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Biomechanical Analysis of the Shot Put at the 2009 IAAF World Championships in Athletics

By Wilko Schaa

(Translated from the original German by Matthias Werner)

ABSTRACT

The techniques of the top eight placers in the men's and women's shot put at the 2009 World Championships in Athletics were studied by a team of researchers from the Institute for Applied Training Science in Leipzig, Germany, with the aim of obtaining the latest data and insight into the technical condition of the world's current best throwers. The throws of the finalists were recorded with video cameras set up in the seating area of the stadium. The release parameters (release velocity, angle of release, etc), spatial and temporal characteristics of the throwing movement and other data were obtained from a three-dimensional photogrammetric analysis. To give guidance for coaches and athletes preparing for future high-level competitions, the mean values and standard deviations were derived and compared with other parameters. It was found that in the women's event the differences in performance distance can be almost completely explained by the differences in release velocity. The technique parameters contributing to these differences are discussed. The men's event was more complicated, as the angle of release and, to a certain extent, the release height were also important factors. Their roles and the differences between the glide and rotational techniques are discussed in detail.

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Introduction

Both the men's and women's shot put competitions at the 2009 World Championships in Athletics in Berlin were exciting affairs with top-level marks achieved by the medallists. The men's winner, Christian Cantwell (USA), reversed the results of the previous year's Olympic Games in Beijing by taking the lead for good in the fifth round with the year's world leading mark of 22.03m, pushing the Olympic Champion Tomaz Majewski (POL), who threw 21.91m, into second place. It was the seventh time in the last eight championships that a thrower from the USA has taken the title. Home country star Ralf Bartels (GER), who led the competition after the third round, had to settle for the bronze medal and a personal best mark of 21.37m. Altogether, five of the finalists threw seasonal bests.

In the women's event, Valerie Vili (NZL) had a slow start but took the lead in the third round and eventually produced three throws that were better than the best by anyone else in the field, topped by a 20.44m, the world's second best throw of the year up to that point. The silver medal went to another home country star, Nadine Kleinert (GER), who threw a personal best 20.06m to lead for the first two rounds and then improved to 20.20, the seventh best throw of the year up to that point (the first six being by Vili). Lijlao Gong (CHN) took third with her own personal best 19.89m.

In this report, the results of biomechanical analyses of the two competitions made by a team from the IAT (Institute for Applied Training Science) in Leipzig, Germany, are presented. The throws of the finalists were recorded with video cameras and then a three-dimensional photogrammetric analysis was used with the aim of obtaining the latest data and insight into the technical condition of world's current best throwers. Specifically, we wanted to quantify key parameters of shot put technique and calculate correlations that could guide athletes and coaches preparing for top-level competitions in the future.

Table 1: Results of the shot put at the 2009 IAAF World Championships in Athletics

Pos	Athlete (Country)	Round					
		1	2	3	4	5	6
Men's Final – 15 August – 20:15							
1	Christian Cantwell (USA)	21.54	20.72	21.03	21.21	**22.03**	-
2	Tomaz Majewski (POL)	21.36	21.19	20.80	21.68	**21.91**	21.18
3	Ralf Bartels (GER)	20.35	20.18	**21.37**	20.80	20.94	21.20
4	Reese Hoffa (USA)	21.02	X	20.95	21.14	20.97	**21.28**
5	Adam Nelson (USA)	**21.11**	20.93	x	x	x	x
6	Pavel Lyzhin (BLR)	X	**20.98**	x	x	x	x
7	Andrei Mikhnevich (BLR)	20.34	20.31	20.62	**20.74**	20.54	x
8	Miroslav Vodovnik (SLO)	19.60	19.50	**20.50**	x	19.82	20.14
9	Hamza Alic (BIH)	**20.00**	X	19.80			
10	Pavel Sofin (RUS)	**19.89**	19.69	19.85			
11	Carl Myerscough (GBR)	**18.42**	X	x			
12	Peter Sack (GER)	X	X	x			
Women's Final 16 August – 20:20							
1	Valeri Vili (NZL)	19.40	X	20.25	20.16	**20.44**	20.25
2	Nadine Kleinert (GER)	20.06	19.52	**20.20**	19.61	x	x
3	Lijlao Gong (CHN)	19.69	**19.89**	19.68	19.75	x	x
4	Natallia Mikhnevich (BLR)	**19.66**	X	19.27	19.51	x	x
5	Anna Avdeeva (RUS)	18.66	18.78	19.48	**19.66**	x	x
6	Michelle Carter (USA)	X	18.93	**18.96**	x	18.30	x
7	Meiju Li (CHN)	**18.76**	18.35	18.66	x	x	x
8	Misleydis González (CUB)	18.73	18.57	x	18.60	**18.74**	18.43
9	Malin Vargas (CUB)	**18.67**	18.10	18.11			
10	Xianqronq Liu (CHN)	**18.52**	X	16.79			
11	Denise Hinrichs (GER)	18.30	**18.39**	x			
12	Christina Schwanitz (GER)	**17.84**	X	x			

Methods

Recording and Camera Set-up

The DV camera and analogous camera used were hardware-synchronised. The frame rate of the video recordings was 50 Hz (25 full frames, 50 half frames). An IAT-developed capture-program enabled synchronised recording of the movements onto a notebook computer. This required the use of an A/D-converter for the analogous camera.

The cameras had to be positioned in the seating area of the stadium, as the research team could not access the infield during the event. This meant that the cameras were about 20-25m above the infield and there were very large distances between their positions and the competition site (between 70 and 100m), making the use of telephoto lenses necessary. There was also a reduction of image quality due to complicated and changing lighting conditions. This was aggravated by the fact that the installation and calibration of the cameras had to be completed before commencement of the afternoon competitions (daylight conditions) and the camera settings could not be changed during the competitions, which ended in the evening (partly floodlight conditions).

Calibration

Due to the difference in height between the camera positions and the infield, increased requirements for calibration were demanded. The process applied was developed at IAT (Figure 1). It is based on a selective entry of spatial co-ordinates, i.e. each point in the calibrated space is allocated to a three-dimensional co-ordinate. The origin of this co-ordinate system (zero point, x, y, and z each 0.00) was a point at the front side of the throwing circle, which lies on an ordinate running through the centre of the throwing circle and the middle of the landing sector. As the cameras were fixed, the analysis of the competition movement could be started immediately after calibration.

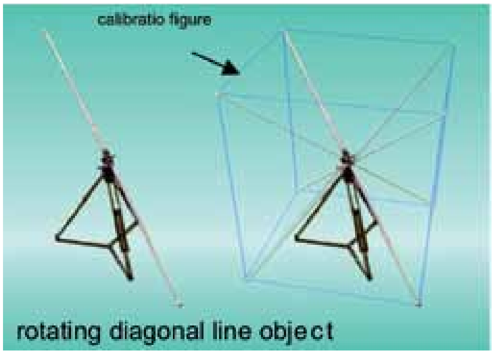

Figure 1: Diagonal rotating object for calibration of spatial co-ordinates

The differences in height between the camera positions and the infield also made verification of angles of the spatial co-ordinates in the release area especially important for the evaluation of the calculated angles (angle of release, etc.). Hence, after calibration, the angle of inclination was determined for a fixed pole by calculating the spatial co-ordinates of six small balls (centres) attached to the pole and comparing them with the actual value, measured by a digital spirit level, also attached to the pole (Figure 2). This was done for three different measurements, each time varying the angle of inclination in the x- and z-axis (side view), as well as the angles of turn in the x-y-level (view from behind). On average the deviations ranged between 0.9 and 1.05%. This means that at an angle of release of 40° the error rate amounted to 0.4°.

Figure 2: Verification of spatial angles on the basis of a previously realised calibration

Data Analysed

As the decisive parameters for the performance or throwing distance, the release parameters (release velocity, angle of release and release height) are the main focus of this report. Generally the best attempt by each of the top eight placers in both the men's and women's competitions was extensively analysed with respect to the whole movement. 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. Additionally, the angle of release and release velocity were both calculated for each valid attempt by the top eight placers in both events. The extensive analysis of the best throws also included a number of biomechanical factors related to the throwing technique. A selection of these has also been addressed in this report.

Analysis of the Men's Competition

Anthropometry and Technique

Table 2 shows the anthropometric data as well as the applied technique for the top eight placers in the men's shot put. The athletes show an increased average age of roughly one and a half years in comparison to the top eight at the previous IAAF World Championships in Athletics in Osaka in 2007 (30.4 ± 2.5 vs. 29.1 ± 2.3 years). Amongst other reasons, this can be explained by the fact that six of the eight current finalists also made it to the final in Osaka in 2007. Moreover, five of them participated in the Olympic Final in Beijing.

Table 2: Anthropometric data and technique of the top men shot putters at the 2009 IAAF World Championships in Athletics

Name	Age [years]	Height [m]	Weight [kg]	Technique
Cantwell	28	1.98	140	Rotational
Majewski	27	2.04	132	Glide
Bartels	31	1.87	135	Glide
Hoffa	31	1.82	133	Rotational
Nelson	34	1.83	115	Rotational
Lyzhin	28	1.89	110	Rotational
Mikhnevich	33	2.02	127	Glide
Vodovnik	31	1.96	145	Rotational
Average	**30.4**	**1.93**	**129.6**	

The prevalence of the rotational technique can also be observed amongst the top eight men and is reflected in a ratio of 5:3 to the glide technique.

Release parameters

In Table 3 we see the release parameters for the best throws by the top eight placers. The average of these throws was 21.24 ± 0.53m. The average release velocity was 13.83 ± 0.24m/s, the mean angle of release was 36.0 ± 2.8° and the average release height was 2.23 ± 0.15m.

As the most important factor of influence on the putting distance, the high level of release velocity reflects the level of performance in the final and confirms that release velocities in the range of 14m/s are an absolute prerequisite for world-class performances. As expected, the average release velocity for the medal winners (13.93m/s) was higher than the athletes in places 4-8 (13.76 m/s). The medallists also had an average angle of release of 36.9°, which was 1.4° steeper than the average for the remaining finalists. Hence the difference between the average of the best throws of these two groups (0.85m) can be almost completely explained by the parameters release velocity and angle of release.

Nevertheless, there is no statistically significant correlation evident (according to Spearmann) between the putting distance and the release velocity ($r = 0.56$; $p = 0.148$).

Going into it a little deeper, we can see that the release velocities of 14.0m/s the third and fourth placers, Bartels and Reese Hoffa (USA), were identical to that of the winner of the competition, Cantwell. At 14.1m/s, Adam Nelson (USA) had the highest release velocity of the top eight placers but ended up fifth overall. In contrast, the second placer had a release velocity of "merely" 13.8m/s but his throw was only 0.12m behind the winner.

Table 3: Release parameters for the best throws of the top men shot putters at the 2009 IAAF World Championships in Athletics ($v0$ = release velocity, $\alpha 0$ = angle of release, $H0$ = release height, H0_%-BH = release height as a percentage of body height)

Name	Distance [m]	v0 [m/s]	α0 [°]	H0 [m]	H0_%-BH [%]
Cantwell	22.03	14.0	37.8	2.29	115.7
Majewski	21.91	13.8	39.3	2.43	119.1
Bartels	21.37	14.0	33.6	2.12	113.4
Hoffa	21.28	14.0	34.4	2.06	113.2
Nelson	21.11	14.1	32.9	2.05	112.0
Lyzhin	20.98	13.6	39.2	2.22	117.5
Mikhnevich	20.74	13.4	37.7	2.43	120.3
Vodovnik	20.50	13.7	33.1	2.25	114.8
Average	**21.24 ± 0.53**	**13.83 ± 0.24**	**36.0 ± 2.77**	**2.23 ± 0.15**	**115.7 ± 2.98**

These situations are explained by the obvious differences concerning the angle of release. With 37.8° and 39.3° respectively, Cantwell and Majewski had the steepest angles of release within the leading group and hence were the closest to the mechanical optimum. In contrast Bartels (33.6°), Hoffa (34.4°) and Nelson (32.9°) were putting much more horizontally and thus were further from the mechanical optimum.

The importance of the angle of release is verified by means of a multiple regression analysis of release of all valid attempts in the final (n = 35) as shown in Table 4. At r2 = 0.89 this amounts to the following correlation:

putting distance = 2.158 x release velocity + 0.174 x angle of release – 14.842

Although there are trends indicating a negative correlation between release velocity and angle of release in the men's shot put final, these cannot be statistically substantiated (r = -0.46; p = 0.247; Figure 3).

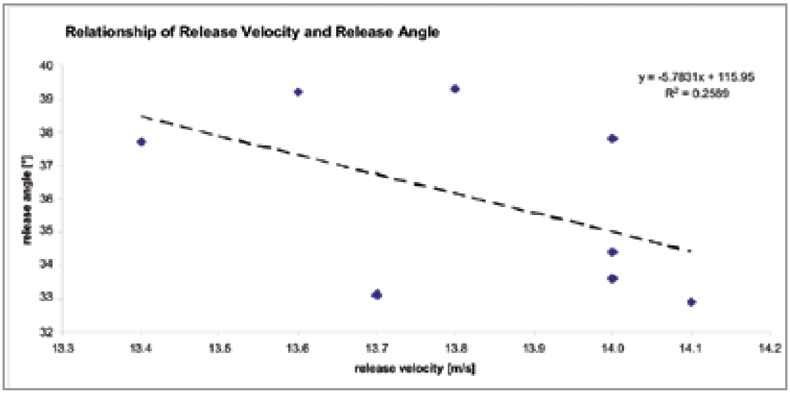

Figure 3: Correlation between release velocity and angle of release for the best throws of the top men shot putters at the 2009 IAAF World Championships in Athletics

Table 4: Summary of official result and angles of release for all valid throws of the top men shot putters at the 2009 IAAF World Championships in Athletics (d = distance, α0 = angle of release)

		Round						
Name		**1**	**2**	**3**	**4**	**5**	**6**	**Average**
Cantwell	d [m]	21.54	20.72	21.03	21.21	22.03	x	21.31 ± 0.5
	α0 [°]	37.7	37.5	40.4	37.1	37.8	x	38.1 ± 1.3
Majewski	d [m]	21.36	21.19	20.80	21.68	21.91	21.18	21.35 ± 0.35
	α0 [°]	34.2	38.8	39.4	39.2	39.3	34.6	37.6 ± 2.5
Bartels	d [m]	20.35	20.18	21.37	20.80	20.94	21.20	20.81 ± 0.43
	α0 [°]	37.7	37.8	33.6	34.9	38.4	36.4	36.5 ± 1.9
Hoffa	d [m]	21.02	X	20.95	21.14	20.97	21.28	21.07 ± 0.14
	α0 [°]	36.3	X	33.5	35.0	33.4	34.4	34.5 ± 1.2
Nelson	d [m]	21.11	20.93	X	x	x	x	21.02
	α0 [°]	32.9	35.6	X	x	x	x	34.25
Lyzhin	d [m]	X	20.98	X	x	x	x	20.98
	α0 [°]	X	39.2	X	x	x	x	39.2
Mikhnvich	d [m]	20.34	20.31	20.62	20.74	20.54	x	20.51 ± 0.18
	α0 [°]	39.7	37.9	39.8	37.7	37.3	x	38.48 ± 1.2
Vodovnik	d [m]	19.60	19.50	20.50	x	19.82	20.14	19.91 ± 0.41
	α0 [°]	32.7	36.3	33.1	x	35.5	34.7	34.46 ± 1.4

Apart from the angle of release as a main criterion of distinction, the release height has an additional, but rather small influence on the differences in the performances at hand.

To a high degree, release height is determined by the anthropometric characteristics of the athlete, and hence can only be partially influenced by technique. Accordingly with $r = 0.97$ a statistically highly significant correlation was found between the achieved release heights in the competition and the heights of the finalists ($p < 0.01$).

The medallists made use of their advantages in height (1.96 ± 0.09m) with respect to the athletes in places 4-8 (1.90 ± 0.09m) and delivered the shot on average from 0.08m higher (Table 3). The two tallest athletes in the field, Majewski and Andrei Mikhnevich (BLR), achieved the highest release heights (2.43m each) and thus delivered the shot on average 0.27 ± 0.10m higher than their competitors.

The reach over the stop board denotes the distance between the vertical projection of the shot's centre of mass and the inner edge of the stop board at the moment of the shot leaving the putting hand in the delivery. It is subject to similar dependencies on the athlete's anthropometric characteristics and applied technique variation as is the case concerning release height. Here differences up to 0.29m are recorded, favouring the athletes applying the glide technique.

The example in Table 5 is intended to clarify the complex interaction of the release parameters and the given special qualities.

At first a putting distance was calculated by means of the equation of the throws parabola on the basis of the angle of release achieved by Bartels (33.6°) and his release height (2.12m), and then the individual release velocities of Cantwell and Majewski. To show the effect of the separate parameters, the individually achieved parameters were inserted step by step into the throws parabola as variables and the resulting increases in distance were added.

The differences relevant to performance become more than obvious. Due to the same release velocity of 14.0 m/s Bartels and Cantwell are at first ahead of Majewski by 0.53m, who achieved the lowest release velocity for the best throw by a finalist. But after the addition of the added distance caused by the steeper angle of release, Majewski and Cantwell clearly pass by Bartels. This gap becomes even more distinct due to the increases brought about by release height and the reach over the stop board.

Due to the optimisation of the angle of release and the maximisation of both the release height and reach over the stop board, Majewski overcomes the initial disadvantage of the lower release velocity compared to Bartels and consequently his throw is clearly longer. He cannot quite compensate the lost ground to the winner Cantwell, but he comes very close (within 0.12m) to the winning distance. If he had been able to achieve the same release velocity as Bartels and Cantwell and maintained the advantages of all the aspects mentioned, Majewski would have won the competition with a result of 22.20 – 22.30m.

Table 5: Interaction and effects of changes in release parameters in the creation of a complex putting performance top three men shot putters at the 2009 IAAF World Championships in Athletics

	Bartels		**Majewski**		**Cantwell**	
Performance* [m]	**21.19**		**20.66**		**21.19**	
Δ alpha 0 [°]**	**+ 0.00**	**= 21.19**	**+ 0.67**	**= 21.33**	**+ 0.61**	**= 21.80**
Δ h0* [m]**	**+ 0.00**	**= 21.19**	**+ 0.31**	**= 21.64**	**+ 0.17**	**= 21.97**
Reach over stop board** [m]**	**+ 0.06**		**+ 0.15**		**+ 0.00**	
Complex performance*****	**21.25*******		**21.79*******		**21.97*******	

* basis for estimation: angle of release (33.6°) and release height (2.12m) of Bartels as well as the individually achieved release velocities (Cantwell: 14.0 m/s; Majewski: 13.8m/s; Bartels: 14.0m/s)

** increase in distance due to a change in angles to the individually achieved results of Majewski and Cantwell (39.3° and 37.8°)

*** increase in distance due to a change in h0 to the individually achieved results of Majewski and Cantwell (2.29m and 2.43m)

**** increase in distance due to reach over the stop board in delivery

***** difference to actual measured distance resulting from measuring mistakes in the 3-D-analysis, measuring mistakes in recording of putting distance by technical officials and possible differences in height between putting circle and sector

Comparing the essential release parameters between the throwers using the glide and rotational techniques, parallels to the overall analysis become apparent. Although the throwers applying the glide technique achieve lower average release velocity (13.73 ± 0.31m/s) than the rotational technique throwers (13.90 ± 0.22 m/s), they achieve a greater average putting distance with 21.34 ± 0.59m in contrast to 21.18 ± 0.56m. Apparently, their compensation is through steeper angles of release and greater release heights.

Achieving an increase in the angle of release without considerable losses in release velocity seems to be at least problematic in the rotational technique. There is the general belief that this is not easy when making full use of the rotational component. Against this backdrop, the angle of release for Cantwell's winning put (37.8°) was unusually steep, but no fluke. The analysis of his other five attempts in the final show an average angle of release of 38.1° ± 1.3°. In comparison to Hoffa (angle of release 34.4°) it becomes clear that Cantwell lifts the trajectory of the shot effectively after touchdown of the left leg and hence influences the angle of release positively.

Selected Additional Results

In respect to the length of the path of the shot, a ratio between glide and power position of 41.9:58.1% is characteristic of the glide technique throwers. In contrast, the rotational technique throwers have a nearly reversed proportion with a ratio of 55.8:44.2% between flight phase and power position.

With regard to the total acceleration path of the shot, there is only a very small difference between the two techniques. Astonishingly the average is slightly longer for the athletes using the glide (3.17 ± 0.11m) compared to those using the rotational technique (3.02 ± 0.07m).

A decisive difference can be found in the final part of the shot's path, which is of primary importance for the acceleration of the shot. Here the glide technique throwers had an average path that was 0.27m longer than the rotational technique throwers. With this they can exert force on the shot for a longer period in the delivery. Apart from being able to follow the shot longer with the putting shoulder, the explanation for the difference can be found in the characteristic and basically different body postures in the power position of the two techniques. In Figure 4 these differences are illustrated by a comparison between Cantwell and Majewski, who have comparable anthropometric characteristics.

The narrow spread between foot positions (0.71m) and the relatively upright upper body of Cantwell (angle between torso axis and the horizontal 57°) are characteristic of rotational technique. In contrast, Majewski is in a considerably wider stance and at the same time leaning the upper body far over the right leg (angle between torso axis and horizontal 41°). This results in the additional length of the path for the final acceleration of the shot mentioned above.

Depending on the individual execution of the technique, this effect can be intensified by holding the shoulder axis further back. Majewski succeeded in this respect as his shoulder axis reaches an angle of 248° in the power position, in contrast to Cantwell's 234°. The rotational style putters in the final, however, achieved an altogether more closed power position. Accordingly Nelson, a rotator, holds the shoulder axis back the best (257°), while Mikhnevich, a glider, opens the shoulder axis the furthest (198°).

Concerning the velocity-time-graph of the shot, different characteristics become apparent for the athletes applying the glide and the rotational techniques (see Figure 5). At the point of time "touchdown right leg", a reduction of the shot velocity can be found in both techniques. During the phases "amortization of the landing pressure" and in the "transition to touchdown of the brace leg", a velocity minimum is achieved (at 0.09 or 0.08 sec prior to touchdown of the brace leg), the average of which was far lower for the rotational throwers (0.88 ± 0.46 m/s or rather 2.02 ± 0.26 m/s) and temporally a little closer to delivery (-0.29 vs. – 0.31 sec).

Table 6: Length of the spatial relocation of the thrower in glide phase (glide technique) or flight phase (rotational technique) and the power positions of the top men shot putters at the 2009 IAAF World Championships in Athletics

Glide Technique	Distance	Length of glide	Foot distance iin power position	Ratio of glide to power position in glide	in power position
Name	[m]	[m]	[m]	[%]	
Majewski	21.91	0.91	1.28	42	58
Bartels	21.37	0.87	1.29	40	60
Mikhnevich	20.74	0.92	1.17	44	56
Average	21.34 ± 0.59	0.90 ± 0.03	1.25 ± 0.07	41.9 ± 1.9	58.1 ± 1.9

Rotational Technique	Distance	Length of spatial relocation in flight phase	in power position	Ratio of glide to power position in flight phase	in power position
Name	[m]	[m]		[%]	
Cantwell	22.03	1.14	0.71	63	37
Hoffa	21.28	1.12	0.70	62	38
Nelson	21.11	1.06	0.80	57	43
Lyzhin	20.98	0.83	0.86	51	49
Vodovnik	20.50	0.96	1.00	51	49
Average	21.18 ± 0.56	1.02 ± 0.13	0.81 ± 0.12	55.8 ± 6.6	44.2 ± 6.6

Figure 4: Comparison of the power positions of Cantwell (left) and Majewski at the 2009 IAAF World Championships in Athletics

Because of a clearly higher increase in velocity after the touchdown of the brace leg, the rotational style shot putters achieve comparably higher release velocities, despite lower initial velocities. That being the case, they realize 86.7% of the final shot velocity in the final delivery phase, compared to 79.7% for the glide technique throwers, corresponding with the statements in literature (HINZ, 1991; JONATH,1995; LANKA, 2000).

Both the glide and rotational throwers commence the main acceleration phase of the shot on average 0.06 sec prior to the touchdown of the left brace leg. Here the acceleration crosses the zero line and moves into positive values.

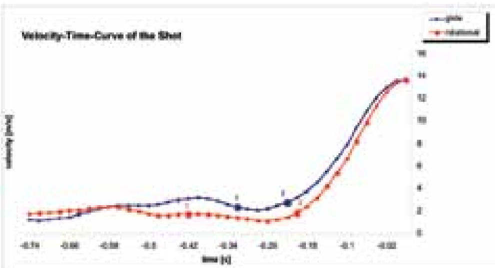

Figure 5: Average of the Velocity-Time curve of the shot for the top men shot putters at the 2009 IAAF World Championships in Athletics (1 = touchdown of right leg; 2 = touchdown of left brace leg)

For the rotational technique throwers, the graph of acceleration is marked by a slightly steeper increase than for the glide technique throwers. With an average of 85.7 ± 6.7 m/s2, the acceleration maximum was greater by 13.5% (75.5 ± 13.1 m/s2) and temporally closer to the delivery (0.06 sec vs 0.08 sec). The rotational technique throwers achieved a higher mechanical performance maximum (6.35 ± 0.51 KW) than the glide throwers (5.54 ± 0.97 KW) as a result of the greater acceleration.

Hence, in the final delivery phase the rotational technique throwers apparently compensate for the shorter acceleration path available to them caused by their body postures with clearly higher acceleration.

Analysis of the Women's Competition

Anthropometry and Technique

Table 7 shows the anthropometric data as well as the applied technique for the top eight placers in the women's shot put. All except Michele Carter (USA) had already reached the finals at major international events in recent years and six of them had been in the final of the 2008 Olympic Games in Beijing. Seven of the eight used the glide technique while Anna Avdeeva (RUS) used a leg reverse technique.

Table 7 Anthropometric data and technique of the top women shot putters at the 2009 IAAF World Championships in Athletics

Name	Age [years]	Height [m]	Weight [kg]	Technique
Vili	24	1.96	120	glide
Kleinert	33	1.90	90	glide
Gong	20	1.80	85	glide
Mikhnevich	27	1.80	85	glide
Avdeeva	24	1.75	74	leg reverse
Carter	23	1.75	95	glide
Meiju	29	1.74	80	glide
Gonzalez	31	1.79	75	glide
Average	26.4	1.80	91.1	

Release parameters

In Table 8 we see the release parameters for the best throws by the top eight placers. The average of these throws was 19.54 ± 0.65m. The average release velocity was 13.3 ± 0.22 m/s, the mean angle of release was 36.8 ± 1.6°and the average release height was 22.00 ± 0.10m.

The differences in the performances at hand are clearly reflected in the distinctness of the release parameters. With only small differences in the angles of release and almost equal release heights, the medallists achieved a far higher average release velocity (13.5 ± 0.1 m/s) than the athletes in places 4-8 (13.1 ± 0.13 m/s), the winner Villi's 13.6 m/s being highest of all.

Table 8: Release parameters for the best throws of the top men shot putters at the 2009 IAAF World Championships in Athletics (v0 = release velocity, α0 = angle of release, H0 = release height, H0_%-BH = release height as a percentage of body height)

Name	Distance [m]	v0 [m/s]	α0 [°]	H0 [m]	H0_%-BH [%]
Cantwell	22.03	14.0	37.8	2.29	115.7
Majewski	21.91	13.8	39.3	2.43	119.1
Bartels	21.37	14.0	33.6	2.12	113.4
Hoffa	21.28	14.0	34.4	2.06	113.2
Nelson	21.11	14.1	32.9	2.05	112.0
Lyzhin	20.98	13.6	39.2	2.22	117.5
Mikhnevich	20.74	13.4	37.7	2.43	120.3
Vodovnik	20.50	13.7	33.1	2.25	114.8
Average	**21.24 ± 0.53**	**13.83 ± 0.24**	**36.0 ± 2.77**	**2.23 ± 0.15**	**115.7 ± 2.98**

Thus, in contrast to the complexity reported above for the men's final, the differences in performance distance can almost completely be explained by differences in release velocity.

The obviously high dependency of the putting distance from the release velocity is also confirmed in the correlation analysis, which shows an almost linear connection with r = 0.88 ($p < 0.01$) (Figure 6).

Hence the influence of the different parameters corresponds almost fully with the throws parabola to be expected and is also verified by the multiple regression analysis:

putting distance = 2.517 x release velocity + 0.106 x angle of release – 17.781

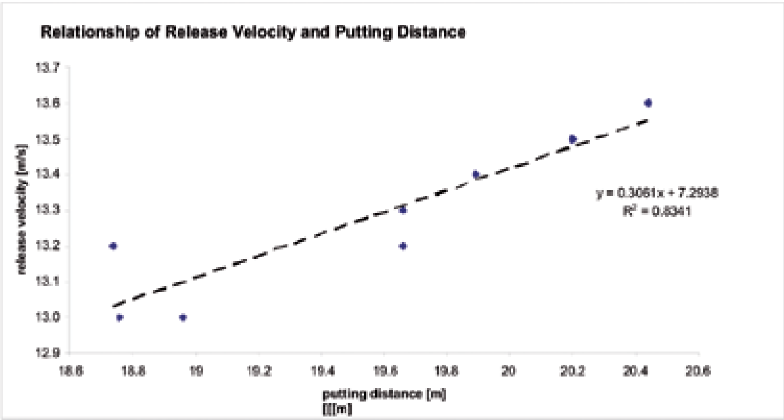

Figure 6: Correlation between release velocity and angle of release for the best throws of the top women shot putters at the 2009 IAAF World Championships in Athletics

Selected Additional Results

Despite the clear superiority concerning their putting distances there are no decisive differences in the analysis of the spatial structure between the medallists and the throwers in places 4-8 (see Table 9).

Overall, the average length of the glide is shorter than the foot distance in the power position, as shown by the ratios of 44.3:55.7% for the medal winners and 46.4:53.6 % for the athletes in places 4-8.

In individual cases there are, however, clear deviations from this structure. Among the medal winners this is especially noticeable in Kleinert, where the length in the glide and power position were almost equal (1.00m and 1.03m). Among the athletes in places 4-8 only Misleydis Gonzales (CUB) showed a similar ratio (glide: 1.02m; power position: 1.08m). The 0.99m shot path in the glide of fifth placer Avdeeva was even longer than for her power position (0.91m), but this can probably be attributed to the leg reverse technique she used.

With regards to the temporal structure, the slightly longer relocation in the glide of the athletes in places 4-8 is accompanied by a slightly longer duration of the interval between lifting the right leg and touchdown of it again. Whereas the following transition to touchdown of the left brace leg is equally long, the delivery phase is slightly shorter with the medallists.

The decisive and performance-relevant differences are apparently caused by the velocity structure of the whole movement. In contrast to the throwers in places 4-8, the medallists were able to increase the average of the velocity of their CMs after the glide in the transition from touchdown of the right leg to touchdown of the brace leg (Table 10). This, however, did not lead to a comparatively higher average velocity of the shot at the beginning of the final acceleration phase. At touchdown of the brace leg, the average velocity was 2.79 ± 0.27 m/s, which

Table 9: Length of the shot path in the glide phase and power position of the top women shot putters at the 2009 IAAF World Championships in Athletics

Name	Distance	Length of glide	Foot Distance in power position	Ratio of glide to power position: in glide	in power position
	[m]	[m]	[m]	[%]	
Vili	20.44	0.89	1.19	42.8	57.2
Kleinert	20.20	1.00	1.03	49.3	50.7
Gong	19.89	0.85	1.23	40.9	59.1
Mikhnevich	19.66	0.88	1.08	44.9	55.1
Avdeeva	19.66	0.99	0.91	52.1	47.9
Carter	18.96	0.99	1.14	46.5	53.5
Li	18.76	0.84	1.25	40.2	59.8
Gonzalez	18.74	1.02	1.08	48.6	51.4
Ø place 1-3	20.18 ± 0.28	0.91 ± 0.08	1.15 ± 0.11	44.3 ± 4.40	55.7 ± 4.4
Ø place 4-8	19.16 ± 0.47	0.94 ± 0.08	1.09 ± 0.12	46.4 ± 4.40	53.6 ± 4.4
Ø place 1-8	19.54 ± 0.65	0.93 ± 0.07	1.11 ± 0.11	45.6 ± 4.23	54.2 ± 4.4

Table 10: Centre of Mass velocities (CM-v) of the top women shot putters at the 2009 IAAF World Championships in Athletics

Name	**Movement Phase**			
	Starting position until lift-off of right leg	**Lift-off right leg until touchdown of right leg**	**Touchdown right leg until touchdown of brace leg**	**Touchdown brace leg until release of shot**
	[m/s]			
Vili	1.91	2.08	2.26	1.89
Kleinert	1.75	2.20	1.97	1.89
Gong	1.32	2.22	2.41	1.97
Mikhnevich	1.69	2.36	2.16	1.98
Avdeeva	1.31	2.07	1.80	1.88
Carter	1.46	2.33	2.27	1.51
Li	1.33	2.05	2.16	1.98
Gonzalez	1.32	2.02	2.01	2.03
Ø place 1-3	1.66 ± 0.31	2.17 ± 0.08	2.21 ± 0.22	1.92 ± 0.05
Ø place 4-8	1.42 ± 0.16	2.17 ± 0.16	2.08 ± 0.18	1.88 ± 0.21
Ø place 1-8	1.51 ± 0.24	2.17 ± 0.13	2.13 ± 0.19	1.89 ± 0.16

was lower than with the athletes in places 4-8 (2.86 ± 0.27 m/s). Nevertheless, in the final acceleration phase the medallist achieve a clearly greater increase in the average velocity of the shot (10.71 ± 0.32 m/s; 79.4%) than the other athletes in the final (10.28 ± 0.37 m/s; 78.3%).

Although with 1.55 ± 0.14m medallists had a shorter average shot path length for the acceleration phase compared to the 1.72 ± 0.11m of the other finalists, they were able co compensate with ~10% greater acceleration maxima (81.1 ± 6.25 m/s2 vs. 73.9 ± 9.59 m/s2).

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