

3-D kinematic analysis of the rotational shot put technique

By Milan Coh, Stanko Stuhec

The purpose of the study was to identify some of the most relevant kinematic parameters defining the competition result in rotational shot put technique. A biomechanical analysis was carried out on an elite shot putter, a member of the Slovene national team who had placed 11th in the 2004 Olympic Games in Athens. A 3-D video system for kinematic analysis was used. A 15-segment model of a shot putter consisting of 18 reference landmarks was defined. The results of the study showed that the top result in rotational technique depended on release velocity, optimal release angle, relation between rotational movement and final acceleration of the shot, and angular velocity in the elbow and shoulder of the throwing arm. The key phases that ensure the correct rhythm and generate high release velocity of the shot are the following: flight phase, second single support phase and second double support phase.

ABSTRACT

Milan Coh, Faculty of Sport, University of Ljubljana, Slovenia

Stanko Stuhec, Faculty of Sport, University of Ljubljana, Slovenia

AUTHORS

motor abilities and technique. The distance thrown is determined by release velocity, angle of release, height of release and distance over which force is applied to the shot (STEPANEK, 1989; BARTONIETZ, 1994; HUBBARD et al., 2001; RASMUSSEN, 2005). The height of release and amplitude of the path of the shot acceleration are determined by genetic factors, primarily by body height and arm length. Therefore, in terms of biomechanics, taller throwers have an advantage over shorter throwers. Release angle is a vector variable resulting from a combination of the horizontal and vertical forces in the release action. The flight distance of a shot is given by the following formula (LINTHORNE, 2001):

$$D f = \frac{v^2 \sin 2 \alpha}{2g} \left[1 + \left(1 + \frac{2gh}{v^2 \sin^2 \alpha} \right)^{1/2} \right]$$

v = release velocity

α = release angle

g = acceleration due to gravity

h = h_{release} – h_{landing}

Introduction

The rotational shot put technique is characterised by very complex movements performed at high speed in a confined space. Many factors determine the results in this event, of which the most important are morphological characteristics,

The rotational shot put technique consists of rotational and linear movement sequences, which must be rhythmically linked. Individual muscles take part in movement based on the principle of parallelism and the principle of sequentiality. Parallelism is manifested in the synchronous involvement of individual muscle groups in a movement. Sequentiality means that muscles take part in a movement following the proximal–distal sequence. The initial movement in the rotational shot put technique is generated by the muscles of the lower body segment (legs) while the final movement is generated by the muscles of the upper body segment (arm–hand). The primary power is generated in the form of ground reaction forces as a result of the action of the lower extremities. It is characteristic of the rotational shot put technique that, when muscles take part in movement, their joints first move away (eccentric muscle contraction) and then move closer (concentric muscle contraction). The efficacy of the eccentric–concentric muscle activity depends on the successive and co-ordinated proximal–distal sequence of muscle chains (STEPANEK, 1989; PALM, 1990; ROBERTSON et al., 2004).

In addition to correct muscle sequence, the distance over which force is applied to the shot is also important in a rational technique. Anatomical characteristics (body height, arm span) of the thrower have the strongest influence on the movement trajectory of the shot. The length of the trajectory is defined by the initial stance of the thrower and the height of release. Height of release in elite shot putters is 220–235cm (STEPANEK, 1989; LUHTANEN et al., 1997; LANKA, 2000).

The purpose of this study was to identify some of the most relevant kinematic parameters of the rotational shot put technique used by an elite Slovene shot putter (M. V.) whose personal record is 20.56m and whose result of 20.04m placed him 11th at the 2004 Olympic Games in Athens. The following selected kinematic characteristics were analysed: single support phase, flight phase and double support phase, release velocity, release angle, release height, dynamics of shot velocity and thrower's centre of mass, shot movement trajectory, angle between hip and shoulder axes, and angle of the elbow and shoulder during release action. The

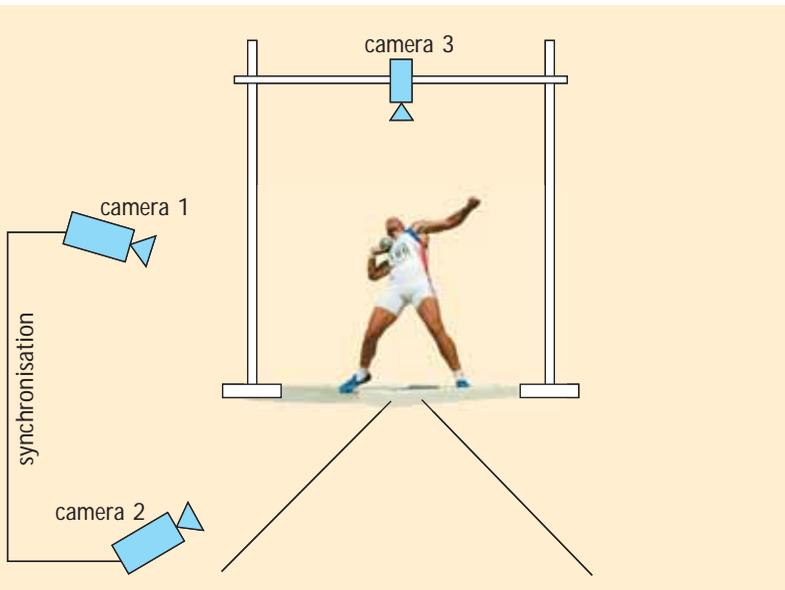


Figure 1: Procedure for recording shot put technique

results of the study represent a good foundation for qualitative and objective analysis of the technique, diagnosis of errors and the control and modelling of technical preparation of throwers.

Methods

The measurements and the biomechanical analysis of the rotational shot put technique of the Slovene national team member M. V. (age: 27 years, height: 1.95m, body mass: 169.5kg; BMI – body mass index: 44.5, right-handed thrower) were carried out in July 2004 during preparations for the Athens Olympic Games. Eight puts were recorded during the testing. Only the best put was

included in the final analysis. Recordings were made with two synchronised cameras (SONY DVCAM DSR-300 PK) fixed at an angle of 90° between their optical axes. The third camera (SONY TRV840E) was set at a height of 4m, directly above the throwing circle (Figure 1). In all three cameras the frequency was 50Hz and the resolution 720 x 576 pixels. The analysed area of the throwing circle was calibrated with a 1m x 1m x 2m reference scaling frame, and the calibration was based on eight reference edges. Length was defined by the "x" axis, height by the "y" axis and depth of analysed movement by the "z" axis. 3-D software APAS (Ariel Dynamics Inc., San Diego, Ca.) was used for establishing the kinematic parameters of the technique. The 15-segment model of the thrower's body was digitised and defined by 18 reference landmarks. The eighteenth landmark was defined by the centre of the shot. The segments of the model represented parts of the body, linked with point-like joints. The masses and centres of mass of the segments as well as the centre of mass of the body were calculated on the basis of the anthropometrical system (DEMPSTER, 1955). The co-ordinates of the body landmarks were smoothed with a digital Seventh-Order Buterworth filter.

The ARIEL software package was used to acquire data on horizontal velocity (VX), vertical velocity (VY), final release velocity (VXYZ), release height (RH), angular velocity of the elbow of the throwing arm (EV), angular velocity of the shoulder of the throwing arm (ES), release distance (RD), release angle (α) and flight distance of the shot (FD). The technique was defined by the following phases (Figure 2):

- Initial stance (B1) – first double support phase – preparation for throw with preliminary swing – the athlete faces away from the direction of the throw.

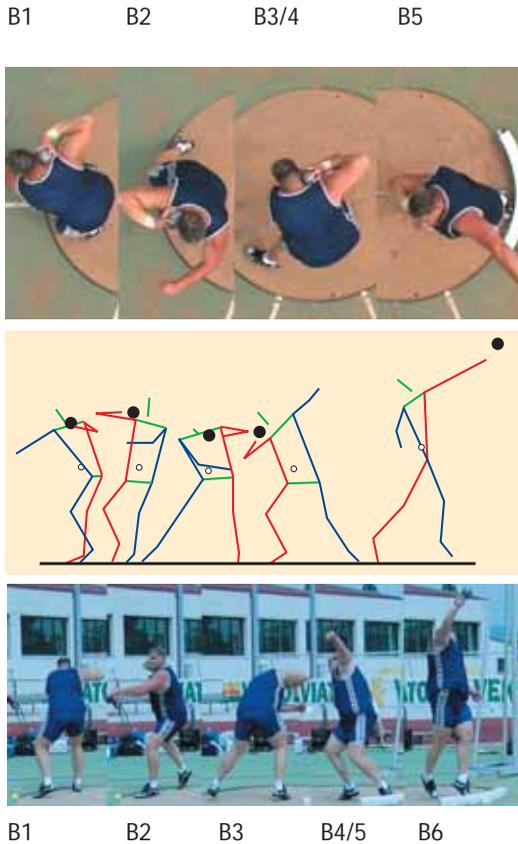


Figure 2: Phases of the rotational shotput technique

- Entering the turn (B2) – this phase starts at the end of the double support phase and continues with the first single support phase on left foot.
- Flight phase (B3) is defined as the transition from the left to the right foot near the centre of the throwing circle; the end of the flight phase is at the same time the beginning of the second single support phase.
- The second single support phase starts, when the right foot is set on the ground (B4), and ends at the instant the left foot makes contact with the front part of the throwing circle.
- In the second double support phase (B5) the final release action of the shot put is performed.
- The release action is performed during the flight phase (B6).

Figure 3 shows duration of individual phases.

Results and Discussion

Due to the fact that only one elite shot putter was the subject of this study, the results cannot be generalised; nevertheless, a biomechanical analysis does yield exceptionally important parameters, which may be useful in objectification of the key phases of rotational shot put technique. On account of the complexity of the problem, the exacting methodology and the measurement technology, there are relatively few comparable studies on elite athletes in the professional literature.

Based on the analysis of the basic kinematic parameters of rotational shot put technique (Table 1) the following may be ascertained:

1) The results of the athlete M. V., namely release velocity (12.94 m/s⁻¹), release angle (α

= 36°), release height (2.27m) and index of release height and body height (release height: BH = 1.17) – Figure 4, are comparable with the results obtained in earlier studies (STEPANEK, 1989; PALM, 1990; BARTONIEZ & BORGSTRÖM, 1995; LUHTANEN et al., 1997; OESTERREICH et al., 1997). Release velocity is undoubtedly one of the most important parameters of the technique and is generated by preceding phases, especially the second double support phase. Our subject had a slightly lower release velocity than some of the other best rotational shot putters (J. Godina – 13.44 m/s⁻¹, M. Halvari – 13.16 m/s⁻¹, R. Barnes – 13.53 m/s⁻¹ and K. Noen – 13.05 m/s⁻¹).

2) The release angle of M. V. is 35.9°, which with respect to his release velocity (12.94 m/s⁻¹) is an optimal value according to LINTHORN's model (2001). It has been established that release angles of some rotational shot putters vary more than those of shot putters using the classic technique. This is due to the fact that during the rotational movement phase, deviations occur in terms of stability and balance. Two functional systems are responsible for keeping balance, namely reticular formation and vestibular nucleus (LUHTANEN et al., 1997). Lack of stability and balance in the rotational phase has direct effects on lower accuracy in the performance of the final shot acceleration phase. Release height and some external factors (adverse wind) impact on the value of release angle, but to a lesser extent than in the javelin throw or discus throw.

3) The path of the shot, the body's centre of mass (CM) and the average velocity in individual phases of the rotational shot put technique are shown in Figure 5 and Figure 6. In the case of our study subject, rotation from the distal phase of the first double support phase to the release of the shot lasted for 1.28 seconds. This is slightly less than the

the first double support phase B1	the first single support phase B2	the flight phase B3	the second single support phase B4	the second double support phase B5	the flight phase B6
0.28 s	0.54 s	0.04s	0.22 s	0.16 s	0.04s

Figure 3: Duration of the phases of the rotational shot put technique (athlete: M.V., result: 19.58m)

Table 1: Kinematic parameters of the rotational shot put technique (athlete: M.V., result: 19.58m)

Parameter	Result
Official distance (D official)	19.58m
Release (resultant) velocity (VXYZ)	12.94 m/s ⁻¹
Horizontal velocity (VX)	10.47 m/s ⁻¹
Vertical velocity (VY)	7.61 m/s ⁻¹
First double support phase T1-T2	2.28 m/s ⁻¹
First single support phase T2-T3	1.67 m/s ⁻¹
Flight phase T3-T4	0.80 m/s ⁻¹
Second single support phase T4-T5	1.45 m/s ⁻¹
Second double support phase T5-T6	7.02 m/s ⁻¹
Flight release phase T6-T7	12.71 m/s ⁻¹
Release angle (α)	35.9°
Release height (RH)	2.28m
Release distance (RD)	0.21m
Distance over which force is applied to the shot in the final phase (DXY)	1.65m
Average angular velocity in the elbow of the throwing arm (EV)	875°/ sec.
Maximum angular velocity in the elbow of the throwing arm (MEV)	1378°/ sec.
Average angular velocity in the shoulder of the throwing arm (ES)	452°/ sec.
Maximum angular velocity in the shoulder of the throwing arm (MES)	652°/ sec.
Flight distance (FD)	19.42m
Landing height (HL)	0.055m

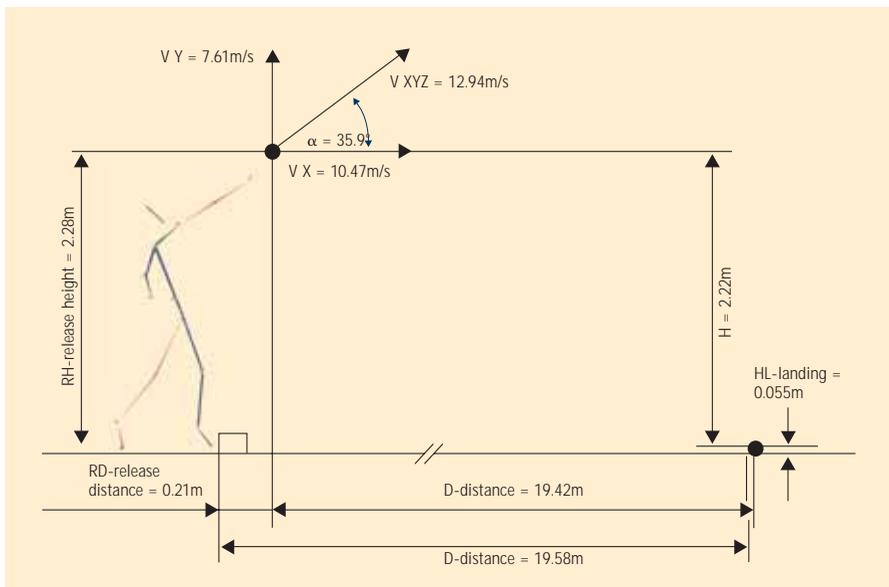


Figure 4: Kinematic parameters of the release and flight data (athlete: M.V., result: 19.58m)

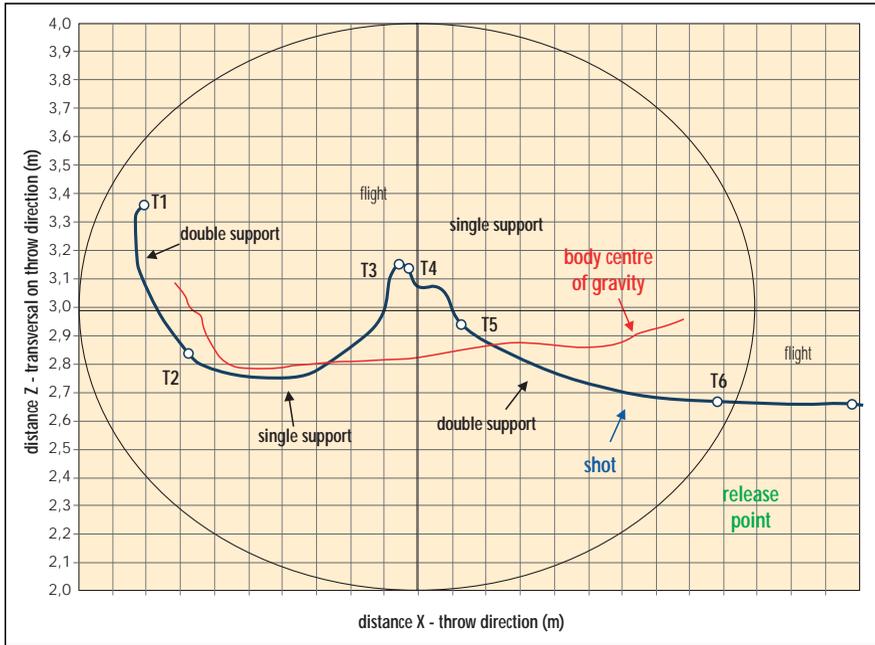


Figure 5: Paths of the shot and the bodies' centre of mass

result reported by LUHTANEN et al. (1997) using a sample of two elite shot putters. The shot's trajectory primarily depends on technique, biomotor abilities and morphological characteristics of the athlete, particularly on the height of the release point. In our subject, the mentioned height was as much as 2.27m, while the velocity of the shot varied distinctively by phase. The average velocity in the first double support phase was 2.28 m/s^{-1} , in the first single support phase 1.67 m/s^{-1} , in the flight phase 0.80 m/s^{-1} , in the second single support phase 1.45 m/s^{-1} , in the second double support phase 7.02 m/s^{-1} and in the flight release phase 12.71 m/s^{-1} . The final velocity of the shot at the moment of release was 12.94 m/s^{-1} (Figure 6). It may be established that the athlete starts moving with a rapid transition to a turn. Nevertheless, this velocity in the first single support phase decreased by 0.61 m/s^{-1} . Transition from a double support phase to a turn depends on morphological and motor abilities, especially co-ordination, balance, orientation in space, power, speed and the

agility of the thrower. The key elements of an efficient transition to a turn are the following: angular velocity of the right leg, balance stance of the trunk during rotation, turning of the left foot outwards, high position of the right elbow and correct eccentric-concentric participation of individual leg and trunk muscles in movement. The right (swinging) leg facilitates shifting of the centre of mass to the centre of the throwing circle. It may be established that M. V. has a wide sweep of the right leg, which means that the moment arm is longer, the momentum higher and the angular velocity smaller.

4) In the flight phase, which lasts for only 0.04 seconds, velocity decreases by another 0.87 m/s^{-1} . This is also the lowest velocity of the shot in the entire trajectory of all six movement phases. As during the flight phase, the thrower is not in contact with the ground and this phase cannot contribute to acceleration of the shot, which is why it has to be as short as possible. In this phase, the legs have to overtake the trunk and the shot as much as

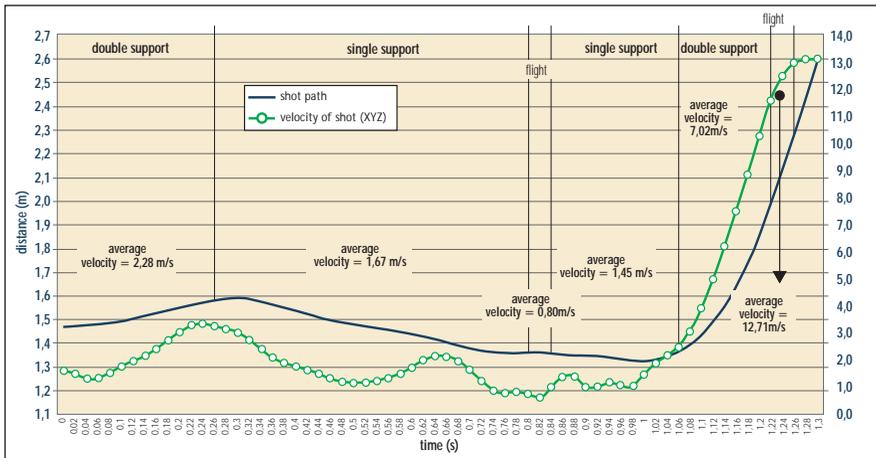


Figure 6: Path and velocity of the shot (athlete: M.V., result: 19.58m)

possible in terms of longitudinal rotation. Too long of a flight phase may break the rhythm of movement of the thrower–shot system as a whole.

5) In the second single support phase on the right leg the shot velocity increases by 0.65 m/s^{-1} and reaches 1.45 m/s^{-1} , accounting for only 12% of velocity in the final release phase.

6) Once the athlete sets his left foot on the ground at the front of the throwing circle, the second double support phase begins, playing a crucial role in efficient performance of release action. In this phase the velocity of shot increases rapidly – by 5.57 m/s^{-1} compared to the previous phase. In this segment of the shot's trajectory, the velocity achieved accounts for 55% of the maximum shot velocity at release. At the end of the second double support phase the shot velocity reaches 12.71 m/s^{-1} . At this moment the subject is already in the flight phase, which is a flaw in terms of biomechanics. Nevertheless BARTONIEZ & BORGSTRÖM, (1995) show that this type of release action is typical of many rotational shot putters. Average velocity achieved in the double support phase accounts for 77% of the shot release velocity. A similar result was obtained in a study by LUHTANEN et al. (1997). Based on the graph

(Figure 6) it may be ascertained that at the beginning of the second double support phase the shot is at its lowest position of the entire path (shot height is 1.35m). Then the shot rises considerably and reaches its maximum height at 2.28m. The distance over which force is applied to the shot in the final acceleration phase is 1.65m. A low position of the shot depends primarily on the angle of a strongly bent right knee, which is 115° in the case of our subject. The angle of the left knee is 122° . Maximum amortisation in the knee joint at the beginning of the second double support phase depends on the strength of leg extensor muscles. In this segment, the subject M. V. shows exceptional biomotor abilities, which are confirmed by good results in the standing long jump (3.11m), jump and reach (0.90m) and squat (370kg).

7) The second double support phase is one of the key elements in the entire structure of the rotational technique. The position of the trunk, particularly the difference between the hip axis and the shoulder axis, is important for the generation of power at release, (Figure 7). The aim of this phase is to increase the torque between the shoulder axis and the hip axis. The athlete achieves this by rotating the lower part of his body. The higher the torsion of the body, the greater the accumulation of potential (elastic) energy for the release

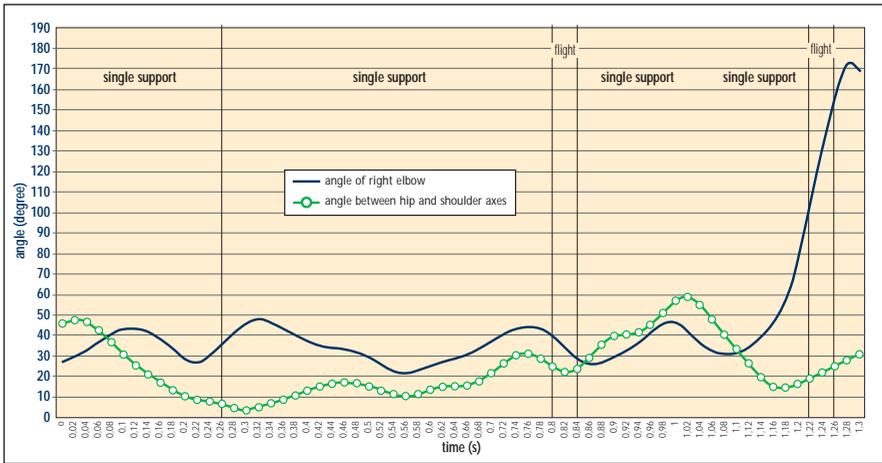


Figure 7: Angle between hip and shoulder axes and angle of elbow of throwing arm (athlete: M.V., result: 19.58m)

phase. Stronger rotation of the hip axis relative to the shoulder axis starts already in the flight phase, continues in the second single support phase and ends in the middle of the second double support phase. The amount of elastic energy depends on eccentric-concentric muscle activity. The faster the transition from one muscle activity regime to another, the more elastic energy is transferred to the concentric phase. The criterion of effectiveness of torsion between the shoulder axis and the hip axis is the angle between the two. At the beginning of the second double support phase the angle between the shoulder axis and the hip axis is 48° , while in the middle of this phase it is only 14° . The 34° decrease in the angle between the shoulder axis and the hip axis shows that the hips rotate faster than the shoulders. The increased torsion leads to extension of the muscles of the trunk, which means generation of potential energy for the execution of the put.

8) The rotational shot put technique is a combination of the initial rotational movement of the thrower-shot system and the final linear movement of the shot in the direction of the release. The aim of the first phase is to create an optimal initial velocity and transform it into maximal release velocity in the final double support phase. The key moment is the transition from rotational

movement to linear movement. In the rotational phase (double support – left-foot support – flight phase – right-foot support), the path of the shot is in the shape of a loop (Figure 5). The thrower's body acts as a component of a great centripetal force. This force increases even further if the centre of mass of the swinging (right) foot is very far from the thrower's rotational axis. Great centripetal force creates major problems with stability, balance and the direction of the shot (LUKES, 1989). In M. V. the swing of the swinging leg is somewhat wider and therefore the athlete has some difficulties with balance and realisation of velocity in this phase of implementing the technique.

9) The planting of the right foot in the middle of the throwing circle is the most important factor in efficient transfer of velocity from rotational movement to release velocity of the shot. Therefore, a thrower must plant his right foot firmly on the ground. Amortisation in the right knee has to be as short as possible. In this phase velocity is still declining, as the centre of mass is located behind the application point of support. At the instant the right foot is planted on the ground, the velocity of the shot is 1.38 m/s^{-1} . After the amortisation, pivoting takes place followed by a push-off with the right leg and a transfer of the

weight of the thrower-shot system to the front (left) leg. When the weight is transferred from the right to the left leg, the shot velocity is 3.01 m/s^{-1} . This result is in congruence with the results obtained by STEPANEK (1989) and LUHTANEN et al. (1997). Fast planting of the front (left) leg stops the rotation of the left side of the body and shoulder girdle, and consequently increases the rotation of the right side of the body. To prevent the angular velocity of hips from decreasing, the rotation of the right foot and knee joint around the right axis of rotation in the upward and forward direction is important.

10) The final action of shot putting in the direction of the throw starts after the rotation of the hips and shoulders stops. At the end of the rotation of the hips and shoulders, the velocity of shot is 6.16 m/s^{-1} . After the right arm has taken part in the release action through the extension of elbow and shoulders, the shot velocity increases by 6.78 m/s^{-1} . The distance over which the arm is activated throughout the shoulder and elbow extension phase is 0.98 m . At the moment of release the final velocity of the shot is 12.94 m/s^{-1} . A very efficient release action of the right arm may be ascertained, demonstrating itself in the parameters of the average angular velocity ($875^\circ/\text{sec.}$) and maximum angular velocity in elbow ($1378^\circ/\text{sec.}$) (Table 1 and Figure 7). The extension action of the shoulder is also synchronised with the extension of the elbow. The average angular velocity of the final shoulder is $452^\circ/\text{sec.}$ The maximum angular velocity of the final shoulder is $652^\circ/\text{sec.}$ It may be concluded that the velocity of release of our study subject is mostly related to his exceptional explosive power of the upper extremities and trunk, as his bench press result is 250 kg and dead lift result is 155 kg . The high release velocity is also connected with the technique of release action, with the following important factors: height of elbow, participation of finger flexor muscles in release action and blocking of left arm while preventing rotation at the moment of shot release.

11) Certain deficiencies in the technique used by the subject, especially in the first single support phase, the flight phase and the second single support phase, are probably due to the athlete's specific morphological constitution. His height is 1.95 m , his body mass is 169.5 kg and his body mass index (BMI) 44.5 ($\text{BMI} = \text{body mass}/\text{body height}^2$). Some of the best known shot putters using the rotational technique have a substantially lower body mass (B. Oldfield – BH 1.92 m , BM 124 kg , BMI = 33.6 ; J. Godina – BH 1.93 m , BM 118 kg , BMI = 31.6 ; M. Halvari – BH 1.90 m , BM 140 kg , BMI = 38.8 ; R. Barnes – BH 1.94 m , BM 137 kg , BMI = 36.3 ; M. Spiritoso – BH 1.76 m , BM 105 kg , BMI = 33.8). A great body mass is an advantage in the final release phase but it is, obviously, a handicap in generating velocity of shot in the rotations.

Conclusion

Based on a biomechanical analysis of an elite shot putter we have identified some of the key elements of the rotational shot put technique that generate the competition result in this exceptionally complex event. This study does not allow absolute generalisation of the data obtained, nevertheless, it may provide us with very valuable information that is important for professional practice as well as the sports science field of biomechanics. Based on the conducted kinematic analysis the following were ascertained:

- One of the most important parameters of rotational shot put technique is the release velocity produced by the horizontal and vertical velocity vectors.
- Release velocity is generated by all preceding phases, of which the second double support phase contributes the most.
- The competition result is a consequence of an optimal combination of release velocity, release angle and release height.
- The velocity of the shot varies by movement phase, and is at its lowest in the flight phase. Therefore, the duration of this phase must be kept as short as possible.

- In the second double support phase the athlete realised 77% of the shot release velocity.
- The length of the path in the final acceleration phase depends on the lowest point of shot (1.35m), maximum amortisation of the right knee (115°) and height of the release point (2.28m).
- Firm planting of the right foot in the middle of the throwing circle is the most important factor of efficient transformation of velocity from the rotational movement to linear release velocity.
- The shot release velocity of the study subject (12.94 m/s⁻¹) is primarily connected to angular velocity in the elbow and the shoulder of the right arm.
- The difference between the hip axis and the shoulder axis is important for generation of power in the release action. The higher the torsion between these two body segments, the stronger the accumulation of elastic energy that will be released at the release phase.
- A modern constitutional type of a shot putter using the rotational technique is characterised by a body mass index (BMI) ranging from 31.6 to 44.5.
- The rotational shot put technique is an extremely complex movement, requiring a high level of motor control, biomotor abilities and an optimal constitution of the thrower.

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