Biomechanical Analysis of the Hammer Throw at the 2009 IAAF World Championships in Athletics

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(Translated from the original German by Matthias Werner)

ABSTRACT

The techniques of the top eight placers in the men's and women's hammer throw at the 2009 World Championships in Athletics were studied to obtain the latest data and insight into the technical condition of the world's current best throwers. Video recordings of the best attempt of each thrower were analysed using a three-dimensional kinematographic measurement method. If this was not possible due to recording problems - usually judges, photographers or others on the infield obstructing the view - the thrower's second best attempt was analysed. A 14-segment body model with 20 body surface landmarks and a landmark for the hammer head, used in previous studies of the event, was the basis for analysis. Using this model, the release parameters (release velocity, angle of release, etc), spatial characteristics of the throwing movement and other data derived could be quantified. To give guidance for coaches and athletes preparing for future high-level competitions, the mean values of the group, the extent of distribution, as well as the standard deviation and range of variation of selected parameters were derived and compared with other parameters. In addition, the correlations between different parameters were quantified by calculation of correlation coefficients.

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Introduction

The women's hammer throw at the 2009 World Championships in Athletics in Berlin is considered by many to be the best ever championship competition in the event. Top honours went to Anita Wlodarczyk (POL), who set a world record with her 77.96m second round throw. Second placer

Betty Heidler (GER) threw 77.12m, the eighth best throw ever, to set a national record and top a six throw series averaging 75.53m while Martina Hrasnova (SVK) threw 74.79m for the bronze medal. Never in the history of the championships has the average of the performances of the medal winners (76.62m) or the top eight (74.08m) been so good.

In comparison, the relative quality of the performances in the men's competition lagged behind those of the women. The winner was the 2008 Olympic Champion Primoz Kozmus (SLO). He and second placer Szymon Ziolkowski (POL) both threw their season's bests, 80.84m and 79.30m respectively, but with the exception of seventh placer Andras Haklits (CRO) all other finalists threw 1.30 to 3.50m below the best marks they had achieved earlier in the year. On only one occasion since the championships began in 1983 has the winning mark been shorter (80.24m in 1999). In recent

Table 1: Results of the hammer throw at the 2009 IAAF World Championships in Athletics (Throws marked in bold were analysed for the report.)

Pos	Athlete (Country)	Round					
		1	2	3	4	5	6
Men's Final – 17 August – 18:05							
1	Primož Kozmus (SLO)	75.14	79.74	77.21	79.28	**80.15**	80.84
2	Szymon Ziólkowski (POL)	77.44	79.30	77.85	77.66	**78.09**	76.89
3	Aleksey Zagornyi (RUS)	76.11	x	77.42	x	75.11	**78.09**
4	Krisztián Pars (HUN)	75.51	x	x	**77.45**	X	x
5	Sergej Litvinov (GER)	74.50	74.49	75.88	76.58	**76.00**	74.45
6	Markus Esser (GER)	68.07	**76.27**	74.07	x	X	x
7	András Haklits (CRO)	72.60	75.12	75.09	x	74.82	**76.26**
8	Pavel Kryvitski (BLR)	73.72	x	72.73	x	X	**76.00**
9	Nicola Vizzoni (ITA)	x	x	73.70			
10	Libor Charfreitag (SVK)	x	72.63	x			
11	Dilshod Nazarov (TJK)	x	x	71.69			
12	Igor Vinichenko (RUS)	x	x	x			
Women's Final 22 August –19:30							
1	Anita Wlodarczyk (POL)	74.86	**77.96**	-	-	-	x
2	Betty Heidler (GER)	75.10	75.38	75.73	73.45	76.44	**77.12**
3	Martina Hrasnová (SVK)	67.84	72.72	73.07	69.50	**74.79**	65.65
4	Kathrin Klaas (GER)	72.02	x	**74.23**	66.28	X	x
5	Wenxiu Zhang (GER)	69.42	72.57	x	**71.80**	70.83	71.03
6	Tatyana Lysenko (RUS)	72.22	x	**71.36**	x	71.51	70.16
7	Jessica Cosby (USA)	x	72.17	69.94	68.10	X	**71.35**
8	Clarissa Claretti (ITA)	**71.56**	69.42	70.97	70.91	70.24	x
9	Stéphanie Falzon (FRA)	71.40	70.80	x			
10	Sultana Frizell (CAN)	69.63	70.88	68.47			
11	Amber Campbell (USA)	64.62	70.08	x			
12	Manuela Montebrun (FRA)	x	69.92	69.75			

years, the mean value for the three medal winners (79.41m) has only been lower at the 1999 World Championships in Athletics and the Olympic Games in 1984 and 2000; the average for top eight placers (77.60m) was the lowest in a top world event since the early 1980s.

In this report, the results of biomechanical analyses of the two competitions are presented. The parameters describing hammer throw technique were recorded with video cameras and analysed using a three-dimensional kinematographic measurement method with the aim of obtaining the latest data and insight into the technical condition of world's current best throwers. The intent was to analyse the best attempt of each of the top eight placers in the two competitions. If this was not possible due to recording problems - usually judges, photographers or others on the infield obstructing the view - the thrower's second best attempt was analysed.

Table 1 gives the complete results of the competition. The analysed throws are highlighted in bold.

Methods

Image Frequency and Exposure Times

Video recording was carried out with two video cameras (Canon XH G1S) identical in construction and capable of being genlocked at an image frequency of 25 frames/s (50 fields/s) at a resolution of 720 x 576 pixels (16:9 format). Depending on the lighting conditions, exposure times of the single frames were adjusted between 1/500sec to 1/1000sec by means of an electronic shutter to avoid in-motion blur.

Synchronisation

Both video cameras were initially synchronised internally by means of the Genlock procedure, so that the single frames of both cameras were exposed at exactly the same point of time. Additionally, an external optical synchronisation was applied by means of LED to make a later allocation of both camera views easier.

Recording Set-up

The cameras were mounted onto the railing of the first row of seating at the front of the stadium, slightly above centre of mass (CM) height of the throwers. This was done in order to record both the thrower and the hammer in all phases of the movement without obstruction. Owing to the position of the hammer throw cage and the requirement to record from the seating area, the side camera could not be positioned, as usual, on the side of release (to right of the throwing direction). Hence the side camera was put up on the opposite side (to the left of the throwing direction). The optical axes of both cameras form an angle of about 90°.

Calibration

The direct linear transformation method (DLT: ABDEL-AZIZ & KARARA, 1971) was used to determine the three-dimensional spatial coordinates. Prior to the competition, a calibration frame with eight fixed points was put into the throwing circle and filmed to serve as a reference system. The calibration system defined the three-dimensional coordinate system in the given object space, with the x-axis pointing towards the throwing direction, the y-axis towards the transverse direction and the z-axis towards the vertical line. The origin of the coordinate system was exactly in the middle of the throwing circle, at the level of the ground.

Body Model

A 14-segment body model with 20 body surface landmarks and a landmark for the hammer head was the basis for analysis. This model has been used in other hammer throw analyses (DAPENA, 1985; OTTO, 1994). The surface landmarks are either the breakthrough points of imagined joint rotation axes onto the body surface, prominent bones or clearly visible points of the body at projection points of these joint axes and the centre of the hammer head (Figure 1).

Figure 1: 21-point-scanning model

Recording of the Spatial Coordinates

Recording of the spatial coordinates was carried out by means of SIMI°Motion® software. It started with the last image of double-supported ground contact after the preliminary swings, the so-called transition into the first turn, and ended in the moment of the hammer head leaving one of the image sections of a camera position, about three to four frames after the release.

Data Processing

As manually captured coordinates are flawed with errors (BAUMANN & PREIß, 1996), it is common practice to first rid the primary data of rough coordinate errors (outliers), and then smooth it with a method of compensation (BAUMANN et al., 1996). The two-dimensional raw coordinates from both angles were checked for outliers and any single missing values (covertness) were interpolated with a spline function. After calculation of the three-dimensional spatial coordinates, a low-pass Butterworth filter with a cut-off frequency of 10Hz was applied as compensation method. To avoid phase shifting, the filter is effective in both directions. Afterwards all analysed characteristics of the movement were directly derived or calculated.

Analysed Characteristics

On the basis of the simplified model of movement at hand, the release parameters (release velocity of the hammer, angle of release, etc), spatial characteristics of the throwing movement and other data derived can be quantified.

For selected parameters the mean values of the group, the extent of distribution, as well as standard deviation and range of variation were derived and compared with other parameters. The correlations between different parameters were additionally quantified by calculation of correlation coefficients. These coefficients are primarily meant as descriptive measures to clarify the relation of parameters within the analysed groups and can be understood only partly as proof of a causal correlation.

Definitions of the parameters studied are given in Table 2. The following are of particular interest:

Temporal and Path Parameters

For description and assessment of hammer throw technique it is interesting to know how the long single-support and double-support phases last. Likewise it is useful to analyze the location of hammer head when these phases begin and end.

Angular Paramaters

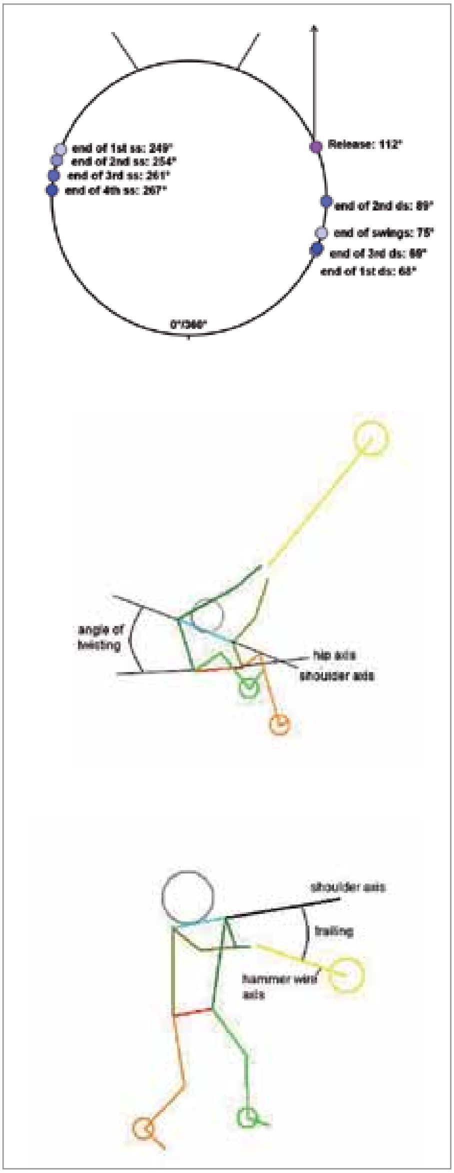
Concerning the azimuth, the following hypothesis is often stated: In an optimal course of the turns one can work on the assumption that the degree values of the azimuth which define the lift-off points of the free leg (end of ds), always shift a few degrees towards the direction of the 0°-point from turn 1 to turn 4 (OTTO, 1990). Accordingly the degree values that define the touchdown points of the free leg (end of ss) always shift a few degrees towards the back in throwing direction, hence become smaller (see Figure 7 and Figure 13). In addition, the throwers strive for a lift-off into the first turn (end of swings) prior to the 90° azimuth.

Table 2: Definitions of analysed parameters

General and Release Parameters	
Attempt	Analysed attempt
Distance	Throwing distance
Release Velocity	Velocity of the hammer head at release
Angle of Release	Angle of release in respect to the horizontal line
Release Height	Height of the hammer head at release
Velocity Parameters	
Starting Velocity	Velocity of hammer head at the end of the starting phase (after the preliminary swings, prior to lift-off of the free leg into turn 1)
Increase of Velocity	Change of hammer head velocity in turns 1/2/3/4
Temporal Parameters	
Time until the end of the support phases	Elapsed time until end of phase: single-support phase (ss), double-support phase (ds), turns 1-4 (1st turn ss, 1st turn ds, 2nd turn ss, 2nd turn ds, 3rd turn ss, 3rd turn ds, 4th turn ss, 4th turn ds)
Duration of Turns	Duration of the respective turns (Turn 1 to Turn 4), measured from last ground contact of free leg prior to lift-off until next ground contact or respectively last image in which the hammer grip has contact to the hand
Duration of Support Phases Sum Time ss/ds	Duration of respective single-support (ss) and double-support (ds) phases and sum of the durations of the ss and ds phases
Path Parameters	
Path of the hammer during turns	Covered distance of the hammer head in the respective turns, aligned according to duration of turns.
Path of the hammer, single and double-support and sum ss/ds	Covered distance by the hammer head in the respective phase. Sum of distance covered by the hammer head in single-support or double-support phases
Angular Parameters	
Azimuthal Angle	The azimuthal angle describes the position of the hammer head within the 360° circle (Figure 2). Viewed from the initial position of the thrower prior to turning, 0° or 360° indicates the position of the hammer head directly in front of the thrower (at the bottom of the figure), 90° means left of the thrower (right in the figure), 180° behind the thrower or in throwing direction (at the top of the figure), and 270° at the right hand side of the thrower (left in the figure). The position of the hammer head at certain end points of phases can be read from the depiction of the azimuthal angle. It is calculated by the angle between the line connecting the hammer head and the XZ-plane.
Angle of Twisting	Angle between the shoulder axis and hip axis (Figure 2, middle). It is calculated by the difference of the orientation angle between the hip axis and shoulder axis.
Angle of Trailing	Angle between the shoulder axis and the connecting line from hammer head to shoulder axis (Figure 2). The angle of trailing equals 90° when the hammer head is exactly in front of the thrower. Trailing the hammer behind, as depicted in the middle frame of Figure 2, increases the angle to values above 90°, whereas when the hammer runs ahead, this effects a reduction of the angle to values below 90°.

The thrower definitely has to strive to arrange the last, in other words the third or respectively fourth, touchdown (end of 3rd / 4th ss), in such a way that the following main acceleration phase leading to the release – which can amount to about 20% of the change in velocity – can be carried out as effectively as possible.

Figure 2: Azimuthal Angle, Angle of Twisting, Angle of Trailing



The differences in angles between shoulder and hip axis should be kept relatively constant throughout the turns to ensure an effective acceleration. Pronounced twisting reduces the radius of the hammer path and consequently reduces the acceleration path in the turns.

Deformations of the hammer path are to be avoided, as they lead to path reductions of the radius and also to interference in the balance of the whole movement and hence to reductions of velocity. These deformations can be caused by what is known as trailing, which is due to lifting the right foot from the ground too early. However, in a broad-based longitudinal and cross-sectional study in hammer throw (OTTO, 1994) covariances between the angle of trailing and throwing distance were only partly found. Nevertheless the results indicate that optimal angles of trailing can influence the increase of velocity positively.

Analysis of the Women's Competition

With the exceptions of fifth placer Zhang (CHN), sixth placer Lysenko (RUS) and seventh placer Cosby (USA), the best throws of each of the top eight placers in the women's event were analysed. For the three named, blockage of one or both of the camera views by persons on the infield of the stadium meant it was not possible to perform the analysis on the best throw. Therefore, the next best throw for which the required quality of video recording was available was analysed instead.

Turns

Six of the top eight women threw from four turns. Third placer Hrasnova and seventh placer Cosby threw from three turns.

Release Parameters

In Table 3 we see that with 27.9 m/s, Heidler achieved the highest release velocity, followed by Wlodarczyk with 27.8 m/s. The average release velocity of the eight analysed finalists was 27.1 m/s with a standard deviation of 0.5 m/s.

The highest angle of release was measured for Klaas (GER) with 42.3°, followed by Wlodarzyk and Lysenko. Hrasnova's 37.6° was clearly low. The average angle of release of the eight analysed finalists was 40.0° with a standard deviation of 1.7°.

With 1.66m Cosby achieved the highest release height, followed by Claretti (ITA), Hrasnova and Lysenko. On average, the finalists achieved a release height of 1.46m with a standard deviation of 0.15m.

Table 3: Release parameters for the analysed throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics

Name	Throw Distance	Release Velocity	Angle of Release	Release Height
	[m]	[m/s]	[°]	[m]
Wlodarczyk	77.96	27.8	41.8	1.50
Heidler	77.12	27.9	39.1	1.27
Hrasnova	74.79	27.5	37.6	1.54
Klaas	74.23	27.1	42.3	1.35
Zhang	71.80	26.8	39.8	1.25
Lysenko	71.36	26.6	41.6	1.54
Cosby	71.35	26.7	38.6	1.66
Claretti	71.56	26.7	39.5	1.55

There is a high correlation between release velocity and throwing distance (r = 0.98) (see Figure 3). Only a very low correlation could be found between angle of release and throwing distance (r = 0.11).

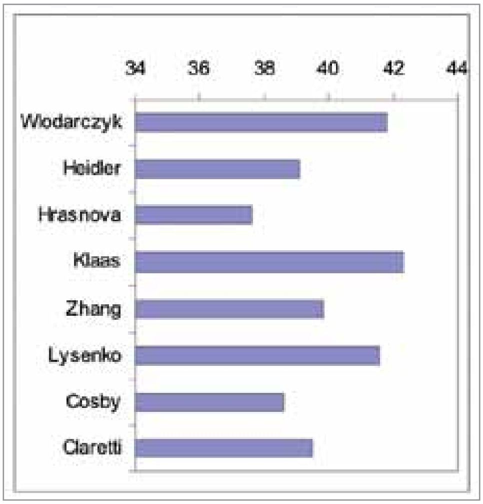


Figure 4: Angle of release [°] for the top women hammer throwers at the 2009 IAAF World Championships in Athletics

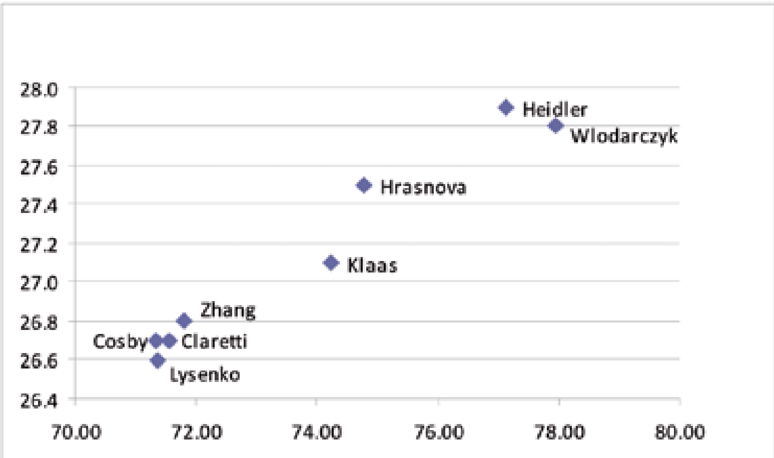


Figure 3: Release velocity [m/s] (y-axis) compared to official result [m] (x-axis) for the top women hammer throwers at the 2009 IAAF World Championships in Athletics

Velocity Parameters

Heidler initiates the first turn with a very high starting velocity (18.6 m/s) created in the preliminary swings. This results in only very small increases of velocity from the first (2.5 m/s), second (1.6 m/s) and third (0.9 m/s) turns. Only in her fourth turn a greater increase of velocity can be noticed (see Table 4).

Cosby (17.5 m/s) and Klaas (16.9 m/s) also start out very fast. Of course, throwing from only three turns, Cosby's starting velocity needs to be high. The other three-turn thrower, Hrasnova, achieves an above average rate of increase with 4.8 m/s in the final turn.

With r = 0.97 there is a high correlation between increase of velocity in the fourth turn and throwing distance.

Temporal Parameters

Heidler needs the shortest duration for the whole movement of the four turns, 1.84 sec, followed by her training colleague Klaas with 1.92 sec (see Table 5). The longest durations were measured for Lysenko with 2.16 sec and Wlodarczyk with 2.04 sec. The average of the six finalists with four turns is 1.99 sec for the whole movement. For the three-turn throwers Hrasnova and Cosby, the average for their whole movement was 1.60 sec.

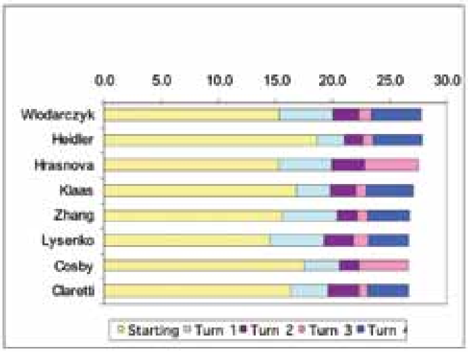


Figure 5: Starting velocity and increase of velocity [m/s] during the turns for the analysed throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics

Until the penultimate turn all throwers except Heidler succeeded in making the next turn temporally shorter than the turn before. None of the throwers made the last turn temporally shorter than the penultimate one. Only for Hrasnova and Zhang did the penultimate and the last turns last equally long.

Table 4: Velocity parameters for the analysed throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics

Name	Throw Distance	Starting Velocity	Increase of Velocity				Release Velocity
			Turn 1	Turn 2	Turn 3	Turn 4	
	[m]			[m/s]			
Wlodarczyk	77.96	15.3	4.7	2.3	1.1	4.4	27.8
Heidler	77.12	18.6	2.5	1.6	0.9	4.4	27.9
Hrasnova	74.79	15.2	4.7	2.8	4.8		27.5
Klaas	74.23	16.9	3.0	2.2	0.9	4.1	27.1
Zhang	71.80	15.7	4.8	1.8	0.9	3.7	26.8
Lysenko	71.36	14.5	4.7	2.6	1.4	3.4	26.6
Cosby	71.35	17.5	3.2	1.7	4.4		26.7
Claretti	71.56	16.4	3.3	2.7	0.8	3.6	26.7

There is a mean negative correlation (r = -0.48) between throwing distance and duration of the turns. One can perceive a trend that the shorter the duration for all the turns the further the throw. Wlodarczyk and Lysenko are exceptions, as they seem to fall outside the usual pattern due to their slow velocities during the first two turns.

All throwers clearly spent more time in the single-support phase than in the double-support (Table 6 and Table 7). With 0.12 sec, Wlodarczyk and Cosby had the smallest differences between the sums of the two phases.

If we consider any one turn, none of the throwers was in the double-support phase longer than the single-support phase. Only in the last turn of Wlodarczyk, Cosby and Claretti were the two phases equally long.

Table 5: Duration of the turns for the analysed throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics

Name	Throw Distance	Turn 1	Turn 2	Turn 3	Turn 4	Total
	[m]			[sec]		
Wlodarczyk	77.96	0.60	0.54	0.42	0.48	2.04
Heidler	77.12	0.54	0.42	0.42	0.46	1.84
Hrasnova	74.79	0.60	0.52	0.52		1.64
Klaas	74.23	0.56	0.48	0.40	0.48	1.92
Zhang	71.80	0.60	0.50	0.46	0.46	2.02
Lysenko	71.36	0.64	0.52	0.48	0.52	2.16
Cosby	71.35	0.56	0.44	0.56		1.56
Claretti	71.56	0.58	0.48	0.40	0.52	1.98

Table 6: Time at the end of the turn phases for the analysed throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics (ss=single-support, ds=double-support)

Name	Throw Distance	Turn 1 ss	Turn 1 ds	Turn 2 ss	Turn 2 ds	Turn 3 ss	Turn 3 ds	Turn 4 ss	Turn 4 ds
	[m]				[sec]				
Wlodarczyk	77.96	0.34	0.60	0.88	1.14	1.36	1.56	1.80	2.04
Heidler	77.12	0.32	0.54	0.80	0.96	1.24	1.38	1.66	1.84
Hrasnova	74.79	0.34	0.60	0.92	1.12	1.42	1.64		
Klaas	74.23	0.30	0.56	0.82	1.04	1.28	1.44	1.70	1.92
Zhang	71.80	0.36	0.60	0.90	1.10	1.38	1.56	1.82	2.02
Lysenko	71.36	0.34	0.64	0.92	1.16	1.46	1.64	1.94	2.16
Cosby	71.35	0.30	0.56	0.82	1.00	1.28	1.56		
Claretti	71.56	0.32	0.58	0.84	1.06	1.30	1.46	1.72	1.98

Table 7: Duration of support phases of the turns for the analysed throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics (ss=single-support, ds=double-support)

Name	Throw Distance	Turn 1 ss	Turn 1 ds	Turn 2 ss	Turn 2 ds	Turn 3 ss	Turn 3 ds	Turn 4 ss	Turn 4 ds	Sum ss	Sum ds
	[m]				[sec]						
Wlodarczyk	77.96	0.34	0.26	0.28	0.26	0.22	0.20	0.24	0.24	1.08	0.96
Heidler	77.12	0.32	0.22	0.26	0.16	0.28	0.14	0.28	0.18	1.14	0.70
Hrasnova	74.79	0.34	0.26	0.32	0.20	0.30	0.22			0.96	0.68
Klaas	74.23	0.30	0.26	0.26	0.22	0.24	0.16	0.26	0.22	1.06	0.86
Zhang	71.80	0.36	0.24	0.30	0.20	0.28	0.18	0.26	0.20	1.20	0.82
Lysenko	71.36	0.34	0.30	0.28	0.24	0.30	0.18	0.30	0.22	1.22	0.94
Cosby	71.35	0.30	0.26	0.26	0.18	0.28	0.28			0.84	0.72
Claretti	71.56	0.32	0.26	0.26	0.22	0.24	0.16	0.26	0.26	1.08	0.90

Spatial Parameters

In Table 8 we see that Lysenko, Zhang and Wlodarczyk showed the longest paths of the hammer. On average the path of the hammer for the six analysed finalists using four turns was 43.1m with a standard deviation of 1.2m.

In this respect it is striking that Klaas and Heidler were clearly below the average with 41.5m and 41.8m respectively.

Hrasnova and Lysenko were the only throwers able to increase the path of the hammer throughout all turns. Zhang showed the same path of the hammer in the first three turns. Heidler shortened the path of the hammer in the second turn, Wlodarczyk and Klaas shortened the path of the hammer in the third turn.

Table 8: Path of the hammer during the turns for the analysed throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics

Name	Throw Distance	Turn 1	Turn 2	Turn 3	Turn 4	Total
			[m]			
Wlodarczyk	77.96	10.5	11.5	9.9	12.2	44.0
Heidler	77.12	10.4	9.5	10.2	11.8	41.8
Hrasnova	74.79	9.7	11.3	12.6		33.6
Klaas	74.23	9.8	10.3	9.3	12.1	41.5
Zhang	71.80	10.9	10.9	10.9	11.5	44.1
Lysenko	71.36	10.2	10.6	10.9	12.6	44.3
Cosby	71.35	9.8	9.7	13.8		33.3
Claretti	71.56	10.0	10.3	9.5	13.3	43.0

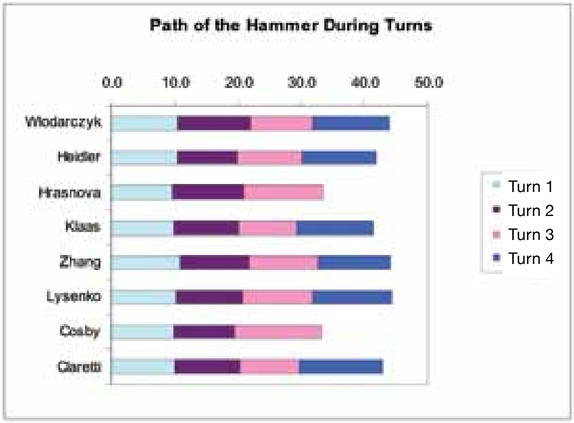


Figure 6: Path of the hammer during the turns [m] for the analysed throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics

Table 9: Path of the hammer in the single and double-support phases of the turns for the analysed throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics (ss=single-support, ds=double-support)

Name	Throw Distance	Turn 1 ss	Turn 1 ds	Turn 2 ss	Turn 2 ds	Turn 3 ss	Turn 3 ds	Turn 4 ss	Turn 4 ds	Sum ss	Sum ds
	[m]				[sec]						
Wlodarczyk	77.96	5.3	5.1	5.7	5.8	5.1	4.9	5.9	6.3	21.7	20.2
Heidler	77.12	5.7	4.7	5.7	3.8	6.7	3.5	6.9	4.9	21.8	21.4
Hrasnova	74.79	5.0	4.7	6.7	4.7	6.9	5.7			20.5	22.0
Klaas	74.23	4.8	5.0	5.4	4.9	5.5	3.8	6.3	5.8	19.6	20.6
Zhang	71.80	5.9	4.9	6.2	4.6	6.4	4.5	6.2	5.3	23.0	20.3
Lysenko	71.36	4.9	5.4	5.5	5.1	6.6	4.3	6.9	5.7	24.3	19.0
Cosby	71.35	4.8	4.9	5.7	4.0	6.7	7.2			21.2	22.1
Claretti	71.56	5.1	4.9	5.4	4.9	5.6	3.9	6.4	6.9	21.6	20.8

Angular Parameters

Angular parameters were analysed for the first two placers Wlodarczyk and Heidler and for fourth placer Klaas.

In Table 10 and Figure 7 we see that at the end of the swing phase, Heidler and Klaas lifted off the free leg very early, at an azimuth of 50° or 41° respectively. Wlodarczyk lifted off at 75°.

For Klaas all touchdown points of the free leg were before the 270° azimuth, the same was true for Wlodarczyk, only closer together. For Heidler the touchdown points were distributed around 270°. None of the three throwers succeeded in touching down on a turn earlier than on the previous one.

Table 10: Azimuthal angle at the end of throw phases for selected throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics (ss=single-support, ds=double-support)

Name	Throw Distance	End of swing	Turn 1 ss	Turn 1 ds	Turn 2 ss	Turn 2 ds	Turn 3 ss	Turn 3 ds	Turn 4 ss	Release
	[m]				[°]					
Wlodarczyk	77.96	75	249	68	254	89	261	69	268	112
Heidler	77.12	50	256	61	267	44	276	46	284	98
Klaas	74.23	41	222	37	239	51	254	33	262	108

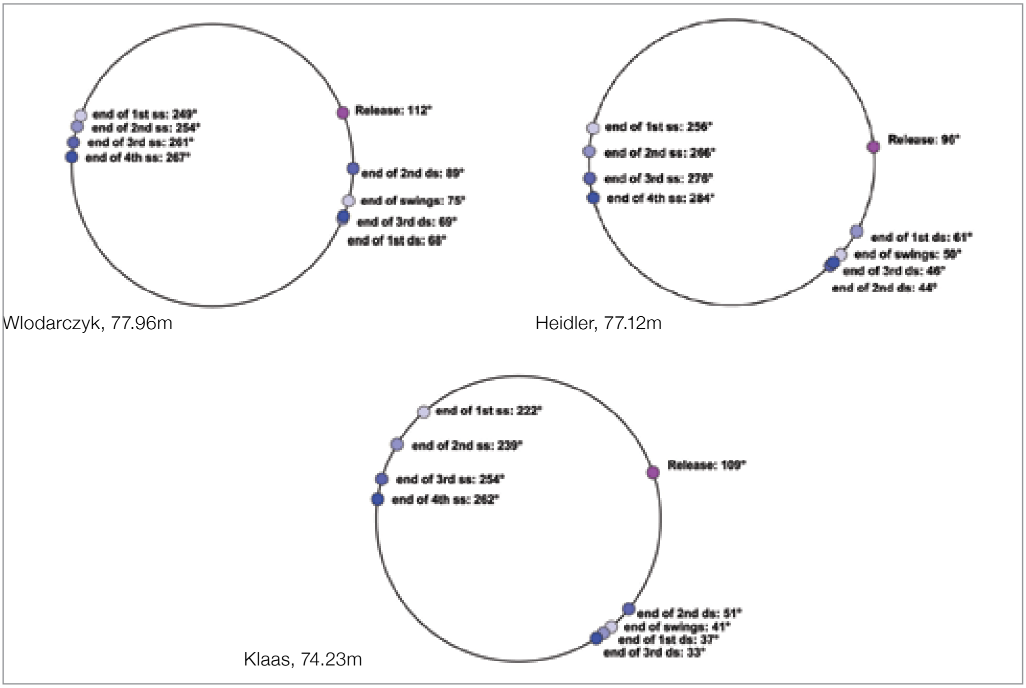


Figure 7: Azimuthal angle at the end of throw phases, displayed in the 360° circle for selected throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics

Table 9: Angle of twisting (between shoulder and hip axis) at the end of throw phases for selected throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics (ss=single-support, ds=double-support)

Name	Throw Distance	End of swing	Turn 1 ss	Turn 1 ds	Turn 2 ss	Turn 2 ds	Turn 3 ss	Turn 3 ds	Turn 4 ss	Release
	[m]				[°]					
Wlodarczyk	77.96	27	51	5	17	35	29	17	36	12
Heidler	77.12	21	53	26	36	25	18	22	13	21
Klaas	74.23	13	59	32	50	21	44	15	39	43

Table 10: Angle of trailing (between shoulder axis and hammer wire) at the end of throw phases for selected throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics (ss=single-support, ds=double-support)

Name	Throw Distance	End of swing	Turn 1 ss	Turn 1 ds	Turn 2 ss	Turn 2 ds	Turn 3 ss	Turn 3 ds	Turn 4 ss	Release
	[m]				[°]					
Wlodarczyk	77.96	71	94	104	120	82	123	97	110	79
Heidler	77.12	85	90	71	99	85	116	88	108	91
Klaas	74.23	93	106	84	100	94	91	100	111	97

The angles of twisting (see Table 9) are to be seen as large at the end of the first single-support phase for all three analysed throwers (51° Wlodarczyk, 53° Heidler, 59° Klaas) and therefore a negative technique characteristic. The same applies to Klaas' twisting at the end of the second (50°) and third (44°) single-support phases. Compare these figures with those for men where OTTO (1990) describes maximal twisting of about 60° and optimal values of about 30° to 40° (1991).

Wlodarczyk's 120° angle of trailing at the end of the second single-support phase and 123° at the end of the third single-support phase (see Table 10) are to be seen as very large. The extreme trailing of the hammer is probably caused in this case by foot work that is too passive, and, resulting from this, too late a touchdown of the right free leg, while at the same time lowering the left shoulder (see photo sequence).

Analysis of the Men's Competition

With the exceptions of third placer Zagornyi (RUS) and fifth placer Livinov (GER), the best throws of each of the top eight placers in the men's event were analysed. For the two named, blockage of one or both of the camera views by persons on the infield of the stadium meant it was not possible to perform the analysis on the best throw. Therefore, the next best throw for which the required quality of video recording was available was analysed instead.

Turns

Seven of the top eight men threw from four turns. Zagornyi threw from three turns.

Release Parameters

In Table 11 we see that with 28.2 m/s, Kozmus achieved the highest release velocity, followed by Ziolkowski with 27.7 m/s. The average release velocity of the top eight was 27.6 m/s with a standard deviation of 0.3 m/s.

The highest angle of release was recorded for Pars (HUN) with 44.5°, followed by Zagornyi with 42.3°. An average release angle of 41.3° was calculated for the top eight with a standard deviation of 1.6°. It is clear that the release angles of Esser (GER) and Litvinov (GER) were well below average at 39.9°.

Ziolkowski achieved a very high release height of 1.91m, the next highest being Litvinov with 1.60m. The average release height measured for the top eight was 1.58m with a standard deviation of 0.16m.

There is a very high correlation between release velocity and throwing distance (r=0.98) (see Figure 8).

Only a low correlation can be found between angle of release and throwing distance (r=0.33).

Table 11: Release parameters for the analysed throws of the top men hammer throwers at the 2009 IAAF World Championships in Athletics

Name	Throw Distance	Release Velocity	Angle of Release	Release Height
	[m]	[m/s]	[°]	[m]
Kozmus	80.84	28.2	41.6	1.43
Ziolkowski	78.09	27.7	40.8	1.91
Zagornyi	78.09	27.6	42.3	1.60
Pars	77.45	27.5	44.5	1.52
Litvinov	76.00	27.4	39.9	1.68
Esser	76.27	27.5	39.9	1.44
Haklits	76.26	27.4	41.4	1.50
Kryvitski	76.00	27.3	40.2	1.59

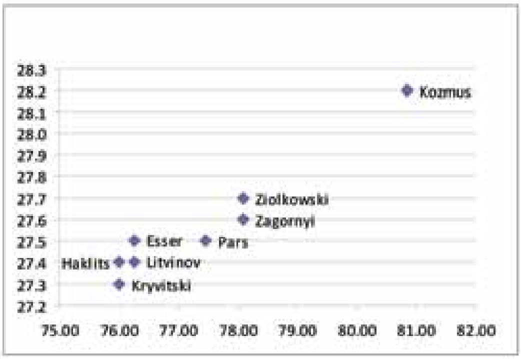


Figure 8: Release Velocity [m/s] (y-axis) compared to official result [m] (x-axis) for the top men hammer throwers at the 2009 IAAF World Championships in Athletics

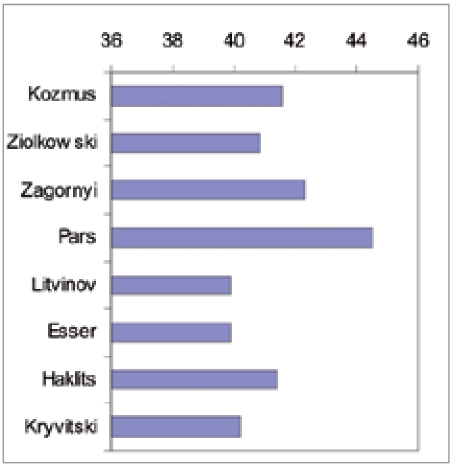


Figure 9: Angle of Release [°] for the top men hammer throwers at the 2009 IAAF World Championships in Athletics

Velocity Parameters

As a three-turn thrower, Zagorgnyi finished his preliminary swings with the highest starting velocity (17.9 m/s). Kozmus and Esser started their turns with 16.8 m/s, followed by Ziolkowski with 16.7 m/s. Pars (15.2 m/s) and Litvinov (15.7 m/s) introduced their first turns rather slowly, but then had a greater increase of velocity in the second turn. Except for Zagornyi, all the top eight generally showed a very small increase of velocity in the third turn (see Table 12).

In contrast to the women, no correlation between the increase of velocity in the fourth turn and throwing distance could be found. But there are highly significant correlations between the velocity at the end of the second double-support phase and throwing distance (r=0.77) and velocity the end of the third double-support phase and throwing distance (r=0.72), as well as a medium correlation between starting velocity and throwing distance (r=0.56).

Table 12: Velocity parameters for the analysed throws of the top men hammer throwers at the 2009 IAAF World Championships in Athletics

Name	Throw Distance	Starting Velocity	Increase of Velocity				Release Velocity
			Turn 1	Turn 2	Turn 3	Turn 4	
	[m]		[m/s]				
Kozmus	80.84	16.8	2.9	2.6	1.4	4.6	28.2
Ziolkowski	78.09	16.7	3.2	2.1	1.7	4.1	27.7
Zagornyi	78.09	17.9	3.1	2.0	4.6		27.6
Pars	77.45	15.2	5.3	1.5	1.0	4.5	27.5
Litvinov	76.00	15.7	4.2	2.0	1.0	4.5	27.4
Esser	76.27	16.8	3.0	1.6	1.0	5.1	27.5
Haklits	76.26	15.1	3.6	2.7	1.9	4.1	27.4
Kryvitski	76.00	15.3	3.3	2.5	1.6	4.6	27.3

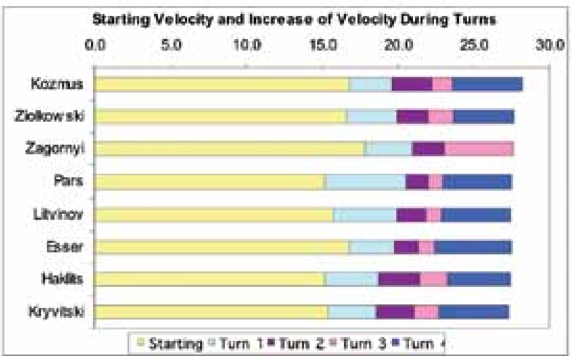


Figure 10: Starting Velocity and Increase of velocity [m/s] during the turns for the analysed throws of the top men hammer throwers at the 2009 IAAF World Championships in Athletics

Temporal Parameters

Disregarding Zagornyi (as a three-turn thrower), Pars and Esser had the shortest duration for their complete movements with 1.98 sec, followed by the winner Kozmus 2.06 sec. Haklits (2.24 sec) needed the longest time for his four turns (Table 13 and Figure 11). On average, the seven four-turn throwers complete their movements in 2.09 sec, with a standard deviation of 0.09 sec.

Until the penultimate turn, all throwers succeed in making the next turn temporally shorter than the turn before. No thrower makes the last turn shorter than the previous one.

Most of the top eight spent clearly more time in the single-support phases than in the double-support phases, the only exception being Haklits, who only showed a difference of just 0.04 sec (see Table 14 and Table 15). Zagornyi had the biggest gap with 0.36 sec.

Table 13: Duration of the turns for the analysed throws of the top men hammer throwers at the 2009 IAAF World Championships in Athletics

Name	Throw Distance	Turn 1	Turn 2	Turn 3	Turn 4	Total
	[m]			[sec]		
Kozmus	80.84	0.62	0.52	0.44	0.48	2.06
Ziolkowski	78.09	0.62	0.50	0.46	0.52	2.10
Zagornyi	78.09	0.60	0.48	0.56		1.64
Pars	77.45	0.58	0.46	0.42	0.52	1.98
Litvinov	76.00	0.62	0.54	0.44	0.50	2.10
Esser	76.27	0.56	0.46	0.44	0.52	1.98
Haklits	76.26	0.72	0.54	0.48	0.50	2.24
Kryvitski	76.00	0.64	0.52	0.48	0.50	2.14

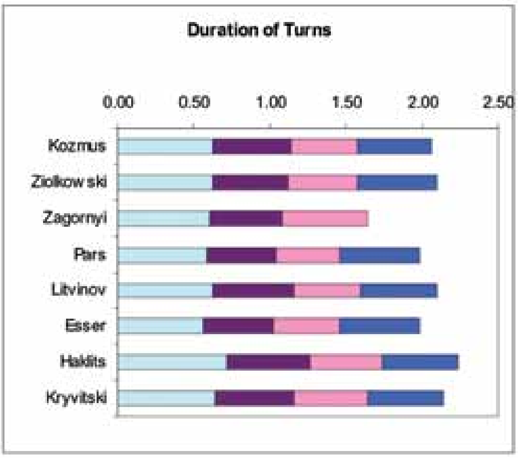


Figure 11: Duration of turns for the analysed throws of the top men hammer throwers at the 2009 IAAF World Championships in Athletics

In turn 4, the double-support phases of Ziolkowski, Litvinov and Haklits were longer than the single-support phases.

There is a mean negative correlation (r = -0.59) between the summed duration of the single-support phases and throwing distance. This means, the less time is spent in the single-support phases, the longer the throw.

Table 14: Time at the end of the turn phases for the analysed throws of the top men hammer throwers at the 2009 IAAF World Championships in Athletics (ss=single-support, ds=double-support)

Name	Throw Distance	Turn 1 ss	Turn 1 ds	Turn 2 ss	Turn 2 ds	Turn 3 ss	Turn 3 ds	Turn 4 ss	Turn 4 ds
	[m]			[sec]					
Kozmus	80.84	0.32	0.62	0.90	1.14	1.40	1.58	1.84	2.06
Ziolkowski	78.09	0.32	0.62	0.92	1.12	1.38	1.58	1.82	2.10
Zagornyi	78.09	0.38	0.60	0.90	1.08	1.40	1.64		
Pars	77.45	0.32	0.58	0.84	1.04	1.30	1.46	1.74	1.98
Litvinov	76.00	0.36	0.62	0.96	1.16	1.42	1.60	1.84	2.10
Esser	76.27	0.32	0.56	0.84	1.02	1.32	1.46	1.76	1.98
Haklits	76.26	0.38	0.72	1.00	1.26	1.52	1.74	1.96	2.24
Kryvitski	76.00	0.32	0.64	0.92	1.16	1.44	1.64	1.90	2.14

Table 15: Duration of support phases of the turns for the analysed throws of the top men hammer throwers at the 2009 IAAF World Championships in Athletics (ss=single-support, ds=double-support)

Name	Throw Distance	Turn 1 ss	Turn 1 ds	Turn 2 ss	Turn 2 ds	Turn 3 ss	Turn 3 ds	Turn 4 ss	Turn 4 ds	Sum ss	Sum ds
	[m]				[sec]						
Kozmus	80.84	0.32	0.30	0.28	0.24	0.26	0.18	0.26	0.22	1.12	0.94
Ziolkowski	78.09	0.32	0.30	0.30	0.20	0.26	0.20	0.24	0.28	1.12	0.98
Zagornyi	78.09	0.38	0.22	0.30	0.18	0.32	0.24			1.00	0.64
Pars	77.45	0.32	0.26	0.26	0.20	0.26	0.16	0.28	0.24	1.12	0.86
Litvinov	76.00	0.36	0.26	0.34	0.20	0.26	0.18	0.24	0.26	1.20	0.90
Esser	76.27	0.32	0.24	0.28	0.18	0.30	0.14	0.30	0.22	1.20	0.78
Haklits	76.26	0.38	0.34	0.28	0.26	0.26	0.22	0.22	0.28	1.14	1.10
Kryvitski	76.00	0.32	0.32	0.28	0.24	0.28	0.20	0.26	0.24	1.14	1.00

Spatial Parameters

Haklits, Ziolkowski and Kozmus had the longest hammer paths with 46.0m, 45.2m and 44.4m respectively (see Table 16). The seven four turned throwers averaged 44.2m with a standard deviation of 1.2m. In this respect, Esser and Pars clearly lagged behind with 42.4m and 43.3m respectively.

Esser and Kryvitski were the only analysed throwers to increase the path of the hammer throughout all the turns. Ziolkowski shortened the path of the hammer slightly in the second turn Haklits arranged the path of the hammer almost evenly throughout the first three turns. In the third turn, Kozmus and Litvinov shortened the path of the hammer slightly, as they touched down too late at the end of the third single-support phase (see Table 17). Additionally, Kozmus decreased the radius in release due to leaning the upper body too far back (see photo sequence).

Taking a look at the summed paths of the hammer, separated according to single and double-support phases (Table 17), Haklits is the only thrower who accomplished a longer path in the double-support (23.7m) than in the single-support phase (22.3m).

Table 16: Path of the hammer during the turns for the analysed throws of the top men hammer throwers at the 2009 IAAF World Championships in Athletics

Name	Throw Distance	Turn 1	Turn 2	Turn 3	Turn 4	Total
			[m]			
Kozmus	80.84	10.8	11.1	10.4	12.2	44.4
Ziolkowski	78.09	10.7	10.5	10.7	13.3	45.2
Zagornyi	78.09	10.8	10.7	13.9		35.3
Pars	77.45	10.5	9.9	9.9	13.1	43.3
Litvinov	76.00	10.4	11.4	10.0	12.3	44.1
Esser	76.27	9.3	9.9	10.3	12.9	42.4
Haklits	76.26	11.3	11.0	11.2	12.5	46.0
Kryvitski	76.00	10.2	10.4	10.9	12.4	43.9

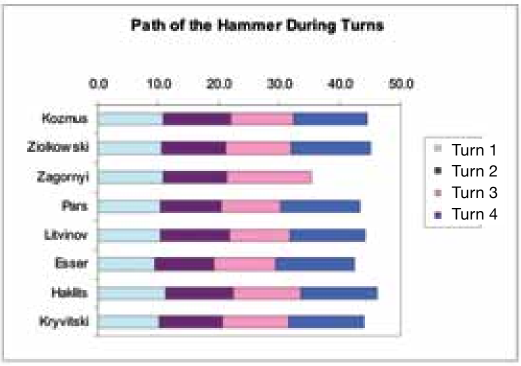


Figure 12: Figure 6: Path of the hammer during the turns [m] for the analysed throws of the top women hammer throwers at the 2009 IAAF World Championships in Athletics

Table 17: Path of the hammer in the single and double-support phases of the turns for the analysed throws of the top men hammer throwers at the 2009 IAAF World Championships in Athletics (ss=single-support, ds=double-support)

Name	Throw Distance	Turn 1 ss	Turn 1 ds	Turn 2 ss	Turn 2 ds	Turn 3 ss	Turn 3 ds	Turn 4 ss	Turn 4 ds	Sum ss	Sum ds
						[m					
Kozmus	80.84	5.1	5.6	5.8	5.4	6.0	4.4	6.3	5.8	23.2	21.3
Ziolkowski	78.09	5.0	5.6	6.1	4.4	5.9	4.8	5.9	7.5	22.9	22.3
Zagornyi	78.09	6.4	4.3	6.5	4.2	7.6	6.3			20.5	14.8
Pars	77.45	5.3	5.2	5.5	4.4	6.0	3.9	6.8	6.3	23.6	19.8
Litvinov	76.00	5.4	5.0	6.9	4.5	5.8	4.2	5.6	6.7	23.8	20.3
Esser	76.27	4.9	4.4	5.9	4.0	7.0	3.3	7.2	5.7	25.0	17.4
Haklits	76.26	5.4	5.8	5.6	5.5	6.0	5.2	5.3	7.2	22.3	23.7
Kryvitski	76.00	4.7	5.6	5.4	5.0	6.2	4.7	6.2	6.2	22.5	21.4

Angular Parameters

Angles were only analysed for the winner Kozmus. Previous throws of Kozmus (79.99m at the IAAF World Athletics Final in 2008) and Ivan Tsikhan (BLR) (82.05m at the IAAF World Athletics Final in 2007) serve as comparative values.

At the 2009 IAAF World Championships in Athletics, after his preliminary swings, Kozmus lifted off his free leg very early, at an azimuth of 21° (see Table 18 and Figure 13). The comparison with his throw at the 2008 IAAF World Athletics Final shows that this is typical of him. Hence he also touches down his right foot early at the end of the first single-support phase (196° in 2009), but in the following turns he touches down increasingly later, so that the last touchdown is at 258°, and therefore not optimal for the final acceleration path. In contrast, a totally different situation can be observed with Tsikhan's throw. After the preliminary swings he lifted off at an azimuth of 61°. The first touchdown after the first single-support phase was carried out at 198° but in the following turns he continues touching down the free leg early, so that a long final acceleration path was achieved.

Tsikhan's throw can also be seen as unusual in another respect: of a total duration of 2.00 sec for the four turns, 1.06 sec could be measured in the double-support phases and 0.94 sec in the single-support phases. Thus, he turns longer in the double-support than in the single-support phases. Additionally it was found that at a temporal distribution of 0.28/0.34 sec, 0.24/0.24 sec, 0.22/0.22 sec, and 0.20/0.26 sec for the respective single or double-support phases of turns 1 to 4 the next turn was always temporally shorter than the previous one.

After the first single-support phase Kozmus touched down the free leg early over the heel in the direction of the hammer (28°), and hence achieved little twisting (see Table 19). He did not succeed in doing so in the second turn (73°) or especially in the third turn (88°), where the free leg was very far in front of the shoulder axis and hence there was large twisting which can have a negative effect on the acceleration of the hammer (see OTTO, 1990). The touchdown is accomplished better again and in the direction of the hammer at the end of the single-support phase of Turn 4 (twisting 29°). Kozmus' comparative throw from 2008 shows that he had a great amount of twisting there,

Table 18: Azimuthal angle at the end of throw phases for the winner of the men's hammer throw at the 2009 IAAF World Championships in Athletics and selected throws from earlier competitions (ss=single-support, ds=double-support)

Name	Throw Distance	End of swing	Turn 1 ss	Turn 1 ds	Turn 2 ss	Turn 2 ds	Turn 3 ss	Turn 3 ds	Turn 4 ss	Release
	[m]				[°]					
Kozmus (2009)	80.84	21	196	28	222	49	250	43	258	95
Kozmus (2008)	79.99	24	205	55	231	53	235	56	247	94
Tsikhan (2007)	82.05	61	198	54	219	39	223	44	223	91

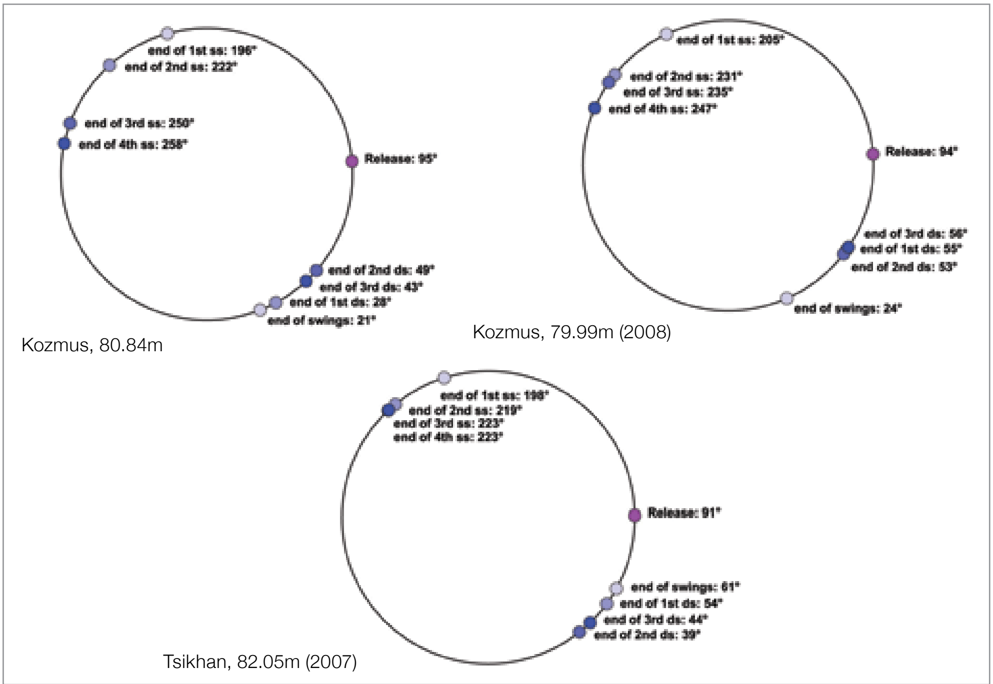


Figure 13: Azimuthal angle at the end of throw phases, displayed on a 360° circle for the winner of the men's hammer throw at the 2009 IAAF World Championships in Athletics and selected throws from earlier competitions

Table 19: Angle of twisting (between shoulder and hip axis) at the end of throw phases for the winner of the men's hammer throw at the 2009 IAAF World Championships in Athletics and selected throws from earlier competitions (ss=single-support, ds=double-support)

Name	Throw Distance	End of swing	Turn 1 ss	Turn 1 ds	Turn 2 ss	Turn 2 ds	Turn 3 ss	Turn 3 ds	Turn 4 ss	Release
	[m]				[°]					
Kozmus (2009)	80.84	21	28	25	73	22	88	9	29	17
Kozmus (2008)	79.99	9	69	6	69	5	60	16	74	27
Tsikhan (2007)	82.05	15	23	26	51	11	52	17	51	47

Table 20: Angle of trailing (between shoulder axis and hammer wire) at the end of throw phases for the winner of the men's hammer throw at the 2009 IAAF World Championships in Athletics and selected throws from earlier competitions (ss=single-support, ds=double-support)

Name	Throw Distance	End of swing	Turn 1 ss	Turn 1 ds	Turn 2 ss	Turn 2 ds	Turn 3 ss	Turn 3 ds	Turn 4 ss	Release
	[m]				[°]					
Kozmus (2009)	80.84	88	113	94	103	96	86	100	126	91
Kozmus (2008)	79.99	102	112	104	101	106	103	95	77	96
Tsikhan (2007)	82.05	110	111	87	110	96	106	93	106	109

with 69°, 69°, 60° and 74° after each single-support phase. In the comparative throw of Tsikhan, he had twisting of 51°, 52° and 51° after the second, third and fourth single-support phases respectively.

Kozmus' angle of trailing at the end of the fourth single-support phase (see Table 20) is very large (126°) and has to do with – for him – the relatively little twisting of 29° (Table 19). We can see that in his comparative throw from 2008 there was a slight trailing, with the exception of his touchdown after Turn 4: here the hammer runs ahead (77°). In Tsikhan's throw there is also a slight trailing in the transition into the double-support phase, but with 111°, 110° and 106°, his values varied much less than those for Kozmus.

Discussion

Achieving the longest possible throwing distance in the hammer (and other throwing events) is primarily the result of producing a release velocity that is as high as possible and achieving an optimal angle of release. The release height is of little influence, as any increase in release height roughly corresponds with the gain in distance. The fourth factor affecting the flight of any object, air resistance, cannot be influenced by a thrower.

In the hammer throw, the angle of release is achieved by a practical, steadily growing inclination of the initially flat path of the hammer up to the biomechanically optimal angle. From the ballistic point of view, the optimal angle of release is 44° for both men and women at top performance level. However, this value is rarely achieved in hammer throw, as a slightly flatter angle of release enables more favourable working conditions for leg, torso and arm muscles (HINZ, 1991). In the analysis at hand, the angle of release averaged 40.0° for the women and 41.3° for the men. Our various analyses of recent years also demonstrate a similar result: On average the women show an angle of release 40.3° in throws over 70m and 40.2° in throws over 75m. The men achieve an average of 41.0° in throws over 77m. These results confirm that the biomechanically optimal angle ranges about 3° to 4° below the optimal ballistic angle.

The release velocity of the hammer is determined by the starting velocity at the end of the preliminary swings and the increases in velocity created during the individual turns. In the study at hand, the women's release velocity averaged 27.1 m/s and the men's averaged 27.6 m/s. According to our analyses, the necessary release velocity for the women is 27.4 m/s for throws over 75m and at least 26.5 m/s for throws over 70m. For the men, the necessary release velocity is least 28.1 m/s in throws over 80m and at least 27.5 m/s in throws over 77m. Hence we can say that the women are coming closer to the men in respect to the release velocity. The differences in distance in favour of the men are caused by the greater influence of air resistance in flight on the lighter women's hammer.

The increase in velocity in the individual turns is affected by the drive of the legs. An additional drive factor is the creation of twisting in the single-support phases and the decrease of twisting in the double-support phases. The quality of the drive can be interpreted by several parameters: the increase in velocity in the turns, the course of the hammer path, the temporal structure in the turns, as well as the angles azimuth, twisting and trailing.

The analysis of the Hammer Throw Final at the 2009 IAAF World Championships in Athletics in Berlin has shown, like previous analyses of international championships and also our own competition analyses of recent years, that various and very individual solutions are applied by top throwers to accelerate the hammer in the single turns in an effort to achieve maximal release velocity.

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Figure 14: Photosequence KOSMUS, 6th, attempt, 80.84m

Figure 15: Photosequence WLODARCZYK, 2nd, attempt, 77.96m