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Biomechanical Factors of Competitive Success With the Rotational Shot Put Technique

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ABSTRACT

The aim of this study was to determine the biomechanical parameters in the rotational technique that have the greatest impact on the distance achieved and thereby on competitive success in the shot put. The sample consisted of 10 top-level putters competing at the 2008 European Cup Winter Throwing in Split, Croatia; the best throw by each of the subjects was selected for examination. A 3D kinematic analysis was made from recordings by two high-frequency cameras and APAS software was used to obtain values for selected parameters. The results confirmed a high correlation between the distance achieved and key release parameters, i.e. shot velocity, angle of release and release height. The analysis also showed the importance of parameters that consider the putter's activity in preceding phases of the movement, i.e. foot placement at the beginning of the 2nd double-support phase and parameters calculated from the angular velocity of the shoulder, hip and knee joints. Using linear regression, the authors can explain 94.7% of competitive success from the studied parameters. The results indicate that release velocity alone is not enough to explain the effective process of acceleration, and that the momentum of the whole-body movement must also be considered.

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Introduction

Putting the shot is an extremely complex motion, which must be performed at high speed in a very limited space. Performance in the shot put is defined by the biological (anthropometrical, physiological and motor parameters of the competitor) and the physical–mechanical parameters defining the technique of the individual athlete.

In any case, the putter must optimise the release angle, release velocity and release height to achieve a maximal distance. The permanent question in theory and practice is how best to coordinate the individual segments of the throwing movement to produce maximum velocity of the shot at the point of release.

The world's top performers currently use one of two basic techniques: the rotational or linear movement sequences, both of which have to be rhythmically correlated.

The rotational technique can be divided into the following elements:

- **Preparation** (1st double-supporphase),
- **Transition** (1st single-support phase, 1st flight phase, 2nd single-support phase, beginning of 2nd double-support phase),
- **Completion**/release (2nd double-support phase, 3rd single-support phase, beginning of 2nd flight phase) and 4) 2nd flight phase.

Existing studies of the shot put mostly focus on analysis of kinematic (mechanical) parameters, with the greatest emphasis on the release phase.

In an analysis of the shot put at the 2004 Olympic Games, ARIEL et al. (2004) calculated an average release height 2.39m, an average release angle of 36° and an average release velocity 13.8 m/sec for a 21m performance. In an analysis of a 19.58m put by the Slovene record holder Miran Vodovnik, COH et al. (2005) calculated a release velocity of 12.94 m/sec, a release angle of 36° and a release height of 2.27m. STEPANEK (1987), TIDOW (1990) and BARTONIETZ (1994) report very similar values for the mentioned parameters.

Analyses of the correlation, impact and importance of individual parameters to the final result, particularly in the rotational technique, have not been seen in the existing studies. The relationship between release velocity and performance was successfully calculated in a study of the finalists at the 2007 IAAF World Championships in Athletics by BYUN et al. (2008), who confirmed the correlation between release velocity and distance ($r=0.87$, $p<0.01$).

However, release velocity is only a consequence of the preceding movements. With that in mind, the main goal of the present study of a sample of top-level putters was to determine which biomechanical parameters in the transition and release phases of the rotational technique have the greatest impact on the final distance and thereby on success in this discipline.

Methods

Subjects and experimental procedure

Measurements were taken in competitive conditions at the 2008 European Cup Winter Throwing in Split, Croatia, the results of which are shown in Table 1. A 3D kinematic analysis of the technique of ten selected throws (in each case the best in the competition by the respective athlete) was made.

The subjects' average age was 28.5 years, the average body weight was 123.6kg, and the average body height was 1.89m. All subjects were right-handed.

Data acquisition and processing

The recordings were made with two synchronised high-frequency cameras (SONY DVCAM DSR-300 PK), placed at 45° and 135° angles in relation to the putting direction. The frequency of both cameras was set to 50Hz with 720 x 576 pixel resolution. The analysed space of the throwing circle was calculated on the reference measure frame dimensions 1m x 1m x 2m, and eight reference angles were considered for calibration. Length was defined by the X-axis, height by the Y-axis, and the depth of the analysed movement by the Z-axis.

The obtained data were processed in the laboratory for kinematics at the Sport Institute of Ljubljana, Slovenia. For determination of biomechanical parameters of the technique APAS software (Ariel Dynamics Inc., San Diego, Ca) was used. Digitalisation was made of

Table 1: Results of the Men's Shot Put at the 2008 European Cup Winter Throwing (analysed throws are highlighted in bold)

	Athlete (Country)	**Round**					
		1	**2**	**3**	**4**	**5**	**6**
1	Rutger Smith (NED)	19.87	19.22	x	19.88	20.30	20.77
2	Marco Fortes (POR)	17.53	x	18.55	19.13	x	20.13
3	Hamza Alic (BIH)	x	18.15	x	20.13	x	x
4	Robert Häggblom (FIN)	19.75	20.06	x	x	x	x
5	Miran Vodovnik (SLO)	19.77	x	x	19.49	19.72	19.10
6	Nedžad Mulabegovic (CRO)	18.96	19.47	x	19.28	19.43	19.58
7	Andrei Siniakou (BLR)	19.12	x	19.29	19.08	x	x
8	Anton Lyuboslavskiy (RUS)	18.21	19.21	18.72	18.85	18.88	18.78
9	Andréas Anastasópoulos (GRE)	18.75	x	18.03	18.60	x	x
10	Marco Schmidt (GER)	17.99	18.57	x	x	18.49	17.70
11	Ivan Emilianov (MDA)	***18.34***	***18.38***	***18.01***	***18.16***	***18.31***	***18.29***
12	Mihaíl Stamatóyiannis (GRE)	18.25	18.12	18.24	x	19.90	18.25
13	Raigo Toompuu (EST)	18.13	x	18.06	x	x	x

a 15-segment model of a putter's body, defined by 18 reference points. The 18th point was the implement's centre of mass (CM). Model segments represent the body parts related with associated joints. The CM of the body segments and whole body were calculated according to the Anthropometric Model of Dempsteret al. (WINTER, 2005). The body-point coordinates were smoothed with a 7-degree digital filter. Using the APAS software, we determined the data for velocities, angles and trajectories of the individual body segments.

Statistical procedures were processed with SPSS Statistics software, version 17.0. To establish correlations between the chosen kinematic parameters and the final result the Pearson's coefficient of correlation was used, and for calculation of the importance of the individual biomechanical parameters a linear regression was used.

Model of Biomechanical Parameters

Based on existing research and studies, we developed a model of 13 biomechanical parameters from two phases of the rotational technique: the second – the transition phase – and the third – the completion/release phase.

The model (see Figure 1 and Figure 2) includes:

- **Vx** – horizontal release velocity,
- **Vy** – vertical release velocity,
- **Vxyz** – absolute release velocity,
- **H** – release height,
- **L** – acceleration path length after 2nd single-support phase,
- α – release angle,
- **KvKM** – angular velocity of the right shoulder at the moment of release,
- **KvKN** – angular velocity of the right knee at the moment of release,
- **Zdif** – deviation from ideal foot placement in "z" axis (width) at the beginning of 2nd double-support phase,
- β – angle of torsion of the trunk (angle between hip and shoulder axes) at the beginning of the 2nd double-support phase,
- **KvDavg** – absolute value of the average angular velocity in the right knee joint in the 2nd double-support phase + difference in absolute value of the average angular velocity in the right knee joint in the 2nd double-support phase and absolute value of

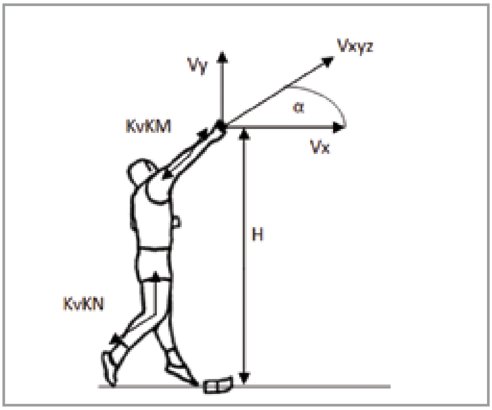

Figure 1: Biomechanical parameters in the release phase

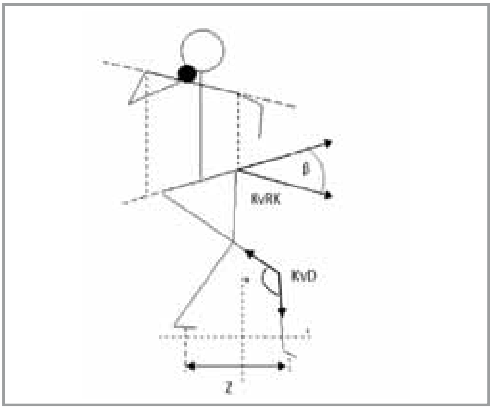

Figure 2: Biomechanical parameters in the transition phase

the average angular velocity in the right knee joint in the 3rd single-support phase,

- **KvRKavg** – the sum of absolute value of the average angular velocity between shoulder and hip axes in the 2nd double-support phase and absolute value of the average angular velocity between shoulder and hip axes in the 3rd single-support phase,
- **TUabs** – absolute technical efficiency, which is the sum of KvDavg and KvRKavg parameters (TUabs = KvDavg + KvRKavg).

Results

Basic statistical data of the selected sample of throws are shown in Table 2.

Table 2: Descriptive statistics of biomechanical parameters.

Variables	**Minimum**	**Maximum**	**Mean**	**SD**
Length [m]	18.06	20.77	19.48	0.884
Vx [m]	9.49	11.58	10.32	0.619
Vy [m]	7.09	8.47	8.09	0.422
Vxyz [m]	12.52	13.58	13.13	0.353
H [m]	2.05	2.31	2.16	0.081
L [m]	1.37	1.64	1.51	0.088
A **[m]**	31.5	41.3	38.13	2.858
B **[m]**	35	61	44.25	8.028
Zdif [m]	2	22	9.20	7.899
KvKM [m]	871	1308	1064	172.597
KvKN [m]	-224	235	9	157.932
KvDavg [m]	104	399	234	94.774
KvRKavg [m]	41	594	331	194.971
TUabs [m]	303	809	565	184.160

Table 4: Linear regression of competitive success

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
a	0.973	0.947	0.880	0.30579

Legend: a = Predictors: (Constant), Zdif, α, H, Vxyz, TUabs.

From the calculated correlations we established that the final distance is most closely related to Vxyz shot velocity (r=0.902, p<0.01) (see Table 3/page 106). The distance also significantly correlates with biomechanical parameters of horizontal shot velocity Vx (r=0.643, p<0.05), release height H (r=0.669, p<0.05), deviation from ideal foot placement Zdif (r=-0.648, p<0.05), average angular velocity between shoulder and hip axes KvRKavg (r=0.651, p<0.05) and absolute technical efficiency TUabs (r=0.746, p<0.05).

The impact of the chosen biomechanical parameters on the competitive success was calculated using the linear regression statistical method, in which only certain biomechanical parameters were included, i.e. Vxyz, H, α, TUabs and Zdif, respectively. With the chosen parameters we managed to explain 94.7% of competitive success (R2=0.947) (see Table 4).

The results show that the chosen model of variables is statistically significant, F (4, 5) = 14.253, p<0.05 (see Table 5).

When reviewing the individual parameters and their contribution to our regression model we can see that only the final Vxyz release velocity is a typical predictor from our model (p=0.011) (Table 6).

Table 5: Analysis of variance (ANOVA) for model of variables

	Sum of Squares	df	Mean Square	F	Sig.
Regression	6.664	5	1.333	14.253	0.012a
Residual	0.374	4	0.094		
Total	7.038	9			

Legend: a = Predictors: (Constant), Zdif, α, H, Vxyz, TUabs.

Table 6: Analysis of variance (ANOVA) for variables in model

	Unstandardised Coefficients		Standardised Coefficients	T	Sig.
	B	Std. Error	Beta		
(Constant)	-23.674	8.541		-2.772	0.050
Vxyz	2.707	0.604	1.082	4.481	0.011
H	1.383	2.141	0.127	0.646	0.554
L	-0.611	2.243	-0.061	-0.273	0.803
A	0.122	0.066	0.395	1.856	0.13
TUabs	3.166E-5	0.001	0.007	0.028	0.979
Zdif	-0.005	0.018	-0.043	-0.271	0.800

Table 3: Pearson's coefficients of correlation

Variables	Length	Vx	Vy	Vxyz	H	L	A	KvKM	KvKN	B	KvDavg	KvRKavg	TUabs	Zdif
Length	1	.643*	.024	.902**	.669*	.621	-.373	-.179	-.232	.017	.112	.651*	.746*	-.648*
Vx	.643*	1	-.734*	.888**	.184	.329	-.946**	.184	-.227	-.116	.047	.661*	.724*	-.586
Vy	.024	-.734*	1	-.342	.297	.101	.914**	-.524	.102	.203	.008	-.285	-.297	.223
Vxyz	.902**	.888**	-.324	1	.466	.534	-.692*	-.102	-.259	-.038	.052	.729*	.799**	-.665*
H	.669*	.184	.297	.466	1	.713*	.035	-.196	-.338	.065	.087	.532	.608	-.462
L	.621	.329	.101	.534	.713*	1	-.143	-.243	-.253	-.145	-.107	.686*	.671*	-.582
A	-.373	-.946**	.914**	-.692*	.035	-.143	1	-.362	.173	.159	-.029	-.530	-.576	.449
KvKM	-.179	.184	-.524	-.102	-.196	-.243	-.362	1	.197	-.347	-.169	-.155	-.251	.178
KvKN	-.232	-.227	.102	-.259	-.338	-.253	.173	.197	1	-.188	-.441	.037	-.188	.816**
B	.017	-.116	.203	-.038	.065	-.145	.159	-.347	-.188	1	.633*	-.222	.091	-.097
KvDavg	.112	.047	.008	.052	.087	-.107	-.029	-.169	-.441	.633*	1	-.354	.140	-.327
KvRKavg	.651*	.661*	-.285	.729*	.532	.686*	-.530	-.155	.037	-.222	-.354	1	.877**	-.396
TUabs	.746*	.724*	-.297	.799**	.608	.671*	-.576	-.251	-.188	.091	.140	.877**	1	-.588
Zdif	-.648*	-.586	.223	-.665*	-.462	-.582	.449	.178	.816**	-.097	-.327	-.396	-.588	1

Legend: * $p<0.05$; ** $p<0.01$.

Discussion

Table 1 and Table 2 show that the competition in Split was at a very high level and that the average distance of the analysed throws was 19.48m (shortest 18.06m, longest 20.77m). For these throws, the average release height was 2.16m (2.05m – 2.31m), the average release angle was 38° (31.5° – 41.3°) and the average release velocity was 13.13 m/sec (12.52 m/sec - 13.58 m/sec).

In their research of top shot putters, ARIEL et al. (2004) got similar results. In their analysis of the best three competitors in the 2004 Olympic final where the average result was 21.13m, the calculated average release height was 2.39m, the average release angle was 36° and the average release velocity was 13.8 m/sec. In their analysis of the finalists at the 2007 IAAF World Championships in Athletics, where the average result was 20.82m, BYUN et al. (2008) calculated an average release height of 2.33m, an average release angle 35° and an average release velocity 13.4 m/sec. Other authors (STEPANEK, 1987; BARTONIETZ, 1994; COH & SUPEJ, 2007) report similar values for individual biomechanical parameters at similar performance levels, strongly suggesting that the above-mentioned values for the three basic release parameters are required to achieve distances of 20m and more.

As was expected, thowing distance most strongly correlates with release velocity ($r=0.902$, $p<0.01$). BYUN et al. (2008) found a similar albeit slightly lower correlation ($r=0.87$, $p<0.01$). According to the physical laws that determine the trajectory of a simple projectile, the other two key parameters are release angle and release height. In our study, the final result is significantly correlated only with release height ($r=0.669$, $p<0.05$), and not with release angle ($r=-0.373$). So, in terms of the physical laws, assuming that satisfactory body height of the top putters is not questionable, the essence of successful shot putting is to accelerate the shot in the best possible manner throughout the whole putting motion with the aim of achieving maximum velocity in the point of release.

From the factors indicating shot put technical efficiency itself, the foot placement at the beginning of the 2nd double-support phase Zdif ($r=-0.648$, $p<0.05$) significantly correlates with the final result. More important than the distance between the rear and front feet is the width between them (see Figure 2), as this is a precondition of efficient leg action in the release phase. This indicates the importance of the first part of the movement in providing optimal conditions for the release phase. The correlation of this parameter with the final result has a negative value, as any bigger deviation from the ideal placement, which is considered to be approximately 20cm, means a worse result.

Significant correlations with the final result were also found for the parameters KvRKavg ($r=0.651$, $p<0.05$) and TUabs ($r=0.746$, $p<0.05$). These indicate an efficient and synchronised activity of the lower and upper parts of the body after the beginning of the 2nd double-support phase. This is reflected in a better rotation of the body when the putter begins the 2nd double-support phase and has a considerable impact on the final release velocity. High angular velocity values between shoulder and hip axes before the beginning of the 2nd double-support phase denote an unsynchronised movement, which was noted in the competitors with worse results on the competition.

The Torsion angle after the 1st flight phase is considered to be a key element of good technique. Correlation analysis in our study showed that the angle between shoulder and hip axes β – torsion angle, which defines the above-mentioned technical element, has no significant importance, as the obtained correlation is statistically non-significant ($r=0.017$). Notwithstanding the result, we have to conclude that this parameter should not be ignored, as the significant correlation of the β parameter with the KvDavg parameter ($r=0.633$, $p<0.05$) indicates that the torsion angle is important for the efficient action of the right leg after the 2nd double-support phase until the release of the shot.

We assume that the angle between the shoulder and hip axes in the beginning of the

2nd double-support phase is more important for the putters using the linear technique, as these athletes do not use the rotation momentum. This suggests the conclusion that in the rotational technique the whole putter's motion or the rotational momentum has a much more important role after the preparatory phase. In our research this momentum is presented in terms of angular velocities between the shoulder and hip axes in relation with the angular velocity of the right knee (parameters KvRKavg and TUabs). This fact is also confirmed by high and significant correlation of the parameter with the final result (KvRKavg, $r=0.651$, $p<0.05$; TUabs, $r=0.746$, $p<0.05$). BYUN et al. (2008) and COH & SUPEJ (2007) obtained similar findings when they analysed the whole movement of the putter in terms of linear and angular momentum or mechanical energy and power differential, respectively.

A high, but non-significant correlation with the final result was found for biomechanical parameter L, the acceleration path length after 2nd single-support phase ($r=0.621$). The higher value of Pearson's correlation coefficient is reinforced by the fact that the longer path, made with the shot, denotes a greater possibility for effective acceleration and thus a higher release velocity. As expected, the acceleration path length significantly correlates with release height ($r=0.713$, $p<0.05$), as well as with the parameter TUabs ($r=0.671$, $p<0.05$). This proves that for rotational momentum efficiency the athlete needs to effectively use the rotation movement, thus making the trajectory of the shot through the whole put as wide as possible.

The correlation calculations (Table 3) also provide some important correlations between individual biomechanical parameters. We would underline the high correlation between Vxyz release velocity and TUabs parameter ($r=0.799$, $p<0.01$), which provides additional evidence of the importance of the body rotation in order to achieve higher release velocity mentioned previously. A very high correlation between angular velocity of the right knee in release phase KvKN and deviation from the ideal foot placement in the beginning of the 2nd double-support phase Zdif ($r=0.816$, $p<0.01$) also has to be pointed out.

The latter additionally confirms our thesis that inappropriate foot placement hinders efficient leg action after the beginning of the 2nd double-support phase.

For the calculation of potential competitive success, we chose those biomechanical parameters that significantly correlate with the shot put distance, where Vx horizontal velocity and KvRKavg parameter were excluded, because of their high correlation with Vxyz and TUabs, respectively. In the selection of variables, the release angle α was also included. With the described selection of variables (biomechanical parameters) with linear regression we managed to explain 94.7% of competitive success ($R2=0.947$) (Table 4), and the chosen model of variables is statistically significant, $F(4, 5) = 14.253$, $p<0.05$ (Table 5).

From the individual parameters in our model, only release velocity Vxyz ($p=0.011$) is a significant predictor of competitive success. Using linear regression, we also calculated the values of Beta coefficients (Table 6), which theoretically present the contribution of the individual parameter to the final result, provided that other parameters are held as constant. Thus we can see that with an increase of release velocity of 1 m/sec, assuming that all other parameters are constant, the distance is longer by 2.71m. In other words, to gain one metre, the release velocity needs to be increased by 0.37 m/sec. When release height parameter is considered, its Beta coefficient shows that with a one metre increase in release height, when the other parameters are constant, shot put distance increases by 1.38m. In practice, the release height is mostly defined by the body height of the athlete. Therefore, it is more appropriate to state that a 10cm increase in release height would mean a 14cm longer throw. Finally, considering the release angle α, we can see that a 1° increase of this parameter would mean a 12cm longer throw, or a 5° increase would mean a 60cm longer throw. It has to be mentioned that this holds true only when the angle is smaller than 45º, as according to the physical laws of projectile flight a further increase of release angle would have a negative impact on the final distance.

Conclusion

The results of our study on a sample of top-level shot putters using the rotational technique confirmed the importance and correlation of certain biomechanical parameters with the final result. Release velocity is the main success factor. But release velocity itself is not enough to explain the process of effective shot acceleration. When examining the rotational technique we have to have in view the putter's whole motion in both the transition and release phases. With calculated parameters, which consider angular velocity between shoulder and hip axes, and angular velocity in the right knee, we showed the importance of rotational momentum efficiency throughout the whole put. We presume this is one of the key factors to ensure the highest possible release velocity when using the rotational technique.

Additionally, we showed the importance of other factors that have a significant impact on the final distance achieved. Foot placement in the beginning of the 2nd double-support phase is a key factor in that it enables effective action of the right leg through the release phase, which must not be too wide or too narrow. Release height is also a significant factor for the final distance, therefore, a large body height in the athlete is a prerequisite for achieving results at the highest level in the shot put. Another important factor is the acceleration path length, as a longer and wider trajectory of the shot through the whole putting movement enables better efficiency of rotation technique, and thereby higher release velocity.

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