

Determination of Critical Parameters among Elite Female Shot Putters

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ABSTRACT

The aim of this study was to determine if critical parameters for elite performance could be identified among a population of female shot putters. The performance of seven of the top women shot putters competing at the 2002 USA National Championships was examined. Video data were captured using two Panasonic 60 Hz cameras and the best throws of each athlete were digitized and analyzed using a Peak Motus three-dimensional motion analysis system. Thirty variables were examined for their effect on the distance of the throw. Correlation analysis indicated that measured distance was positively correlated with release speed ($r = 0.97$, $p < 0.0003$) and shoulder-hip separation ($r = 0.72$, $p < 0.06$) and negatively correlated with release angle ($r = -0.74$, $p < 0.056$), rear knee angle at rear foot touchdown ($r = -0.93$, $p < 0.003$) and rear knee angle at release ($r = -0.76$, $p < 0.047$). Greater knee flexion angle at both rear foot touch down and release along with a neutral shoulder-hip angle at release were identified as the most critical parameters for success among this sample of elite women shot putters. The unique observation about the knee positions at specific events should assist in new training and coaching developments.

Keywords: critical parameters, elite females, knee positions, release parameters, shot put

INTRODUCTION

Much research has been performed on the shot put (see review Zatsiorsky *et al.*, 1981). Several of these studies have examined the theory and practice of determining optimal release conditions, such as release speed, release angle and release height (Lichtenberg and Willis, 1978; McWatt, 1982; Maheras, 1995; Hubbard *et al.*, 2001; Linthorne, 2001). Although these parameters directly determine the projected distance of the throw, they do not give any indication of the events leading up to the release. Consequently, they offer limited information to coaches seeking to improve the aspects of technique that will result in the best release parameters. Some other studies have been descriptive; these have ranged

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from quantitative (Dessurealt, 1978; Ariel, 1979; Knudson, 1989; Bartonietz, 1996; McCoy, 1990; Štěpánek, 1990; Liu *et al.*, 2000) to completely qualitative (Ward, 1974; Wilt, 1982; Grigalka and Papanov, 1984). Although these studies do provide information about the kinematics of the performance, they too offered limited evidence as to which parameters were most influential on the performance.

Several studies have speculated or made suggestions about the important parameters in achieving success in the shot put (Dessurealt, 1978; Lichtenberg *et al.*, 1978; Knudson, 1989; Štěpánek, 1990; Maheras, 1995; Alexander *et al.*, 1996; Bartonietz, 1996; Liu *et al.*, 2000; Hubbard *et al.*, 2001; Linthorne, 2001). Only one, however, has quantitatively examined which parameters were most critical for success in the event (Alexander *et al.*, 1996). In this study, Alexander and colleagues examined 30 males and 31 females in an attempt to determine the relative importance of selected anthropometric, strength and technique parameters to their performance. They reported quantifiable predictors of performance in both males and females and that the predictors were differentiated by the sex of the athlete. The critical parameters for female throwers included knee extension during the glide, elbow speed during delivery, and a greater shoulder flexion angle at release. For the male throwers, centre of mass speed during glide, vertical acceleration of centre of mass during delivery, and trunk angle at the start of glide were the most important parameters to produce longer throws.

Despite the shortage of work examining critical parameters in the shot put, attempting to determine critical parameters in sporting events is not unique. The most common method for identification is regression analysis. Hay *et al.* (1976) and, later, Hay *et al.* (1981) developed a theoretical model for the standing vertical jump by describing the performance parameters in the skill and analyzing data from a large number of male athletes to evaluate the model. They calculated the correlation between each of the parameters in the model with the height jumped to determine which parameters might be most important, and then conducted a multiple regression analysis to determine which of the parameters contributed most to explaining the performance of each individual. The results suggested that the torques developed at the shoulder, hip, knee and ankle joints were important in the performance of males. Triple jumping (Yu and Hay, 1996), sprinting and hurdling (Mann and Herman 1985a; b), discus throwing (Hay and Yu, 1995; Yu *et al.*, 2002), and the acceleration phase in ice skating (Marino, 1983) are other sporting techniques that have been analyzed in this manner. This research has provided insights into the technical parameters of these events that were most closely related to success and which could best be used as predictors of performance.

Previous research has indicated that the overwhelming majority of shot put research that has been conducted largely on male athletes may not be applicable to female athletes (Alexander, 1989; Alexander *et al.*, 1996). In addition, very few attempts have been made to uncover critical parameters for success in the event in either males or females. The aim of this study was to address these gaps in the literature and determine if there are identifiable critical parameters for elite performance among elite female shot putters.

METHODS

Operational terminology

Push off leg: The leg that is last in contact with the throwing circle before the flight phase.

Knee angle: The relative angle defined by the thigh and leg segments.

Shoulder-hip separation (Figure 1): The orientation of the hips relative to the shoulders. A neutral position (0° separation) occurs when the shoulders and hips are aligned with one another. A positive angle occurs when the throwing side shoulder is posterior to the throwing side hip.

Trunk angle (Figure 2): The angle formed between the shoulder-hip line and the horizontal plane.

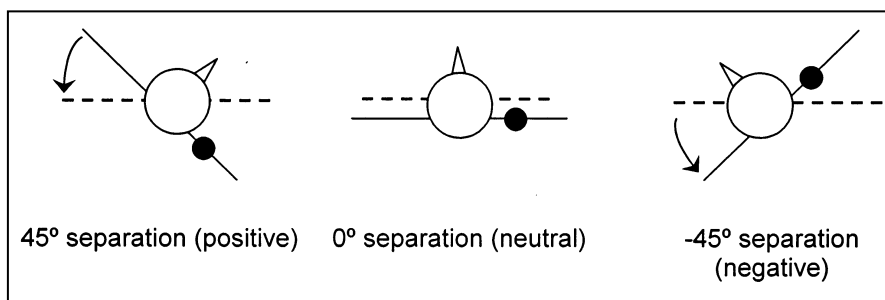


Figure 1 Shoulder-hip separation for right handed thrower. The dashed line represents the orientation of the hips and the solid line represents the orientation of the shoulders. The small black circle represents the shot. The angle between the line of the shoulder and the line of the hip represents the shoulder-hip separation. For left handed throwers, these angles were reversed.

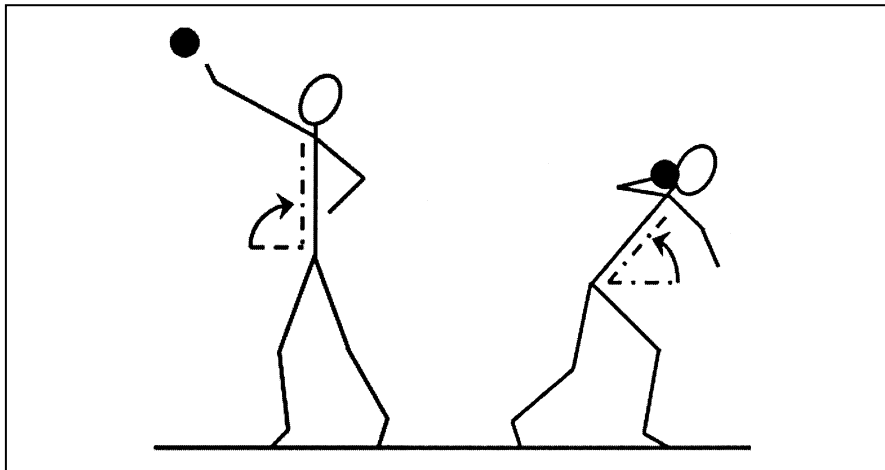


Figure 2 Definition of trunk angle. Trunk angle was defined as the angle formed between the shoulder-hip line and the horizontal plane. The dashed lines represent the shoulder-hip line and the horizontal plane formed by the ground.

Release speed: The magnitude of the shot velocity at release.

Release angle: The relative angle between the trajectory of the shot and the horizontal.

Release height: The height of the centre of mass of the shot above the surface of the circle at release.

Horizontal release distance: The horizontal distance between the centre of mass of the shot and the innermost edge of the toe board at release (negative if the shot is released with its centre of mass behind the toe board).

Toe board: the metal border of the shot put circle whose innermost edge serves as the boundary of the circle and the point of measurement for all legal throws.

Projected distance: The horizontal displacement of the shot from the point of release to landing.

Measured distance: The horizontal displacement of the shot from the innermost edge of the toe-board to landing. This is the distance recorded as the official result. More specifically, the measured distance is the sum of the projected distance and the horizontal release distance.

Participants

Seven of the top eight women who competed at the 2002 USA Track and Field National Championships in Palo Alto were used as participants in this study. Clothing was not standardized. Four of the athletes performed the glide technique and three performed the rotational technique. The method used in this study to breakdown the throw into phases by predetermined events allowed for both techniques to be analyzed together based on the similar phases of support and flight (Figure 3).

Video data collection

The Direct Linear Transformation (DLT) procedure (Abdel-Aziz and Karara, 1971) was used to collect three-dimensional coordinates of 22 body land marks and also the centre of the shot for each trial. Two time-synchronized S-VHS Panasonic 60 Hz cameras were used to record the control object and the performances. The cameras were placed around the shot put circle spaced about 90° apart. Video data were collected for the best trial of each putter. After collection of the performance data, a calibration frame (Peak Performance, Englewood, Colorado, USA) was placed in the centre of the throwing circle and used to calibrate and synchronize the two fields of view.

Data reduction

The videotape records of the control and performance data were manually digitized and analyzed using a Peak Motus three-dimensional motion analysis system (Peak Performance, Englewood, Colorado, USA). The digitized control object coordinates were used to estimate the DLT parameters for each camera. The video record of the best throw for each athlete was manually digitized at a sampling rate of 60 Hz from two frames before the initiation of the throw to two

Fig 3 is poor quality, therefore high resolution TIFF, EPS or JPEG file required, or good quality artwork for scanning

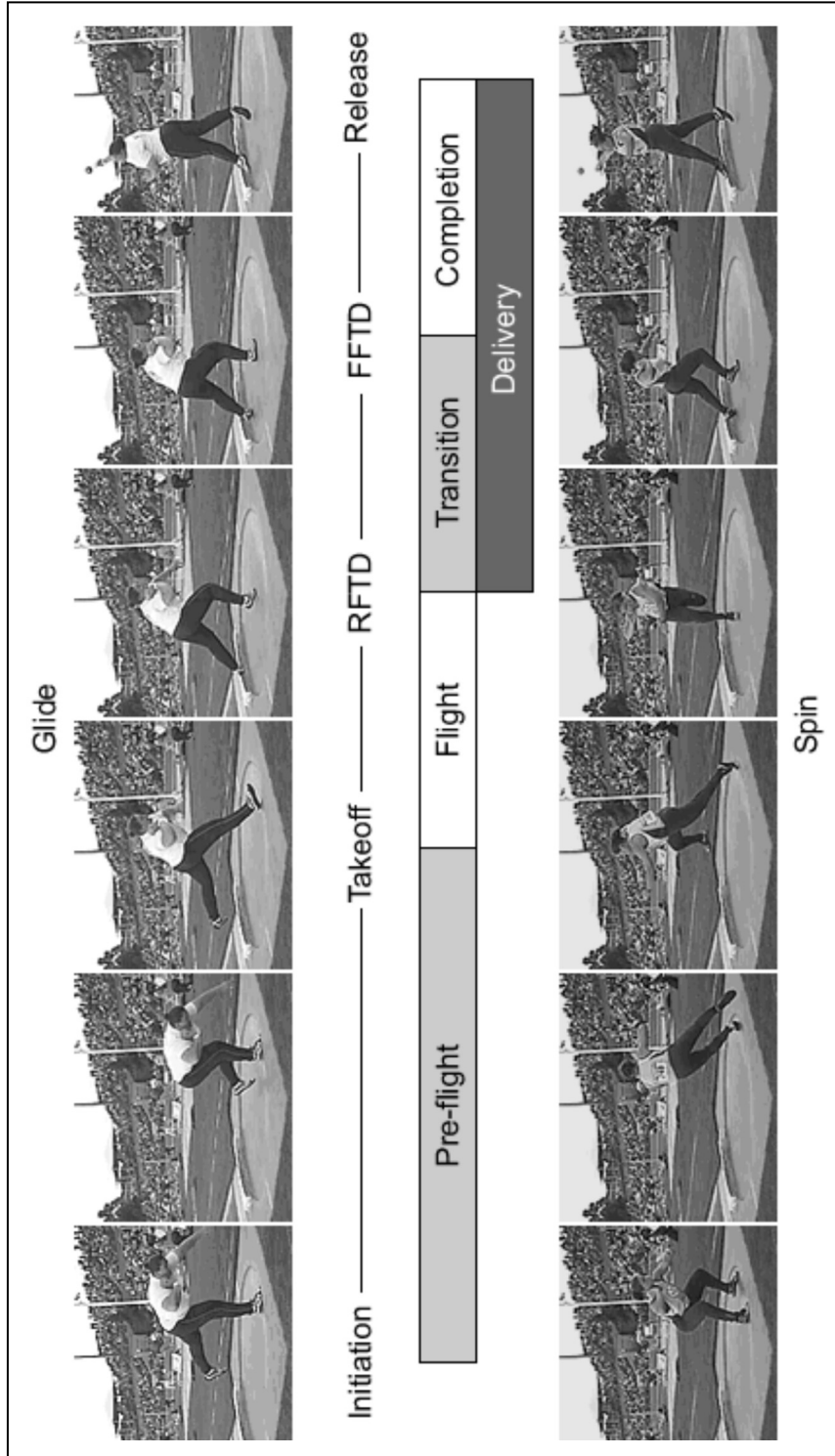


Figure 3 Method of technical evaluation for each technique. Both techniques had similar instances of support and flight.

frames after the release of the shot. In each digitized field, the following 23 points were manually digitized for the model of the athlete-plus-shot system: forehead, chin, left and right shoulder, elbow, wrist, hand, tip of index finger, hip, knee, ankle, heel, toe, and the shot. Some of these points were not included in the analysis of this study and were used only to provide additional information for athlete's personal reports. The throwing circle was also digitized so that parameters relative to the diameter of the circle could be calculated. The digitized two-dimensional data were time synchronized based on the release of the shot. A second event, front foot touch-down, was used to verify the accuracy of the synchronization. All analyzed clips met both synchronization criteria. The three-dimensional coordinate data were smoothed using a second-order Butterworth digital filter (Winter *et al.*, 1974).

Parameter selection

Thirty parameters were selected as independent variables and distance was used as the dependent variable. The independent variables were selected based on suggestions from the coaching literature and from results of descriptive biomechanical studies. The selected variables were sub-grouped into the categories of release parameters, athlete kinematics, implement speeds and accelerations, and temporal parameters. The independent variables examined are presented in Table 1.

Data analysis

Means and the range for all of the independent variables were determined. Pearson product moment correlation coefficients were examined to find which variables were correlated with measured distance. In addition, the correlation between each independent variable was examined. When independent variables were found to be closely related to one another – multicollinearity – only one was retained for further inclusion in the multiple regression analysis (Hay *et al.*, 1981). An analysis of variance with stepwise selection was then performed. A stepwise procedure similar to that used by Alexander *et al.* (1996) eliminated parameters from the multiple regression equation that were not significant predictors of measured distance. A Type I error (per comparison) of 0.10 was selected to indicate statistical significance as has been used by previous research examining similar activities (Yu *et al.*, 2002). All statistical procedures were performed using SAS statistical software (Cary, North Carolina, USA). Clearly, we have performed many comparisons and correlations, in an aggressive statistical approach to control Type II errors and identify important independent variables; this will, however, have resulted in a large familywise Type I error rate. Because of this, and the limited sample size, we suggest that readers regard our findings as essentially exploratory and descriptive.

Table 1 Parameters examined in the study and literature supporting their inclusion.

<i>Sub-group / Parameter</i>	<i>Event</i>				<i>Supporting literature</i>
	<i>TO</i>	<i>RFTD</i>	<i>FFTD</i>	<i>RLS</i>	
<i>Release parameters</i>					
Release speed				X*	Hubbard <i>et al.</i> , 2001
Horizontal velocity				X	Dessurealt, 1978
Vertical velocity				X	Dessurealt, 1978
Lateral velocity				X	Dessurealt, 1978
Release angle				X	Hubbard <i>et al.</i> , 2001
Release height				X	McCoy <i>et al.</i> , 1984
Horizontal release distance				X	Hubbard <i>et al.</i> , 2001
<i>Athlete kinematics</i>	<i>TO</i>	<i>RFTD</i>	<i>FFTD</i>	<i>RLS</i>	
Trunk angle	X	X	X		Alexander, 1996
Shoulder-hip separation		X	X	X	Schmolinsky, 2000
Rear knee angle		X	X	X	Alexander <i>et al.</i> , 1996
Front knee angle			X	X	Alexander <i>et al.</i> , 1996
Push-off knee angle	X				Alexander <i>et al.</i> , 1996
<i>Implement parameters</i>	<i>TO</i>	<i>RFTD</i>	<i>FFTD</i>	<i>RLS</i>	
Resultant velocity	X	X	X	X*	Marhold, 1973
Resultant acceleration	X	X	X	X	Marhold, 1973
<i>Temporal parameters</i>	<i>Flight</i>	<i>Trans.</i>	<i>Comp.</i>	<i>Deliv.</i>	
Time	X	X	X	X	Tsirakos <i>et al.</i> , 1995

* Release speed and resultant velocity at release (RLS) in the implement parameters are the same.

TO – Take-off

RFTD – Rear foot touchdown

FFTD – Front foot touchdown

RLS – Release

Trans. – Transition phase

Comp. – Completion phase

Deliv. – Delivery phase

RESULTS

Stepwise regression analysis

Stepwise regression analysis indicated that five of the 30 independent variables, or parameters, (Table 2) had a significant impact on the measured distance of the throw ($F = 739$, $r^2 = 1.0$, $p < 0.001$). The selected parameters were from either the release parameters or the athlete kinematics group. Greater release speed, greater horizontal release distance, greater rear knee flexion at both rear foot touch-down and at release, as well as less shoulder-hip separation at release, were strong predictors of greater measured distance. A summary of the release and kinematic parameter data is presented in Tables 3 and 4 respectively.

None of the temporal parameters had any observable effect on the measured distance of the throw. Likewise, none of the implement speeds or accelerations at any of the events observed before the instant of release had an observable effect on the outcome of the throw. See Tables 5 and 6 for summaries of the implement speeds and accelerations and the temporal parameters at the selected events.

Table 2 Results of the stepwise regression analysis.

<i>Parameter</i>	<i>Parameter estimate</i>	<i>F value</i>	<i>p</i>
Intercept	69.07	699	0.024
Rear knee angle at RFTD	-0.267	804	0.022
Release speed	-0.925	68.8	0.076
Rear knee angle at release	-0.097	2457	0.013
Shoulder-hip separation at release	-0.899	2233	0.014
Horizontal release distance	-0.255	122	0.058

RFTD – Rear foot touchdown

Table 3 Release parameters (mean \pm SD).

	<i>Group</i>	<i>Glide</i>	<i>Spin</i>	<i>Places 1–3</i>	<i>Places 5–8</i>
Measured distance (m)	17.26 \pm 1.20	17.40 \pm 1.33	17.07 \pm 1.26	18.43 \pm 0.81	16.38 \pm 0.20
Release speed (m/s)	12.4 \pm 0.6	12.5 \pm 0.6	12.3 \pm 0.6	12.9 \pm 0.3	12.0 \pm 0.2
Release angle ($^{\circ}$)	35 \pm 3	35 \pm 2	36 \pm 4	33 \pm 1	37 \pm 1
Horizontal release distance (m)	0.17 \pm 0.20	0.20 \pm 0.25	0.13 \pm 0.13	0.28 \pm 0.09	0.08 \pm 0.22
Release height (m)	1.97 \pm 0.04	1.97 \pm 0.03	1.98 \pm 0.06	1.97 \pm 0.05	1.97 \pm 0.04

Table 4 Mean kinematic parameters at selected events ($^{\circ}$) (mean \pm SD).

	<i>TO</i>	<i>RFTD</i>	<i>FFTD</i>	<i>Release</i>
Push-off knee angle	165 \pm 11	–	–	–
Rear knee angle	–	104 \pm 6	111 \pm 5	147 \pm 7
Front knee angle	–	–	122 \pm 5	173 \pm 4
Trunk angle	58 \pm 7	50 \pm 3	53 \pm 5	77 \pm 8
Shoulder-hip separation	–	57 \pm 3	28 \pm 4	-20 \pm 6

TO – Take-off

RFTD – Rear foot touchdown

FFTD – Front foot touchdown

Table 5 Mean instantaneous implement speeds and accelerations at selected events (mean \pm SD).

	<i>TO</i>	<i>RFTD</i>	<i>FFTD</i>	<i>Release</i>
Velocity (m/s)	1.85 \pm 0.83	1.99 \pm 0.55	3.02 \pm 0.59	12.40 \pm 0.51
Acceleration (m/s ²)	-2.57 \pm 6.26	0.51 \pm 4.05	15.6 \pm 16.8	7.25 \pm 9.07

TO – Take-off

RFTD – Rear foot touchdown

FFTD – Front foot touchdown

Table 6 Mean temporal parameters (s) for selected phases (mean \pm SD).

	<i>Flight phase</i>	<i>Transition phase</i>	<i>Completion phase</i>	<i>Delivery phase</i>
Group	0.16 \pm 0.04	0.12 \pm 0.10	0.14 \pm 0.15	0.26 \pm 0.06
Glide	0.18 \pm 0.03	0.06 \pm 0.05	0.23 \pm 0.09	0.30 \pm 0.05
Spin	0.12 \pm 0.04	0.21 \pm 0.09	0.02 \pm 0.12	0.22 \pm 0.04

Correlation analysis

Among the release parameters, the measured distance was positively influenced by the release speed ($r = 0.97$, $p < 0.0003$, Figure 4A) and negatively influenced by the release angle ($r = -0.74$, $p < 0.056$, Figure 4B). Release angle and resultant speed were also negatively correlated ($r = -0.85$, $p < 0.016$, Figure 5).

Among the athlete kinematic parameters examined, the measured distance was inversely associated with rear knee angle at rear foot touch-down ($r = -0.93$, $p < 0.003$, Figure 6A) and rear knee angle at release ($r = -0.76$, $p < 0.0472$, Figure 6B). Also, both push-off leg angle at take-off ($r = -0.78$, $p < 0.04$) and release angle ($r = 0.84$, $p < 0.019$) were also observed to be highly correlated with rear knee angle at rear foot touch-down. Shoulder-hip separation at release was found to be correlated with distance ($r = 0.72$, $p < 0.06$, Figure 7).

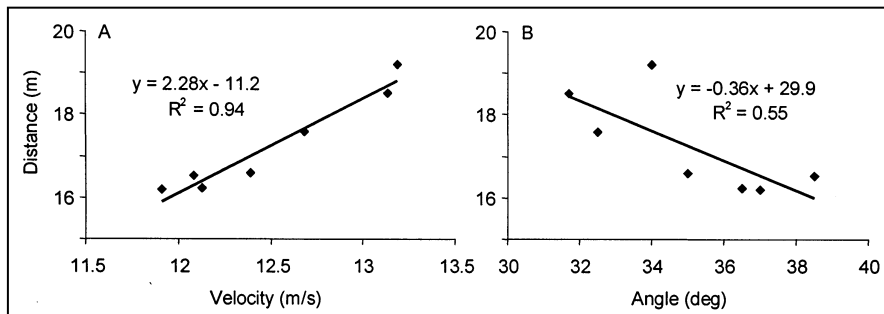


Figure 4 Relationship between distance and release velocity (A) and angle (B). The solid diamonds are the raw data. The solid line is the regression line. The regression equation and the r^2 value of the regression are also presented in the graph.

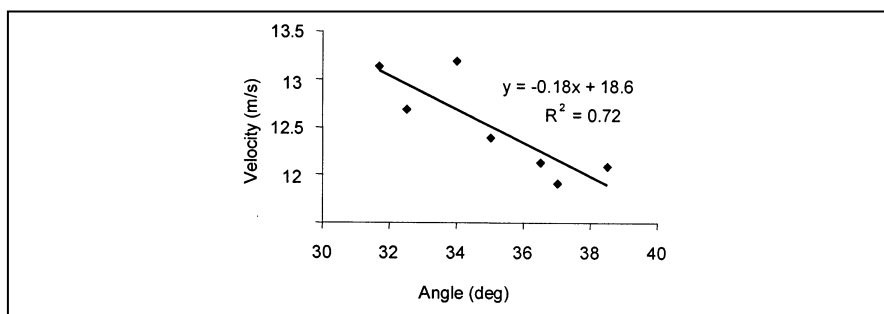


Figure 5 Relationship between release velocity and release angle. The solid diamonds are the raw data. The solid line is the regression line. The regression equation and the r^2 value of the regression are also presented in the graph.

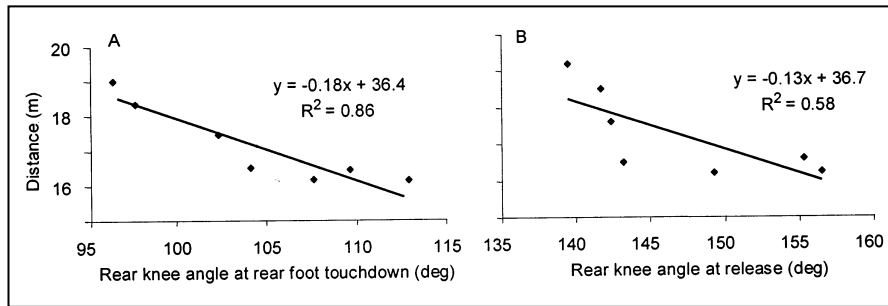


Figure 6 Relationship between distance and the rear knee angle at rear foot touchdown (A) and release (B). The solid diamonds are the raw data. The solid line is the regression line. The regression equation and the R^2 value of the regression are also presented in the graphs.

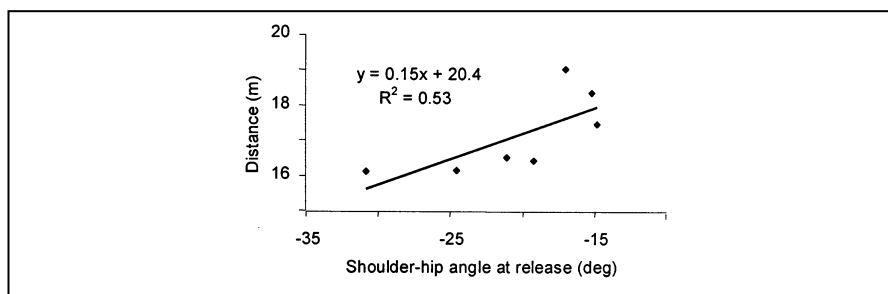


Figure 7 Relationship between distance and the shoulder-hip separation at the moment of release. The solid diamonds are the raw data. The solid line is the regression line. The regression equation and the r^2 value of the regression are also presented in the graph. Shoulder-hip separation is the difference in the separation of the shoulders and hips relative to the anatomical position.

DISCUSSION AND IMPLICATIONS

The most important observation of the study was the identification of critical parameters for performance among a population of elite shot putters. Previous research has successfully identified critical parameters for other sporting events and this study indicates that the same may be done for shot putting. This points out that specific parameters are important for achieving elite distances in shot put. The model resulting from the step-wise regression analysis indicated greater rear knee flexion at both rear foot touch-down and release, greater release speed, less shoulder-hip separation at release, and greater horizontal release distance relative to the toe board as being the best predictors of performance in elite female shot putters. No crucial relationship was observed between the measured distance and either the temporal parameters or the implement speeds or accelerations before release.

The mean release speed observed in the present study was 12.4 m/s with a range of 11.9 to 13.2 m/s. These values are similar to those reported in studies of elite female athletes throwing similar distances, as well as other studies

examining males putting the shot similar distances (Dessureault, 1978; McCoy *et al.*, 1984; Bartonietz and Borgstrom, 1995; Alexander *et al.*, 1996). The linear correlation observed in this study between release speed and the projected distance is different from the prediction of the classical projection equation. Theory predicts a quadratic relationship between the two parameters. The discrepancy may be explained by the very limited range of projection speeds observed in this study. Varying release angles and heights may have also contributed to the linear approximation of this relationship. The release angles observed in this study ranged from 32 to 39° with a mean of 35°. These release angles are similar to those reported in studies on both elite and non-elite shot putters (McCoy *et al.*, 1984; Štěpánek, 1990; Bartonietz and Borgstrom, 1995; Tsirakos *et al.*, 1995; Alexander *et al.*, 1996; Linthorne, 2001). The interdependency of release speed and release angle observed here has been previously suggested by several authors (McCoy *et al.*, 1984; Dyson, 1986; Hubbard, 1988; Hay, 1993) and is supported by the results of previous research (de Mestre, 1990; Maheras, 1995; Hubbard, 2000; Hubbard *et al.*, 2001; Linthorne, 2001). In fact, Hubbard and colleagues (2001) suggested that, other than speed, the optimal release parameters depend largely on their effect on release speed. The mean release height observed in the present study was 1.97 m and ranged from 1.92 to 2.04 m. These values are close to those reported by other studies of female shot putters (McCoy *et al.* 1984; McCoy, 1990; Bartonietz and Borgstrom, 1995; Alexander *et al.* 1996). It has been suggested that the height of release is determined largely by the anthropometric parameters of the athlete, the body position at release and the angle of the arm at release (Štěpánek, 1990; Hay, 1993). As a result, trying to increase release height would probably have negligible results. The horizontal release distances observed in this study ranged from of -0.17 to 0.39 m with a mean of 0.17 m. These results are similar to previously reported data (McCoy, 1990). This parameter may be significant for both its potential to create an advantageous, or disadvantageous, release point and as an indication of a greater range of force application to the implement. The latter has been suggested as being critical for success in the shot put (Štěpánek, 1990; Schmolinsky, 2000).

The results of this study indicated that none of the temporal parameters had an observable effect on the outcome of the throw. Another study (Tsirakos *et al.*, 1995) examining the shot put using similar temporal parameters had similar results. In their study, Tsirakos *et al.* compared the release and temporal parameters of two groups of performers who were grouped by their performance (Group A had performances greater than 18.0 m and Group B had performances less than 18.0 m). No significant differences between the temporal parameters of the two groups of athletes were observed.

The importance of shoulder-hip separation suggested in the coaching literature was only partially supported by the results of this study. The results indicate that while shoulder-hip separation may not be critical at rear foot touch-down or front foot touch-down, its magnitude at release was an important indicator of success (Figure 7). This position has been mentioned in the coaching literature as being indicative of a strong blocking action of the non-throwing side, which may create a greater transfer of momentum to the implement (Bartonietz

and Borgstrom, 1995; Godina and Backes, 2000; Schmolinsky, 2000).

The current study observed that the action of the rear leg was very important to the outcome of the throw. Greater flexion of the rear knee at both rear foot touch-down and release were highly influential on greater measured distance. The benefit of greater flexion at rear foot touch-down is in agreement with the coaching literature (Schmolinsky, 2000). The same observation at release, however, contradicts the coaching literature (Bartonietz and Borgstrom, 1995; Godina and Backes, 2000; Schmolinsky, 2000). Several authors have identified the importance of complete or near complete extension of the rear (Godina and Backes, 2000) or both legs (Šttepánek, 1990; Schmolinsky, 2000) for achieving maximum distance. We suggest that complete extension of the knee may not be a critical parameter for shot put success, for the same reasons that it is not critical – and potentially disadvantageous – in sprinting (Mann and Sprague, 1980) and weightlifting (Escamilla *et al.*, 2000). Under this assumption, the initial force generated by the proximal-to-distal sequencing of hip extension, knee extension, and plantar flexion would accelerate the athlete and shot system with such rapidity that either the shot would be released before the complete extension of the more distal joints or the athlete would break contact with the ground, making further extension irrelevant. As such, while greater extension might not necessarily be harmful, lesser extension might be an indication of greater power and, thus, implement acceleration. In support of this contention, Bartonietz (2000) has suggested that power summation is a primary factor separating elite throwers from lesser skilled throwers. This may also help to explain why a more complete extension of the front leg was not observed as being critical to measured distance in the current study.

Our observations of no difference in the magnitude of the rear knee range of motion among the sample and greater knee flexion at both rear foot touch-down and release among the best throwers might indicate that a shift in the range of motion of the rear knee may be advantageous. A proposed mechanism for this advantage is that shifting the range of motion of the rear knee joint would result in greater force output by placing the leg extensor muscles in a stronger contraction range owing to the force-length relationship of muscle (Gordon *et al.*, 1966, see Figure 8). At the greater muscle lengths that accompany a shifted range of motion, a muscle's capacity to produce torque is enhanced because the muscular contraction coincides with the peak of the force-length curve. Without a shift in range of motion, the muscular contraction occurs before the peak of the force-length curve, resulting in less force output. This proposed mechanism is supported by previous research indicating that knee extensor torques are greatest at angles that fall within the range of motion observed among the best throwers in this study (Thorstensson *et al.*, 1976; Tihanyi *et al.*, 1982; Pincivero *et al.*, 2001).

The previously stated mechanism has several implications for the training of elite shot putters. The benefit of shifting the rear knee range of motion to one with greater knee flexion indicates that it may be advantageous to incorporate heavily loaded strength training exercises, which enhance strength through this particular range of motion. Exercises such as deep squats, which develop leg extensor strength in similar ranges of motion to those observed in this study,

Fig 8 is poor quality, therefore high resolution TIFF, EPS or JPEG file required, or good quality artwork for scanning

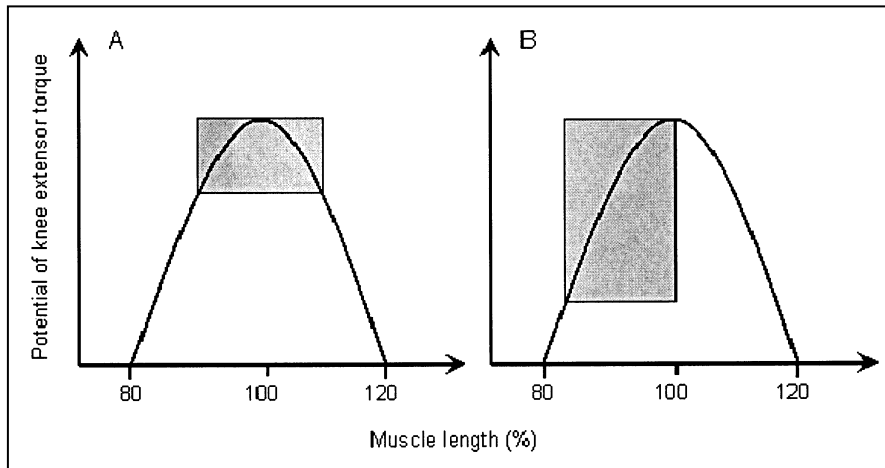


Figure 8 The curves illustrate the force-length relationship of knee extensor muscle. The shaded box represents the potential extensor torque the knee extensors are capable of producing through a shifted (A) and unshifted (B) range of motion. A shifted range of motion will stretch the leg extensors to a greater extent resulting in increased torque due to the muscular contraction coinciding with the peak of the force-length curve (A). Without a shift in range of motion, the muscular contraction occurs before the peak of the force-length curve (B).

would probably be advantageous. Likewise, it might be beneficial to perform plyometric exercises with loads similar to those of experienced in shot putting to mimic the load placed on the rear leg at rear foot touch-down, so that athletes can learn how to use the strengthened muscles.

For implement speeds and accelerations, previous literature has noted the importance of achieving maximum speed of the shot early in the performance (Doherty, 1950; Marhold, 1973; Simonyi, 1973). Other authors have claimed that speed should increase gradually throughout the duration of the throw (Fidelus and Zienkowicz as cited in Zatsiorsky *et al.*, 1981). Marhold (1973) found that the best German male throwers were superior in their ability to increase the speed of the shot before rear foot touch-down. The results of this study, however, indicate that implement speeds and accelerations at the selected events before release do not have an observable effect on the outcome of the throw but also undulate, with implement speed approaching zero at rear foot touch-down before reaccelerating before release. The implement speeds observed at rear and front foot touch-downs were similar to those observed by Knudson (1989) at the same events. These findings suggest that the role of the glide and rotational techniques may be to put the throwers in a position in which they are able to achieve greater distances rather than to accelerate the implement directly before rear foot touch-down. More specifically, the flight phase of the glide or spin may serve as a means of plyometrically loading the rear leg at touch-down. This would be expected to create greater force output owing to the stretch reflex effect on the knee extensors.

Some of the differences in results between the present study and previous ones can be explained by this being one of the first studies to examine the shot

puts of female athletes quantitatively. Research has indicated that the temporal and anthropometric parameters related to performance in females are different from those for males (Ballreich, 1983; Schulte, 1983; McCoy *et al.*, 1984; McCoy, 1990; Štěpánek, 1990; Alexander *et al.*, 1996). Alexander *et al.* (1996) also stated that important kinematic parameters differentiate male and female shot putters. Another confounding factor is that it may be difficult to make comparisons of males and females because of differences in equipment (Kentner, 1983) and their anthropometry (Kentner, 1983; Komi and Mero, 1985; Atwater, 1988; Alexander *et al.*, 1996). This suggests that the findings of research conducted on men may not be applicable to women.

Another possibility for differences in the findings of this study and previous research is the inclusion of athletes using the spin technique. Previous literature has largely focused on athletes using the glide technique. Literature is divided on the comparability of the two techniques of putting the shot. Several authors have noted differences between the two techniques (Bosen, 1985; Štěpánek 1987; Oesterreich *et al.*, 1997). However others have found them similar enough to make comparisons (McCoy *et al.*, 1984). Previous research, however, did not use a method of analyzing the two techniques that would permit grouping the two techniques together as in this study.

CONCLUSION

The most important observation of the study was the identification of critical parameters for successful performance by elite female shot putters. This research fills gaps that have not been previously addressed in research on the shot put. This study is the first to examine critical parameters for success in elite women shot putters and indicates specific parameters that are important for achieving the highest standard in the event. The results of this study suggest that, among elite shot putters, greater rear knee flexion at rear foot touch-down and release, increased release speed, a more neutral shoulder-hip angle at release and a greater horizontal release distance were the best predictors of measured distance. More specifically, new training methods should be devised which focus on the technical aspects of the rear knee mentioned in this study. While the implications of this study may not be applicable to a different or wider population of throwers, the results may provide important information to coaches and elite female shot putters and provide direction for future biomechanical studies on this event.

We would reiterate that we have performed many comparisons and correlations in this study, which will have resulted in a large familywise Type I error rate. Because of this, and the limited sample size, we suggest that readers regard our findings as essentially exploratory and descriptive.

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