starting characteristics and achieve the same effective jump distance and jump distance. Groups 1 and 2 from the men and groups 1 and 3 from the women produced the same starting energy. During the take off the energy loss for group 1 from the men and group 3 from the women was more than the other groups. The importance of this observation is that both groups showed less energy and a larger take off angle at the end of the take off phase in comparison to groups 2 (men) and 1 (women) (tables 68 and 70). The relationship between the horizontal and vertical velocities in groups 1 (men) and 3 (women) also varied. Group 1 from the women produced a higher horizontal and a lower vertical take off velocity as group 3 (table 70). Men's groups 1 and 2 differ significantly ($p<0.05$) only in the horizontal take off velocity, by which group 2 demonstrated the higher value (table 75). The touchdown angles of groups 1 and 2 (men) and groups 1 and 3 (women) were the same (tables 70 and 75). From these findings it doesn't seem productive to search through experimental data trying to determine which of the take of parameters, vertical or horizontal velocity, plays a larger role in the jump distance (Ballreich 1970, Kollath 1980, 1982; Quade and Sahre 1989, Lees et al. 1993, 1994). As the group specific data from elite long jumpers indicates, various combinations of the two components can result in the same jump distances.

Group 3 from the men had farthest jump distance and group 2 from the women had the shortest jump distance (tables 68 and 73). During the take off phase the relationship between group 3 and the other groups varied. Group 3 had the largest energy loss and the lowest transformation index (table 73). The joint angles and angles of projection at touch down and take-off from group 3 showed no obvious differences with the other groups (table 74). One possible explanation for this relationship is that differing muscle stiffness may have played a role. It is very possible that the muscle stiffness differed between the groups.

Because group 3 produced the highest starting energy as well as the highest energy loss they were able to achieve a higher end energy than group 1 and a higher take-off angle than group 2 (table 73). Group 3 also had the highest horizontal touch down velocity and the highest vertical take off velocity (table 75). Group 2 of the women demonstrated similar attributes during the take off phase (similar energy loss and transformation index). But because group 2 produced the lowest starting energy they also showed a lower end energy than group 1 (table 68). In spite of this the take-off angle of group 2 was higher. It is clear that at this level of competition that the starting energy, which is determined by the horizontal velocity at touch down, plays an important role in jump performance. It can not be concluded that the beginning energy alone determines the jump distance. There is a significant ($p<0.05$) correlation between beginning energy and jump distance but the corelation coefficients for the women ($r=0.57$) and the men ($r=0.54$) are very low. This indicates that the jump technique of the athletes plays an important role in the jump distance. During the take off phase there is always a decrease in energy. This energy loss does not necessarily directly effect the end energy, the take off angle, the horizontal or the vertical CM take off velocity. The energy loss showed no significant ($p<0.05$) corelation with these parameters. The results (comparison between men's groups 1 and 2 and women's groups 1 and 3) indicate that an energy loss does not necessarily result in a decrease in jump performance.

The transformation index is the quotient of take off angle divided by energy loss during the take off phase. As it was already mentioned in the methods section the distance (D_{TFL}) can be calculated as the function of the starting energy the energy loss and the transformation index (equation 6). Figure 33 shows the distance (D_{TFL}) as a function of energy loss with various transformation indexes and a given starting energy ($E_{init}=56.12$ Joule/kg, initial energy from Galkinas best jumps). In figure 33 the actual values (effective distance and energy loss) of the world champion were used. It is important to note that an improvement in jump distance (D_{TFL}) can be achieved through a higher transformation index with the same energy loss or with a greater energy loss with the same transformation index. The examination of figures 29 and 31 shows that there is a relationship between energy loss and the transformation index. The correlation coefficient of the two parameters is $r=-0.91$, $p<0.001$ for both the men's and women's groups. This means that a higher energy loss with a lower transformation index can be achieved.

The transformation index appears also to be dependant on the beginning energy. A significant ($r=-0.67$, $p<0.001$ for the men and $r=-0.63$, $p<0.001$ for the women) correlation between the two parameters was found. This finding coincides with the results from Witters et al. (1992). They found that with an increase in approach velocity the conversion efficiency at take off was decreased. All of these relationships indicate that a) an optimal combination of energy loss and the transformation index exist, and b) the optimal combination is dependant on the initial conditions (initial energy). Through a multiple regression equation it was possible to calculate the relationship between the transformation index and both the start energy and the energy loss during the take-off phase for both the men's and women's groups. In both cases the multiple correlation coefficients were very high (r=0.94 for the women and r=0.91 for the men). Naturally these results can not be assigned to other sample groups. They do have a very high validity in the researched group and can be used here. The formula (6) can be altered so that the distance ($\boldsymbol{D_{TFL}}$) can be calculated as a function of beginning energy and the energy loss. Then it is possible to individually diagnose whether the beginning energy is effectively used to create the optimal take-off characteristics (figure 34 and table 78). For example, Drechsler has the highest beginning energy and therefore the possibility to jump the farthest. But in comparison to Galkina her take-off phase is not as effective and therefore the jump distance of Drechsler is less than that of Galkina. If Drechsler had an energy loss of about 5.3-5.8 J/kg she could jump 7.22 m with a take-off angle of 18.6-19 degrees. Galkina, in contrast, demonstrates almost optimal take-off characteristics and effectively uses the beginning energy that she produces. On the other hand Tiedtke and Jaklofsky showed too much energy loss during the take-off phase and were quiete far from attaining their optimal technique. Jaklofsky could jump farther than Tiedtke if she had an energy loss from 5.5 to 5.7 J/kg and therefore a take-off angle from 20.14 to 20.4 degrees (figure 34). In the men's group Walder had a starting energy of 69.5 J/kg which would allow him to jump 8.83 m if his take-off was optimal. An optimal take-off for him would be an energy loss from 7.7 to 8.3 J/kg (figure 34) and a take-off angle of 19.25 to 19.60 degrees. Sosunov demonstrated both too much energy loss (jumps 6 and 2) as well as too little energy loss (jumps 3 and 5) (figure 34). On his last jump he produced a starting energy of 67.35 J/kg which in the best case scenerio would produce an energy loss of 7.5- 8.1 J/kg, a take-off angle of 19.32 to 19.80 degrees and a jump distance of 8.57. With this information we can explain the results of the various groups (figure 35). Men's groups 1 and 2 produced the same amount of beginning energy and neither group demonstrated an optimal take-off phase. Group 1 demonstrated too much energy loss and group 2 too little. Both groups could have produced jumps of 8.24 m with an energy decrease of 7.7 to 8.0 J/kg and a take-off angle between 20.44 and 20.74 degrees. Group 3 demonstrated an even worse take-off phase. They could have jumped 28 cm further if they had had an energy loss between 7.4 and 8.4 J/kg and a take-off angle from 19.38 to 20.14 degrees.

In this study there were athletes and there were cases in which the transformation index from the two regression equations was not enough (figure 36). This variation could be explained through the differing conditional factors of the individual athletes. This means that the correlation between the transformation index and the energy loss and the beginning energy could be individual and should therefore be individually determined for use in daily practice. This information can be used to develop both long and short term strategies for maximizing jump distance. Long term, for example, planning would could be to prepare the athlete conditionally so that they can achieve a greater transformation index with the same energy loss. Short term could be to determine how much energy loss should take place so that the beginning energy can be optimally used.

Over the last three strides group 3 showed the highest beginning energy and also the best values for total energy and horizontal velocity (table 76). The two other groups showed no differences. Obvious differences among the various men's groups for stride length distribution and the lowering of the CM were not found (table 77). The lowering of the CM was seen in the men's and women's groups. The amount of CM lowering was the same in all three men's groups (table 72 and 77). Women's groups 1 and 3 had the same initial energy at the take-off phase and also no differences in total energy or horizontal velocity over the last three steps (table 71). Group 2 produced the lowest values for these parameters as well as for the beginning energy at touch down. These observations show that within the groups the athletes did not show any obvious changes in their initial parameters over the last three strides. The advantages/ disadvantages that the athletes in the various groups demonstrate with the initial energy is determined during the approach. Over the last three strides no obvious improvement or deterioration could be seen. For practical purposes it could be mentioned that - in respect to the analysed sample - the basic speed of the athlete is more important than is it modification in the preparation for the take-off.

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Table 68: Energy, transformation index, distances and angle of projection during the take off phase for the women's groups

Parameter	**Group1** (n=9)	**Group2** (n=11)	**Group3** (n=11)
Initial energy (Joule/kg)	55.73 (1.01)	52.38 (1.13)*	55.90 (1.08)$^{\perp}$
$E_{decrease}$ (Joule/kg)	5.40 (1.04)	5.21 (0.92)	7.83 (0.71)$^{*\perp}$
T_{index} (degrees/Joule/kg)	3.61 (0.69)	4.21 (0.72)	2.70 (0.32)$^{*\perp}$
Take off energy (Joule/kg)	50.32 (1.70)	47.17 (1.31)*	48.07 (1.10)*
angle of projection (degrees)	18.96 (1.54)	21.41 (1.73)*	20.97 (1.66)*
D_{eff} (m)	7.01 (0.17)	6.76 (0.15)*	6.98 (0.26)$^{\perp}$
D_{off} (m)	6.82 (0.13)	6.60 (0.12)*	6.73 (0.17)$^{\perp}$
D_{TLO} (m)	0.20 (0.14)	0.16 (0.07)	0.25 (0.14)
D_{TB} (m)	0.09 (0.05)	0.09 (0.04)	0.12 (0.09)

* : Statistically significant difference between groups 1 and 2, and between 1 and 3 ($p<0.05$)
⊥ : Statistically significant difference between groups 2 and 3 ($p<0.05$)

Table 69: Body angle at touch down, body angle at take-off and joint angles of the support leg during the take off phase for the women (degrees).

Parameter	**Group1** (n=9)	**Group2** (n=11)	**Group3** (n=11)
Hip angle at touch down	146 (5)	147 (6)	151 (5)*
Hip angle at take off	202 (6)	197 (9)	205 (5)$^{\perp}$
Knee angle at touch down	159 (6)	161 (5)	162 (3)
Minimum knee angle	137 (3)	139 (7)	131 (6)$^{*\perp}$
Knee angle at take off	173 (5)	171 (6)	175 (4)
Body angle at touch down	51 (4)	53 (3)	52 (3)
Body angle at take off	107 (4)	107 (4)	108 (4)

* : Statistically significant difference between groups 1 and 2, and between 1 and 3 ($p<0.05$)
⊥ : Statistically significant difference between groups 2 and 3 ($p<0.05$)

Table 70: Horizontal and vertical CM velocities during the take off phase for women (m/s)

Parameter	**Group1** (n=9)	**Group2** (n=11)	**Group3** (n=11)
Horizontal velocity at touch-down	9.62 (0.09)	9.53 (0.11)*	9.65 (0.14)$^{\perp}$
Horizontal take off velocity	8.29 (0.23	7.83 (0.24)*	7.97 (0.21)*
Vertical take off velocity	2.84 (0.18)	3.05 (0.19)*	3.07 (0.23)*

∗ : Statistically significant difference between groups 1 and 2, and between 1 and 3 ($p<0.05$)
⊥ : Statistically significant difference between groups 2 and 3 ($p<0.05$)

Table 71: Mechanical energy and CM velocities over the last three strides before take off for the women.

Parameter	**Group1** (n=9)	**Group2** (n=11)	**Group3** (n=11)
Total mechanical energy at take off from the last step (Joule/kg)	55.73 (1.01)	52.38 (1.13)*	55.90 (1.08)$^{\perp}$
Total energy at take off into the second to last step (Joule/kg)	56.85 (1.47)	53.23 (1.53)*	55.01 (1.36)$^{\perp}$
Total energy at take off into the third to last step (Joule/kg)	55.85 (1.55)	53.42 (1.38)	56.14 (0.67)$^{\perp}$
Energy change during the last two support phases prior to take off (Joule/kg)	-0.23 (1.16)	-1.08 (1.22)	-0.25 (1.06)
Horizontal CM velocity at take off of the last step (m/s)	9.62 (0.09)	9.26 (0.11)*	9.65 (0.14)$^{\perp}$
Horizontal CM velocity at take off of the second to last step (m/s)	9.64 (0.13)	9.28 (0.16)*	9.50 (0.17)$^{\perp}$
Horizontal CM velocity at take off of the third to last step (m/s)	9.52 (0.13)	9.31 (0.16)*	9.59 (0.08)$^{\perp}$

∗ : Statistically significant difference between groups 1 and 2, and between 1 and 3 ($p<0.05$)
⊥ : Statistically significant difference between groups 2 and 3 ($p<0.05$)

Table 72: Stride lengths and CM height during the last three strides Prior to take off for the women's groups (m)

Parameter	Group1 (n=9)	Group2 (n=11)	Group3 (n=11)
Length of the last stride	2.12 (0.14)	2.21 (0.18)	2.17 (0.15)
Length of the second to last stride	2.46 (0.16)	2.24 (0.24)*	2.23 (0.11)*
Length of the third to last stride	2.22 (0.08)	2.03 (0.24)*	2.28 (0.13)$^{\perp}$
CM height at take off	1.21 (0.06)	1.21 (0.04)	1.18 (0.05)
CM height at touch down for the take off	0.94 (0.06)	0.93 (0.03)	0.90 (0.05)
CM height at take off in the last step	0.97 (0.06)	0.97 (0.02)	0.95 (0.05)
CM height at touch-down into the last stride	0.99 (0.05)	0.98 (0.04)	0.99 (0.05)
CM height at take off of the second to last step	1.06 (0.06)	1.03 (0.04)	1.01 (0.04)
CM height touch-down of the second to last step	1.05 (0.07)	1.01 (0.03)	1.00 (0.03)

* : Statistically significant difference between groups 1 and 2, and between 1 and 3 ($p<0.05$)

⊥ : Statistically significant difference between groups 2 and 3 ($p<0.05$)

Table 73: Mechanical energy, transformation index, distances and angle of projection during the take off phase for the men's groups

Parameter	Group1 (n=12)	Group2 (n=6)	Group3 (n=13)
Initial energy (Joule/kg)	64.19 (1.43)	64.33 (1.16)	67.78 (1.13)$^{*\perp}$
$E_{decrease}$ (Joule/kg)	9.12 (0.72)	7.03 (0.52)*	11.02 (1.12)$^{*\perp}$
T_{index} (degrees/Joule/kg)	2.20 (0.24)	2.69 (0.18)*	1.91 (0.17)$^{*\perp}$
Total energy (Joule/kg)	55.07 (1.51)	57.30 (1.11)*	56.76 (1.56)*
a (degrees)	19.98 (1.50)	18.85 (0.24)*	20.78 (1.49)$^{\perp}$
D_{eff} (m)	8.10 (0.18)	8.17 (0.04)	8.37 (0.18)$^{*\perp}$
D_{off} (m)	7.94 (0.17)	7.95 (0.09)	8.08 (0.22)$^{*\perp}$
D_{TLO} (m)	0.17 (0.12)	0.23 (0.08)	0.29 (0.13)*
D_{TB} (m)	0.05 (0.03)	0.10 (0.09)	0.11 (0.07)*

* : Statistically significant difference between groups 1 and 2, and between 1 and 3 ($p<0.05$)

⊥ : Statistically significant difference between groups 2 and 3 ($p<0.05$)

Table 74: Body angle at touch down, body angle at take-off and joint angles of the support leg during the take off phase for the men (degrees).

Parameter	**Group1** (n=12)	**Group2** (n=6)	**Group3** (n=13)
Hip angle at touch-down	149 (5)	149 (4)	152 (6)
Hip angle at take off	201 (6)	196 (5)	197 (9)
Knee angle at touch-down	166 (5)	167 (3)	166 (6)
Minimum knee angle	131 (7)	131 (9)	135 (10)
Knee angle at take off	176 (6)	169 (7)	171 (10)
Body angle at touch down	48 (4)	47 (5)	47 (4)
Body angle at take off	109 (4)	110 (4)	108 (5)

* : Statistically significant difference between groups 1 and 2, and between 1 and 3 ($p<0.05$)
⊥ : Statistically significant difference between groups 2 and 3 ($p<0.05$)

Table 75: Horizontal and vertical CM velocities during the take off phase for men (m/s)

Parameter	**Group1** (n=12)	**Group2** (n=6)	**Group3** (n=13)
Horizontal velocity at touch-down	10.51 (0.14)	10.49 (0.10)	10.81 (0.10)$^{*\perp}$
Horizontal take off velocity	8.75 (0.23)	9.01 (0.13)*	8.84 (0.20)*
Vertical take off velocity	3.18 (0.19)	3.08 (0.05)	3.35 (0.21)$^{*\perp}$

* : Statistically significant difference between groups 1 and 2, and between 1 and 3 ($p<0.05$)
⊥ : Statistically significant difference between groups 2 and 3 ($p<0.05$)

Table 76: Energy and CM velocities during the last three strides before take off for the men

Parameter	**Group1** (n=12)	**Group2** (n=6)	**Group3** (n=13)
Total mechanical energy at take off from the last step (Joule/kg)	64.19 (1.43)	64.33 (1.16)	67.78 (1.13)$^{*\perp}$
Total energy at take off into the second to last step (Joule/kg)	64.82 (2.41)	66.43 (2.77)	67.62 (3.09)*
Total energy at take off into the third to last step (Joule/kg)	65.63 (1.96)	-	69.50 (2.27)*
Energy change during the last two support phases prior to take off (Joule/kg)	-1.62 (1.55)	-	-1.30 (2.37)
Horizontal CM velocity at take off of the last step (m/s)	10.51 (0.14)	10.49 (0.10)	10.81 (0.10)$^{*\perp}$
Horizontal CM velocity at take off of the second to last step (m/s)	10.47 (0.22)	10.61 (0.27)	10.70 (0.29)*
Horizontal CM velocity at take off of the third to last step (m/s)	10.55 (0.19)	-	10.86 (0.21)*

$*$: Statistically significant difference between groups 1 and 2, and between 1 and 3 ($p<0.05$)

$\perp$: Statistically significant difference between groups 2 and 3 ($p<0.05$)

Table 77: Stride lengths and CM height during the last three strides before take off for the men's groups (m)

Parameter	**Group1** (n=12)	**Group2** (n=6)	**Group3** (n=13)
Length of the last stride	2.24 (0.19)	2.35 (0.07)	2.28 (0.09)
Length of the second to last stride	2.32 (0.11)	2.40 (0.10)	2.41 (0.17)
Length of the third to last stride	2.31 (0.16)	-	2.35 (0.12)
CM height at take off	1.19 (0.08)	1.21 (0.02)	1.22 (0.05)
CM height at touch-down for the take-off	0.90 (0.06)	0.94 (0.03)	0.93 (0.04)
CM height at take off for the last step	0.92 (0.05)	0.95 (0.02)	0.94 (0.04)
CM height at touch-down into the last stride	0.95 (0.06)	0.98 (0.03)	0.96 (0.04)
CM height at take off of the Second to last step	1.01 (0.06)	1.04 (0.02)	1.04 (0.03)
CM height at touch-down of the second to last step	1.01 (0.06)	1.04 (0.03)	1.05 (0.04)

$*$: Statistically significant difference between groups 1 and 2, and between 1 and 3 ($p<0.05$)

$\perp$: Statistically significant difference between groups 2 and 3 ($p<0.05$)

Table 78: Measured and optimal values of the effective jump distance, the energy decrease and the take off angles

Name	D_{eff} (m)	$E_{decrease}$ (J/kg)	a (degrees)	D_{opt} (m)	$E_{decrease/opt}$ (J/kg)	a_{opt} (degrees)
Drechsler	7.13	4.38	16.9	7.22	5.30–5.80	18.60–19.00
Tiedtke	6.98	6.71	21.4	7.06	5.40-5.90	20.88–21.47
Jaklofsky	6.64	8.47	20.2	7.13	5.50-5.70	20.14–20.40
Galkina	7.17	5.88	19.5	7.16	5.56-5.80	19.96–20.18
Walder(3)	8.58	10.35	19.5	8.79	7.45-8.30	19.12–19.75
Walder(4)	8.43	11.03	21.2	8.83	7.70-8.30	19.25-19.60
Sosunov(6)	8.46	12.05	22.3	8.57	7.40-8.30	19.23–19.87
Sosunov(3)	8.18	6.41	18.5	8.30	7.50-8.20	20.31–20.92
Sosunov(2)	8.05	9.87	20.7	8.22	7.70-8.30	20.75–21.19
Sosunov(5)	8.12	6.81	19.0	8.20	7.35-8.30	20.35–21.24

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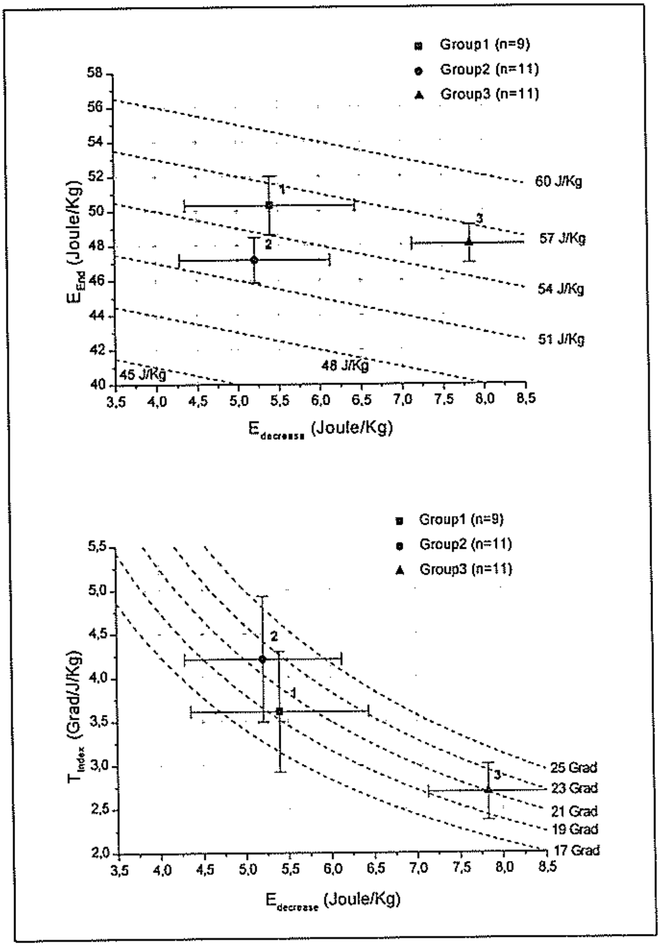


Figure 29: Energy at take-off in relation to the initial energy and the energy decrease. Transformation index in relation to the energy decrease and the take-off angle (women)

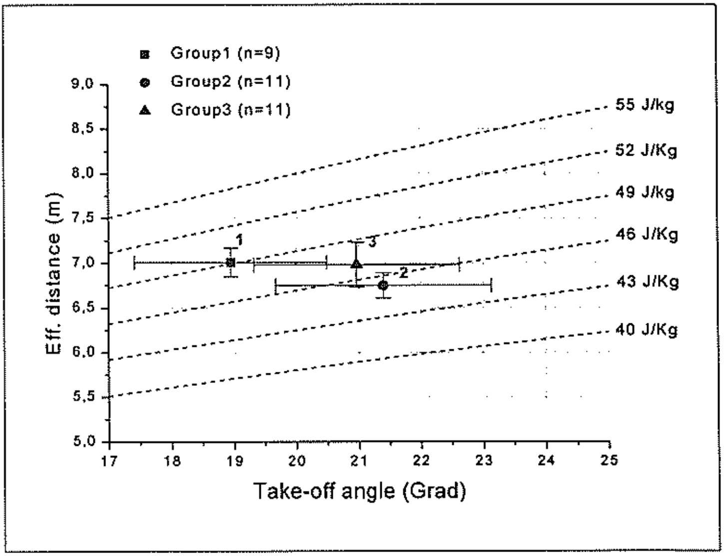


Figure 30: The effective distance in relation to the total energy at take-off and angle of projection (women)

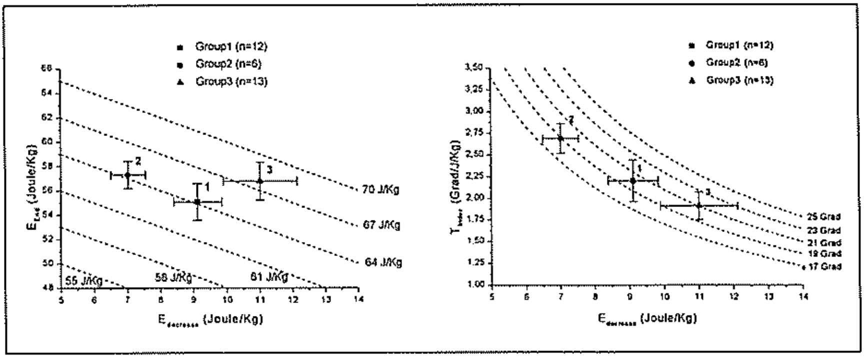


Figure 31: Total energy at take-off in relation to the initial energy and the energy decrease. Transformation index in relation to the energy decrease and angle of projection (men)

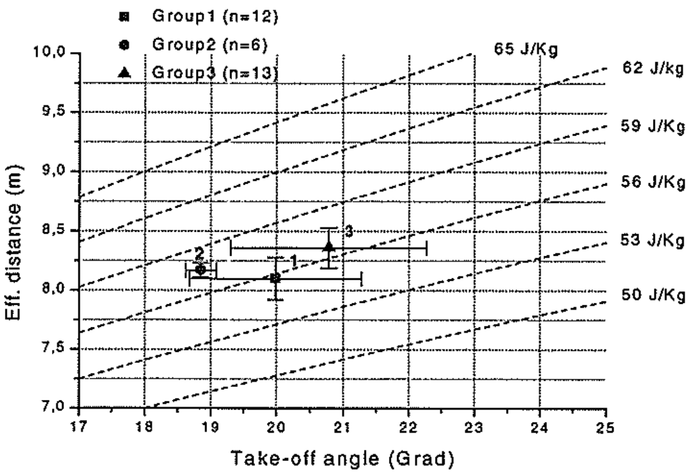


Figure 32: The effective distance in relation to the end energy and the take-off angle (men)

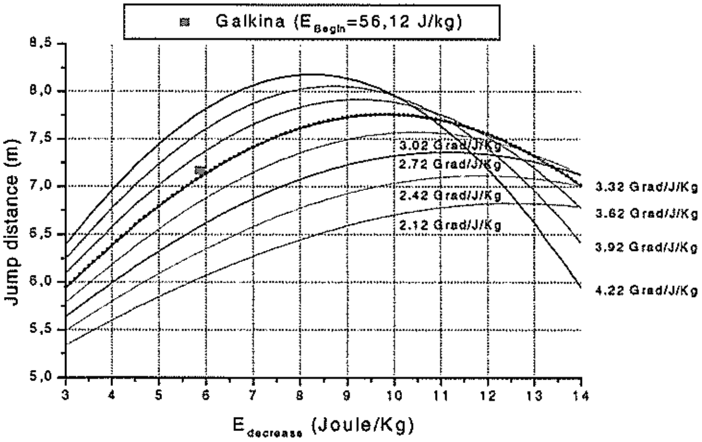


Figure 33: Distance in relation to energy decrease with various transformation index and a constant initial energy

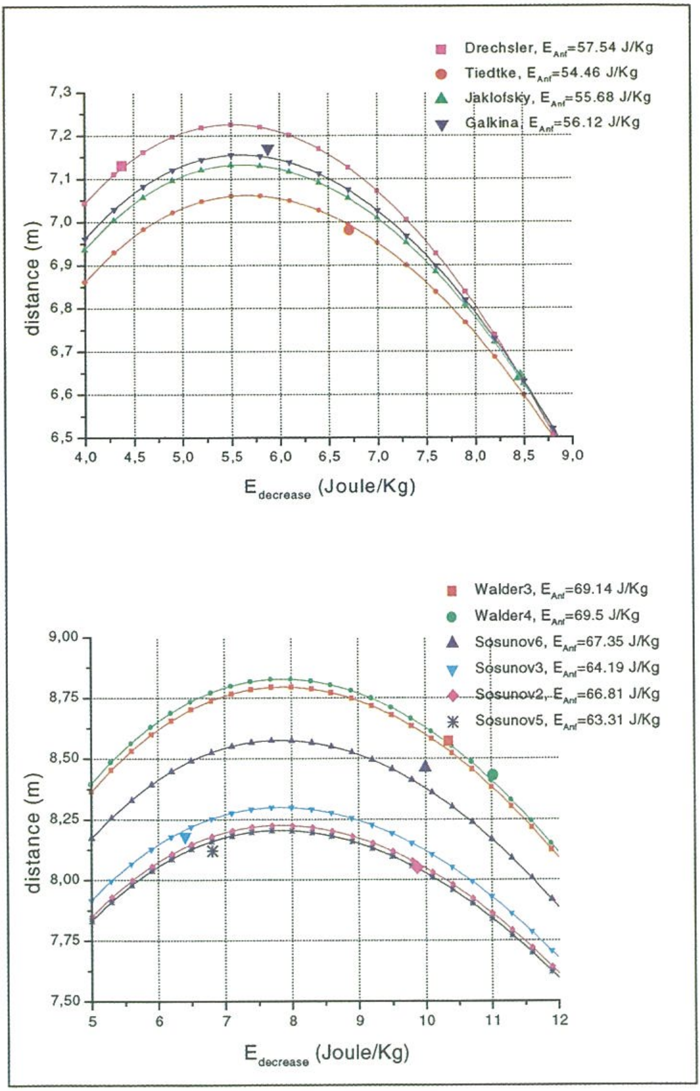


Figure 34: Distance in relation to the energy decrease

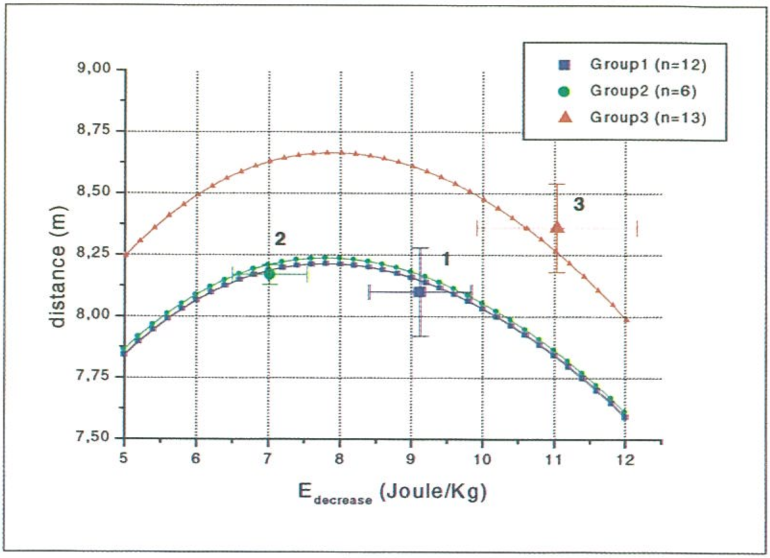


Figure 35: Distance in relation to the energy decrease (men)

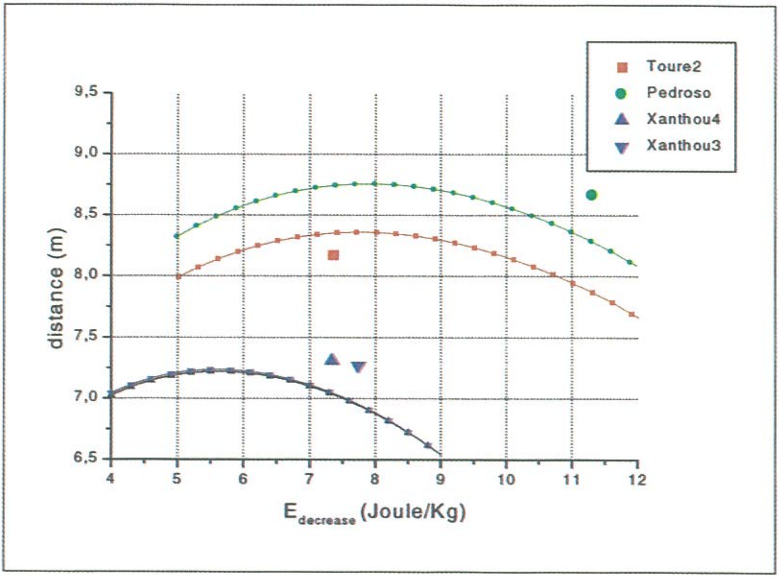


Figure 36: Distance in relation to the energy decrease

2.2.2 Triple Jump

G.-P. Brüggemann and A. Arampatzis

Introduction

Multiple jumps were popular events at ancient town festivals in many cultures. Triple jumps were a well known exercise with Gutsmuths and Jahn. In the 19th century German gymnastic pioneers practiced a so-called German triple jump“ (left-right-left or vice versa). The Irish technique (hop-hop-jump) was dominant when modern athletics became established. In 1887 the Irishman J.Purcell jumped 15.11 m with this technique. The present technique (hop-step-jump) was already becoming dominant by the end of the 19th century. J.Connolly (USA) was the first Olympic champion in 1896 with a jump of 13.71 m. The first IAAF world record was registered in 1911 with a jump of 15.12 m by D.Ahearn (USA). The triple jump scene in the 1930’s was dominated by various Japanese, e.g. N.Tajima won 1936 in Berlin with 16.00 m. The Brazilian Ferreira da Silva attracted a lot of attention after 1955. He set five world records (1955: 16.56 m) and was Olympic champion in 1952 and 1956. In 1960 J.Schmidt (POL) was the first to break the 17 m barrier with a jump of 17.03 m. W.Banks (USA) was the first to approach the 18 m mark with 17.97 m in 1995. The Olympic gold medalist 1992 could not officially break the barrier either despite jumping 18.17 m to win the Olympic competition in Barcelona. This distance could only be acknowledged for the Olympic victory because it was wind assisted. J.Edwards achieved considerable improvements of the world record and became world champion in 1995 with 18.29 m. The second person to jump further than 18.00 m was K.Harrison (USA) 1996 in Atlanta (18.09 m).

Despite the fact that the IAAF did not introduce the triple jump for women for a long time because the injury risk to the ankles, due to extreme forces during the take off being regarded as too high, many women’s triple jump distances are known from earlier times. The first known distance is 8.805 m jumped by C.Hand (USA) in 1909. In the 1980’s more and more countries introduced the triple jump into their national competitions. The IAAF holds a world record list since 1.1.1990. 1990 Li Huirong (CHN) jumped 14.54 m. When the event was first included in the World Championships programme, 1993 in

Stuttgart, A.Birykowa (RUS) was the first female to jump further than 15.00 m with 15.09 m. I.Krawets (UKR) improved the record to 15.50 m at the World Championships in Gothenburg 1995.

Recently the top female triple jumpers have been able to reach approximately 84 % of the total distance of the male athletes. The increase or change of percentage from the World Championships 1993 to 1997 is negligible (see table 79).

Table 79: 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)	17.26 m	17.41 m	17.42 m	14.32 m (82.96%)*	14.77 m (84.8 %)*	14.57 m (83.6%)*
std. dev.	± 0.34 m	± 0.46 m	± 0.30 m	± 0.39 m	± 0.50 m	± 0.44 m
maximum	17.86 m	18.29 m	17.85 m	15.09 m (84.5%)*	15.50 m (84.7%)*	15.20 m (85.1%)*
minimum	16.65 m	16.93 m	17.11 m	13.80 m	14.18 m	14.02 m

* percentage of the men's values

It is remarkable that the means of the official distances in the men's and women's final did not differ significantly ($p<0.05$) from 1993 to 1997. This means the average performance in the triple jump did not significantly increase in the last three World Championships when studying the eight finalists of each event.

In the short sprint events the relative difference between men's and women's performances is smaller and is indicated by a percentage of approximately 10 %. If the capacity to reach a high running speed, and to produce a high amount of kinetic energy in the sprint run, is very high in females in relation to male athletes, and if the difference in the performance in the triple jump (and in other horizontal and vertical jumps) between men and women is higher in relation to sprint, the question arises what are the biomechanical reasons why female athletes are not using their energy potential in multiple jumps. Technical deficits or training strategies may play a significant roll in explaining this phenomenon.

The purpose of this study is to present the first description of biomechanical data from the women's triple jump final from an international competition and to proceed in the approach on the utilisation of mechanical energy during multiple jumping. In order to perform a basis for data comparison the data of the men's final will also be presented.

Methods and procedures

The triple jump finals of the Track and Field World Championships 1997 were recorded 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 steps of the approach, cameras 2, 3, and 4 were focused on the hop, the step, and the jump, respectively. In addition to the described set-up one highspeed video camera (motionscope, redlake) operating at 250 frames per second filmed the take off for the step and a second highspeed 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 of the relevant video sequences these 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 3D-DLT was used for camera calibration and coordinate reconstruction. The coordinate system used had its x-axis along the runway, pointed in the jumping direction. The y-axis was vertical and perpendicular to the x-axis. The origin was fixed in the middle 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. Two feet, two shanks, two thighs, a trunk, the upper arms, the forearms with hands, and the head with the neck represented the rigid body model. The best valid jump from each of the eight finalists of men's and women's competition were selected for further analysis.

In order to get more run-up information a photocell system was installed at 11 m, 6 m, and 1 m to the board. The instantaneous run-up speed of the athletes was measured by a laser system installed behind the runway. The system's operator used an optical control device to follow the athlete's low back during the entire approach run, the hop, the step, and the jump. Using the known speed of infra-red 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 field.

Results

Distances: In the triple jump the success or the total distance of the jump depends on the distribution of the effort of the jumper over the three phases the hop, the step and the jump. Major emphasis of coaches and scientists has therefore been on the understanding of an optimal distribution of distances of the three jumps in the men's triple jump. No scientific data are available for women's competitive triple jumps. Effort distribution is usually analyzed by the absolute and relative distances achieved in each of the jumps. The distances are usually measured perpendicular to the pit edge of the take off board. The partial distances are defined 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 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 for the jump to the nearest mark made in the sand by the heels at the instant of touching the ground.

The **effective** distance D_{eff} 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 distance ratios, or distance percentages, of hop, step and jump are calculated as a percentage of the effective distance.

The **official distance** D_{off} 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** D_{TB} (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 or toe-to-board space are summarised to the **total lost distance** D_{TLO}.

The data for all the absolute distances are given in table 80 for the women's final and in table 81 for the men's final. The tables include the data for the best valid jump of each competitor.

Table 80: Official, effective, total lost and toe-to-board distances - **women's** final World Championships 1997

Name	D_{off} [m]	D_{eff} [m]	D_{TLO} [m]	D_{TB} [m]
Kasparkova	15.20	15.46	0.26	0.07
Mateescu	15.16	15.44	0.28	0.08
Govorova	14.67	14.82	0.15	0.12
Vasdeki	14.62	14.72	0.10	0.08
Hansen	14.49	14.69	0.20	0.09
Marinova	14.34	14.54	0.20	0.11
Blazevica	14.06	14.29	0.23	0.15
Lise	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 81: Official, effective, total lost and toe-to-board distances - **men's** final World Championships 1997

name	D_{off} [m]	D_{eff} [m]	D_{TLO} [m]	D_{TB} [m]
Quesada	17,85	18,08	0,23	0,12
Edwards	17,69	17,91	0,22	0,14
Urrutia	17,64	17,77	0,13	0,10
Kapustin	17,59	17,86	0,27	0,14
Wellman	17,22	17,66	0,44	0,13
Romain	17,14	17,57	0,43	0,37
Meletoglou	17,12	17,50	0,38	0,24
Owusu	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**

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

The partial distances and the ratios are listed in tables 82 and 83. The men's data give an average effort distribution of 36.14% (±0.88) - 29.39% (±1.20) - 34.46% (±1.15) while the mean ratio of the female is 36.63 %(±1.22) - 27.70% (±1.71) - 35.67% (±1.05). The analysis of variance indicate a significant ($p<0.05$) difference in the relative step and jump lengths between the male and the female triple jumpers.

To simplify the discussion of different ratios or distance distribution strategies 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 then the jump percentage. A jump dominated technique is one in which the jump percentage is at least 2 % greater then the hop percentage and a balanced technique is one in which neither the hop or the jump percentage is at least 2 % greater then the other. On the background of this definition the means of both groups indicate a more balanced technique in average. This general trend does not hold when regarding the individual distribution strategies. Two women and four men used the hop dominated technique, six female and four male jumpers chose a more balanced technique. No jump dominated trial was identified. The subgroups with the hop dominated technique reached average effective distances of 17.76 m (men) and 14.53 m (women). For the groups using the balanced technique 17.69 m (men) and 14.86 m (women) was measured as the effective distance. 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 balanced and the hop dominated technique showed slightly better results.

Table 82: Absolute and relative phase distances
- **women's** final World Championships 1997

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

Table 83: Absolute and relative phase distances
- **men's** final World Championships 1997

name	**hop**	**step**	**jump**	**technique**
Quesada	6.68 m (37.0 %)	5.21 m (28.8 %)	6,19 m (34.2 %)	hop dominated
Edwards	6.34 m (35.4 %)	5.21 m (29.1 %)	6.35 m (35.5 %)	balanced
Urrutia	6.54 m (36.8 %)	5.47 m (30.8 %)	5.76 m (32.3 %)	hop dominated
Kapustin	6.26 m (35.1 %)	5.20 m (29.1 %)	6.40 m (35.8 %)	balanced
Wellman	6.33 m (35.8 %)	5.44 m (30.8 %)	5.90 m (33.4 %)	hop dominated
Romain	6.57 m (37.4 %)	4.88 m (27.8 %)	6.12 m (34.8 %)	hop dominated
Meletoglou	6.16 m (35.2 %)	5.36 m (30.6 %)	5.98 m (34.2 %)	balanced
Owusu	6.38 m (36.5 %)	4.92 m (28.2 %)	6.18 m (35.3 %)	balanced
mean	**6.41 m (36.14 %)**	**5.21 m (29.39 %)**	**6.11 m (34.46 %)**	
std. dev.	**± 0.17 m (0.88 %)**	**± 0.22 m (1.20 %)**	**± 0.22 m (1.15 %)**	

No statistically significant ($p<0.05$) correlations could be found between the partial distances 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 precision in high 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 mostly balanced technique in the female triple jumpers.

Approach: In horizontal jumps the run-up velocity is of major importance for a successful performance. A high horizontal centre of mass (CM) velocity at the instant of touch-down for the take off into the hop is the necessary prerequisite for a top 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 view it is to analyze if the individual jumper has the capacity to manage and use the maximum energy available or producable during the approach run. In addition to the production of sufficient kinetic energy for the jump the run-up has to be as precise as possible in order to minimize the loss of distance on the board. Therefore the speed of the CM during the last strides and the stride lengths have been analyzed for the female and male competitors in the finals.

Table 84: Lengths of the last strides of the run-up and CM's horizontal velocity at take off into the 2nd last and the last strides

	stride length (m)		**CM velocities (m/s)**			**stride length (m)**		**CM velocities (m/s)**	
women	**2nd last**	**1st last**	**2nd last**	**1st last**	**men**	**2nd last**	**1st last**	**2nd last**	**1st last**
Kasparko.	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	Meletog.	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**

The means of the stride lengths of the women and the men were longer than the reported stride lengths during the long jump finals in Rome 1987. While the men demonstrated with no exception the strategy long-short for the last strides, a strategy generally observed in the long jump (Hay 1974, Hay and Miller 1984), for the women an exception to the rule could be found in 3 of 8 jumpers. The variation of 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 ±0.15m/s for the male finalists. The initial velocity of the women was calculated as 89 % of the men's. This data supports the hypothesis that the female athletes are able to produce about 90 % of the amount of kinetic energy produced by the men while running (see above). The men's data in average are as high as reported from top jumpers by Miller and Hay 1986. The mean is higher than ever described in the literature. All men accelerated in the last two steps 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 stabilized 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 to minimize speed reduction and energy loss during the hop.

The correlation analysis indicates a significant ($p<0.05$) linear correlation between the CM's 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 the point that a high run-up speed or a high initial velocity prior to the take off for the hop is a necessary precondition but not sufficient 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's horizontal velocity prior to take off into the hop and the horizontal speed of the CM 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 major importance of the run-up speed for the women, whereas the male triple jumpers have to have a speed of more than 10.0 m/s as a prerequisite but additional parameters during the three take off actions are of major influence to total performance.

Hop, step and jump: During the take off for the hop the horizontal CM velocity decreases and vertical velocity is achieved. The horizontal velocities at take off for the hop were 8.40 ±0.23m/s for the women and 9.77 ±0.15m/s for the men. The decreases in the horizontal velocity were 0.92±0.08m/s and 0.71±0.10m/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 both group of competitors. The mean men's vertical velocity is measured as 2.40 ±0.16m/s and the speed of the female jumpers as 2.34±0.25m/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 more flat in relation to the women's. This is caused by the higher horizontal CM velocity and a more or less same vertical speed at take off.

Table 85: Horizontal (vx) and vertical (vy) CM velocities at take off for the hop, the step and the jump - **women's** final World Championships 1997 (m/s)

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 86: Horizontal (vx) and vertical (vy) CM velocities at take off for the hop, the step and the jump - **men's** final World Championships 1997 (m/s)

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**

The kinetic energy achieved in the approach and available at the touch-down 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 of the means is highly significant ($p<0.001$). The male elite triple jumpers demonstrated the capacity to take off with only very little energy loss. Such an extreme low value of energy decrease implies an excellent capacity to re-utilize 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 segment seems to play the important role in minimizing the 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 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 degrees more in the female group than in the male group. The range of maximum knee flexion during the take off support in the women's finalists was recorded as 34 to 55 degrees and in the men's group as 31 to 51 degrees. With some reservations it can be concluded that the male jumpers are able to perform the take off with a more stiff support leg and thus the men are able to take off with less energy dissipation than the female triple jumpers. Further research using the high speed recordings will allow a deeper inside view into the adequate strategy to take off with minimum loss of mechanical energy.

Table 87: Changes of horizontal CM velocities - **men's** and **women's** final World Championships 1997(m/s)

rank	**hop**		**step**		**jump**	
	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 of the mean,** indicates high significant ($p<0.01$) differences between the means of the male and female competitors.

As described for the hop the CM's horizontal velocity also decreased during the take off for the step. The horizontal velocities at take off for the step were 7.58 ±0.27m/s for the women and 8.61 ±0.27m/s for the men. The decreases were 1.15 ±0.19m/s and 0.81±0.21m/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 ($p<0.01$) between both groups of competitors. The mean men's vertical velocity was measured higher (1.94 ±0.22m/s) than the speed of the female jumpers (1.52 ±0.27m/s). The men's take off angle of projection for the hop is little more steep than the women's, but the means of the angles of projection show no significant ($p<0.05$) difference. The men's steeper take off was caused by the higher vertical CM velocities.

Table 88: Relative changes of total mechanical energy - **men's** and **women's** final World Championships 97(all data are given in percentage to mechanical energy at touch-down for the take off into hop, step and jump respectively)

rank	**hop**		**step**		**jump**	
	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 of the mean, ** indicates high significant ($p<0.01$) differences between the means of the male and female competitors.

The kinetic energy achieved during the approach and available at the touch-down for the take off into the hop decreases during the take off of the hop. During the take off for the step additional energy reduction could be identified for all measured subjects. The losses of the total mechanical energy prior to touch-down for the take off into the step expressed as percentage are 17.49 ±2.05% and 20.15 ±2.42% for the female and male competitors respectively. The difference of the means is significant ($p<0.05$). The male elite triple jumpers show little more energy loss than the female finalists. Regarding the loss of mechanical energy from the initial condition prior to the hop both groups have a nearly balanced energy decrease throughout the first two take off's. The remaining total mechanical energy (%) at touch-down for the jump are 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 analyzed 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 minimization 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 ±0.29m/s for the women and 7.01 ±0.33m/s for the men. The decreases were measured as 1.13 ±0.13m/s and 1.59±0.27m/s for women and men respectively. The difference of 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 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 measured higher (2.79 ±0.26m/s) than the speed of the female jumpers (2.52 ±0.13m/s). The means of the take off angle of projection for the jump was similar for the men and the 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 of the means is highly significant ($p<0.001$). The male elite 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 run-up.

The male finalists decreased the total mechanical energy achieved in the run-up more during the hop, the step and the take off for the jump than the female athletes. This could be interpreted that the male jumpers distribute their initial mechanical energy more effectively than the females.

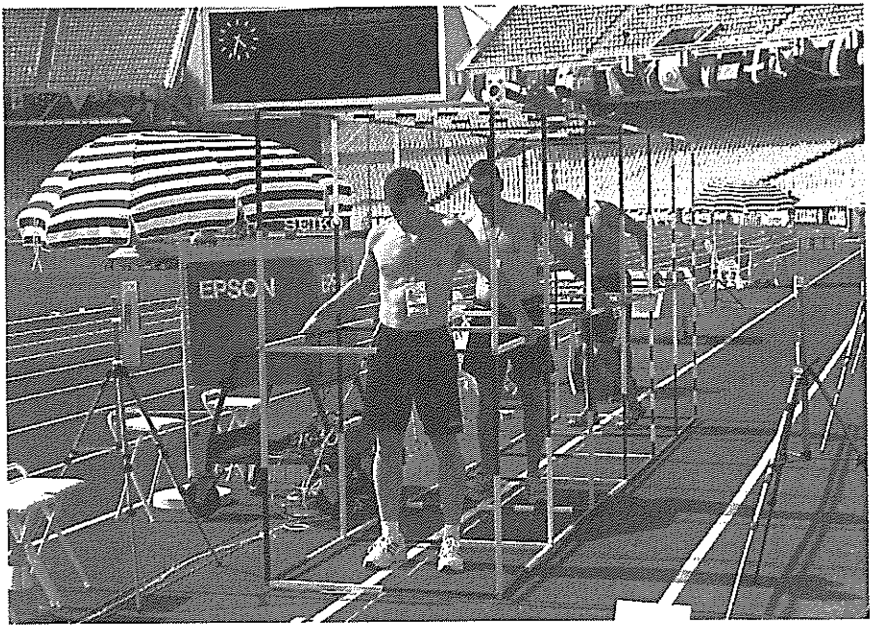
Summary and Conclusion

The best trials of the eight male and female finalists of the Track and Field World Championships in Athens 1997 were recorded and analyzed using video based motion analysis techniques. The data extracted give detailed information on the effort distribution during the consequent jumps and on biomechanical parameters of the approach run, the hop, the step and the jump.

The distance distribution of the females are different from that 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 strategy. In the men's group the better performers used the hop technique while the more successful women jumped using the balanced style.

The results of the analysis of the approach run indicate the fastest run-ups ever recorded and published in an international meeting in regard to the mean of the sample. For the female group no comparable data is available from 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 approach.

All subjects decrease horizontal speed of CM during the take off for the hop. The male subjects' decrease is significantly lower than those of the women. The loss of men's total mechanical energy during the take off into the hop is approximately half the loss of the women. This phenomenon is maybe related to an optimal stiffness regulation of the lead-leg musculature prior to or during the take off. In the step and the jump the two groups decrease horizontal speed of the CM. The loss of energy is higher in men's than in the women's take off's. This is probably due to more strength related take off activities during the step and the jump in the triple jump performance. Further research will use the high-speed recordings of the single take off and will provide a deeper inside view into the take off strategies and especially the use of elastic properties of the skeletal muscle system in jumping with high initial mechanical energy.



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2.2.3 High Jump

A. Arampatzis, G.-P. Brüggemann

History

High and long jumps were performed by all primitive peoples. The Watussis supposedly jumped well over two meters high by taking off from springy termite hills. The athletic high jump originated in acrobatic exercises (wall running and table jumping) in the 15th and 16th centuries. The philanthropists, especially Gutsmuths and more recently the gymnastics pioneer Jahn devised the first high jump apparatus: stands with variable height string attachments. Today's athletics high jump was developed at the beginning of the 19th century at the Highland Games in Ireland and Scotland. In 1861 the Scotsman Tivendal from Fife in Cupar supposedly jumped 1.85 m. The first English championships were staged in 1866, the first in the USA in 1876. Specific techniques developed over the decades. The original long-high jump style was replaced by the scissors-technique at the end of the 19th century. In 1890 the Englishman William Byrd Page (starting for the USA) jumped 1.97 m with this technique. Ellery Clark (USA) was the first Olympic champion in 1896 with 1.81 m. New techniques, frequently named after their „inventors“ followed in almost every subsequent decade: the Michael Sweeney or Eastern technique, the Horine technique with which George Horine was the first to clear 2 m in 1912, an improved technique, the Harald Osborne technique, diving rolls, parallel rolls, dive rolls. The straddle technique was more and more refined following the second world war. At the end of the 50's the so-called catapult shoe (a shoe with an approximately 6 cm thick, arched sole) was devised in the USSR and Yuriy Stepanov (URS) jumped a world record 2.16 m wearing these. In 1958 the IAAF banned these shoes and in 1960 John Thomas (USA) raised the world record to 2.22 m in normal shoes. Valeri Brumel (URS) next broke the world record and raised it another six times to a final height of 2.28 m.

When Dick Fosbury demonstrated the new technique he had developed and with which he became Olympic champion with 2.24 m in Mexico City in 1968, he revolutionized previous training techniques and technique learning methods. Fosbury's technique was easier to learn and permitted greater heights sooner. The "Fosbury flop“ only became possible due to the introduction of foam and soft floor mats. Dwight Stones (USA) was the first to jump over 2.30 m in 1973 and Rudolf Povarnitsyn (URS) the first over 2.40 m in 1985. The present world record of 2.44 m was jumped by the Cuban Javier Sotomayor in 1991 in St. Juan, Puerto Rico.

The high jump has been an Olympic athletic discipline since 1896. For a long time the IAAF regulations automatically recognized the Olympic champion as world champion. The first world champion in the present format was Gennady Awdejenko (URS) in Helsinki with a jump of 2.32 m. Troy Kemp (BAH) is the present world champion. The method of deciding the winner at an equal final height has been changed on a number of occasions: from „same height = same placing“ to the „multiple attempts rule“ (less attempts at the same height) to a „jump-off“ at equal height and the same number of attempts.

Nomenclature

v:	CM velocity at the end of the take off phase (CM take off velocity)
a:	Take off angle
h:	CM height at the end of the take off phase
g:	the acceleration of gravity
E_{tot1}:	total energy at the beginning of the take off phase (initial energy)
E_{tot2}:	total energy of the CM at the end of the take off phase
E_{kin2}:	CM kinetic energy at the end of the take off phase
E_{pot2}:	CM potential energy at the end of the take off phase
m:	Mass of the athletes
$E_{decrease}$:	decrease in total energy of the CM during the take off phase
T_{index}:	Transformation index during the take off phase
h_{eff}:	effective height of CM
h_{off}:	official jump height
v_{TD}:	CM velocity at the beginning of the take off phase

Introduction

The CM height during the high jump can be calculated using the following formula:

$$H = H_1 + \frac{v^2 \sin^2 a}{2g} \quad (1)$$

It is clear from this formula that the height (H) is dependent on the CM height at take off, the CM take off velocity and the take off angle. H1 is strongly influenced by anthropometric measurements. The CM take off velocity (v) and the take off angle (a) characterize the vertical CM take off velocity. The athletes produce their initial energy during the approach. During the take off phase the athlete attempts to transform this energy into jump energy. This transformation always leads to a decrease in the athlete's total energy (Brüggemann and Arampatzis 1997). The correlation between the approach velocity and the vertical take off velocity appears not to be linear but rather to be individually determined (Dapena et al. 1990). This individual optimum can be influenced by the conditional abilities of the athlete (Dapena and Chung 1988, Dapena et al. 1990). In the international literature it has not yet been reported how this individual optimum can be determined. The understanding of this would be valuable for use in training and competition.

The purposes of this study are:

1. To examine the approach and take off strategies of high jumpers at world class level.
2. To determine how to estimate the optimal take off behaviour from given beginning characteristics.

Methods

Data collection

Twenty six jumps from 12 finalists in the 1997 Track and Field World Championships high jump competition were analyzed. All of the analyzed jumps were valid jumps. The movement of the athletes was recorded using 4 stationary cameras (2 for left jumpers and 2 for right jumpers) operating at 50 Hz. The cameras were calibrated using a 2x2x2 m^3 calibration cube. The origin of the co-ordinate system was at ground level at the middle point of the high jump cross bar. The Y axis was parallel to the cross bar and was positive to the left. The Z axis was oriented upward positive, and the X axis was perpendicular to the other two axes. From each athlete 15 frames from 2 cameras were digitized.

The positions analyzed in the 15 frames were the following:

Frame 1: Last frame of the flight phase of the second to last step.
Frame 2: First frame of the support phase of the last step.
Frame 3: Minimum knee angle of the support phase of the last step.
Frame 4: Last frame of the support phase of the last step.
Frame 5: First frame of the flight phase of the last step.
Frame 6: Last frame of the flight phase of the last step.
Frame 7: First frame of ground contact at take off.
Frame 8: Minimum knee angle during take off.
Frame 9: Last frame of ground contact at take off.
Frame 10: First frame in which the athlete has no ground contact.
Frames 11-15: Frames of the athlete over the cross bar when the CM is at its highest point.

The video data was digitized using a Peak-Motus system. The following parameters were calculated using a fast information programme developed at the German Sport University Cologne: CM position, body angle, CM velocities and total energy. The spatial co-ordinates (x,y,z) of the 19 digitized points per frame were calculated through DLT.

Data Analysis

Formula 1 can be converted to the following:

$$E_{k2} = \frac{E_{kin\,2}}{m}, \qquad H = \frac{E_{p2}}{g} + \frac{E_{k2}\sin^2 a}{g},$$

$$E_{p2} = \frac{E_{pot\,2}}{m}, \qquad E_{kin2} = \frac{1}{2}mv^2, \qquad E_{pot\,2} = mgh \tag{2}$$

The effective height (H) can be calculated as a function of the total CM energy at the end of the take off phase and the take off angle.

During the take off phase a loss of total CM energy always occurs during the transformation of the initial energy to jump energy. To quantify this transformation an index was created that shows the directional change of the movement dependent of energy loss. The transformation index is defined as the quotient of the take off angle divided by the energy loss.

$$T_{Index} = \frac{a}{E_{decrease}} \qquad (3)$$

The total CM energy at the end of the take off phase can be written the following way.

$$E_{T2} = E_{T1} - E_{decrease} \quad \Rightarrow$$

$$E_{p2} + E_{k2} = E_{T1} - E_{decrease} \quad \Rightarrow \quad E_{k2} = E_{T1} - E_{decrease} - E_{p2} \qquad (4)$$

$$E_{T1} = \frac{E_{tot1}}{m}, \quad E_{T2} = \frac{E_{tot2}}{m}$$

The potential energy difference among jumps was very small and can therefore be given as a constant value for each jumper. From formula 3 we get the following:

$$a = T_{Index}.E_{decrease} \qquad (5)$$

From formulas 2, 4 and 5 the effective height (H) can be calculated as a function of the beginning energy, energy loss and the transformation index.

$$H = \frac{E_{p2}}{g} + \frac{(E_{T1} - E_{decrease} - E_{p2})\sin^2(T_{Index}.E_{decrease})}{g} \qquad (6)$$

The beginning energy represents the starting conditions for the jump and the energy loss and the transformation index represent the jump behaviour. Using a cluster analysis two distinct groups were formed. The factors used in creating the groups were beginning energy, energy loss and the transformation index. The difference between the two groups was tested using a T-test for a sample group.

Results

Group 1 showed higher values ($p<0.05$) than Group 2 for the beginning energy as well as horizontal CM touch-down velocity (table 89, figure 37 and table 92). All other parameters up until touch-down, including trunk angle, touch-down and take off angle, foot, knee and hip angle as well as CM height, showed no significant difference (table 90, 91 and 93). At take off Group 2 showed a higher ($p<0.05$) energy loss than Group 1 (table 89 and figure 37). The decrease in CM horizontal velocity was also larger in Group 2 (table 92). Group 1 produced a higher value ($p<0.05$) for the transformation index. The take off parameters, final energy, take off angle, CM flight height, horizontal and vertical CM velocity showed no significant differences (table 89, 92 and 93 and figure 37). Also for jump height and effective height no significant ($p<0.05$) differences could be found.

The beginning and horizontal touch-down show no significant ($p<0.05$) correlation with the effective height, the jump height or the CM take off velocity. The decrease in total CM energy, and the decrease in CM horizontal velocity during the take off also show no significant ($p<0.05$) correlation with the effective height, the jump height or the vertical CM take off velocity. The decrease in CM total energy during the take off phase did show a very high correlation with the transformation index (figure 39). The transformation index could be estimated using an exponential function with a correlation co-efficient of $r=0.99$ dependent on the energy decrease. This exponential correlation between the energy decrease and the transformation index shows that the maximum CM vertical velocity occurs at a specific value for energy loss (figure 40). A further reduction of total CM energy and the horizontal CM velocity does not result in an increase in vertical CM velocity (figure 40).

Discussion

The two groups demonstrate varying beginning conditions and varying jump behaviour. Group 2 had both a higher beginning energy and a higher energy loss during the take off phase. The transformation index for Group 2 is lower and so the two groups show approximately the same final energy and take off angle at the end of the take off phase. This leads to the fact the two groups show no significant difference in the effective or jump heights. This observation shows that the energy loss of Group 2 is too large and therefore gives Group 2 no advantage. Through a lower energy loss and a higher transformation index Group 1 was able to make up their deficit in the initial energy in relation to Group 2. The large energy loss demonstrated by Group 2 seems to be an important mistake. The horizontal CM velocity of Group 2 was reduced more than that of Group 1 without producing further increase in the vertical CM velocity. The natural question that arises, why is the energy decrease of the two groups different in spite of the fact that the body positioning at touch-down showed no clear differences. One possible explanation for this is that muscle stiffness of the two groups varied. The muscle stiffness affects the coordination of the muscle-tendon complex and can therefore change the amount of energy lost. The exact effects of muscle stiffness on the energy loss can not be quantified in this study. Furthermore it seems that during the take off phase the initial energy influences the energy loss. These two factors show a high correlation ($r=0.93$, $p<0.05$).

The transformation index showed a very close relationship with the energy loss (figure 39). The transformation index can be estimated using an exponential function of the energy loss. This makes it possible to calculate the effective height as a function of the initial energy using formula 6. Figure 41 shows the possible effective heights of the two groups. Group 1 showed a near optimal take off and therefore reached almost 100% of their potential height. In contrast Group 2 had a less effective take off and could have achieved an effective height approximately 10% higher than what was actually achieved. The optimal energy loss would be between 4 and 5 J/Kg and the take off angle between 47.8 and 49.3 degrees. Figure 40 illustrates that the vertical CM velocity increases with a decrease in horizontal velocity. This relationship has an optimal point, after which a greater horizontal velocity loss doesn't result in a greater vertical velocity gain. On the contrary, with too high of a horizontal velocity loss the resultant vertical velocity also decreases. The optimum horizontal approach velocity for Group 1 is 3.13 – 3.35 m/s and for Group 2 it is 3.40 – 3.61 m/s. This indicates that those athletes who produce a higher approach velocity also need to have a larger energy loss to achieve their optimum take off velocity.

It is also possible to diagnose to what extent the athletes are taking advantage of their starting energy (figure 42 and table 94). Athletes such as Sotomayor or Janku both showed deficits during their take off phases (table 94). On the other hand jumpers such as Forsyth, Hoen and Papakostas demonstrated optimum take offs. A further improvement for these jumpers can only be achieved through an increase in the initial energy. Particularly interesting to examine are the three jumps from Partyka (figure 43 and table 94). He demonstrated optimal take off characteristics only during his best jump (2.35m). Through the examination of the initial energy and the take off characteristics of the athlete we can gather important information that can be used during training sessions to improve the take off phase. Or if an athlete already demonstrates favourable take off characteristics an effort can be made to increase the athletes initial energy. Further research needs to be done to determine the effect of muscle stiffness on the energy loss during the take off phase.

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Table 89: Energy, Transformation index, height and take off angle

Parameters	**Group 1** (n=16)	**Group 2** (n=10)
Initial energy of the athlete (Joule/kg)	35.15 (1.38)	39.04 (2.06) *
$E_{decrease}$ (Joule/kg)	4.26 (0.99)	9.23 (2.06) *
T_{index} (degrees/Joule/kg)	12.05 (3.34)	5.47 (1.01) *
Take off energy (Joule/kg)	30.88 (1.14)	29.81 (0.74)
Take off angle a (degrees)	48.83 (1.99)	48.67 (2.94)
h_{eff} (m)	2.35 (0.04)	2.31 (0.09)
h_{off} (m)	2.29 (0.04)	2.26 (0.07)

* : Statistically significant difference between groups 1 and 2 ($p<0.05$)

Table 90: Joint angles of the support and swing legs during the take off phase (degrees)

Parameter	**Group 1** (n=16)	**Group 2** (n=10)
Ankle angle of the support leg at touch-down	130.6 (8.6)	129.9 (4.8)
Ankle angle of the support leg at take off	142.2 (8.1)	140.3 (6.3)
Knee angle of the support leg at touch-down	163 (11)	164.4 (5.1)
Knee angle of the support leg at take off	171.1 (5.2)	169.4 (5.7)
Hip angle of the support leg at touch-down	146.9 (6.4)	150.8 (5.1)
Hip angle of the support leg at take off	164.5 (4.9)	167.1 (5.6)
Knee angle of the swing leg at touch-down	99.9 (14.1)	96.6 (12.5)
Knee angle of the swing leg at take off	83.4 (18.9)	95.1 (15.1)
Hip angle of the swing leg at touch-down	154.3 (11.5)	156.4 (11.5)
Hip angle of the swing leg at take off	97.5 (9,5)	104.1 (10.5)

* : Statistically significant difference between groups 1 and 2 ($p<0.05$)

Table 91: Running- and body angle (degrees)

Parameter	**Group 1** (n=16)	**Group 2** (n=10)
Running angle 1LS	52.4 (3.3)	48.6 (7.8)
Running angle Jump	56.9 (2.9)	54.7 (6.7)
Body angle at touch-down	57.0 (5.2)	55.6 (6.1)
Body angle at take off	93.5 (1.4)	94.3 (1.8)

* : Statistically significant difference between groups 1 and 2 ($p<0.05$)

Table 92: Horizontal and vertical CM velocity during the take off phase (m/s)

Parameter	**Group 1** (n=16)	**Group 2** (n=10)
Horizontal touch-down velocity	7.11 (0.29)	7.83 (0.43) *
Horizontal take off velocity	3.89 (0.27)	3.77 (0.22)
Decrease in horizontal velocity	3.22 (0.30)	4.05 (0.56) *
Vertical take off velocity	4.44 (0.11)	4.29 (0.26)

* : Statistically significant difference between groups 1 and 2 ($p<0.05$)

Table 93: CM heights during the last stride and take off (m)

Parameter	**Group 1** (n=16)	**Group 2** (n=10)
Height of the CM at take off from the penultimate step	0.89 (0.04)	0.92 (0.04)
Height of the CM at touch-down of the take off step	0.90 (0.04)	0.90 (0.05)
Height of the CM at take off into the jump	1.34 (0.05)	1.37 (0.06)

* : Statistically significant difference between groups 1 and 2 ($p<0.05$)

Table 94: Analyzed jumps

Name	h_{off} (m)	h_{eff} (m)	E_{init} (J/kg)	$E_{decrease}$ (J/kg)	**Opt. height** (m)	**Opt.** $E_{decrease}$ (J/kg)	**Group**
Sotomayor	2.37	2.50	41.07	10.11	2.75	4.40 - 5.40	2
Sotomayor	2.35	2.39	42.41	12.94	2.77	4.45 - 5.47	2
Sotomayor	2.32	2.36	40.90	11.36	2.70	4.45 - 5.35	2
Partyka	2.35	2.38	36.53	4.42	2.38	3.70 - 4.50	1
Partyka	2.29	2.29	36.77	6.31	2.41	3.70 - 4.50	2
Partyka	2.20	2.20	37.53	7.47	2.45	3.70 - 4.60	2
Forsyth	2.35	2.42	35.82	3.77	2.44	3.80 - 4.64	1
Forsyth	2.32	2.37	35.50	3.08	2.42	3.80 - 4.70	1
Forsyth	2.29	2.35	34.10	3.80	2.35	3.85 - 4.50	1
Hoen	2.39	2.39	35.32	5.05	2.39	3.70 - 4.90	1
Hoen	2.29	2.31	35.12	3.78	2.33	4.00 - 4.80	1
Grand	2.32	2.33	35.43	4.28	2.35	4.00 - 4.70	1
Papakostas	2.32	2.38	35.84	5.02	2.39	4.00 - 4.60	1
Papakostas	2.25	2.38	34.99	3.76	2.36	4.00 - 4.60	1
Matusevitch	2.20	2.25	36.65	7.56	2.45	3.95 - 4.70	2
Lee	2.29	2.32	35.30	4.47	2.35	3.90 - 4.70	1
Lee	2.25	2.28	35.33	5.66	2.33	3.90 - 4.70	1
Lee	2.20	2.26	37.33	8.50	2.45	4.00 - 4.80	2
Buss	2.25	2.29	35.27	4.78	2.33	4.00 - 4.60	1
Buss	2.20	2.29	37.89	8.28	2.50	4.10 - 4.90	2
Mayo	2.29	2.33	35.71	5.71	2.39	3.90 - 4.80	1
Mayo	2.25	2.34	33.67	3.76	2.32	3.70 - 4.60	1
Kliugin	2.29	2.34	34.73	3.13	2.38	3.70 - 4.40	1
Kliugin	2.25	2.33	33.69	3.66	2.33	3.70 - 4.50	1
Janku	2.25	2.31	39.60	8.74	2.56	4.10 - 5.00	2
Janku	2.20	2.26	40.23	11.00	2.61	4.10 - 5.00	2

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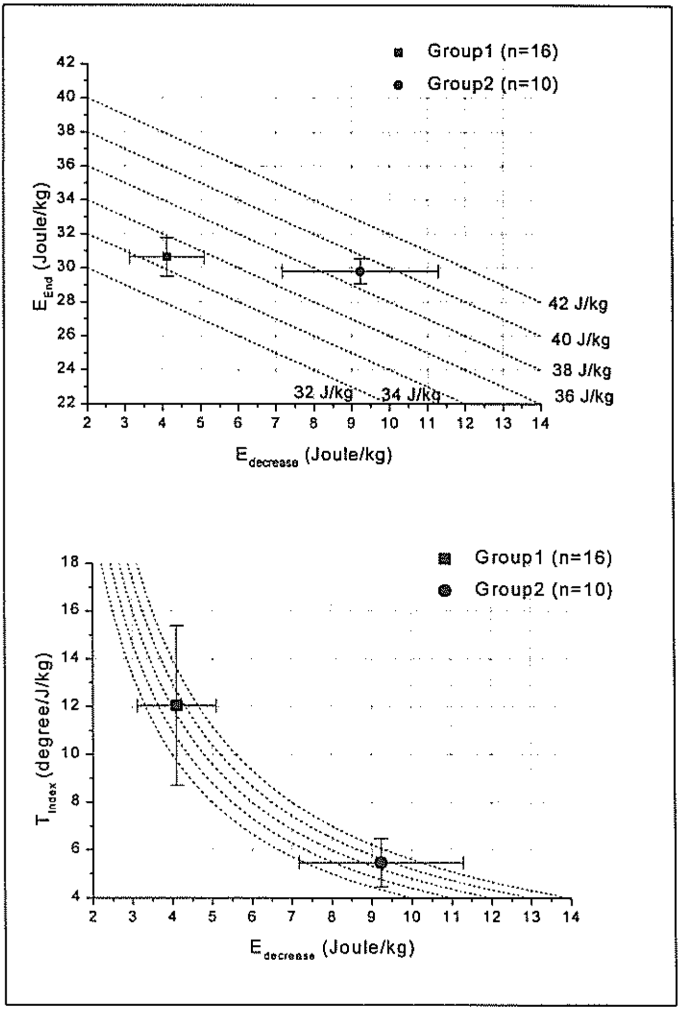

Figure 37: Total energy at take off in relation to the initial energy and the energy decrease. Transformation indiex in relation to the energy decrease and angle of projection.

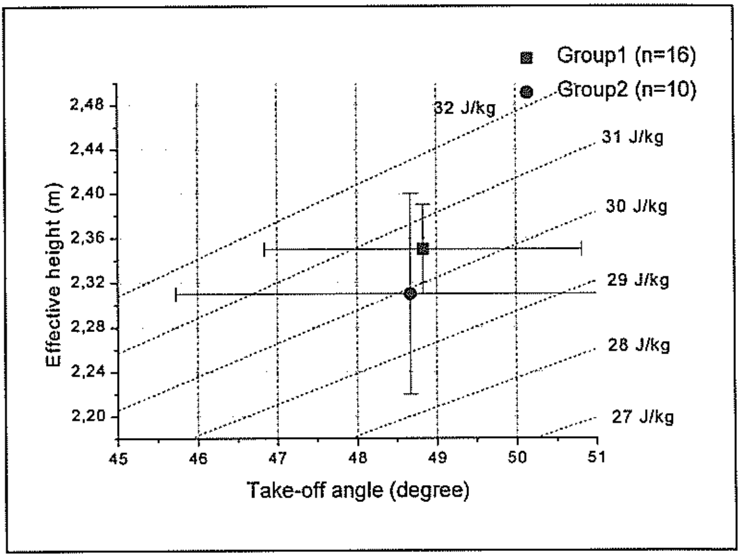

Figure 38: The effective height in relation to the end energy and the take off angle

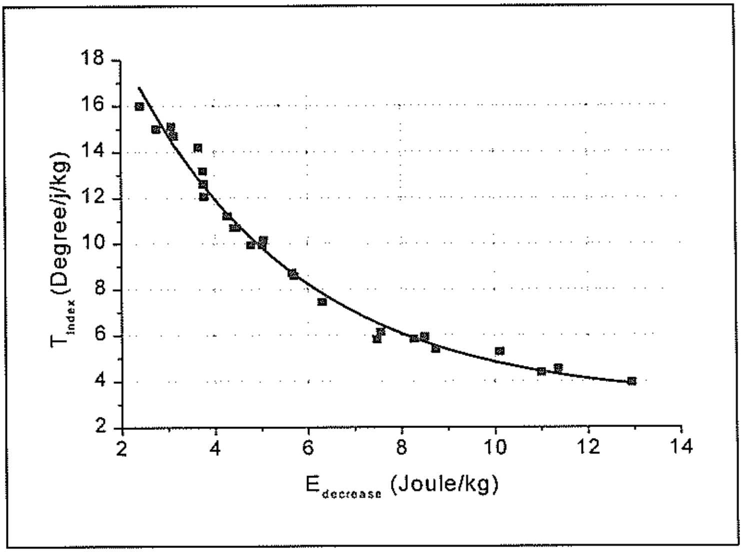

Figure 39: The transformation index in relation to the energy decrease

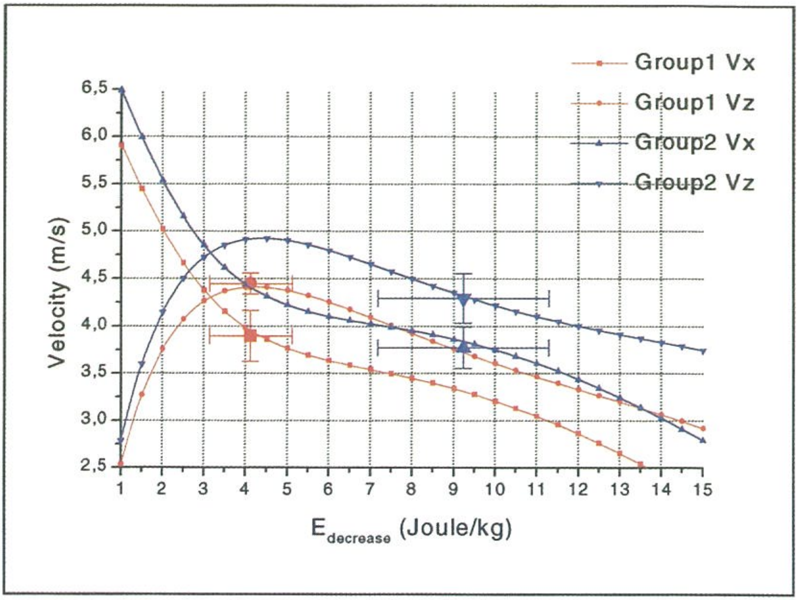

Figure 40: Horizontal and vertical CM velocity in relation to the energy decrease

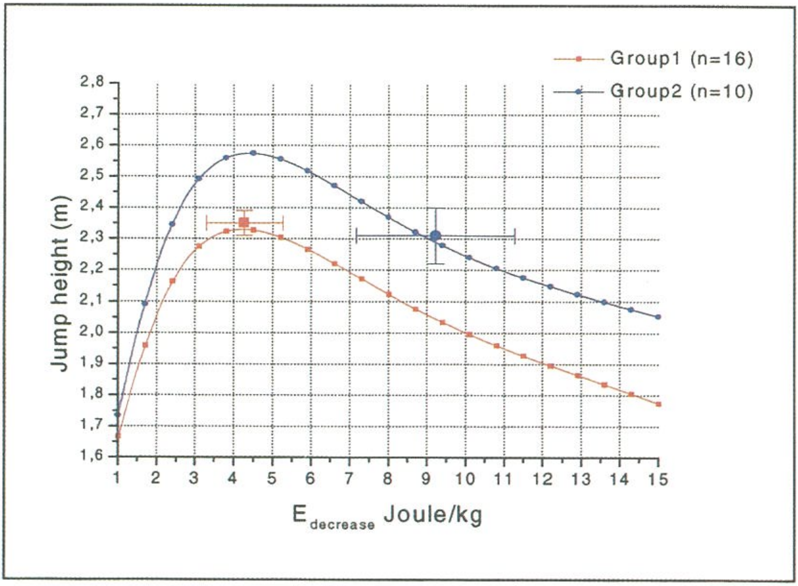

Figure 41: Effective height in relation to the energy loss

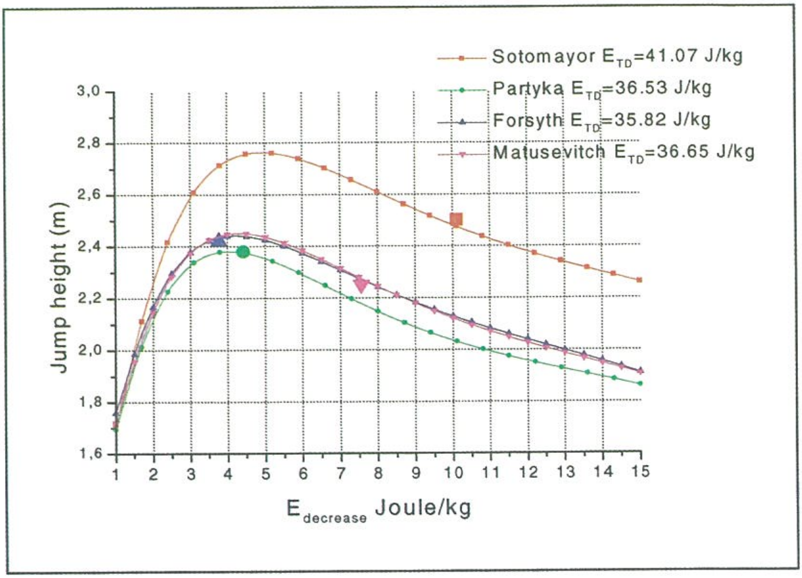

Figure 42: Effective height in relation to the energy loss

2.2.4 Pole Vault

A. Arampatzis / F. Schade / G.-P. Brüggemann

History

People have been using poles, spears and lances to jump over ditches, creeks, canals, hedges and crevices since ancient times. This tradition is still continued today in Frisia where people try to jump over wide canals with long sticks. The philanthropist Gutsmuths claims his students jumped 2.70 m high over a string. Pole vaulting for height and distance was also an exercise enjoyed by German and Czech gymnastic pioneers. It became an important discipline when modern athletics were developed in England. Results of 3.20 and 3.40 m are known from the 1860's and 1870's. The poles were manufactured from ash, oak, cedar, spruce or hickory until bamboo was introduced at the beginning of the 20th century.

The bar was crossed with squatted knees and in England it was sometimes permitted to climb up the pole. In some periods separate competitions were staged and separate records kept. Pole vaulting was one of the 17 athletic disciplines included in the 1896 Olympic Games. William Hoyt (USA) was the inaugural Olympic champion with 3.30 m. The best height at that time was 3.58 m achieved by Richard Dickinson (GBR).

The technical ability of the athletes continually improved similar to the high jump. Greater approach speeds permitted considerably higher grip positions and jumps. The 4.02 m jumped by Marc S. Wright (USA) at the Olympic trials in Cambridge/Mass. in 1912 was the first time four metres were cleared. The dominant personality in the period following the first world war was Charles Hoff (NOR) who increased the world record from 4.12 m in 1925 to 4.25 m. When he jumped 4.32 m in 1931 he had already been regarded as a professional for a considerable time. The best performance with a bamboo pole was achieved by Cornelius Warmerdam (USA) when he jumped 4.77 m in 1942 in Modesto/USA. His record stood for 15 years until Robert Gutowski (USA) raised it by one centimeter. Gutowski was, however, already using an aluminium pole. The greatest height achieved with this apparatus was 4.80 m by Donald Bragg (USA) at the Olympic trials in Rome, 1960 who not only subsequently became Olympic champion but also acted in the role of Tarzan as successor to Johnny Weismuller (USA).

The introduction of the fiberglass pole has led to the world record being raised in rapid succession a number of times per year since 1961. Brian Sternberg (USA) was the first to jump over five metres in 1963. In the period between 1961 and the first six metre jump by Sergei Bubka (URS, now UKR) in 1985 the world record was equalled or raised 52 times - more than in any other discipline (more than twice annually!).

Bubka himself raised the world record more than 30 times between 1984 (5.85 m) and 1993 (6.15 m indoors). He won the world championships five successive times but the Olympic title only once in 1988 because his high risk tactics frequently resulted in three unsuccessful attempts at the first height. Only three athletes beside Bubka have jumped higher than 6.00 m. Bubka has managed this in 42 competitions to date. He could afford to raise the world record by a centimetre at a time to increase his prize money.

Women have been active in the pole vault for over 10 years and are presently approaching the 4.50 m mark. They were already officially represented at the last world indoor championships in Paris, 1997. Women's pole vault was not an official event in Athens, 1997. It will possibly have its Olympic debut in the year 2000 in Sydney.

Abstract

The main goals of this study were:

1. To examine the behaviour and practical application of 3 criteria in the pole vault at world class level. The 3 criteria concern the starting conditions of the pole vault and the behaviour of the athletes during the pole phase.
2. To determine the amount of influence of the initial conditions as well as the influence of the athletes behaviour during the pole phase on pole vault performance.

Data for this study was gathered at the 1997 Track and Field World Championships in Athens, Greece. A total of 25 successful jumps from 11 participants in the final competition were analyzed. The data was recorded using two synchronized stationary video cameras operating at 50 Hz. For the analysis of the data the pole vault was divided into the following phases:

1. The energy production phase. This phase begins with the approach and ends with contact of the jump foot and the ground at take off.
2. The energy exchange phase. This phase begins with contact of the jump foot and the ground at take off and ends when the athlete releases the pole at the end of the jump.

During the first part of the energy exchange phase energy is transferred into the pole therefore reducing the athlete's total energy. The difference between the decrease of the athletes total energy and the maximum pole energy indicates if the pole elasticity was effectively used (Criterion 1). During the second part of the energy exchange phase the energy is transferred back from the pole to the athlete and the athlete's total energy increases. The difference between the returned energy and the energy gain of the athlete indicates to what extent the athlete used muscular work to increase his total energy (Criterion 2). The approach energy (initial energy) represents the starting conditions of the pole vaulter (Criterion 3). From the analyzed jumps it was possible to create 3 groups which demonstrated similar values for the initial energy, Criterion 1 and Criterion 2. The results indicate that both individual and group specific technique deficits of the athletes can vary and still produce the same jump performance. At the elite level the initial energy determines the initial conditions for good or poor jump performance. The actual jump heights achieved are dependent on the behaviour of the vaulter during the energy exchange phase. From the examination of the initial energy, Criterion 1 and Criterion 2 it was possible to diagnose individual technical deficits of the athletes.

Nomenclature

E_{init}	Initial CM energy at the start of the take off phase
E_{End}	Total CM energy (potential and kinetic) at pole release
W_m	Muscular work defined as E_{End} minus E_{init}
E_{MPB}	Total CM energy at the moment of maximum pole bend
$E_{pole\ max}$	Maximum strain energy of the pole
$E_{decrease}$	E_{init} minus E_{MPB}
$E_{increase}$	E_{End} minus E_{MPB}
Criterion 1	$E_{pole\ max}$ minus $E_{decrease}$
Criterion 2	$E_{increase}$ minus $E_{pole\ max}$
h_{eff}	Maximum CM height
h_{off}	Height of the cross bar
h_{rel}	CM height at pole release
a_{MPB}	Angle defined by the vertical axis and a line through C7 and CM of the athlete with the vertex at C7
v_{TD}	CM velocity at the initial of the take off phase
v_{MPB}	CM velocity at the instant of maximal pole bend
v_{rel}	CM velocity at pole release
v_{TH}	The horizontal distance from the top hand to the tip of the jump foot.

Introduction

One of the main differences between the pole vault and the other jumping disciplines is that the transformation of the approach energy to jump energy can take place without an energy loss and sometimes even with an energy gain (Groß and Terauds 1983; Groß and Kunkel 1990, Arampatzis et al. 1997). In all the other track and field jump disciplines (high jump, long jump and triple jump) a large decrease in the athlete's total energy occurs during this transformation (Brüggemann and Arampatzis 1997a, 1997b; Müller and Brüggemann 1997). The reason for this difference is the elasticity of the pole vault poles. Several authors (Dillman and Nelson 1968; Braff and Depena 1985; Ekevad and Lundberg 1995, 1997) have attempted to determine the influence of the length and stiffness of the poles on jump performance. The results indicate that an optimum pole stiffness and length exists which would allow for the pole vaulter to jump to his maximum height (Ekevad and Lundberg 1995, 1997). During the pole phase muscular energy from the athlete is used to store energy in the pole (Hubbard 1980; Groß and Terauds 1983; Groß and Kunkel 1990). The resultant shoulder joint moments are much higher than the resultant hip and knee moments (McGinnis and Bergman 1986). Using only the amount of muscular energy production during the pole phase (Groß and Terauds 1983; Groß and Kunkel 1990) it is not possible to identify differentiated deficits in the technical components of the athletes (Arampatzis et al.1997).

Other authors (Woznik and Geese 1980; Woznik 1986, 1992; Angulo-Kinzler et al. 1994) oriented their work from the partial height model from Hay (1978). The partial height model may seem to be a clear and selective subdivision of the maximum centre of mass (CM) height but it is dependent on the technique and anthropometric attributes of the athletes. For instance, the bordering event between the pole phases H2 and flight height H3 can be troublesome because release of the top hand from the pole is difficult to identify on video and film. A difference in one or two frames can cause significant and incomparable differences. Furthermore the partial height model ignores the energy exchange between the athlete and the pole which is a very important factor for pole vault performance (Dillman and Nelson 1968, Hubbard 1980; Ekevad and Lundberg 1995, 1997).

Arampatzis et al. (1997) outlined 3 criteria which characterize the initial conditions in the pole vault as well as the pole vaulter's behaviour during the pole phase. During the first part of the pole phase energy is transferred into the pole and the total energy of the athlete decreases (Hubbard 1980; Groß and Terauds 1983; Groß and Kunkel 1990; Woznik 1992). The difference between the energy decrease of the athlete and the pole energy indicates whether the pole elasticity was effectively used (Criterion 1) (Arampatzis et al. 1997). During the second phase of the energy exchange energy is transferred back into the athlete and the total energy of the athlete increases (Hubbard 1980; Groß and Terauds 1983; Groß and Kunkel 1990; Woznik 1992). The difference between the returned pole energy and the amount of energy increase of the athlete defines Criterion 2 (Arampatzis et al. 1997). The end energy of the athlete is the sum of the start energy, Criterion 1 and Criterion 2. In this structure the initial energy (Criterion 3) represents the initial conditions of the pole vaulter and Criterion 2 and 3 represent the behaviour of the athlete during the energy exchange phase.

The main goals of this study were:

1. To examine the behaviour and practical application of 3 criteria in the pole vault at world class level.
2. To determine the amount of influence of the initial conditions as well as the influence of the athletes behaviour during the pole phase on pole vault performance.

Methods

The data for this study was collected at the 1997 World Track and Field Championships in Athens, Greece.

A 4x5x1 m3 calibration cube was used to calibrate the space in which the analysis was performed. The horizontal axis of the inertial co-ordinate system is positive with relation to the direction of movement and the vertical axis is defined that upward is positive. 25 successful jumps from 11 pole vaulter during the finals were analyzed. A total of 22 frames from each jump were digitized at the following vault positions:

Frame 1	Last picture of the flight phase of the second to last step.
Frame 2	First frame of the support phase during the last step.
Frame 3	Minimum knee angle during the support phase of the last step
Frame 4	Last frame during the support phase of the last step.
Frame 5	First frame during the flight phase of the last step.
Frame 6	Last frame during the flight phase of the last step.
Frame 7	First frame of the take off support phase.
Frame 8	Minimum knee angle at take off.
Frame 9	Last frame of the take off support phase.
Frame 10	First frame in which the athlete has no more ground contact.
Frames 11-15	Frames at the point of maximum pole bend.
Frame 16	Last frame in which the athlete still has contact with the pole.
Frame 17	First frame after the athlete released the pole.
Frames 18-22	Frames in which the CM was at it's highest point.

The video data was digitized using the Peak-Motus system. The calculation of the following parameters was possible using a fast information programme developed by the Department of Track and Field and Gymnastics at the German Sport University in Cologne, Germany; CM position, joint angles, CM velocities and total CM energy. For analysis purposes the pole vault was divided into the following phases:

1. The energy production phase – this phase begins with the approach and ends at foot-ground contact of the jump foot.
2. The energy exchange phase – this phase begins with foot-ground contact of the jump foot and ends at pole release.

Calculating the strain energy of the pole at the MPB phase, the elasticity modulus of the pole and the pole bend, taken from the shortening of the pole chord, have all been taken into account.

Using a cluster analysis groups were formed on the basis of similar initial energy, Criterion 1 and Criterion 2 values. A total of 3 groups were formed (table 95). The differences between the groups was tested using a T test for an independent sample group.

Results

The initial centre of mass (CM) energy was the highest in Group 1 (table 96 and figure 43). Group 2 had the lowest initial energy (table 96 and figure 43). During the energy exchange phase Groups 2 and 3 produced the same amount of energy through muscular work (table 96 and figure 43). The energy achieved through muscular work for Group 1 was almost zero (table 96). The result of the above mentioned relationships is that Groups 1 and 3 showed no significant difference ($p<0.05$) in the final energy value (table 95 and figure 44). The effective heights attained by the three groups showed a similar relationship as the end energy values of the three groups. Groups 1 and 3 produced higher jumps than Group 2 (table 96). The pole energy at the point of maximum bend was the highest for Group 3 (table 96). The CM energy decrease among the three groups showed no significant ($p<0.05$) difference. Group 1 had the highest total CM energy at the point of maximum pole bend (table 96). Additional energy during the first phase of energy exchange was only produced during this phase by Group 3. For Criterion 1 Group 3 achieved a significantly ($p<0.05$) higher value than the other groups (table 96 and figure 44).

The energy increase during the second part of the energy exchange phase was significantly ($p<0.05$) higher in Groups 2 and 3 than in Group 1 (table 96). Additional energy produced through muscular work was only achieved during this phase by Group 2. Group 2 was the only group to clearly produce positive values for Criterion 2 (table 96 and figure 44). The pole release height was the highest for Group 1 and the lowest for Group 2 (table 96). The body angles among the three groups during the energy exchange phase were almost the same. The only differences were from Group 1 which showed different values for knee angle of the support leg at touch-down and hip angle of the swing leg at take off (table 97).

The horizontal velocity values showed a pattern similar to that of the initial CM energy. Group 1 showed the highest value and Group 2 the lowest (table 98). The groups showed no significant difference between horizontal take off velocity values ($p<0.05$) (table 98). The vertical touch-down velocity and horizontal MPB velocity values showed significant differences only between Groups 1 and 3. Both of these values were higher in Group 1 (table 98). The vertical MPB velocity is also the highest in Group 1 (table 95). The vertical CM velocity at pole release was lower for Group 1 than for Group 2 (table 98). Groups 2 and 3 showed no significant ($p<0.05$) difference in the vertical pole release velocity.

The CM height during the take off phase was the highest for Group 1 (table 99). The height of the top hand and the top hand distance at touch down were also the highest in Group 1 (table 99). Differences between Groups 2 and 3 were only found in the height of the top hand at take off and the CM height at take off. Both heights were greater for Group3 (table 99).

Discussion

Individually the athletes who are at this elite level all demonstrated similar initial conditions and similar characteristics during the energy exchange phase regardless of their jump height; this can be seen in table 92. The various jumps from one athlete were always in the same group with one exception. Dean Starkey produced one jump at 5.80 m which had different group characteristics than his other jumps (table 95). Group 1 was composed of only the 4 jumps from Tarasov. These results indicate that not only jumps which produced maximal CM heights can be taken to diagnose various technical advantages or disadvantages.

A total of three groups were made in which the athletes demonstrated different initial conditions and energy exchange characteristics. The CM end energy determined both the jump height as well as the effective jump height. The CM end energy showed a high correlation with both parameters ($r=0.99$, $p<0.05$ with effective height and $r=0.83$, $p<0.05$ with jump height). This indicates that the goal of the pole vaulter should be to attain the highest end energy possible. The end energy is the algebraic sum of the initial energy and the energy produced through muscular work during the energy exchange phase. Group 1, jumps only from Tarasov, produced the highest initial energy and demonstrated the worst energy exchange characteristics. Tarasov, in all his jumps, could not manage to create additional energy through muscular work. During the first part of energy exchange where he could take advantage of the pole`s elasticity he showed large deficits. The elasticity of the pole can only be effectively used when the athlete transfers additional energy into the pole through muscular work. This means that for an optimum jump the athlete's CM energy loss has to be less than the maximum pole energy (Criterion 1). The amount of pole energy in excess of the decrease in the athlete's CM energy represents muscular work performed by the athlete during the first part of the energy exchange phase which was stored in the pole as elastic energy. If the CM energy loss is higher than the maximum pole energy than a net energy loss has occurred. During the second part of the energy exchange phase the elastic energy which was stored in the pole is returned to the athlete. Through straightening of the body the athlete can once again add energy to the system through muscular work. During this part the athlete can achieve a greater CM energy if the increase in CM energy is greater than the decrease in pole energy (Criterion 2). The increase in energy is a result of muscular work performed by the athlete during this phase. If the increase of CM energy is less than the maximum pole energy then an energy loss has occurred. The technique of Tarasov showed a deficit during this part. He did not perform the proper muscular work and therefore achieved no clear energy gain (table 96). The high initial energy he produced was the factor that allowed for his good jump performance.

Groups 2 and 3 showed significant differences in initial energy. Group 3 had the greater value. The muscular work performed by these two groups during the energy exchange phase was the same. This means that the energy gain was also the same between the two groups. In spite of this the behaviour of Groups 2 and 3 during the energy exchange phase was different. Group 3 achieved a higher value for Criterion 1 and Group 2 achieved a higher value for Criterion 2. The athletes in Group 3 were able to effectively store energy in the pole through muscular work during the first part of the energy exchange phase. They showed a deficit during the second part of the energy exchange phase. During the straightening of the body Group 3 showed no clear energy gain. Even Bubka showed a high deficit during the second part of the energy exchange phase (table 95) indicating that the best pole vaulter in the world over the past 15 years has room for improvement. Bubka used the pole elasticity most effectively and achieved the highest value for Criterion 1 (table 95). Group 2 achieved a large energy gain in the second part of the energy exchange phase and a deficit in the first part. The athletes from this group did not effectively use the pole's elasticity. One possible explanation for this is that maybe the rock back was too passive and therefore not enough positive work was performed by the athlete. Criteria 1 and 2 express the performance of the jumpers during the two parts of the energy exchange phase. Both Groups 2 and 3 achieved the same energy gain during the energy exchange phase. The deficits of these groups are different. Group 2 had problems during the rock back movement and Group 3 had problems during the straightening movement. From the observation of total CM energy alone (Groß and Terauds 1983; Groß and Kunkel 1990) it would not be possible to make this diagnosis. Furthermore the consideration of the two Criteria makes it clear for both the groups as well as the individual athletes that improvement of the individual performance is attainable.

The end energy in Groups 1 and 3 showed no significant difference. Group 2 achieved the lowest end energy. The high end energy value of Group 1 was achieved through a high initial energy. Group 3, which had a lower initial energy than Group 1, attained the same end energy through a more effective energy exchange phase. The initial energy, which is dependant on the horizontal touch-down velocity, shows a significant correlation ($p<0.05$) with end energy. The correlations coefficient is very small ($r=0.47$, $p<0.05$). This observation makes it clear that even at world class level competition the initial energy determines the jump height potential, but that the behaviour of the athlete on the pole during the energy exchange phase influences the jump performance.

Groups 2 and 3 showed no significant difference ($p<0.05$) in knee and hip angle during the energy exchange phase. Noteworthy differences between these two groups were seen only in the CM height and top hand height at take off (table 99). Group 3 achieved a higher take off position which can be a positive factor for jump performance (Woznik 1986, Linthorne 1994). These differences were not caused by anthropometric differences as the two groups showed no differences in the remaining parameters during the last steps and take off (table 99). The statistical difference ($p<0.05$) between Group 1 and the other groups (table 99) can probably be accounted for by the different anthropometric characteristics of Tarasov.

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Table 95: Analyzed jumps

Name	**Jump height** (m)	**Effective height** (m)	E_{init} (J/kg)	**Criterion 1** (J/kg)	**Criterion 2** (J/kg)	**Group**
Bubka	6.01	6.50	59.23	4.73	0.27	3
Bubka	5.91	6.17	57.56	4.08	-0.03	3
Bubka	5.70	6.27	58.45	3.51	0.48	3
Tarasov	5.96	6.23	60.85	1.83	-0.71	1
Tarasov	5.91	6.08	60.99	0.14	-0.35	1
Tarasov	5.86	6.11	60.78	-1.37	1.38	1
Tarasov	5.80	6.08	63.17	-3.48	0.91	1
Starkey	5.91	6.12	55.68	3.70	1.30	3
Starkey	5.86	6.09	57.51	2.11	0.89	3
Starkey	5.80	5.95	55.45	2.01	1.62	2
Starkey	5.70	5.94	55.88	1.97	0.94	3
Starkey	5.50	5.84	56.10	2.04	0.23	3
Lobinger	5.80	6.00	56.57	2.72	0.34	3
Lobinger	5.50	5.83	58.84	1.63	-1.97	3
Buckfield	5.70	5.85	55.90	-0.42	2.50	2
Buckfield	5.50	5.69	55.90	-1.10	1.55	2
Manson	5.70	5.97	55.78	-1.13	4.58	2
Manson	5.50	5.87	54.59	0.94	3.05	2
Smiryagin	5.70	5.96	55.73	1.38	2.06	2
Smiryagin	5.50	5.92	55.52	1.26	2.00	2
Strogalyov	5.70	6.03	56.40	2.53	1.17	3
Strogalyov	5.50	5.84	56.74	1.49	-0.29	3
Barthel	5.50	5.80	57.13	1.25	-0.82	3
Eriksson	5.50	5.73	58.31	-1.49	0.69	2
Krasnov	5.50	5.79	55.80	1.18	0.59	2

Table 96: Analyzed parameters during the energy exchange phase

Parameter	**Group1** (n=4)	**Group2** (n=9)	**Group3** (n=12)
Initial energy (Joule/kg)	61.45 (1.15)	55.89 (0.99)*	57.17 (1.17)$^{*\perp}$
End energy (Joule/kg)	61.03 (0.62)	58.25 (0.97)*	60.03 (1.99)$^{\perp}$
Muscular work (Joule/kg)	-0.42 (1.55)	2.36 (1.64)*	2.86 (1.70)*
CM energy at MPB (Joule/kg)	36.04 (0.24)	31.32 (0.66)*	32.80 (0.69)$^{*\perp}$
Maximum pole energy (Joule/kg)	24.69 (1.27)	24.86 (0.79)	27.02 (1.90)$^{*\perp}$
Energy decrease of CM (Joule/kg)	25.41 (1.25)	24.57 (1.09)	24.38 (1.17)
Energy increase of CM (Joule/kg)	25.00 (0.46)	26.93 (1.25)*	27.23 (2.11)*
Criterion 1 (Joule/kg)	-0.72 (2.25)	0.29 (1.32)	2.65 (1.11)$^{*\perp}$
Criterion 2 (Joule/kg)	0.31 (0.99)	2.07 (1.22)*	0.21 (0.92)$^{\perp}$
Effective height (m)	6.13 (0.07)	5.86 (0.10)*	6.04 (0.21)*
Jump height (m)	5.88 (0.07)	5.60 (0.12)*	5.72 (0.18)
Release height (m)	5.93 (0.04)	5.52 (0.15)*	5.68 (0.23)$^{*\perp}$

$*$: Statistical significant ($p<0.05$) difference between groups 1 and 2 and between 1 and 3.

$\perp$: Statistical significant ($p<0.05$) difference between groups 2 and 3.

Table 97: Body angles during the energy exchange phase (degrees)

Parameter	**Group1** (n=4)	**Group2** (n=9)	**Group3** (n=12)
Hip angle of the support leg at touch-down	152 (4)	149 (4)	150 (7)
Hip angle of the support leg at take off	208 (5)	208 (6)	205 (8)
Knee angle of the support leg at touch-down	169 (5)	160 (6)*	161 (4)*
Knee angle of the support leg at take off	171 (5)	176 (5)	176 (4)
Hip angle of the swing leg at touch-down	205 (9)	203 (6)	204 (7)
Hip angle of the swing leg at take off	107 (5)	120 (12)*	126 (14)*
Knee angle of the swing leg at touch-down	86 (12)	86 (13)	99 (15)
Knee angle of the swing leg at take off	45 (7)	41 (12)	37 (8)
MPB angle	68 (2)	64 (11)	64 (5)

$*$: Statistical significant ($p<0.05$) difference between groups 1 and 2 and between 1 and 3.

$\perp$: Statistical significant ($p<0.05$) difference between groups 2 and 3.

Table 98: Horizontal and vertical CM velocities during the energy exchange phase (m/s)

Parameter	**Group1** (n=4)	**Group2** (n=9)	**Group3** (n=12)
Horizontal touch-down velocity	10.10 (0.11)	9.61 (0.11)*	9.73 (0.12)$^{*\perp}$
Vertical touch-down velocity	-0.50 (0.16)	-0.35 (0.16)	-0.20 (0.19)*
Horizontal MPB velocity	3.21 (0.10)	2.94 (0.32)	2.90 (0.09)*
Vertical MPB velocity	3.34 (0.14)	2.97 (0.18)*	3.08 (0.22)*
Horizontal take off velocity	1.36 (0.09)	1.24 (0.17)	1.27 (0.19)
Vertical take off velocity	1.96 (0.21)	2.51 (0.70)*	2.46 (1.03)

* : Statistical significant ($p<0.05$) difference between groups 1 and 2 and between 1 and 3.

⊥ : Statistical significant ($p<0.05$) difference between groups 2 and 3.

Table 99: CM height and grip height of the top hand during the take off phase

Parameter	**Group1** (n=4)	**Group2** (n=9)	**Group3** (n=12)
CM height at touch-down of the take off	1.05 (0.01)	0.98 (0.03)*	1.00 (0.03)*
CM height at the take off	1.23 (0.02)	1.14 (0.04)*	1.19 (0.03)$^{*\perp}$
CM height at touch-down of the last step	1.05 (0.01)	0.96 (0.02)*	0.98 (0.03)*
CM height at take off of the last step	1.05 (0.01)	0.97 (0.01)*	0.98 (0.03)*
Top hand height at touch-down of the take off phase	2.05 (0.02)	1.96 (0.06)*	1.96 0.05)*
Top hand height at take off of the take off phase	2.37 (0.03)	2.12 (0.07)*	2.20 (0.04)$^{*\perp}$
Horizontal distance between the top hand and the tip of the jump foot at touch-down	0.93 (0.04)	0.73 (0.10)*	0.77 (0.11)*
Horizontal distance between the top hand and the tip of the jump foot at take off	0.05 (0.10)	0.21 (0.11)*	0.18 (0.13)

* : Statistical significant ($p<0.05$) difference between groups 1 and 2 and between 1 and 3.

⊥ : Statistical significant ($p<0.05$) difference between groups 2 and 3.

List of figures

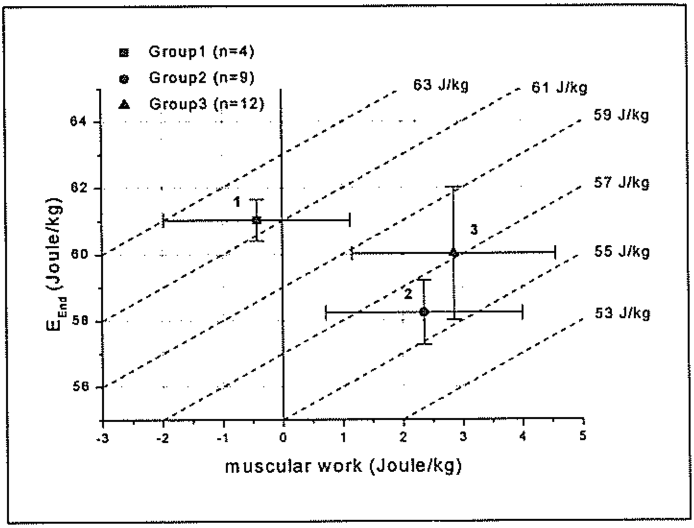


Figure 43: The total energy resulting from muscular work of the athlete and the initial energy

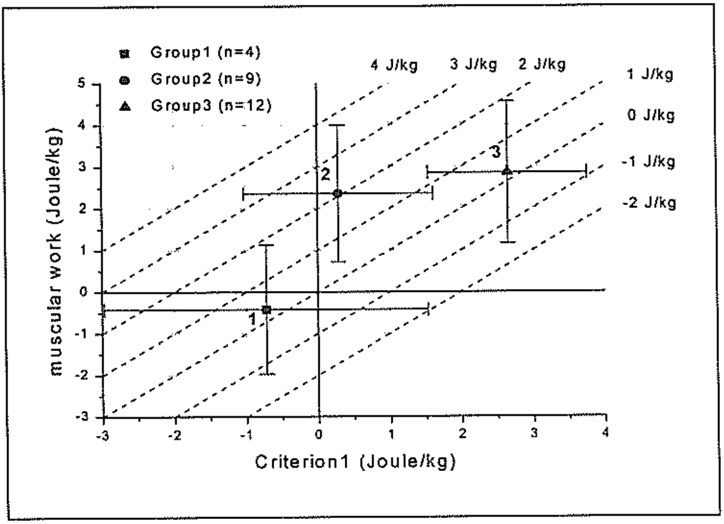


Figure 44: Muscular work depending on Criterion 1 and Criterion 2

2.3 Biomechanical Analysis of the Throwing Events

2.3.1 Discus Throw

A. Knicker

Introduction

On the occasion of the World Athletics Championships 1993 in Stuttgart the German Athletics Federation initiated a scientific research and service project according to those conducted on behalf of the IAAF at former major athletic events. The purpose of the project was to update and increase the kinematic data base of track and field events and to give the coaches a fast information feedback of their athletes' techniques. Updating existing kinematic data is supposed to shape the discipline's performance profile where kinematic analyses are only one constituent. Mere description of the techniques in terms of kinematic parameters must not be the aim. The height of their influence on the athletes' results is the least demand which should be met.

In discus throwing we are facing a principle delemma of kinematic performance diagnostics. The kinematic prerequisites of the athletic result are rather well known and their relationship is sufficiently understood. Nevertheless it is nearly impossible to tell a good from a bad throw with the help of kinematic parameters as not enough is known about the act of their generation.

Performance development

The progression of the performance in men's discus throwing shows a steady increase until the mid 80s with the still currently valid world record of Juergen Schult from 1987 representing the turning point for the elite throwers. The group of the world's best 10 throwers starts the decline in performance level in the early 80s. The decrease of achievable distances was evident until the World Championships in Stuttgart in 1993. After that the performance level appears to be rising again. This is not only true for the annual record but also for the top 3 throwers as well as for the top 10 athletes. The distances achieved are comparable to those thrown in 1989 with Lars Riedel well ahead of the rest of the throwers in 1996/97.

Purpose of the study

The study conducted at the World Athletics Championships in Athens in 1997 wants to give information on performance limiting factors in discus throwing. On the basis of data from earlier investigations at top level competitions a comparison of parameters describing throwing techniques is intended.

Methods

Data acquisition procedures followed a standard procedure with a standardized camera setup which was also used at the WAC 1993 in Stuttgart. Two Panasonic S-VHS cameras running at 50 frames per second videoed the men's final from the rear and from the side of the throwing arm. A 2mx2mx2m calibration frame was filmed before and after the competition to enable kinematic analysis related to real coordinates. The analysis was performed with a Peak Performance Motion Analysis System.

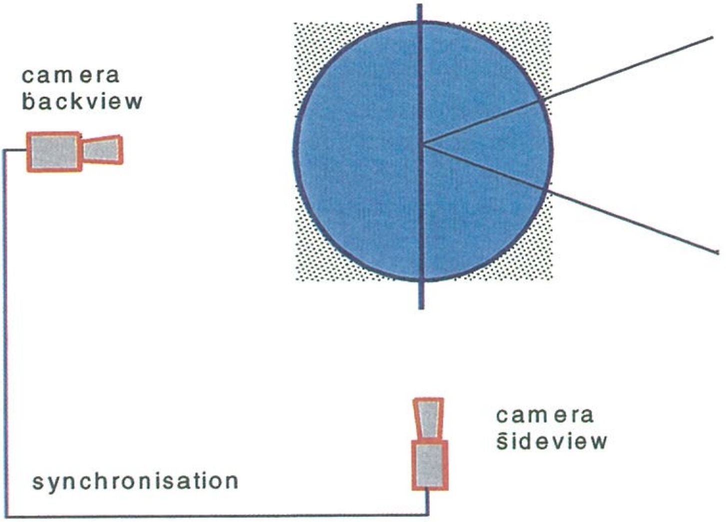


Figure 45: Standard 3-D camera (K1, K2) setup for discus throwing

Eighteen body landmarks defined 12 body segments:

- left and right foot
- left and right shank
- left and right thigh
- trunk
- left and right upper arm
- left and right lower arm and hand
- head
- and the discus

The kinematic analysis focused on parameters related to the moment of discus release as well as on time patterns of selected parameters in the main acceleration phases.

Phase structure of discus throwing

The throwing action is generally devided into

- preliminary swing
- double support start phase
- single support start phase
- transition or flight phase
- single support final acceleration phase
- double support final acceleration phase
- discus release

This subdivision of the throwers‘ movement in the ring is based on the consecutive foot ground contacts neccesary to perform a 540° turn around the body’s longitudinal axis prior to release. The rotation of the throwers is accepted to be the optimum solution in order to accelerate the implement within the limits of the competition rules. Discus throwers accelerate the discus to about 30% to 40% of the release velocity before they start the final acceleration after the transition phase. Thus the main acceleration starts when the right foot (for right handed throwers) has landed after the flight phase. Textbooks on training methodology and technique descriptions emphasise a short flight phase and a power position (= position when both feet have made contact to the ground before release) with a pronounced twist of the shoulder axis relative to the hipaxis and a throwing arm well behind the shoulder axis. Such a position is believed to influence positively the final acceleration by firstly providing an optimum length of the discus‘ acceleration path and by secondly pre-stretching the musculature of the trunk and shoulder arm complex. This is meant to increase the forces applied to the discus and consequently also increase release velocities.

Results

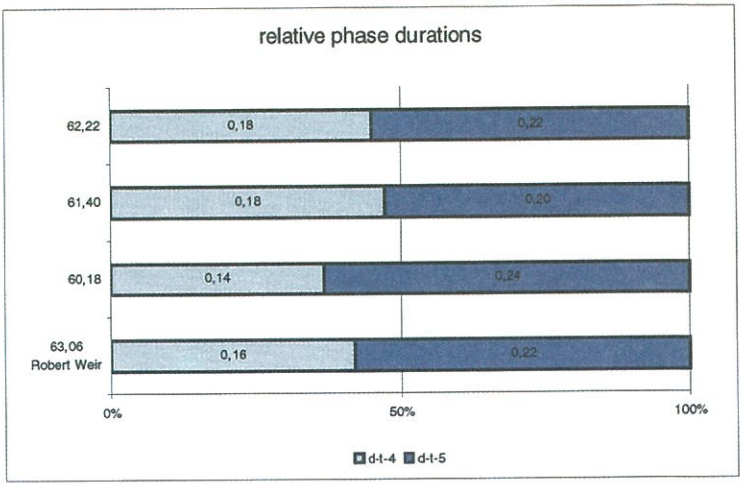
Release velocity and angle of release are those parameters that contribute most to the achieved distance. However in homogeneous samples for elite athletes no high correlations can be found between the parameter patterns and the official distance [5]. Table 100 gives all components of release velocity and the resulting angle of release for all finalists in Athens.

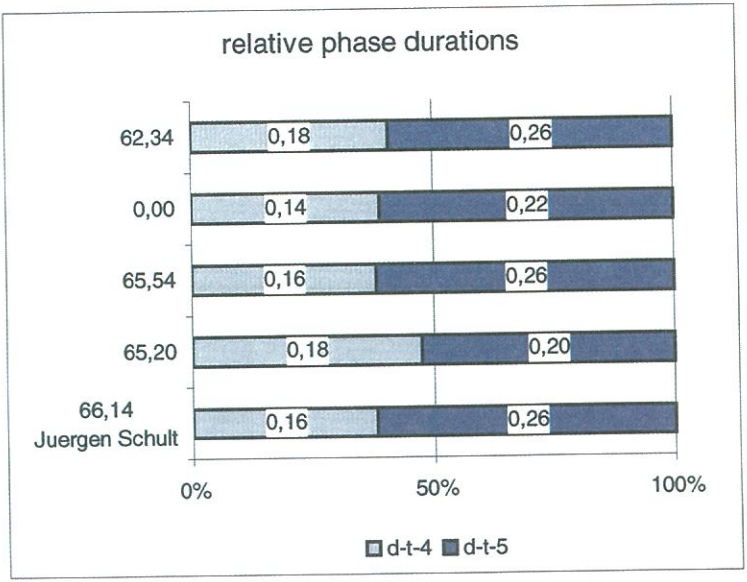
Table 100: Official results and release parameters

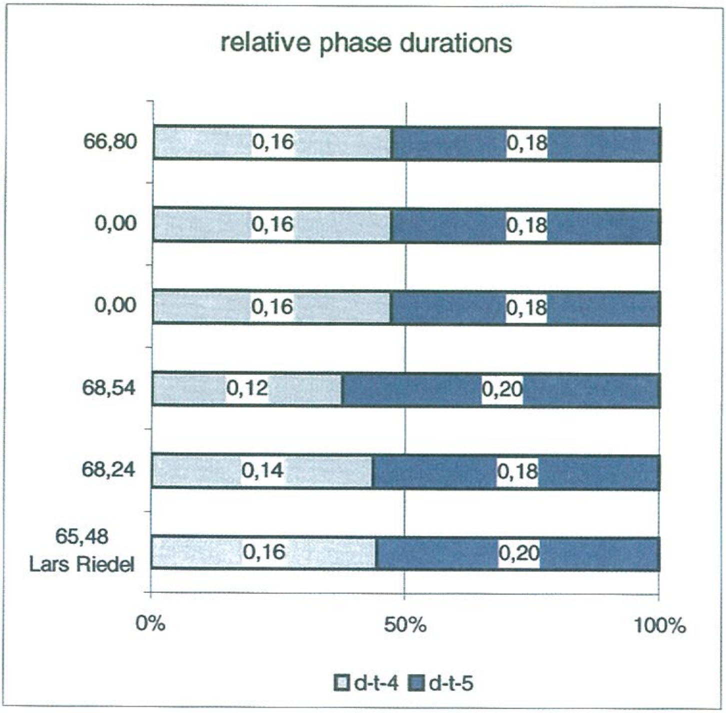
Name	official distance [m]	**release velocity** v_x [ms^{-1}]	v_y[ms^{-1}]	v_r[ms^{-1}]	**angle of release** [°]
A. Settliff	62,32m	21,5	12,9	25,1	31,0
A. Settliff	62,80m	21,5	13,0	25,1	31,2
A. Settliff	61,84m	21,1	13,4	25,0	31,9
A. Settliff	63,44m	20,7	13,8	24,9	33,7
R. Weir	63,06m	20,3	11,1	23,1	28,7
R. Weir	60,18m	21,3	11,8	24,4	29,0
R. Weir	61,40m	20,5	11,8	23,7	29,9
R. Weir	62,22m	20,5	11,8	23,7	29,9
R. Weir	58,70m	21,1	13,5	25,1	32,6
V. Dubrovshik	62,98m	19,5	13,4	23,7	34,5
V. Dubrovshik	65,36m	20,0	13,7	24,2	34,4
V. Dubrovshik	65,46m	22,7	12,2	25,8	28,3
V. Dubrovshik	62,44m	18,7	15,4	24,2	39,5
V. Dubrovshik	66,12m	19,9	13,0	23,8	33,2
J. Godina	65,40m	19,2	14,8	24,2	37,6
J. Godina	64,82m	21,5	15,1	26,3	35,1
J. Godina	64,92m	19,2	16,4	25,1	40,5
J. Godina	64,30m	17,3	16,0	23,6	42,8
J. Schult	66,14m	18,7	14,0	23,4	36,8
J. Schult	65,20m	18,7	14,2	23,5	37,2
J. Schult	65,54m	19,2	14,7	24,2	37,4
J. Schult	x	18,3	13,3	22,6	36,0
J. Schult	62,34m	19,1	14,5	24,0	37,2
V. Alekna	62,44m	19,5	13,8	23,9	35,3
V. Alekna	66,70m	20,7	14,3	25,2	34,6
V. Alekna	63,20m	20,5	12,9	24,2	32,2
V. Alekna	63,12m	20,5	13,4	24,5	33,2
V. Alekna	x	20,2	12,5	23,8	31,7
V. Alekna	x	18,4	12,4	22,2	34,0

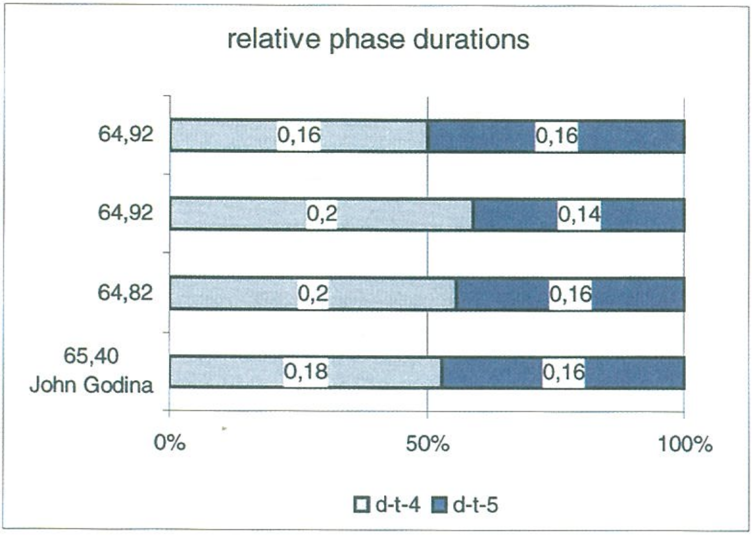
Name	official distance [m]	**release velocity** v_x [ms^{-1}]	 v_y[ms^{-1}]	 v_r[ms^{-1}]	**angle of release** [°]
L. Riedel	65,48m	23,6	12,0	26,5	27,0
L. Riedel	68,24m	22,4	12,8	25,8	29,7
L. Riedel	68,54m	21,4	12,5	24,8	30,3
L. Riedel	x	19,7	13,1	23,7	33,6
L. Riedel	x	17,9	11,4	21,2	32,5
L. Riedel	66,80m	21,6	13,2	25,3	31,4
A. Seelig	63,00m	20,3	12,6	23,9	31,8
A. Seelig	64,48m	19,3	12,7	23,1	33,3
A. Seelig	62,80m	20,9	14,0	25,2	33,8
A. Seelig	64,12m	19,8	12,8	23,6	32,9
A. Seelig	63,64m	19,0	14,3	23,8	37,0
J. Tunks	59,16m	18,5	13,5	22,9	30,5
J. Tunks	62,30m	18,2	15,2	23,7	39,9
J. Tunks	61,88m	18,6	13,1	22,8	35,2
V. Sidarov	60,32m	17,2	14,5	22,5	40,1
V. Sidarov	59,68m	19,7	13,8	24,1	35,0
A. Tammert	59,44m	17,9	13,3	22,3	36,6
A. Tammert	59,18m	21,2	14,2	25,5	33,8

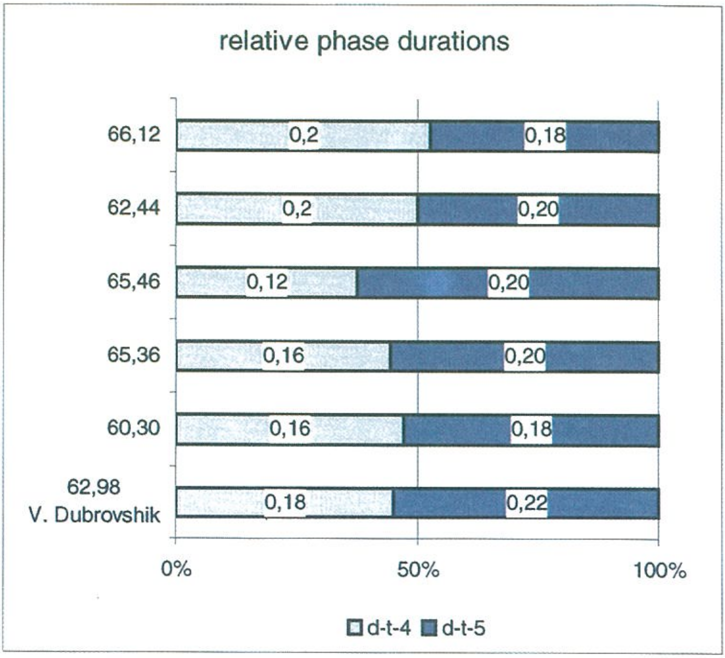
Figure 46: Phase durations displayed as relative fractions of final acceleration phase (=100%), d-t-v = single support phase, d-t-5 = double support phase

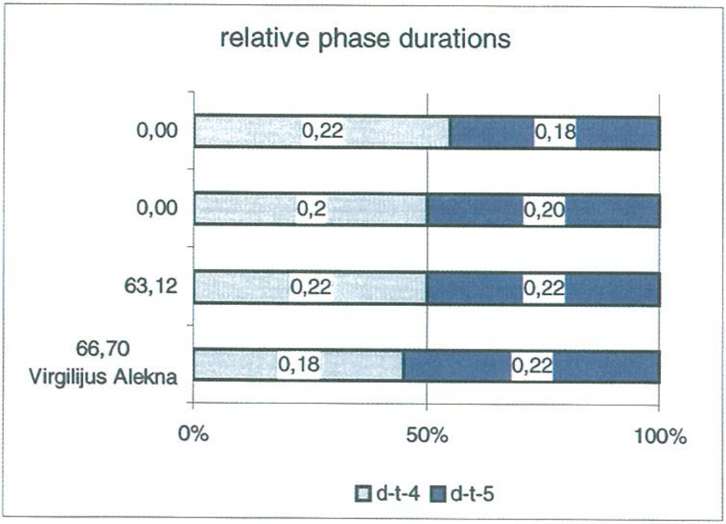





relative phase durations
66,80
0,16
0,18
0,00
0,16
0,18
0,00
0,16
0,18
68,54
0,12
0,20
68,24
0,14
0,18
65,48
Lars Riedel
0,16
0,20
0%
50%
100%
□ d-t-4 ■ d-t-5

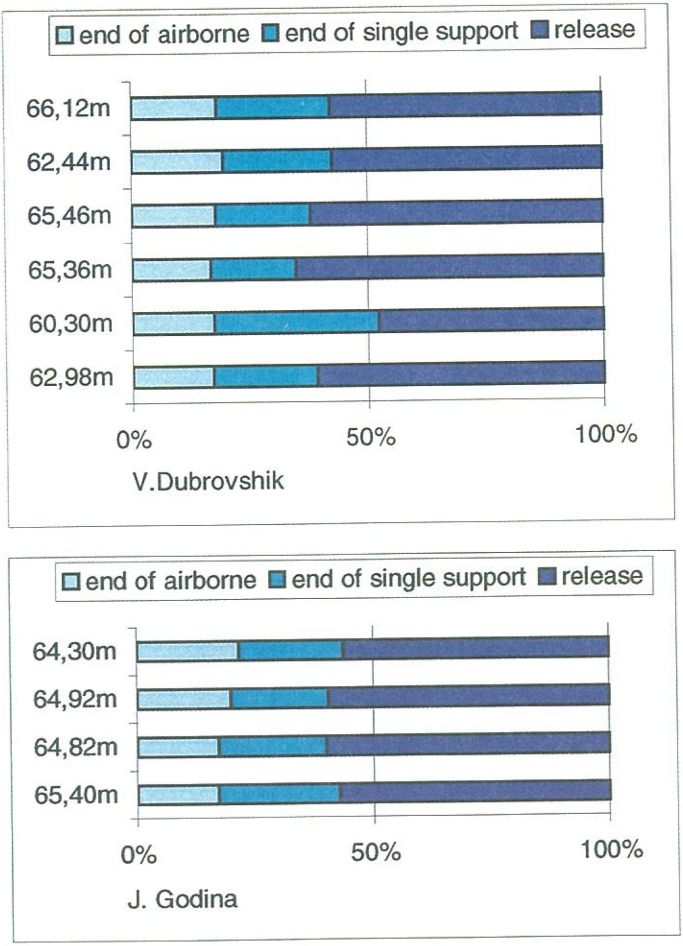

relative phase durations
64,92
0,16
0,16
64,92
0,2
0,14
64,82
0,2
0,16
65,40
John Godina
0,18
0,16
0%
50%
100%
□ d-t-4 ■ d-t-5

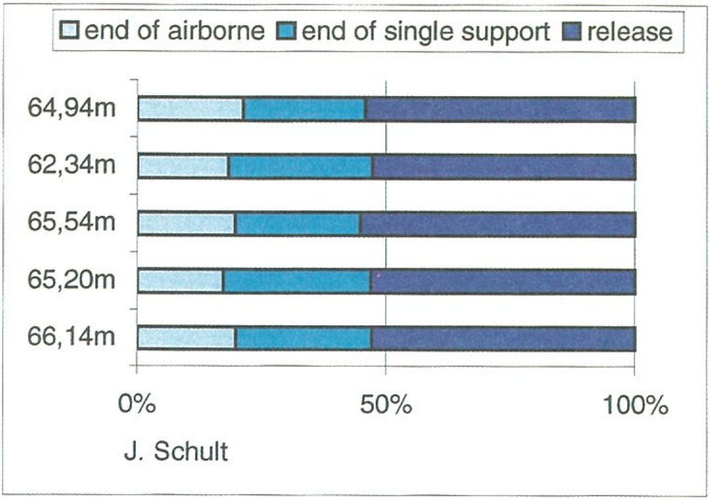

relative phase durations
66,12
0,2
0,18
62,44
0,2
0,20
65,46
0,12
0,20
65,36
0,16
0,20
60,30
0,16
0,18
62,98
V. Dubrovshik
0,18
0,22
0%
50%
100%
d-t-4
d-t-5

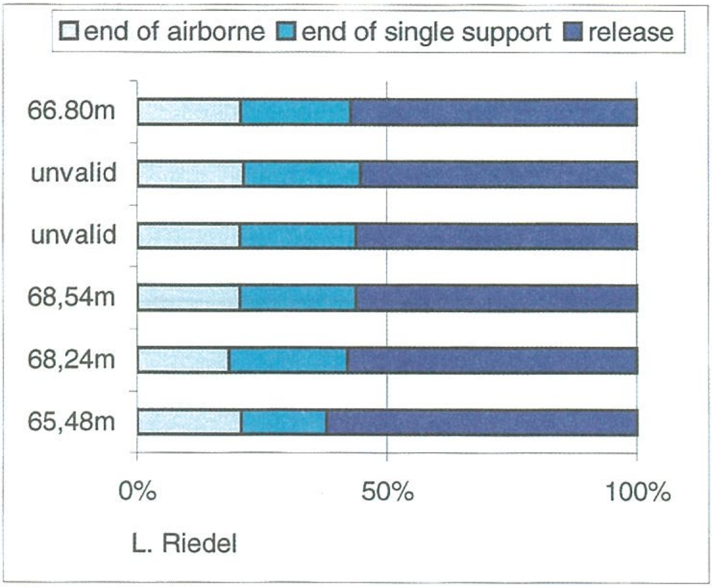

relative phase durations
0,00
0,22
0,18
0,00
0,2
0,20
63,12
0,22
0,22
66,70
Virgilijus Alekna
0,18
0,22
0%
50%
100%
d-t-4
d-t-5

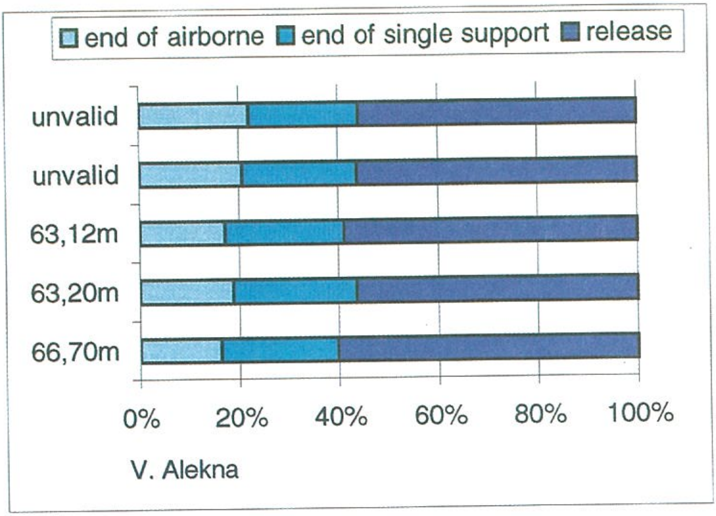
The graphs in Figure 46 reveal that most throwers performed a double support phase (d-t-5) which was longer than their single support phase (d-t-4) before discus release. The only exception was John Godina who performed a longer single support phase in all of his analysed throws. It is though remarkable how constant the timing patterns are performed by the single athletes. The variations in phase duration are considerably small.

Figure 47: Relative discus velocities for the phases prior to release (release velocity=100%) for throwers who achieved more than 65m




end of airborne
end of single support
release
64,94m
62,34m
65,54m
65,20m
66,14m
0%
50%
100%
J. Schult


end of airborne
end of single support
release
66.80m
unvalid
unvalid
68,54m
68,24m
65,48m
0%
50%
100%
L. Riedel



All throwers built up about 20% of the release velocity in the phases prior to touchdown after the flight phase. During the following single support phase the athletes added another 20%. The main acceleration thus occurs during double support directly prior to release (see graphs in figure 47). The absolute change of discus velocities in the release phases for the best throws of the athletes ranked 1 to 5 are given in table 101. The highest change in discus velocity was reached by V. Dubrovshik with 17,6m/s which was though not his best. A slight trend can be recognized by looking at the numbers in the table. It is noticeable that the best throws can obviously be performed when a certain level of discus velocity has already been reached during the preliminary phases, and a considerable gain in discus velocity can already be achieved during single support. The final acceleration then does not need to be so pronounced as if the discus velocity after the airborne phase is still low. Comparably high accelerations in the single support phase (d-v-4) often correspond well to the official results. This is particularly true for Dubrovshik, Godina and Alekna who all reached their best result of the competition when they showed highest values for the change of discus velocity in the single support phase (d-v-4).

Table 101: Changes of discus velocities in the single support (d-v-4) and double support (d-v-5) phases prior to discus release

Athlete	**distance**	**d-v-4**	**d-v-5**
V. Dubrovshik	65,36	0,5	17,6
	65,46	1,0	16,5
	66,12	2,4	14,0
J. Godina	65,40	3,6	13,4
	64,82	2,4	16,4
	64,92	0,2	16,5
L. Riedel	68,24	2,3	15,3
	68,54	1,1	14,1
	66,80	0,6	15,6
J. Schult	66,14	3,4	11,6
	65,20	5,4	10,5
	65,54	2,5	13,2
V. Alekna	66,70	3	15,4
	63,20	2,6	13,8
	63,12	3	15,3

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8. see BARTLETT (1992) for extensive list of references.
9. see KNICKER et al. (1994) for more details on all finalists of the WAC 1993 in Stuttgart.

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