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Biomechanical analysis of the shot put at the 12th IAAF World Indoor Championships

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ABSTRACT

The variability expressed in the descriptive research about the shot put indicates the existence of successful individual techniques that do not correspond to any common ideal pattern. The aim of this study was to make a descriptive analysis of the techniques of the finalists in the 12th IAAF Indoor World Championships. To do this, three-dimensional photogrammetric techniques were used and the action was recorded with two video cameras temporally synchronized at 100Hz. Six puts were recorded for each of the men's and women's finalists and the longest put of each thrower was studied. A temporal analysis of the put was made and the throwing action was divided into six phases. Starting from these phases, graphs of the tangential velocity of the thrower's CM and the time taken are described. Then the factors that determine the trajectory of the shot during flight (product factors) and the contribution of the other causal factors to the put were measured. As well as confirming the relation between the product factors, the results show that each thrower uses his/her own temporal sequence and rhythm of execution, confirming that the technical execution is individual and conditioned by anthropometrical characteristics, muscular capacity and the degree of automation of the individual temporal sequence.

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Introduction

The shot put is an athletic discipline that involves making a series of complex movements at a relatively high speed in a limited space[1]. Starting within the confines of the throwing circle, the thrower's initial movement follows one of the two different techniques currently in use: the conventional, also called the glide, or the rotational. This movement then progresses into a final acceleration of the shot, the drive, where great force must be developed within a very short period of time.

The interdependency of the factors that determine the length of a throw is closely connected to the anthropometrical, muscular and technical characteristics individual to each thrower. The variability expressed in the descriptive research indicates the existence of successful individual techniques that do not correspond to any common ideal pattern.

Starting from this conception of the individuality of technique, the aim of this study is to make a descriptive analysis of the techniques of the eight men and eight women finalists in the shot put at the 2008 IAAF Indoor World Championships in Valencia. To do this, temporal analyses of throws by each of the subjects have been made taking into account the phases described by GOSS-SAMPSON & CHAPMAN (2003)[8], as adapted for this particular study. In addition, we have considered the throwers' anthropometrical parameters, the product factors of their technique and certain process factors that contribute to their technique.

Describing the shot put action

Instants of time are used to determine and describe the temporal phases of the technique used by each thrower. According to the technique used, the initial movement can be divided into four or five phases (for the conventional and rotational techniques, respectively). Although the difference in the two techniques is evident in the initial movement, the final movement, the drive, is very similar. During the drive, the thrower has to apply force against the shot using a temporal sequence of the segments that begins with a rapid extension of the legs, accompanied by extension and rotation of the trunk and followed by a rapid extension of the arm in the direction of the throw[2].

After the release from the thrower's hand the shot behaves like a projectile; its trajectory is largely determined at the instant of release by three basic factors: a) tangential velocity ($v_{t(RELEASE)}$), b) release height ($H_{(RELEASE)}$) and c) release angle ($\theta_{(RELEASE)}$). When seeking to determine the length of the throw we must also take into account the horizontal distance from the inside edge of the stop board to the centre of mass (CM) of the shot at the instant of release ($D_{(RELEASE)}$), and the possible effect of aerodynamic resistance. Figure 1 provides a schematic representation of the factors that contribute to the distance of the throw[2].

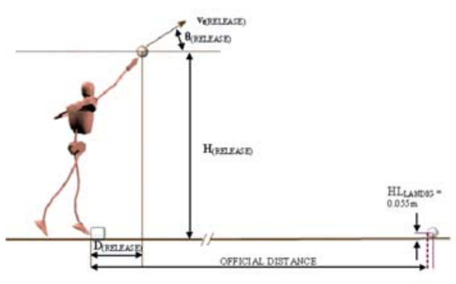

Figure 1: Diagram of the product factors that contribute to the distance of the throw (Adapted from LINTHORNE, 2001)

According to BARTONIETZ (1994)[3], LUHTANEN et al. (1997)[1], LANKA, (2000)[4] and ZATSIORSKY (1990)[5], the release tangential velocity ($v_{t(RELEASE)}$) is the determining factor for the length of the throw, although analysing the factors that decide its value is a complex task that involves identifying the optimal interaction of the participation of the segments in the temporal sequence[2,6].

The release height ($H_{(RELEASE)}$) is conditioned by the anthropometrical parameters of the thrower (especially height and arm length), the position of the shot's CM at the instant of release, the angle of the arm to the horizontal and the technique used in the final movement of acceleration[6]. According to STEPANEK (1989)[15], LUHTANEN et al. (1997)[1], LANKA, (2000)[4] and LINTHORNE (2001)[2], the height of the throw for elite putters varies between 2.20-2.35m, but is lower in women due to their shorter average height.

The release angle ($\theta_{(RELEASE)}$) is perhaps the product factor that has aroused most controversy among researchers. From a theoretical perspective, LICHTENBERG & WILLS (1978)[16] determined that the optimal angle of the throw should be around 42º for world class throws. In reality, the release angles reached by the majority of elite putters have been less than 42º, varying between 26º and 45º, with an average value of 37º[1,17,18]. The differences between the theoretical and true measures have been explained by the interdependence of the three variables and the independent use of one of the variables, as LICHTENBERG & WILLS did in their study, is thought to be an error. ZATSIORSKY (1990)[5] and LINTHORNE (2001)[2] explained this interdependency between the product factors by the muscular structure as well as the effects of gravity. For this, it must be remembered that, due to gravity, more force is required to produce acceleration in the vertical plane than the horizontal at the end of the throw. Experimentally, HUBBARD, MESTRE & SCOTT (2001)[19] have shown that the tangential release velocity lessens as the release angle increases to around 1.7m/s/rad. The same study also showed how tangential velocity lessened as the release height increased to around 0.8m/s/m, so confirming what had been stated in earlier studies on the relationship existing between the product variables.

In addition to the temporal analysis of the movement and the product factors that determine the length of the throw, other causal factors that develop as the action is being carried out, called process factors, must be considered. COH et al. (2007)[6] have argued that certain anthropometrical characteristics are relevant, highlighting height and mass, or body mass index, among others. LINTHORNE (2001)[2], has considered the contribution of muscular force to determine models of individual technique related to the optimal values of the product factors. From the kinematic point of view, COH & STUHEC (2005)[7] have not only analysed the trajectories and tangential velocities of the CM of both the shot and the thrower throughout the throw, but have also considered certain process factors such as the distance of application of forces during the drive (length of the final acceleration), the variation of the angle made by the axes of the hips and the shoulders (angle of trunk torque) and the angular velocities of the elbow and shoulder joints. LUHTANEN et al. (1997)[1] consider that the change in velocity produced during the double support phase is the determining factor for the distance of the throw and that a critical phase may be that of the flight, where the velocity of the CM is at its lowest point. GOSS-SAMPSOM & CHAPMAN (2003)[8] have correlated certain process factors with the distance of the throw, including left foot flight time ($R=-44$: $p<0.005$); the angle of flexion of the right hip and the angle of trunk torque at the beginning of the drive – left knee flexion at initiation of the throw - shoulder-hip separation before delivery ($R=-0.41$; $p<0.005$ and $R=0.34$; $p<0.05$, respectively) and the angle of trunk torque at the instant of release ($R=0.38$; $p<0.01$).

Methods

Participants

The subjects of this study were the shot put finalists in the 12th IAAF World Indoor Championships (8 men and 8 women), which took place in Valencia, Spain, 7-9 March 2008. Table 1 details the throwers analysed together with certain relevant anthropometrical data, such as height and weight, the technique used, the longest distance obtained in this championship and analysed in this study (Val08-Result), and the thrower's season best mark (Season 07-08).

Data collection

Three-dimensional photogrammetric techniques (3D) were used to film the action with two video cameras at 100Hz and synchronized temporally through the Gen-lock system. A cube with twelve points distributed proportionally in the space of the throw was used as a reference system. After obtaining the coordinate planes of the 21 points that make up the 14 segments of the body plus the one corresponding to the centre of the shot, an adjustment of the coordinates was made through fifth-degree splines (WOOD & JENNINGs, 1979)[9]. Finally, DLT techniques,

Table 1: Throwers analysed in this study (Val08-Result corresponds to the best throw made and analysed in the 2008 World Indoor Championships and Season 07-08 is the best throw in the 2007-08 season.)

Athlete	Country	Technique	Height (m)	Mass (kg)	Val08-Result (m)	Season 07-08 (m)
MEN						
Cantwell	USA	Rotation	1.98	145	21.77	22.18
Hoffa	USA	Rotation	1.83	118	21.20	21.40
Majewski	POL	Glide	2.04	132	20.93	20.51
Mikhnevich	BLR	Glide	2.02	115	20.82	20.77
Smith	NED	Rotational	1.97	125	20.78	20.89
Scout	JAM	Rotational	1.85	105	20.29	20.36
Martin	AUS	Rotational	1.90	130	20.13	20.13
Sack	GER	Rotational	1.90	135	20.05	20.88
WOMEN						
Vili	NZL	Glide	1.96	120	20.19	20.19
Ostapchuk	BLR	Glide	1.80	90	19.74	20.35
Li	CHN	Glide	1.74	80	19.09	18.55
González	CUB	Glide	1.80	76	18.75	18.75
Rosa	ITA	Rotational	1.76	80	18.68	18.63
Schwanitz	GER	Glide	1.80	108	18.55	19.68
Borel-Brown	TRI	Glide	1.71	95	18.09	18.26
Omarova	RUS	Glide	1.80	103	17.13	19.09

* Due to technical problems Omarova's best throw was not analysed

developed by ABDEL-ASIZ & KARARA (1971)[10] were used to obtain the space coordinates for a reference system where the Z axis is the vertical, Y is the horizontal in the theoretical direction of the throw, coinciding with the bisection of the release angle, and X is perpendicular to the other two. The segmentary masses and the position of the shot's CM, as proposed by ZATSIORSKY & SELUYANOV (1985)[11] and adapted by LEVA (1996)[12], were used to calculate the thrower's CM.

Data analysis

Following GOSS-SAMPSON & CHAPMAN (2003)[8], six phases were considered for the temporal analysis of puts made rotational technique:

B_1) The first single support phase- This begins at the instant when the right foot is lifted from the ground, (for right-handed putters) (T1), and finishes at the instant in which the left foot leaves the ground (T2).

B_2) The first flight phase- This finishes at the instant when the right foot makes contact with the ground (T3).

B_3) The second single support phase- This finishes when the left foot makes contact with the ground or the stop board (T4).

B_4) The double support phase or acceleration phase of the shot in the double support phase- This ends when one foot is lifted from the ground (T5).

B_5) Third single support phase or acceleration of the shot in the single support phase- This ends when the second support is lifted from the ground (T6).

B_6) Second flight phase or acceleration of the shot in flight- This ends at the instant when the shot is released from the putter's hand (T7).

Figure 2 shows the phases and instants defined, using the trajectory of the shot projected on the transversal plane (XY).

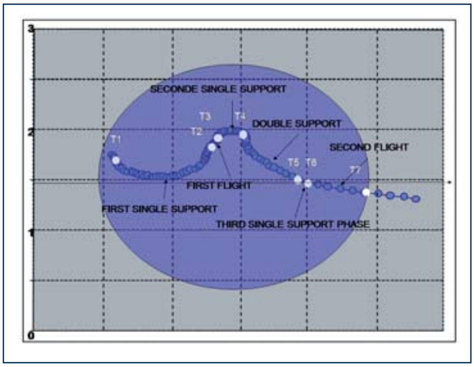

Figure 2: Graph showing the phases and the instants that define them in the trajectory of the shot projected on the transversal plane (XY)

With the aim of unifying the temporal criteria of the two styles used by the throwers analysed, the descriptive phases describing the throws made with the glide technique have been adapted as follows:

B_1) The first single support phase or the glide of the foot across the throwing circle- In this case, for right-handed throwers, this begins at the instant of the backward movement of the left foot (T1) and finishes at the instant in which the right foot is lifted from or begins to glide over the ground (T2).

B_2) The first flight phase or glide- This ends at the instant in which the right foot makes contact with or brakes its glide over the ground (T3).

The rest of the phases correspond to those described for the rotational technique.

To calculate the rectangular components of instantaneous velocity of the shot and the thrower's CM, the first derivation from the function corresponding to the positions of X, Y, Z, was correlated with the time employed. The functions corresponding to each component have been obtained through fifth power quintic spline techniques- with a zero level of smoothing. After obtaining the functions corresponding to the velocity components of time, the resultant tangential velocity was calculated. For the tangential release velocity of the shot ($v_{t(RELEASE)}$), we took the average between that obtained at the instant of the release of the shot from the thrower's hand (T7) and that obtained 0.01 sec subsequent to that instant (T8). The release angle of the shot ($\theta_{(RELEASE)}$) was calculated from the scale product between the displacement vector of the shot after release, defined by the positions in instants T7 andT8 and their projection in the transversal plane (X, Y).

The angles made by the axes of the hips and shoulders at the instant when the double support phase began ($\theta_{(HIPS-T4)}$, $\theta_{(SHOULDERS-T4)}$, respectively) and at the instant of release ($\theta_{(HIPS-T7)}$ and $\theta_{(SHOULDERS-T7)}$, respectively) has been calculated using the scale product of the projection, in the transversal plane (X, Y), of the vectors that define the axes of the shoulders and hips and the vector defined by the bisection of the release angle, taking its value as negative when the right shoulder went beyond the left shoulder (for right-handed throwers). This same procedure was used to calculate the angle between the supporting legs in position T4 ($\theta_{(SUPPORT)}$), taking the points that defined the vector between them as the average of the coordinates X and Y of the heel and the tips of the toes when both legs were completely supported on the ground, giving a negative value when the left foot did not go beyond the right foot. The angles described for positions T4 and T7 are represented by the graph in Figure 3.

Finally, the angular velocities of the axes of the hips and the shoulders at the beginning of the double support phase ($\omega_{(HIIPS)}$ and $\omega_{(SHOULDERS)}$, respectively) and at the instant of release ($\omega_{(HIPS-T7)}$ and $\omega_{(SHOULDERS-T7)}$, respectively) have been calculated from the angular displace-

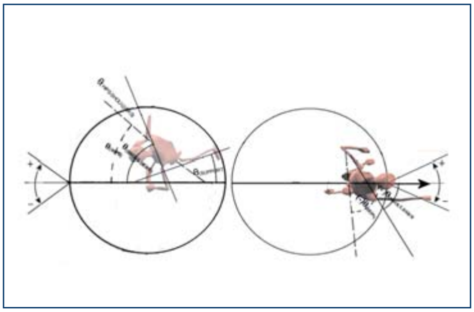

Figure 3: Graphic representation of the thrower's position at instant of making contact with the ground with the left foot (T4) (The angles determined by the axis of the shoulders and of the hips ($\theta_{(SHOULDERS)}$ and $\theta_{(HIPS)}$, respectively) and the angle of torque between the shoulders and hips ($\theta_{(HIPS-SHOULDERS)}$) and the angle between supports ($\theta_{(SUPPORT)}$) are shown.)

ment between the angles described for the instants T4 and T7, respectively and those calculated after a temporal increment of 0.01sec, in each case.

Results

Initial phases

Table 2 gives the times corresponding to the phases in which the throw has been divided. The purpose of the first three phases is to accelerate the CM of the system of thrower plus shot, as well as getting into the right position to develop the explosive movement for the final acceleration of the shot. It can be seen that all the men take a similar time in the single support phase (0.45±0.03 sec), even though two athletes are using the glide technique (Majewski and Mikhnevich), although this regularity may be only a coincidence. However, there is a certain temporal variation among the throwers in the next two phases. With respect to the data shown for the women, Schwanitz's very low value in the single support phase (0.9 sec) is worth noting; this is due to a release position different from the other throwers.

Although as mentioned, the throwers, regardless of the technique used, maintain a certain variability in the temporal components of these three phases, the first phase of the flight time tends to be shorter when the rotational technique is used (0.06±0.03 sec and 0.15±0.03 sec, for the release in the rotational and traditional techniques, respectively), whilst the second single support phase tends to be shorter when the traditional technique is used (0.21±0.03 sec and 0.13±0.05 sec for the rotational and traditional techniques, respectively). However, no relation could be proved between the times taken in these three phases prior to the drive or with the tangential velocity of the CM at the instant of initiating the final movement (T4) and the result of the throw.

The drive

For this study, the drive has been divided into three phases: B_4) the double support phase, B_5) the third single support phase and B_6) the second flight phase. Although a slight variation in the time of the drive was to be expected, the fact is that the results demonstrate that the men use times varying between 0.28 sec, like Scott (6th with 20.29m) and the 0.18 sec of Martin (7th with 20.13m). Moreover, the temporal data show that Cantwell (the winner with 21.77m) made the whole of the final drive in support, while Scott took 0.07 sec of the final drive in flight. Something similar occurs with the women's times, varying between the 0.26 sec used by González (4th with 18.75m) and the 0.14 sec of Rosa (5th with 18.63m). As was to be expected, the data also reveal a temporal variation between the throwers in respect to the phases that make up the movement of the final drive, so confirming the existence of an individual technique and the lack of any pre-established temporal pattern.

Although the temporal sequence of the execution of the phases is different for each thrower, the graphs of the tangential velocities of the shot and the thrower's CM of the time employed in the phases (Figures 4-5 for men and 6-7 for women) reflect a certain general tendency in the rhythm of the execution of the phases. Thus, the movement commences with a progressive increase of the tangential

Table 2: Temporal study of the throws analysed (First Single Support corresponds to the period between instants T1-T2 ; First Flight to the period between T2-T3; Second Single Support to the period between T3-T4 ; Double Support to the period between T4-T5; Third Single Support to the period between T5-T6 and Second Flight to the period between T6-T7.)

Athlete	First Single Support (sec)	First Flight (sec)	Second Single Support (sec)	Double Support (sec)	Third Single Support (sec)	Second Flight (sec)
MEN						
Cantwell	0.48	0.03	0.21	0.18	0.03	0.00
Hoffa	0.44	0.04	0.21	0.19	0.00	0.04
Majewski	0.41	0.10	0.11	0.17	0.04	0.03
Mikhnevich	0.44	0.11	0.05	0.20	0.03	0.03
Smith	0.45	0.06	0.25	0.16	0.03	0.02
Scott	0.41	0.05	0.18	0.20	0.01	0.07
Martin	0.44	0.12	0.17	0.16	0.00	0.02
Sack	0.49	0.08	0.21	0.16	0.02	0.02
WOMEN						
Vili	0.50	0.16	0.12	0.18	0.01	0.05
Ostapchuk	0.26	0.14	0.10	0.12	0.06	0.03
Li	0.27	0.15	0.18	0.16	0.04	0.00
González	0.26	0.20	0.12	0.20	0.04	0.02
Rosa	0.54	0.06	0.23	0.08	0.02	0.04
Schwanitz	0.09	0.16	0.12	0.18	0.07	0.00
Borel-Brown	0.22	0.18	0.22	0.12	0.06	0.02
Omarova	0.24	0.18	0.18	0.14	0.04	0.06

velocity of the CM during the first single support phase, is maintained during the rest of the phases and is reduced at the end of the drive (during the third single support phase). During the first single support phase in the rotational technique, the tangential velocity of the shot is higher than that of the thrower's CM, while during the first flight phase and the second single support phase, this situation is reversed, that is, the tangential velocity of the shot is less than that of the thrower's CM. In the glide technique, the tangential velocity of the shot remains at the same speed as that of the thrower's CM during the first three phases. Finally, during the drive there is a definitive increase in the tangential velocity of the shot until release.

In general, the analysis of the execution of the individual technique and, specifically the distance of the throw shows that the latter is greatly influenced by the final drive. Therefore, the instant in which this final drive is initiated (T4) is usually a critical factor that is conditioned by what has occurred during the earlier phases. In theory, this instant should coincide with the commencement of the increase in the tangential velocity of the shot, as happens in the analysed throws by Cantwell and Hoffa (Figure 4). In the case of Scott (Figure 5), the contact of the left foot with the ground (T4) is made before the final drive with the shot, causing the final drive to be excessively long (0.28 sec). The opposite occurs with Martin's throw (Figure 5), where the left foot

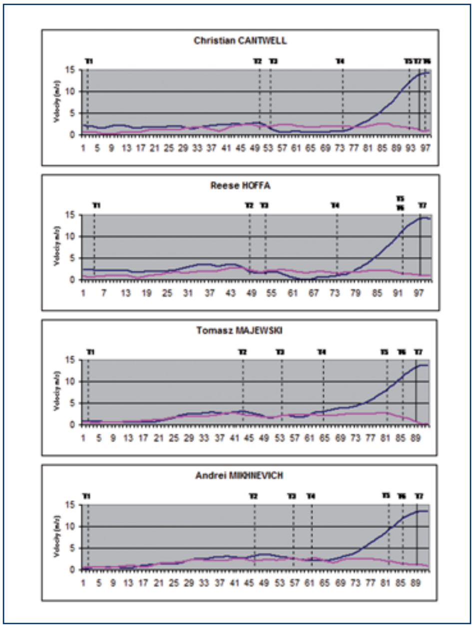

Figure 4: Graphs of the tangential velocity of the shot correlated with time and CM for Cantwell (winner), Hoffa (2nd), Majewski (3rd) and Mikhnevich (8th)

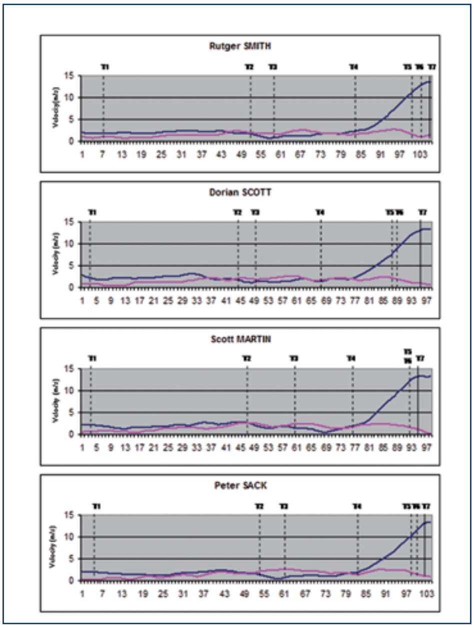

Figure 5: Graphs of the tangential velocity of shot and CM of Smith (5th), Scott (6th), Martin (7th) and Sack (8th)

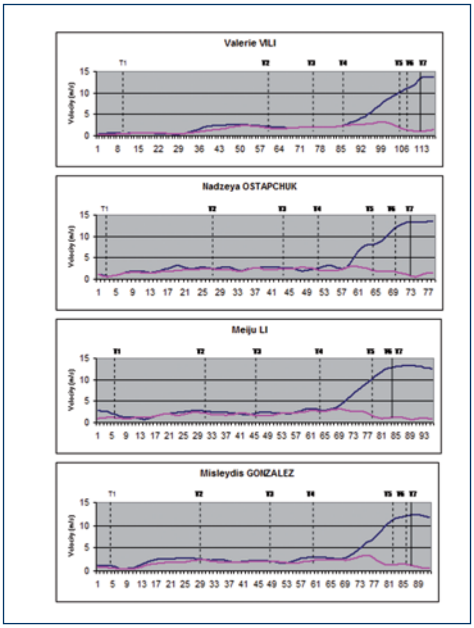

Figure 6: Graphs of tangential velocity of the shot and CM of Vili (winner), Ostapchuk (2nd), Li (3rd) and Gonzalez (4th)

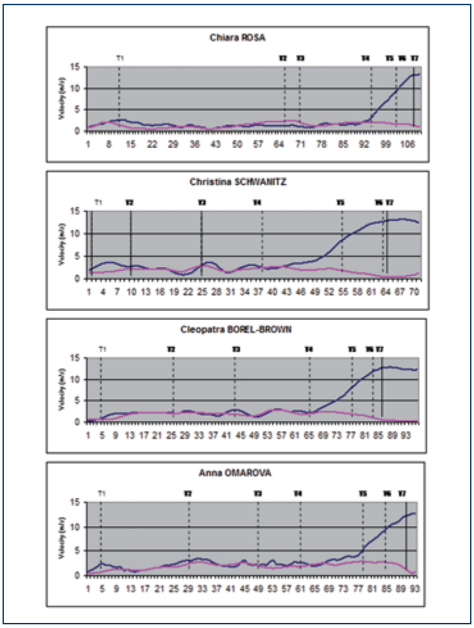

Figure 7: Graphs of tangential velocity of shot and CM of Rosa (5th), Schwanitz (6th), Borel-Brown (7th) and Omarova (8th).

Table 3: Product factors of the throws analysed ($v_{t(RELEASE)}$ is the tangential velocity of the shot at release; $H_{(RELEASE)}$ is the release height, expressed in m and in % of the putter's height; $\theta_{(RELEASE)}$ is the release angle and $D_{(RELEASE)}$ is the horizontal release distance of the throw in the circle, expressed in m and in % of the thrower's height.)

Athlete	$v_{t(RELEASE)}$ (ms^{-1})	$H_{(RELEASE)}$ (m)	(%)	$\theta_{(RELEASE)}$ (º)	$D_{(RELEASE)}$ (m)	(%)
MEN						
Cantwell	14.13	2.10	106.0	35	0.10	5.0
Hoffa	13.99	2.08	113.7	34	0.20	10.9
Majewski	13.63	2.29	112.3	37	0.15	7.4
Mikhnevich	13.58	2.25	111.4	39	0.07	3.5
Smith	13.61	2.21	112.2	37	0.15	7.6
Scout	13.39	2.15	116.2	41	0.08	4.3
Martin	13.38	2.12	111.6	39	0.03	1.6
Sack	13.38	2.16	113.4	37	0.07	3.7
WOMEN						
Vili	13.33	2.34	119.4	36	0.20	10.2
Ostapchuk	13.31	1.93	107.2	39	-0.03	-1.7
Li	13.10	1.93	110.9	36	0.12	6.9
González	12.83	2.12	117.8	43	0.04	2.2
Rosa	12.90	1.88	106.8	43	-0.05	-2.9
Schwanitz	12.80	1.83	101.7	38	0.01	0.6
Borel-Brown	12.83	1.87	109.4	36	0.15	8.8
Omarova	12.24	1.92	106.7	40	0.08	4.4

makes contact with the ground (T4) when the tangential velocity of the shot has already begun to increase slightly, so that the final acceleration of the shot is excessively reduced (0.18 sec).

In the women, both Vili and Borel-Brown initiate the acceleration of the shot at the instant of T4 and maintain it relatively constant until release. The opposite occurs with Schwanitz and Omarova, who begin to increase the velocity of the shot excessively late. Rosa is a special case where, although the drive is rather short (0.14 s), she achieves a relatively high acceleration from the instant that her left foot makes contact with the ground (T4) until release. Finally, the strange behaviour of the velocity of the shot during Ostapchuck's final drive should be pointed out. She initiates the final acceleration of the shot instants after T4 and then produces two accelerations, the first until her right foot loses contact with the ground (T5) and, after maintaining the velocity for some instants, makes a second acceleration of the shot, although rather less than the first.

Product factors

Table 3 sets out the product factors obtained in the throws analysed for both men and women. As was to be expected, the greatest tangential velocity of the shot in the release ($v_{t(RELEASE)}$) was found in the longest throws. In men, Cantwell achieved the highest velocity (14.13 m·s^{-1}) while his release angle ($\theta_{(RELEASE)}$) is one of the lowest (35º), maintaining a relatively high horizontal release ($D_{(RELEASE)}$)

(0.10m). Hoffa achieves a similar relationship between these three factors (13.99 $m \cdot s^{-1}$, 34º and 0.20m). However, the opposite happens with Martin's throw, where the release velocity of the shot (13.38 $m \cdot s^{-1}$) was the lowest among the men, with the one of the highest release angles (39º) and a much reduced horizontal release distance (0.03m).

Something similar to that described for the men occurs with the women. Vili, the winner, obtains the greatest tangential velocity of the shot in the release (13.33 $m \cdot s^{-1}$), while her release angle is one of the lowest (36º), and the horizontal release distance of the shot is the longest (0.20m). A special case is that of the throw analysed for Ostapchuk, where the thrower achieves a tangential velocity of the release of the shot similar to that of Vili (13.31 $m \cdot s^{-1}$) and a relatively high release angle (39º), although she loses 0.23m in the horizontal release distance ($D_{(RELEASE)}$).

According to the data shown in Table 3 (N=16), it can be seen that when the release angle ($\theta_{(RELEASE)}$) is higher, the horizontal release distance ($D_{(RELEASE)}$) is less, with a correlation coefficient of R= -0.73 ($p<0.005$), maintaining that correlation when the data of the distance of the throw as a percentage of the thrower's height is used. These data also show that when higher tangential velocities of the shot at release are achieved ($v_{t(RELEASE)}$), the release angles obtained ($\theta_{(RELEASE)}$) tend to be lower, with a correlation coefficient of R=-0.55 ($p<0.05$).

The release height of the shot ($H_{(RELEASE)}$) confirms the relationship of this factor with the thrower's height (R=0.86; $p<0.001$). On the other hand, when this factor is expressed in percentags of the thrower's height, it does not correlate with the release tangential velocity of the shot ($v_{t(RELEASE)}$) nor with the release angle of the shot ($\theta_{(RELEASE)}$). So Majewski, with a height of 2.04m, is the thrower with the greatest release height (2.29m), but when this factor is expressed as a percentage of the thrower's height, it is Scott with the highest percentage (116.2%), coinciding with the highest release angle (41º) and his making the final phase of the drive in a jump (Table 2). Cantwell records the lowest value of $H_{(RELEASE)}$ when expressed as a percentage of his height (106%), with a relatively low release angle and making the last phase of the drive with his feet on the ground. Vili is the woman who achieves the greatest height, both when expressed in absolute values and as a percentage of her own height (2.34m and 119.4%, respectively). Although her release angle has an average value (36º), she makes the last phase of the throw as a jump. Schwanitz's throw is quite the reverse with the lowest release height (1.83m and 101%), while the release angle is rather higher than average (38º), even though she makes the last phase of the drive in support.

Process factors

Table 4 presents the kinematic variables that can be related to efficiency in the application of forces during the drive. The tangential velocity of the shot at instant T4 ($v_{t(TIME-T4)}$), does not seem to be a factor that by itself conditions the final velocity of the shot. In this sense, Cantwell and Hoffa obtained the lowest values (1.18 $m \cdot s^{-1}$ and 1.11 $m \cdot s^{-1}$, respectively), with the highest release tangential velocities. With the women, too, it cannot be proved that this velocity is related to release tangential velocity ($v_{t(RELEASE)}$). Although the distance of the drive ($D_{(TIME\ T4-T7)}$) when force is exerted on the shot may be a factor closely related to the possibility of acceleration of the shot and, consequently, with its release tangential velocity ($v_{t(RELEASE)}$), according to the data here, it does not seem to be in itself a factor that is related to $v_{t(RELEASE)}$. In general this distance has a direct relationship with the thrower's height (R=0.63; $p<0.01$). When expressed as percentages of the thrower's height, $D_{(TIME\ T4-T7)}$ tends to increase when the height of the CM or of the shot is lower at T4 ($H_{CM(TIME\ T4)}$, $H_{PUT(TIME\ T4)}$, respectively), with correlation coefficients of R=-0.53 and -0.60, respectively ($p<0.05$).

In the men, Majewski is the thrower who achieves the greatest distance in the drive (1.84m; 90.2%, in absolute values and in per-

Table 4: Kinematic factors of the throws analysed ($v_{t(TIME-T4)}$ corresponds to the tangential velocity of the shot at the instant T4 ($D_{(TIME\ T4-T7)}$ and $a_{m(TIME\ T4-T7)}$ correspond to the distance and average acceleration of the shot, respectively, during the drive, between T4 and T7; $H_{CM(TIME\ T4)}$ and $H_{PUT(TIME\ T4)}$ are the height of the CM and the shot, respectively, at instant T4.)

Athlete	$v_{t(TIME-T4)}$ ($m \cdot s^{-1}$)	$D_{(TIME\ T4-T7)}$ (m)	(%)	$a_{m(TIME\ T4-T7)}$ ($m \cdot s^{-2}$)	$H_{CM(TIME\ T4)}$ (m)	(%)	$H_{PUT\ (TIME\ T4)}$ (m)	(%)
MEN								
Cantwell	1.18	1.51	76.3	61.66	0.96	48.5	1.39	70.2
Hoffa	1.11	1.60	87.4	56.00	0.91	49.7	1.24	67.8
Majewski	3.22	1.84	90.2	43.37	0.95	46.6	1.26	61.8
Mikhnevich	2.26	1.79	88.6	43.54	0.95	47.0	1.27	62.9
Smith	2.49	1.59	80.7	52.95	0.95	48.2	1.26	64.0
Scott	1.57	1.69	91.4	42.21	0.86	46.5	1.22	65.9
Martin	2.04	1.41	74.2	63.00	0.96	50.5	1.36	71.5
Sack	2.13	1.45	73.3	56.25	0.96	50.5	1.31	68.9
WOMEN								
Vili	2.77	1.72	87.8	44.00	0.90	45.9	1.21	61.7
Ostapchuk	2.76	1.48	82.2	50.24	0.84	46.7	1.18	65.6
Li	2.97	1.46	83.9	50.65	0.78	44.8	1.06	60.9
González	3.10	1.65	91.7	37.42	0.81	45.0	1.10	61.1
Rosa	3.06	1.14	64.8	70.29	0.89	50.6	1.26	71.6
Schwanitz	2.48	1.55	86.1	41.28	0.79	43.9	1.04	57.8
Borel-Brown	2.38	1.44	84.2	52.25	0.83	48.5	1.12	65.5
Omarova	2.17	1.48	82.2	41.96	0.73	40.5	0.98	54.4

centage of his height, respectively), and he is lowest at T4 when expressed as a percentage of his height. In women, Rosa is again a special case (the only woman to use the rotational technique). Her distance in the drive is very short (1.14m; 64.8%, in absolute values and in percentage of her height, respectively), the explanation lying in the excessive height of her CM in T4, especially when expressed as a percentage of her height (50.6%). In general, the data also show that $D_{(TIME\ T4-T7)}$ tends to be longer when using the traditional technique (86.58±3.37% and 78.00±8.27%, for the traditional and rotational techniques, respectively) and the height of the CM in T4 ($H_{CM(TIME\ T4)}$) tends to be lower when using the traditional technique(45.4±1.3% and 49.2±1.5%, for the traditional and rotational techniques, respectively). As was to be expected, the data set out in Table 4 show that when the distance of the drive is longer ($D_{(TIME\ T4-T7)}$), the average acceleration ($a_{m(TIME\ T4-T7)}$) tends to be more reduced with a correlation coefficient of R=-0.74 ($p<0.005$).

Table 5 sets out the data referring to the position of the axes of the hips and shoulders with respect to the bisection of the release angle ($\theta_{(HIPS\ T4)}$ and $\theta_{(SHOULDERS\ T4)}$, respectively) The difference between these angles gives the angle of trunk torque. The two men who use the glide technique (Majewski and Mikhnevich) achieved the highest angles of torque (75° and 61°, respectively), due to an excessive rotation of the axis of the hips ($\theta_{(HIPS\ T4)}$). In both cases, the axis of the hips reached

Table 5: Kinematic factors to describe the instant that the double support phase (T4) begins ($\theta_{(HIPS\ T4)}$ and $\theta_{(SHOULDERS\ T4)}$ correspond to the angles of the axes of the hips and shoulders, respectively, with respect to the bisection of the release angle at T4; $\omega_{(HIPS\ T4)}$ and $\omega_{(SHOULDERS\ T4)}$ correspond to the angular velocities of the axis of the hips and shoulders, respectively, and $\theta_{(SUPPORT)}$ corresponds to the angle between supports with respect to the bisection of the release angle.)

Athlete	θ (HIP T4) (º)	ω (HIPS T4) (rads^{-1})	θ (SHOULDERS T4) (º)	ω (SHOULDERS T4) (rads^{-1})	Θ (SUPPORT) (º)
MEN					
Cantwell	36	1.03	70	13.68	17
Hoffa	32	7.74	87	17.37	19
Majewski	-9	0.27	66	7.28	27
Mikhnevich	-11	4.42	50	3.15	18
Smith	32	8.99	61	6.01	13
Scout	48	6.16	115	9.13	-21
Martin	15	11.57	53	11.83	15
Sack	16	16.45	47	7.54	41
WOMEN					
Vili	40	6.48	58	7.16	18
Ostapchuk	26	8.23	42	9.09	15
Li	45	2.65	62	9.31	7
González	54	6.24	72	3.59	8
Rosa	17	9.27	31	3.49	19
Schwanitz	40	1.70	60	7.51	3
Borel-Brown	37	1.17	66	5.38	14
Omarova	30	7.75	67	7.29	23

negative values (-9 and -11, respectively), showing that the axis of the hips is oriented in the direction of the throw. In the women's throws analysed, lower values of trunk torque than in men were obtained, particularly the throw of Rosa (the only woman using the rotational technique), who arrived at T4 with torque of 14º.

According to the data shown in Table 5, the angular velocity of the axis of the hip at T4 ($\omega_{(HIPS\ T4)}$) tends to be greater when the rotational technique is used rather than the traditional technique (8.74±4.74 rads^{-1} and 4.32±2.98 rads^{-1}, for the rotational and traditional techniques, respectively). When the angular velocity angular of the axis of the shoulders at T4 ($\omega_{(SHOULDERS\ T4)}$) is analysed, this difference is maintained (9.96±4.76 rads^{-1} and 6.64±2.18 rads-1, for the rotational and traditional techniques, respectively). Cantwell and Hoffa had values of $\omega_{(SHOULDERS\ T4)}$ that reached (13.68 rads^{-1} and 17.37 rads^{-1}, respectively), while Mikhnevich only reached a relatively low value (3.15 rads^{-1}).

Finally, Table 6 presents the positions of the axes of the hips and shoulders at the instant of release ($\theta_{(HIPS\ T7)}$ and $\theta_{(SHOULDERS\ T7)}$, respectively), as well as the respective angular velocities ($\omega_{(HIPS\ T4)}$ and $\omega_{(SHOULDERS\ T4)}$, respectively). Among the men, Coutt showed an excessively high negative angle of the axis of the hips (-104º), indicating that, at the instant of

Table 6: Factors to describe the instant of the release of the shot from the thrower's hand (T7) ($\theta_{(HIPS\ T7)}$ and $\theta_{(SHOULDERS\ T7)}$ correspond to the angles of the axes of the hips and shoulders, respectively, with respect to the bisection of the release angle in T7 and $\omega_{(HIPS\ T7)}$ and $\omega_{(SHOULDERS\ T7)}$ correspond to the angular velocities of the axes of the hips and shoulders, respectively)

Athlete	θ (HIPS T7) (º)	ω (HIPS T7) (rads⁻¹)	θ (SHOULDERS T7) (º)	ω (SHOULDERS T7) (rads⁻¹)
MEN				
Cantwell	-82	13.50	-75	17.32
Hoffa	-74	12.71	-57	18.25
Majewski	-90	11.9	-72	10.11
Mikhnevich	-89	8.11	-74	10.92
Smith	-86	15.4	-63	15.05
Scout	-104	6.95	-84	7.74
Martin	-78	16.01	-66	16.05
Sack	-71	11.95	-63	16.86
WOMEN				
Vili	-122	5.03	-81	10.80
Ostapchuk	-82	16.23	-78	16.63
Li	-124	1.33	-99	12.64
González	-90	14.80	-86	16.64
Rosa	-77	17.73	-75	15.91
Schwanitz	-111	3.72	-87	1.37
Borel-Brown	-104	9.85	-105	20.06
Omarova	-108	9.88	-99	8.86

release, the axis of the hips had not reached the perpendicular of the bisection of the release angle (90º), possibly made more difficult because of the negative angle of his feet during the double support phase ($\theta_{(SUPPORT)}$). This same reason may be the cause for the angle of the shoulder axes reaching excessively high negative values (-84º). Among the women, the angles of the hip axes reached by Vili and Li (-122º and -124, respectively) stand out, indicating that they released the shot before the hip had stopped turning, although this may be an aspect of their particular techniques. Such low velocities in their respective angular velocities (5.03 rads^{-1}and 1.33 rads^{-1}) leads one to think that the left leg blocked the hip turn during the double support phase.

Discussion and Conclusions

Temporal pattern

On the basis of the temporal data it cannot be stated that there is only one temporal pattern; on the contrary, each thrower uses his or her own individual temporal sequence and rhythm in the execution of the shot put. The technique is individual and conditioned by certain anthropometrical characteristics, muscular capacity and the degree of automation of the individual temporal sequence[6]. A previous study[7] had concluded that the key phases that ensured a correct rhythm of the throw and enabled the thrower to obtain a high tangential velocity when releasing the shot were: a) The first flight phase, b) the second support phase and c) the double support phase. Although we share these authors' conclusions, the temporal variation between the throwers analysed in this study (Table 2), does not enable us to confirm the temporal relevance of those phases, at least as a general criterion. Considering only the three phases[7], the first flight phase varies between 0.03 sec of Cantwell and the 0.12 sec of Martin; For the second single support phase the times vary between 0.17 sec for Martin and 0.25 sec for Smith and in the double support phase, between 0.10 sec for Rosa and 0.20 sec for Scott. Something similar occurs when analysing the data for throwers using the glide technique, although the times are less varied in the first flight phase.

A certain general tendency can be inferred in the rhythm of execution, which differs according to the technique used. In the rotational technique, during the first flight phase and the second single support phase, the velocity of the CM is rather higher than that of the shot (Figures 4 to 7) with the purpose of advancing the rotating body before advancing the shot, as also happens in the hammer throw[13] demonstrated by RASMUSEN (1998)[14] for the shot put. We concur with LUHTANEN et al. (1997)[1] about the relevance of the rhythm of execution of these phases in indicating that the first flight phase is critical for the efficiency of the throw, although this term should be widened to include the second single support phase. In this sense, the data given by GOSS-SAMPSON & CHAPMAN (2003)[8] for the rotational technique, together with the relatively low values of tangential velocity of the shot in the second single support phase (Figures 4, to 7), confirm the relevance of this phase for the final result. The rhythm of execution of these two phases is different for throws made with the traditional technique, where the tangential velocity of the shot and the CM maintain similar values despite advancing the rotation of the hip to come to the beginning of the double support phase (T4) with a certain torque of the trunk. During the drive a definitive increase in the velocity of the shot is produced, this phase being similar in both techniques, as LINTHORNE (2001)[2] states, although with a certain variation among the throwers analysed in the rhythm of acceleration of the shot, an aspect that will now be analysed.

The sequence of the participation of the segments produced in the drive begins with a rapid extension of the legs accompanied by the extension and rotation of the trunk and is followed by a rapid extension of the arm in the direction of the throw[2]. This sequence of movement brings about a great change in the velocity of the shot from the initiation of the double support phase (T4) until release (T7), and is the most important determining factor for the result of the throw[1]. According to the data in Figures 4 and 5, in the throws analysed using the rotational technique, the putters Cantwell, Hoffa, Smith and Sack achieved this great change in velocity (acceleration) from the instant T4. On the other hand, in the throws of Majewski and Mikhnevich (the glide technique), the definitive acceleration of the shot is initiated later when the left foot makes contact with the ground (T4). Among the women only Vili and Borel-Brown (the glide technique) were able to make that definitive change in velocity from T4.

Although the data show that it appears to be easier to accelerate from T4 using the rotational technique, the results do not show that the delay in the definitive acceleration of the shot is due to only one factor; possibly aspects connected with the position adopted in T4, the angular velocities of the axes of the hips and of the shoulders, together with certain muscular characteristics, are the factors that cause the variation found in the acceleration of the shot during the drive.

The example of Scott

An exceptional case that enables us to explain the possible relation among the factors indicated above is Scott's throw. In spite of using the rotational technique, during the first instants of the double support phase the

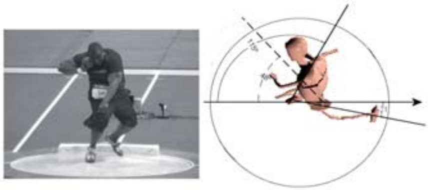

Figure 8: Position adopted by Scott at the instant of initiating the double support phase (T4)

expected increase in the tangential velocity of the shot (Figure 5) does not occur. This only happens when he reaches the beginning of the double support phase (T4) in a position that does not favour the commencement of the temporal sequence of the participation of the segments for the drive. Although he attains a relatively high value for the torque of the trunk (67º), this value is achieved by supporting the left foot on the ground too early. This precipitation causes the angle between the supporting legs ($\theta_{(SUPPORT)}$) to reach relatively high negative values (-21º), demonstrating that the support of the left foot does not go beyond that of the right foot. This will later cause difficulties in orienting the hip in the direction of the throw, as shown in the data given in Table 6. The consequence is that the axis of the hips is turned too far in the opposite direction to the throw at T4 (48º) and the axis of the shoulders even more (115º), putting the thrower in a position that does not enable him, at that instant (T4), to start the sequence of the participation of the segments for the drive (Figure 8). In this position, the thrower has to delay the rapid extension of the legs and trunk that produce the increase of the tangential velocity of the shot.

This example shows that although each thrower uses an individual temporal sequence and a unique relationship among the factors, there are limits to certain factors that, if ignored, can cause the thrower to have problems in his/her technique. Some of the most critical factors are connected to the instant in which the final movement is initiated (T4). Although the values of these critical factors are usually determined by what has happened in the earlier phases, their relevance for the efficiency of the final movement of acceleration and, consequently, with the distance of the throw has to be highlighted.

Process variables

With respect to the product variables, tangential release velocity of the shot is the determinant factor for the length of the throw[1,3,4]. Equally, the data in this study confirm that there is a clear relationship between the release height of the shot ($H_{(RELEASE)}$) and the thrower's height ($p<0.001$), with values similar to those of STEPANEK (1989)[15], LUHTANEN et al (1997)[1], LANKA, (2000)[4] and LINTHORNE (2001)[2] for elite throwers. However, the figures obtained do not confirm a correlation between the release height of the throw ($H_{(RELEASE)}$) and tangential release velocity ($v_{t(RELEASE)}$), as claimed by HUBBARD, MESTRE & SCOTT, (2001)[19]. Possibly this discrepancy is due to the variability among the throwers in this study. The data of the release angle of the shot ($\theta_{(RELEASE)}$) give values similar to others studies[1,17,18] confirming that when the release angle is increased, the tangential release velocity of the shot ($v_{t(RELEASE)}$) tends to be lower ($p<0.01$), as HUBBARD, MESTRE & SCOTT, (2001)[19] have stated.

The release horizontal distance of the shot ($D_{(RELEASE)}$) obtained in this work varies between the 0.20m of Hoffa's throw and the -0.05m in Rosa's throw. In general these data show a somewhat lower average than those of COH & STUHEC (2005)[7]. The data set out in Table 3 show that this distance tends to be shorter when the release angle of the shot increases ($\theta_{(RELEASE)}$), with a correlation coefficient of R=-0.73 ($p<0.001$). The results of the product factors (Table 3) confirm that when the release angle ($\theta_{(RELEASE)}$) is less, the release tangential velocity of the shot ($v_{t(RELEASE)}$) and the release horizontal distance ($D_{(RELEASE)}$) increase, two correlations confirming the interdependence of the product factors[2,5]; it is also a warning to be wary of excessively high values in the release angle of the shot.

Generally, importance has been given to the tangential velocity of the shot during the first flight phase and the second single support phase, especially that in which the right foot makes contact with the ground (T3). As well as being the periods of time when the transition between the rotational movement and release takes place (for the rotational technique), three problems must be resolved with the contact of the right foot (T3): reduce the displacement of the initial flight phase, continue with the rotational movement plus crossing the circle and maintaining stability for the next phase[1,7,20]. Our data (Figures 4 to 7) confirm this critical situation on obtaining lower values for tangential velocity of the shot during these phases, although from the data in Table 4, we cannot confirm that the tangential velocity of the shot at the end of the second single support phase ($v_{t(TIME-T4)}$) is a factor that conditions release tangential velocity of the shot.

Another of the factors that traditionally has been considered as related to release tangential velocity of the shot is the distance over which force is exerted against the shot during the drive/($D_{(TIME\ T4-T7)}$). That relationship cannot be confirmed from the data in Table 4. Considering this factor from an exclusively mathematical perspective, we can say that the greater the distance of acceleration, the higher the final velocity will be. But this only happens when acceleration is constant, which does not occur in all throws; on the contrary, each thrower employs an time of acceleration that, probably, is related to the individual capacity to apply forces, factors resulting from the thrower's own technique and anthropometrical characteristics. In this sense, $D_{(TIME\ T4-T7)}$ is correlated with the thrower's height ($p<0.001$) and when the values are expressed in percentages of that height, the distance of force against the shot in the drive tends to increase when the height of the shot at T4 ($H_{PUT(\ TIME\ T4)}$) tends to be reduced ($P<0.05$).

Finally, the data confirm that when the distance of the drive ($D_{(TIME\ T4-T7)}$) increases, the average acceleration ($a_{m(TIME\ T4-T7)}$) tends to be less ($p<0.01$), leading to the conclusion that, to the extent that the distance of acceleration is reduced (to certain minimum values), the force applied to the shot increases. This fact is based on the HOCHMUTH's (1967)[21] theories on the optimum distance of acceleration for the high jump and those developed by PERRINE & EDGERTON (1978)[22] on the individual capacity of musculature to develop force.

Our data do not confirm a correlation between the angle of trunk torque at T4 and the distance of the throw[8]. The reason for this discrepancy is simply the variability between the throwers analysed, as shown in Table 5. This variability among the throws analysed is even greater when observing the positions of the axis of the hips with respect to the direction of the throw. The negative values of Majewski and Mikhnevich (-9º and -11º, respectively) indicate that the hips are already oriented in the direction of the throw at T4, while the 54º of González shows that the thrower practically has his back to the direction of the throw at T4. The same variability is found with the position of shoulders, from the 31º of Rosa to the 115º of Scott. As was to be expected, both the axis of the hips and that of the shoulders reach greater angular velocity at T4 when the rotational technique is used, which would favour the transition between the second single support phase and the double support phase of the drive, although it creates problems of stability for the thrower[6].

GOSS-SAMPSON & CHAPMAN (2003)[8] suggest facilitating the rotation of the axis of the hips during the double support phase by increasing the angle of the supporting legs ($\theta_{(RELEASE)}$).This suggestion has aroused a certain controversy among those who consider that the left leg should block the hip before the release. With some exceptions, our data confirm that the left leg does not reduce the angular velocity of the axis of the hips. In this sense, the angular velocities of the axis of the hips at the instant of release ($\theta_{(HIP\ T7)}$ for most of the throws analysed exceed 9 rads^{-1}. For the throws made with the rotational technique, only that of Scott obtained a lower value (6.95 rads^{-1}), although it must be remembered that he is the only thrower to obtain negative values in $\theta_{(RELEASE)}$, making the rotation of the hip difficult during the double support phase, as mentioned earlier. In the case of throwers using the glide technique, Li and Schwanitz both blocked the rotation of the hip with the left leg so preventing the hip from continuing to turn at the end of the double support phase, although as happened with Scott, they were the two women who obtained the lowest values in $\theta_{(RELEASE)}$.

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