THE INFLUENCE OF SELECTED TECHNICAL PARAMETERS ON DISCUS THROWING PERFORMANCE

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ABSTRACT

Steve Leigh: The Influence of Selected Technical Parameters on Discus Throwing Performance
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The purpose of this study was to determine the effects of the technical parameters: throwing phase time, hip-shoulder and shoulder-arm separation, trunk tilt, and throwing-arm elevation on discus throwing performance. Videographic data of male and female discus throwers' competitive performances were captured during major meets. Real-life, three-dimensional coordinates of 21 body landmarks and the discus were obtained for 283 trials using direct linear transformation. The technical parameters were reduced at six critical instants during the throwing procedure. Canonical correlation and hierarchical stepwise multiple regression analyses were performed to determine the relative influence of linear combinations of the technical parameters on release characteristics and performance. Specific techniques associated with linear combinations of certain technical parameters were identified for males and females separately. Vertical release velocity was identified as the principal determinant of the difference in performance between athletes. Suggestions for increasing vertical release velocity using effective and efficient technique were made.

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CHAPTER I

INTRODUCTION

The official distance thrown by each athlete during a discus throwing competition determines the winner. The longest throw achieved during any round in the final wins. The official distance is defined as that distance measured by the officials. The true distance thrown can be decomposed into three components: vacuum flight distance, aerodynamic distance and distance lost at release. The true distance thrown is related to, but not equal to the official distance measured (Figure 1). The sum of the vacuum flight distance and the aerodynamic distance is the flight distance. The most important component of official distance is the vacuum flight distance (Hay and Yu, 1995). The vacuum flight distance is the theoretical distance calculated using the range equation. The discus is treated as a point mass traveling through a vacuum. The range is then calculated using discus release characteristics: the speed of release, the angle of release, and the height of release; as well as the acceleration due to gravity:

$$R = v\cos\theta \times \frac{v\sin\theta + \sqrt{v^2\sin^2\theta - 2gh}}{g} \qquad \text{(Equation 1)}$$

Where R = vacuum flight distance, v = speed at release, θ = angle of release, g = constant acceleration due to gravity, and h = height of release.

To achieve the longest vacuum flight distance, and therefore the longest throw, athletes must carefully control their releases so the discus is thrown at the maximum height possible, combined with an optimal release angle, and the maximum possible speed. Secondary release characteristics include the angle between the relative wind velocity and the discus's longitudinal-lateral plane – known as the angle of attack (Taylor, 1932) (Figure 2), as well as other aerodynamic factors.

The aerodynamic flight of the discus influences the official distance. The range equation neglects the effects of aerodynamic lift and air resistance, or drag, forces which are an important consideration for any thrown implement. The upper and lower surfaces of the discus have the same shape, therefore, in cross section the discus can be considered a symmetric aerofoil (wing-shaped) (Ganslen, 1964) (Figure 3). If thrown oriented at an optimal angle of attack, then the discus will produce lift and fly further. This can be explained by the Bernoulli Principle. The stagnation point of the air flow moves to the lower surface of the discus when it is inclined. Air then travels over the upper surface faster than the lower surface. This creates a pressure difference in the air flow around the discus and causes lift. The wind's velocity may increase or decrease the speed of the air traveling over the discus's surfaces, which is why the angle of attack must be relative to the wind conditions. Drag is a frictional force which resists the flight of the discus, and so will reduce the official distance. An experienced discus thrower using effective technique may increase their official distance by 5 meters or more by taking advantage of the aerodynamic properties of the discus. A significant increase, but smaller than the vacuum flight distance.

The distance lost at release is the horizontal distance traveled by the discus for which the athlete does not get credit. The official distance is measured as the distance “from the nearest mark made by the fall of the discus, to the inside of the circumference of the circle along a line to the centre of the circle” (IAAF, 2006) (Figure 1). If an athlete releases the discus while still within the confines of the circle, then the distance traveled by the discus before it reaches the inside circumference of the circle is not included in the official distance measurement. This is a relatively small loss of distance, and can be minimized by careful control of the position of release.

The discus’s speed at release is the single most important factor contributing to long throws. Release speed has the greatest effect on the vacuum flight distance, which is the largest factor contributing to the official distance. A larger release speed will increase the vacuum flight distance, since the two are directly proportional. Therefore, the athlete will throw further. A larger release speed may also cause greater lift of the discus, if an efficient angle of attack is maintained, since the air passing across the discus’s surfaces will travel faster and create a greater pressure differential.

The flight of the discus may be considered in two orthogonal planes: horizontal and vertical. The horizontal range is the most important, since this is the official distance. The vertical distance traveled during flight is essentially irrelevant, however, the vertical velocity is still important, since this determines the time of flight:

$$T = \frac{v_v + \sqrt{v_v^{\,2} + 2gh}}{g} \qquad \text{(Equation 2)}$$

Where T = time of flight, v_v = vertical component of discus release velocity, g = constant acceleration due to gravity, and h = height of release. The range of the discus is dependent on both the time of flight and the horizontal component of velocity:

$$R = v_h \times \frac{v_v + \sqrt{v_v^{\,2} + 2gh}}{g} \qquad \text{(Equation 3)}$$

Where R = vacuum flight distance, v_h = horizontal component of discus release velocity, v_v = vertical component of discus release velocity, g = constant acceleration due to gravity, and h = height of release. Therefore, the athlete should strive to maximize the horizontal release velocity, the vertical release velocity, and the height of release simultaneously.

The angle of release should be maximized as long as the maximum horizontal velocity can be maintained. The angle between the horizontal and vertical components of velocity is the angle of release:

$$\theta = \sin^{-1}\left(\frac{v_v}{v_h}\right) \qquad \text{(Equation 4)}$$

Where θ = angle of release, v_v = vertical component of discus release velocity, and v_h = horizontal component of discus release velocity. This angle is different than the angle of attack, and is independent of the orientation of the discus. A relatively large vertical velocity at release will be associated with a large angle of release. If a large horizontal velocity is maintained, the discus will fly for a long time at a high horizontal velocity and a long distance will be achieved.

The path traveled by the discus around the discus thrower throughout the throwing procedure can be thought of as an orbit. The orbit's shape resembles a bowl-shaped curved surface. The orbit of the discus should be oriented in such a way as to optimize the angle it makes with the ground so that the angle of release is large. Referenced to the direction of throw, the orbit should be low at the back of the circle and high at the front of the circle.

The height of release should also be maximized, since a greater height of release will prolong the flight time, because the discus has longer to fall before it reaches the ground. If the height of release is large the time of flight, calculated using equation 2, is increased. This increase in the time of flight will also have the effect of increasing the horizontal range, calculated using equation 3.

Athlete's techniques can determine the release characteristics of speed, angle, and height. The discus's release speed is increased throughout the throwing procedure by force applied to it by the athletes. The path traveled by the discus determines the time for which the force is applied. A longer path means force is applied to the discus for a longer time, thereby increasing discus release velocity (Bartlett, 1992). The magnitude of the force applied to the discus is primarily dependant on the strength of the athlete. Any technique employed by athletes should increase the horizontal and vertical distances traveled by the discus during the throwing procedure, as well as maximize the force applied. This will allow for large magnitude velocities to be developed before release.

Techniques which increase the force applied to the discus, and the path traveled by the discus are related to the separation of the hips, shoulders and throwing arm. The discus should be released tangentially to the athlete's body. This allows the discus to be thrown with maximal velocity in the intended throwing direction. An angle between the imaginary lines joining the hip joint centers and the shoulder joint centers is defined as the hip-shoulder separation angle (Figure 4). An angle between the imaginary lines joining the shoulder joint centers and the line of the throwing arm is defined as the shoulder-arm separation (Figure 5). Increasing these separations early in the throwing procedure, then reducing them later in the throwing procedure should have the effect of increasing the path traveled by the discus, increase the time for which force is applied, and allow for a tangential release. All these positive outcomes should increase the distance thrown by maximizing the release speed.

For athletes to throw maximum distances, the discus should be released at a steep inclination and as high as possible. The angle of attack should also be considered. Techniques which incline the orbit of the discus and maximize the angle of release are related to the tilt of the trunk and the elevation of the throwing arm. An angle between the true horizontal plane and the line of the throwing arm is defined as the throwing arm elevation angle (Figure 6). Changes in this angle will increase the vertical distance traveled by the discus. Changes from smaller to greater inclines will increase the discus's vertical velocity and prolong the time of flight. An angle between the true vertical plane and the imaginary line joining the midpoint of the line of the hips and the midpoint of the line of the shoulders in the sagittal plane of a reference frame relative to the line of the hips is defined as the trunk tilt angle (Figure 7). By combining changes in the trunk tilt and throwing arm elevation angles, it is possible for the discus thrower to keep the discus high at the front of the circle and low at the back of the circle. This will incline the orbit upwards relative to the intended throwing direction and increase the angle of release. The height of release will also be large. The distance thrown will be maximized as long as the release speed is maintained. Therefore, optimizing technique to achieve the largest release speed at optimal release angles and heights is vital in discus throwing.

The hip-shoulder separation angle, shoulder-arm separation angle, trunk tilt angle and throwing arm elevation angle are technical parameters which can describe an athlete's technique throughout the throwing procedure. The parameters may be especially important at certain specific times during the throwing procedure. Six critical instants during the discus throwing procedure have been identified as: maximum backswing, right foot takeoff, left foot takeoff, right foot touchdown, left foot touchdown, and release (Bartlett, 1992; Hay and Yu, 1995). The hip-shoulder and shoulder-arm separation, and trunk tilt and throwing arm elevation angle can be reduced at each critical instant to provide a method of standardizing and comparing techniques across different athletes. The six critical instants divide the discus throw into five phases: first double support phase, first single support phase, flight phase, second single support phase, second double support phase (Hay and Yu, 1995). The absolute and relative times spent in each phase may be important technical considerations. Contact with the ground is needed to aid with force and velocity generation, but friction resists the athlete's motion across the circle. This suggests there may be an optimal time for each phase.

The speed of the discus release is the most important factor influencing long throws. The angle of release and the height of release are other important determinants of the distance thrown. The horizontal and vertical components of the speed of release can be considered separately. The technical parameters of hip-shoulder and shoulder-arm separations, trunk tilt, throwing arm elevation, and absolute and relative phase time are related to the release characteristics and performance. Therefore, it is of benefit to both athlete and coach to investigate in which way technical parameters influence real life performances.

It is possible to describe a theoretical, deterministic model linking the technical parameters, the release characteristics and performance. This model will assist with the testing of any hypotheses generated to investigate the effects of the technical parameters on discus throwing performance. The top level of the deterministic model is performance as described by official distance. This is determined by the release characteristics of the speed of release, the angle of release and the height of release (equation 1). An optimum combination of these release characteristics will result in the best performance. The speed of release can be subdivided into a horizontal and a vertical component with a Pythagorean relationship between the three. The two components are strongly inter-correlated, and also determine the angle of release (equation 3). These release characteristics make up the second level of the deterministic model. The technical parameters of hip-shoulder separation and shoulder-arm separation affect the horizontal release velocity most strongly. This is due to the impulse-momentum equation, and the fact they act primarily in the horizontal plane, although when combined with trunk tilt they will also influence the angle of release and vertical release velocity. The shoulder-arm separation has greater importance due to the greater distance of the discus from the center of rotation of the discus thrower than either hip or shoulder joint center. The technical parameter of trunk tilt affects the vertical speed of release and the angle of release most strongly. This is because of it primarily acting to change velocity in the vertical plane and the orientation of the orbit, although when combined with the separations it will also influence the horizontal release velocity. The technical parameter of throwing arm elevation affects the vertical speed of release, the angle of release and the height of release most strongly. This is due to the same reason as trunk tilt, as well as its large effect on the vertical position of the discus, especially at release. Its relatively greater importance is also due to the greater distance of the discus from the center of rotation of the discus thrower than either hip or shoulder joint center. The absolute and relative phase times are likely to affect all release characteristics, directly from the time portion of the impulse momentum equation, as well as indirectly by allowing for less or more separation, elevation or tilt during the throwing procedure. The technical parameters make up the third level of the deterministic model. The technical parameters will be correlated with each other and with themselves at sequential critical instants, making it important to identify any inter-relationships involved in the model. A graphical depiction of this deterministic model can be seen in Figure 8.

Critical technical parameters have been identified for other disciplines (Mann and Herman, 1985; Yu & Hay, 1996; Young and Li, 2005) using multiple regression analyses. The correlation between each technical parameter and a chosen measure of performance was used to determine which parameters to include. The multiple regression equation allowed an explanation to be given on which parameters best explained the success of any trial in the given discipline. This method has previously been used in discus throwing (Hay and Yu, 1995); however, the independent variables chosen for the regression analysis were not directly related to the athlete’s technique or body positions. An analysis of the effect on performance of technical variables, such as hip-shoulder and shoulder separations, trunk tilts, throwing arm elevations, and absolute and relative phase times, which can be easily interpreted into body positions and then incorporated into training by athletes and coaches, would also be beneficial.

Canonical correlations have been performed between theoretically linked sets of variables in the social sciences to analyze the underlying relationships between sets of variables (Wingard, *et al.*, 1979; Cohen, *et al.*, 1979; Fornell, 1979). Canonical analyses generate pairs of linear combinations of variables, one linear combination from each set, with maximum correlation between the two linear combinations. More pairs may be generated if they are uncorrelated with the first pair, but still with significant correlation between linear combinations from the two sets, after variance due to the first pair has been partialed out. Canonical correlation should be a descriptive analytical procedure, not a hypothesis testing procedure. Its role in this analysis is to identify the different dimensions along which technique is related to performance, and is only useful if those dimensions are interpretable (Tabachnik and Fidell, 1983). Since this technique investigates the relationship between linear composites of sets of variables, and human performance is often non-linear, any results should be regarded as exploratory and interpreted with care.

Purpose

The primary purpose of this study is to determine which combination of hip-shoulder and shoulder-arm separation angles, trunk tilt and throwing arm elevation angles, and absolute phase time and relative phase time of elite discus throwers during competition account for the most variation in performance. This will be achieved through use of a hierarchically ordered stepwise multiple regression, based on the deterministic model, of the technical parameters on discus throwing performance. Performance will be assessed with the criterion of official distance, and differentiated by gender. A value of each technical parameter will be reduced at each of the six critical instants for every trial included in the analysis. This will make four sets of six similar technical parameters for hip-shoulder and shoulder-arm separation, trunk tilt and throwing arm elevation, and two sets of five similar technical parameters for absolute phase time and relative phase time. The total time taken for each throw will be grouped in the absolute phase time set. The relative importance of each of the 35 technical parameters on discus throwing performance will be assessed through the deterministic model by inspecting the correlations of the release characteristics with official distance and the relationships of the 6 sets of technical parameters with the release characteristics, thereby giving an order of entry for each set into the stepwise regression equation (Meyers, et al., 2006). The most parsimonious model will be determined and the relative influence of each technical parameter on every other technical parameter will be investigated. A simplified model relating only the most important technical parameters, as they relate to performance, will be determined for each gender, and allow key instants and body positions which may improve performance to be identified. The use of a multiple regression model to identify the linear combination of technical parameters which account for variations in performance is acceptable in these circumstances, because the technical parameters have been linearly related to performance via the inherently linear equations used in the deterministic model, and as such the regression is mainly testing the deterministic model.

The secondary purpose of this study is to identify which aspects of technique are related to the different aspects of performance. This will be achieved through use of canonical correlation between the technical parameters and the release characteristics to identify interpretable dimensions. Technique will be assessed with the technical parameters, performance will be assessed with the release characteristics and each relationship will be differentiated by gender. Combinations of technical parameters which correlate with combinations of release characteristics will be inspected for the relative contribution of each variable to the relationship. A linkage between specific aspects of technique which determine specific aspects of performance will be determined and interpreted so the relationships usefulness is increased. This will allow recommendations to be provided for individually improving certain aspects of technique.

The research questions this study will attempt to answer are as follows:

1. Which simple combination of technical parameters accounts for maximum variation in discus throwing performance?
2. Which of the technical parameters are correlated with each other, and which make a unique contribution to explaining variation in discus throwing performance?
3. Which technical parameters can be combined into one or more technique factors that may be used to explain variation in one or more performance factors?

CHAPTER II

REVIEW OF THE LITERATURE

Discus throwing is one of the only track and field events that has been a part of the Olympic Games from ancient times. Changes to the rules of competition have occurred, thereby altering the nature of the event. Before 1896 competitors were restricted to throwing ‘Greek style’ from a pedestal, where the thrower only moved their arms (Jarver, 1985). Athletes depended on physical strength rather than technique to achieve long throws. In 1896, the throwing circle was introduced, which allowed athletes to move across the circle before releasing the discus. Movements prior to release increase the importance of effective throwing techniques, because from complex, high speed movements made within the confined space of the throwing circle, an athlete may be able to increase the release speed above that possible with a standing throw, alone (Hay, 1985; Hay and Yu, 1995). In 1910 the throwing circle was enlarged (Jarver, 1985). Advancements in the aerodynamic characteristics of the discus, the composition of the circle, and footwear have also influenced throwing technique. These changes have made discus throwing both a technically, as well as a physically demanding event.

Scientific studies on the technical aspects of discus throwing are limited. Quantitative research studies into discus throwing can be differentiated into those focusing on the flight of the discus after release and those investigating how movements made by the athlete during the throwing procedure affect performance. Studies investigating how throwing technique influences performance are particularly important to coaches and athletes. Research into the technical aspects of discus throwing can scientifically evaluate the techniques suggested in coaching literature which have been designed to improve performance. Scientific support for the coaching literature is lacking and this line of enquiry is limited. Not enough relevant and reliable biomechanical data exists to answer questions about the technical aspects of discus throwing. Three dimensional cross sectional and longitudinal studies are necessary to identify important elements of technique, those which most influence performance.

Coaching literature emphasizes technical parameters, which athletes can focus on achieving during training and competition (Davenport, 1961; Bosen, 1963; Maughan, 1964; Lockwood, 1969; Pryor & Lockwood, 1970; Ecker, 1971; Tancred & Carter, 1980; Hay, 1985; Jarver *et al.*, 1985; Knicker, 1993). These technical parameters repeatedly include hip-shoulder and shoulder-arm separations, trunk tilts, and arm elevation angles (Maughan, 1964; Ecker, 1971; Hay, 1985; Knicker, 1993). These technical parameters are currently based on physical theories and from techniques which have been successful for other discus throwers (Maughan, 1964; Tancred & Carter, 1980; Jarver *et al.*, 1985). The lack of biomechanical data available on the technical aspects of discus throwing means scientific evaluations on the actual importance of these technical parameters to the flight phase of the discus have not yet been made.

The flight phase of the discus throw describes the motion of the discus after release by the athlete (Hubbard, 1989). This phase has been thoroughly examined. The forces acting on the discus attributable to air have been investigated using of a wind tunnel. This allowed the gravitational and aerodynamic forces acting on the discus during flight, as well as the aerodynamic properties of the discus itself, to be estimated (Taylor, 1932; Cooper *et al.*, 1959; Ganslen, 1964; Terauds, 1978b; Frohlich, 1981;). These studies have shown that the aerodynamic effects on the flight of the discus may be an important consideration for throwers. If the angle of attack is too high, lift will be lost as the air flow separates, and the discus stalls (Tipler, 1998). For a discus, this loss of lift occurs at approximately 27 to 29 degrees (Ganslen, 1964). Lift forces may counterbalance the drag forces to allow distance to be maintained. Soong (1976, 1982) and Frohlich (1981) have shown this does tend to happen. This may explain why the theoretical vacuum flight distance is so close to the recorded official distance. However, only Terauds (1978) and Hay and Yu (1995) have assessed the magnitude of the contribution made by aerodynamic forces to actual throws. Their data confirm the importance of aerodynamic considerations and that the distance gained or lost is significant in terms of several meters of performance.

Optimal release characteristics to maximize the distance thrown have been suggested by Taylor (1932), Cooper, *et al.* (1959), Ganslen (1964), Terauds (1978a), Frohlich (1981), and Knicker (1990). These investigators have calculated the release speeds, angles of release, and heights of release to calculate the range of optimal values necessary to maximize the theoretical distance thrown. The values of these release characteristics were calculated from simulated discus flights and solutions of flight equations. Release speeds and heights are not optimisable quantities, since any increase will increase the distance thrown. Release speed is the most important factor contributing to the vacuum flight distance. Release speed is also the principal determinant of the difference in vacuum flight distance among athletes (Bartlett, 1992; Hay and Yu, 1995). The angles of release relative to the wind velocity and a global reference frame are optimisable. The suggested ranges of values for the angle of release are 35 to 37 degrees, and -9 to -10 degrees for the angle of attack. These simulated optimal values agree well with values measured during real competition. All other release characteristics lie within a limited range of values, and may only be important in the manner in which they affect release speed (Hubbard *et al.*, 2001). To achieve the longest vacuum flight distance, and therefore the longest throw, the athletes must carefully control their releases so the discus is thrown at the maximum height possible, combined with optimal release angles, and most importantly with the maximum possible speed.

The relevance to coaches and athletes from studies into the flight of the discus alone is limited. Athletes cannot influence the discus unless they are in physical contact with it, and they are unable to control environmental conditions. Studying the flight of the discus in isolation to the athletes' throwing technique does not allow for a cause and effect relationship between technique and discus flight to be determined. However, the optimal release characteristics determined from simulations of discus flight give the athletes and coaches optimal values to achieve and may be compared with those release characteristics calculated from real life throws to evaluate the efficiency and effectiveness of individual trials. None of the effects of technique on any release characteristic may be determined if this is not included in the analysis. Therefore, kinetic and kinematic investigations into athlete's real-life techniques and the influence their technique has on the release characteristics are necessary to determine how different techniques affect performance.

Kinetic analyses of discus throwing during competition are difficult because instrumentation of the circle with force plates during competition is not often allowed. Therefore, the extrapolation of kinetic data obtained in a lab setting, such as that from Yu *et al.* (2002), is most practical. The relationships between official distance and ground reactions, and ground reactions and lower extremity kinetics was investigated. Conclusions drawn from this study suggest that driving forwards and vertically during the first single support phase of the throwing procedure increases the forward and vertical velocity of the thrower. The results also suggest that a hard right foot landing after the flight phase increases the forward velocity of the thrower. Forward and vertical thrust can be achieved with hip and knee actions of the lower extremities and leads to greater official distances.

Kinematic analysis is best suited to use during competition, since it causes minimal interference to the athletes. Few kinematic analyses of discus throwing technique have been made, and three-dimensional investigations are especially rare. While discus release characteristics, such as velocities, heights, and angles have been reported (Terauds, 1978a,b; Gregor *et al.*, 1985; McCoy *et al.*, 1985; Stêpánek and Sušanka, 1986; Lindsay, 1991; Hay and Yu, 1995; Ariel, 2000), these have rarely been linked to variations in technique, and sample sizes have been small. Sušanka *et al*. (1988), Gregor *et al.* (1985), McCoy *et al.* (1985), Lindsay (1991), Knicker (1990 & 1993) and Hay and Yu (1995) investigated the kinematics of the thrower, as well as the implement. Some of these studies were limited in the analysis techniques used, often two-dimensional (2-D) instead of three-dimensional (3-D) videographic analyses were performed. Hence, limited information about the effects of technique on performance was provided.

Temporal parameters, as well as foot contact and placement data have been studied. Six critical instants during discus throwing have been identified as: maximum backswing, right foot takeoff, left foot takeoff, right foot touchdown, left foot touchdown and release (Bartlett, 1992; Hay and Yu, 1995). These six critical instants divide the discus throw into five phases: first double support phase, first single support phase, flight phase, second single support phase, second double support phase (Hay and Yu, 1995). The relative time spent in each phase has been examined with the conclusion drawn that throwers should start slow and finish fast.

Technical parameters of separations between the hips, shoulders and throwing arms were investigated by Sušanka *et al*. (1988), Knicker (1990) and Lindsay (1991). The force applied to the discus force can be increased by taking advantage of the elastic properties of muscles by generating pre-delivery torsion (Bartlett, 1992). Discus throwers enhance their performance by dynamically stretching their trunk rotators and arm horizontal adductors (Hay, 1985) during the throwing procedure. This allows energy to be stored in the non-contractile element of these muscles, which can then be utilized during release and supplement the force applied by the contractile muscle element. The amount of stretch is directly proportional to the amount of separation between the hips, shoulders and throwing-arm. Sušanka *et al*. (1988), Knicker (1990) and Lindsay (1991) concluded that these separations were of greatest importance in the later stages of the throwing procedure. Up to 73% (reported in Bartlett, 1992) of the discus's horizontal release velocity is obtained immediately before release of the discus. Data from Sušanka *et al*. (1988) demonstrates the possible greater importance of a shoulder-arm leading angle to the generation of release speed, since this angle correlated with official distance more frequently than the separation between the hips and the shoulders. The optimum hip-shoulder and shoulder-arm separations at release are reported to be 0 degrees (Sušanka *et al*., 1988; Knicker, 1990; Lindsay, 1991). Release of the discus when the throwing arm has traveled past parallel may be both a sign of flawed technique, and a reliance on arm strength (Knicker, 1990; Lindsay, 1991). A trend between trunk tilt at release and release angle was reported by Gregor *et al.* (1985). A trend between throwing arm elevation and height of release was reported by Gregor *et al.* (1985) and McCoy *et al.* (1985). Gregor *et al.* (1985) also suggested that the discus should be released from shoulder height to maximize the height of release, while still maintaining control of the discus. Hip, shoulder and arm separations, trunk tilt, and arm elevation are the only technical parameters reported in the literature and their influence on performance has not been thoroughly investigated.

Critical technical parameters related to variations in performance have been identified in other events in track and field. For example, triple jumping (Yu and Hay, 1996), sprinting (Mann and Herman, 1985) and shot-putting (Young and Li, 2005). Any reported relationships between technical parameters and performance is informative to coaches and athletes since it provides them with insights into which techniques may directly affect performance.

This method was used by Hay and Yu (1995) to investigate discus throwing; however, the independent variables chosen for the regression analysis were indirectly related to the athlete's techniques. The conclusions drawn by this study determined the main factors influencing official distance, namely the vacuum flight distance, the speed of release, the angle of release, the height of release and the aerodynamic distance. Information was also provided on changes in speed of the discus at different instants during the throwing procedure. This is related to performance, since discus release speed is a major factor influencing official distance. The change in speed of the discus during the throwing procedure, especially during the second double support phase, was an important factor differentiating between good and poor performances for both male and female discus throwers. However the different correlations between the change in speed of the discus during the second double support phase and official distance highlight the need to consider both genders separately.

An analysis of technical parameters, such as hip-shoulder and shoulder separations, trunk tilts and throwing arm elevations, and absolute and relative phase time and their relative effects on performance would also be beneficial. Technical parameters which can be easily interpreted into body positioning during the throwing procedure provide useful information for athletes and coaches as to the effectiveness of various techniques.

CHAPTER III

METHODS

Subjects

Two-hundred and eighty-three legal discus throwing trials by 48 male and 42 female discus throwers were included in this study. The trials were collected during the men's and women's discus throw finals of the 1990 Goodwill Games, the 1990 US Olympic Festival, the 2000 New Zealand Open, and the US National Outdoor Championships and Olympic Team Trials from 1997 to 2005. All throwers were right handed. Every trial was entered into the Centre for Human Movement Science at the University of North Carolina at Chapel Hill (CHMS) Discus Throwing Database for reduction and analysis.

Data Collection

Two Super Video Home System (S-VHS) video camcorders were used to record data of all throwers' performances at a sampling frequency of 60 frames per second. Focus and shutter speed were manually adjusted for each competition for the purposes of reducing camera noise, and setting optimal resolution and contrast. One of the camcorders was placed behind the discus-throwing circle, while the other camera was placed at the right side of the circle (Figure 9). The angle between the optical axes of the two camcorders was approximately 90°. After each competition, a calibration frame (Peak Performance, Englewood, Colorado, USA) was placed in the throwing circle. This was used to calibrate camcorder positions and orientations. The calibration frame consisted of 8 rods radiating outwards from a central core with 3 control points, each mm in diameter fixed to the rods at set distances from the core, for a total of 24 control points (Figure 10). Twenty-four points is greater than the minimum number of 16 points necessary for acceptable accuracy (Chen *et al*, 1994). The calibration frame covered a calibration volume of 2.5 m long × 2 m wide × 2.5 m high above the discus throwing circle. The volume covered by the calibration volume was large enough to limit extrapolation to the extreme corners of the volume. Five global reference markers were also placed in the discus-throwing circle at this time for establishing a global reference frame during data reduction.

Data Reduction

Two-dimensional (2-D) coordinate data of throwers' performances were obtained from the video clips. The video clips from both camcorders of every trial, as well as the calibration frame and global reference markers specific to each meet, were digitized using a Motus videographic data acquisition system (Peak Performance Technology, Inc., Englewood, CO) with a 21-inch computer monitor. For the throws, 21 critical body landmarks and the centre of the discus were manually digitized in each frame (Hay and Yu, 1995) from a minimum of five frames before maximum backswing to a minimum of four frames after release of the discus. The landmarks were: 1) vertex of the head, 2) midpoint of the chin-neck axis, 3) suprasternal notch, 4) right shoulder joint center, 5) right elbow joint center, 6) right wrist joint center, 7) head of the 3rd right metacarpal 8) left shoulder joint center, 9) left elbow joint center, 10) left wrist joint center, 11) head of the 3rd left metacarpal, 12) right hip joint center, 13) right knee joint center, 14) right ankle joint center, 15) right calcaneus, 16) head of the 3rd right metatarsal, 17) left hip joint center, 18) left knee joint center, 19) left ankle joint center, 20) left calcaneus, 21) head of the 3rd left metatarsal, 22) center of the discus (Figure 11). For any landmark that was obscured in any frame, the best qualitative estimate of its position was digitized. The 2-D landmark coordinates were conditioned to correct any poorly digitized 2-D coordinates. For the calibration data, every control point on the calibration frame and the 5 global reference markers were digitized in order for one frame (Figure 10) from a clip of approximately 25 seconds in duration.

The Direct Linear Transformation (DLT) procedure (Abdel-Aziz and Karara, 1971) was used to obtain real-life three-dimensional (3-D) coordinates of the global reference markers, critical body landmarks, and the centre of the discus from the 2-D coordinates. The 2-D calibration coordinates were used to obtain 11 DLT parameters for each camera based on the relative locations and orientations of the cameras and the calibration frame. The 2-D calibration coordinates were also used to estimate digitizing and calibration errors, and to define the global reference frame. The calibration errors are the difference between the known distances of the calibration frame's control points and the distances calculated from the digitized points. The mean error was deemed acceptable if less than 10mm following removal of any poorly digitized points. The global reference frame was established so that the origin was set at the centre of the discus throwing circle with the X-axis pointing toward the throwing direction, the Y-axis pointing to the left side of the discus throwers when they were facing the throwing direction, and the Z-axis pointing upward (Figure 9).

The 2-D coordinates were mathematically synchronized. The critical instants of right foot takeoff, left foot takeoff, right foot touchdown, left foot touchdown and release of the discus were identified from each camcorder for every trial. The identification was made qualitatively by visual inspection of the video clip. The frame numbers of these five critical instants were used for mathematical synchronization of the digitized 2-D coordinates of corresponding video clips. The use of 5 critical events for mathematical synchronization increased the accuracy of the synchronization; however, errors of up to 0.2 seconds could still be present. The real-life 3-D coordinates of the critical body landmarks and the centre of the discus were estimated from the synchronized, digitized 2-D coordinates and the 11 DLT parameters of the two camcorders. The estimated real-life 3-D coordinates were filtered through a Butterworth low-pass digital filter at an estimated optimum cut-off frequency of 7.14 Hz (Yu and Andrews, 1998). The synchronization of the digitized 2-D coordinates, direct linear transformation of the digitized 2-D coordinates to real-life 3-D coordinates, and data smoothing were performed using software which was custom written for the task in visual basic by MotionSoft, Chapel Hill, NC. The MSDLT computer program package version 5.5 was used.

Six critical instants during the discus throwing procedure have been identified as: maximum backswing, right foot takeoff, left foot takeoff, right foot touchdown, left foot touchdown, and release (Bartlett, 1992; Hay and Yu, 1995). These six critical instants divide the discus throw into five phases: first double support phase, first single support phase, flight phase, second single support phase, and second double support phase (Hay and Yu, 1995). The hip-shoulder separation angle, shoulder-arm separation angle, trunk tilt angle, and arm elevation angle were reduced at these critical instants for each trial, again using software which was custom written for the task in visual basic by MotionSoft, Chapel Hill, NC. The DiscAnz computer program package, version 2.0 was used. The absolute and relative times spent in each phase of the discus throw were also reduced using the same computer program package.

Technical Parameters

A trunk reference frame was established at each critical instant to calculate the hip-shoulder and shoulder-arm separation angles. The trunk reference frame was established in such a way that the X-axis was pointing toward the thrower's anterior direction relative to the line joining their hip joint centers, the Y-axis was pointing from their right hip joint center to their left hip joint center, and the Z-axis was pointing toward the superior direction from the midpoint of the right and left hips to the midpoint of the right and left shoulders. The 3-D coordinates of the right and left hips and shoulders and the centre of the discus in the global reference frame were transferred to the trunk reference frame using a directional cosine matrix at each critical instant.

The hip-shoulder separation angle (α) was calculated as the inverse cosine of the dot product of the vector joining the shoulder joint centers with the vector joining the hip joint centers, divided by the cross product of the vector joining the shoulder joint centers with the vector joining the hip joint centers. The shoulder-arm separation angle (β) was calculated as the inverse cosine of the dot product of the vector joining the right shoulder joint center and the center of the discus with the vector joining the shoulder joint centers, divided by the cross product of the vector joining the right shoulder joint center and the center of the discus with the vector joining the shoulder joint centers. Both angles are calculated in the trunk reference frame as follows:

$$\alpha = \arccos\left(\frac{\mathbf{v}_s \bullet \mathbf{v}_h}{|\mathbf{v}_s||\mathbf{v}_h|}\right)$$

$$\beta = \arccos\left(\frac{\mathbf{v}_d \bullet \mathbf{v}_s}{|\mathbf{v}_d||\mathbf{v}_s|}\right)$$

Where $\mathbf{v}_h$, $\mathbf{v}_s$, and $\mathbf{v}_d$ are location vectors of the right hip relative to the left hip, right shoulder relative to the left shoulder, and centre of the discus relative to the right shoulder, respectively, in the XY (horizontal) plane of the trunk reference frame (Figures 4 and 5 respectively).

The value of α was positive if the vector cross product of $\mathbf{v}_s$ with $\mathbf{v}_h$ was pointing toward the superior direction, which meant that the right hip was leading the right shoulder. The value of α was negative if the vector cross product of $\mathbf{v}_s$ with $\mathbf{v}_h$ was pointing toward the inferior direction, which meant that the right shoulder was leading the right hip. The value of β was positive if the vector cross product of $\mathbf{v}_d$ with $\mathbf{v}_s$ was pointing toward the superior direction, which meant that the right shoulder was leading the right arm. The value of β was negative if the vector product of $\mathbf{v}_d$ with $\mathbf{v}_s$ was pointing toward the inferior direction, which meant that the right arm was leading the right shoulder.

The throwing-arm elevation angle was calculated in the global reference frame at each critical instant. A hip reference frame was established at each critical instant to calculate the trunk tilt angles. The hip reference frame was established in such a way that the X-axis was pointing toward the thrower's anterior direction relative to the line joining their hip joint centers, the Y-axis was pointing to from their right hip joint center to their left hip joint center, and the Z-axis was pointing along the true vertical from the right hip joint center to a point one meter directly above the right hip joint center. The 3-D coordinates of the right and left hips and shoulders in the global reference frame were transferred to the hip reference frame using a directional cosine matrix at each critical instant.

The throwing arm elevation angle (δ) was calculated as the inverse tangent of the distance between the global Z coordinates of the discus and the right shoulder joint center, divided by the hypotenuse of the right triangle, whose sides were the distance between the global X coordinates of the discus and the right shoulder joint center and the global Y coordinates of the discus and the right shoulder joint center. This was calculated in the true vertical plane of the global reference frame as follows:

$$\delta = \arctan\left[\frac{z_d - z_{s,r}}{\sqrt{(x_d - x_{s,r})^2 + (y_d - y_{s,r})^2}}\right]$$

Where: $\mathbf{x}_{s,r}$, $\mathbf{y}_{s,r}$, and $\mathbf{z}_{s,r}$ were 3-D coordinates of the right shoulder; and $\mathbf{x}_d$, $\mathbf{y}_d$, and $\mathbf{z}_d$ were 3-D coordinates of the centre of the discus (Figure 6).

The 3-D coordinates measured in the global reference frame of: the right and left hips, and the right and left shoulders were used to calculate the trunk tilt angle (χ). The designations of: $\mathbf{x}_{h,r}$, $\mathbf{y}_{h,r}$, and $\mathbf{z}_{h,r}$; $\mathbf{x}_{h,l}$, $\mathbf{y}_{h,l}$, and $\mathbf{z}_{h,l}$; $\mathbf{x}_{s,r}$, $\mathbf{y}_{s,r}$, and $\mathbf{z}_{s,r}$; and $\mathbf{x}_{s,l}$, $\mathbf{y}_{s,l}$, and $\mathbf{z}_{s,l}$ were used for the 3-D coordinates of the right hip, left hip, right shoulder, and left shoulder respectively. A ground and a trunk reference frame were defined at each critical instant. The ground reference frame ($\mathbf{i}_G$, $\mathbf{j}_G$, $\mathbf{k}_G$) was defined as:

$$\mathbf{j}_G = \frac{(x_{h,r} - x_{h,l})\mathbf{i} + (y_{h,r} - y_{h,l})\mathbf{j}}{\sqrt{(x_{h,r} - x_{h,l})^2 + (y_{h,r} - y_{h,l})^2}}$$

$$\mathbf{k}_\mathrm{G} = \mathbf{k}$$

$$\mathbf{i}_\mathrm{G} = \mathbf{k}_\mathrm{G} \times \mathbf{j}_\mathrm{G}$$

Where **i**, **j**, and **k** were the unit vectors of the x, y, and z axes of the global reference frame. The trunk reference frame ($\mathbf{i}_T$, $\mathbf{j}_T$, $\mathbf{k}_T$) was defined as:

$$\mathbf{j}'_T = \frac{(x_{h,r} - x_{h,l})\mathbf{i} + (y_{h,r} - y_{h,l})\mathbf{j} + (z_{h,r} - z_{h,l})\mathbf{k}}{\sqrt{(x_{h,r} - x_{h,l})^2 + (y_{h,r} - y_{h,l})^2 + (z_{h,r} - z_{h,l})^2}}$$

$$\mathbf{k}_T = \frac{(x_{s,r} + x_{s,l} - x_{h,r} - x_{h,l})\mathbf{i} + (y_{s,r} + y_{s,l} - y_{h,r} - y_{h,l})\mathbf{j} + (z_{s,r} + z_{s,l} - z_{h,r} - z_{h,l})\mathbf{k}}{\sqrt{(x_{s,r} + x_{s,l} - x_{h,r} - x_{h,l})^2 + (y_{s,r} + y_{s,l} - y_{h,r} - y_{h,l})^2 + (z_{s,r} + z_{s,l} - z_{h,r} - z_{h,l})^2}}$$

$$\mathbf{i}_\mathrm{T} = \mathbf{k}_\mathrm{T} \times \mathbf{j}'_\mathrm{T}$$

$$\mathbf{j}_\mathrm{T} = \mathbf{i}_\mathrm{T} \times \mathbf{k}_\mathrm{T}$$

Where $\mathbf{i}_T$, $\mathbf{j}_T$, and $\mathbf{k}_T$ were unit vectors of axes about which the rotations of trunk lateral flexion, flexion-extension, and left-right rotation, respectively, were assumed to be made. Trunk angles were defined as the Euler angles between the trunk reference frame and the ground reference frame. The order of rotation was: first rotation = anterior-posterior flexion-extension, second rotation = left-right lateral flexion, and third rotation = left-right rotation. The first rotation was chosen to be the trunk tilt angle (Figure 7).

A positive value of δ indicated that the position of the discus was higher that that of the right shoulder, while a negative value of δ indicated that the position of the discus was lower than that of the right shoulder. A positive value of χ indicated an anterior, or forward, trunk tilt, which meant that the midpoint of the line between the right and left shoulders was in front of the midpoint of the line between the right and left hips. A negative value of χ indicated a posterior, or backward, trunk tilt, which meant that the midpoint of the line between the right and left shoulders was behind the midpoint of the line between the right and left hips. This can be thought of as pure anterior-posterior trunk tilt. Lateral trunk tilt was not calculated, but is incorporated in the calculation of the throwing-arm elevation angle since this is calculated in the global reference frame.

The absolute time spent in each phase was calculated from the number of frames from one critical instant to the next critical instant divided by the sampling frequency. The relative time spent in each phase was calculated from the number of frames between critical instants compared with the number of frames from maximum backswing to release of the discus. The relative time spent in each phase was calculated as a percentage of the total time for the throwing procedure as:

$$\left(\lfloor F_i - F_{(i-1)} \rfloor \big/ F_n \right) \times 100$$

Where F_i and $F_{(i-1)}$ are the frame numbers at two consecutive critical instants and F_n is the total number of frames between maximum backswing and release of the discus.

Data Analysis

To assess for inter-digitizer reliability, 5 trials from the 2004 USA Track and Field National Outdoor Championships were selected to be digitized and synchronized, have their 3-D coordinates estimated using the DLT procedure, and reduce all technical parameters by two different digitizers. Reliability was assessed by qualitative inspection of the mean absolute and relative differences between every variable reduced by the different digitizers. The mean absolute difference for each of the variables was defined as the absolute differences between the two values of each technical parameter reduced by the two digitizers for the same trial, which were then averaged over all five trials. The mean relative difference was defined as the absolute differences between the two values of each technical parameter reduced by the two digitizers for the same trial, divided by the mean value for that technical parameter, which were then averaged over all five trials. Intra-digitizer reliability has previously been assessed (Hay and Yu, 1995).

For all statistical analyses, male and female discus throwers were analyzed separately to reduce the possible influences of gender and strength. An *a priori*, type I error rate of alpha = 0.05 was chosen to indicate statistical significance. All statistical analyses were performed with SPSS version 11.5 statistical software (SPSS Inc., Chicago, IL.).

The entire dataset was screened for the presence of outliers and to check the assumptions of univariate normality and homogeneity of variance were not violated. The presence of outliers was checked by qualitatively comparing the extreme values of any variable. Any case with a value significantly greater or smaller than the next closest value was considered a possible outlier which required further inspection and possible exclusion from the dataset. Each case's Mahalanobis distance on a combination of all 45 variables (technical parameters plus release characteristics) was compared with a criterion value of $\chi^2_{(0.001,\,45)} = 89.07$, since the chi square distribution most accurately models a multivariate distribution with degrees of freedom equal to the number of dependent variables (Tabachnick & Fidell, 1983). Values greater than 89.07 were considered for removal from the dataset. The univariate normality of each variable was checked by inspecting its standard deviation, skewness, and kurtosis. A distribution was considered significantly skewed if the value of skewness divided by its standard error was greater than ±3, since a normal distribution has no skewness (Howell, 2004). A distribution was considered significantly leptokurtic if the value of kurtosis was greater than 3, since a normal distribution has kurtosis = 3. A distribution was considered significantly platykurtic if its kurtosis divided by its standard error was less than -3 (Howell, 2004). Significant departures from normality will be considered when interpreting any results.

Hierarchical, stepwise multiple regression analyses were conducted to investigate if any linear relationship existed between combinations of technical parameters and discus throwing performance. A power analysis was performed to investigate if the size of the database was adequate to detect variation in performance. The criterion values used in the equation to compute the number of cases necessary to have 80% probability of rejecting the null hypothesis at the a priori level of alpha = 0.05, were: ten independent variables, since more independent variables increase the risk of redundancies, and ten was qualitatively determined as enough for the purpose of describing technique, power = 0.8, alpha = 0.05, and variance explained = 10%, since these are the most common values used in statistical literature (Cohen & Cohen, 1983).

Discus throwing performance, assessed by official distance thrown, was used as the dependent variable for the multiple regression, the release characteristics were used as intermediate variables, and the technical parameters were used as the independent variables. Zero-order bivariate correlations between the release characteristics and official distance were inspected to determine the magnitude of the relationship between them. Using the deterministic model and the correlations, an order of entry into the stepwise multiple regression equation was qualitatively determined by the researcher for the six sets of independent variables: hip-shoulder separations, shoulder-arm separations, trunk tilts, throwing-arm elevations, absolute phase times, and relative phase times. Each set of variables was entered in the order determined according to the performance model and the final model used the technical parameters to account for variation in discus throwing performance. An individual technical parameter's inclusion or removal from the final model was determined in a stepwise fashion according to the R^2 change of official distance brought about by its inclusion. The possible inclusion of any variable from a set was determined for the entire set before inspecting a subsequent set and variables were not reconsidered after the next set were entered (Meyers, *et al.*, 2006).

Commonality analyses were subsequently performed on each model to determine whether the variation in performance explained by each technical parameter was unique, to identify incidents of multi-colinearity, and to describe fully the interrelationships among the predictor variables. In the event of a predictor variable not making a unique contribution to the equation, it was removed from the analysis and the regression was performed again, but with that variable excluded. This ensured the most streamlined regression equation was developed. Part and partial correlations were used to determine the percentage of unique variance in performance explained by each independent variable. It has been suggested that multi-colinearity may be considered problematical with bivariate correlations of r = 0.6 or higher between independent variables, and bivariate correlations of r = 0.3 or higher between independent variables indicating possible multi-colinearity (Tacq, 1997; Meyers, *et al.*, 2006).

The presence of outlying cases unduly influencing any model was checked by comparing each case's Mahalanobis distance on the linear composite of the independent variables with a criterion value according to a χ^2 distribution, with values greater than this considered as possible outliers.

Canonical correlation analyses (Tacq, 1997; Tabachnick & Fidell, 1983) were conducted to determine the relationships between linear combinations of the technical parameters and linear combinations of the release characteristics. All technical parameters were examined simultaneously and compared with two different sets of release characteristics. The release characteristics of the speed of release, the angle of release, and the height of release were entered as the first set of release characteristics, and the horizontal and vertical components of the speed of release and the height of release were entered as the second set of release characteristics. Custom written syntax was used to modify SPSS's MANOVA procedure and produce three canonical variates for each set of release characteristics (Green and Salkind, 2004). Each variate was rotated to maximize the relationship between the release characteristics and their corresponding technical parameters.

Any variates found were uncorrelated with any other variates, but needed to be interpreted for any functional use. Correlations of the technical parameters and release characteristics with the canonical variates were calculated. Any correlation of 0.3 or greater (Tabachnik & Fidell, 1983) of a technical parameter or release characteristic with a canonical variable was determined to be statistically significant, and its canonical weighting subsequently inspected for interpretation of the relationship between the related technical parameters and release characteristics. Any variable with a correlation with the variate of less than 0.3 was not considered as important to describe the relationship between the release characteristics and technical parameters.

Any model revealed by the multiple regression or canonical correlation was qualitatively interpreted, and the independent variables linked to the performance indicating variables according to the deterministic model.

CHAPTER IV

RESULTS

Inter-Digitizer Reliability

The release characteristics and technical parameters reduced by two different digitizers were inconsistent across the 5 trials, and different values were reported. The release characteristics showed relatively good inter-digitizer agreement and exhibited mean relative differences of less than 10%, except aerodynamic distance which was 234%. The aerodynamic distance's mean absolute difference was large at 5.5 m compared to the mean value of 1.6 m. The mean relative differences for the hip-shoulder separations were all less than 20%, with mean absolute differences of less than 10°. The mean relative differences for the shoulder-arm separations, trunk tilts, and throwing-arm elevations were generally less than 20% for the critical instants of right foot off, left foot off, and right foot down, and greater than 20% for the critical instants of maximum backswing, right foot down, and release. The maximum mean absolute difference for the shoulder-arm separations, trunk tilts, and throwing-arm elevations was 13°, but mean absolute differences were generally less than 7 degrees. Mean absolute differences for absolute phase times were less than 0.01s, which was a mean relative difference of 5% or less. Means, standard deviations, and the mean absolute and relative differences for the variables considered in this study are displayed in Table 1.

Data Screening

The CHMS Discus Throwing Database contains 138 legal discus throwing trials by 42 female discus throwers and 144 legal discus throwing trials by 48 male discus throwers. One trial met the criteria to be considered an outlying case on 9 of the 45 variables. This case was deleted from the database. No other cases exceeded the Mahalanobis distance to be considered multivariate outliers.

Screening of the dataset for reasonable means and standard deviations identified the arm elevation angles at maximum backswing and right foot off as having large variances for female discus throwers. Inspecting the values of skewness identified: the hip-shoulder separation angle at left foot off, the trunk tilt angles at left foot off, right foot down, and left foot down, the arm elevation angle at left foot down, and the first single support phase time for females; and: the hip-shoulder separation angle at left foot off, the trunk tilt angle at right foot down, the arm elevation angle at right foot off, the first double support phase time, the time for the throwing procedure, and the relative flight phase time for males as having significantly skewed distributions. Inspecting the values of kurtosis identified: the trunk tilt angle at right foot down, and the arm elevation angles at maximum backswing and right foot off for females as having significantly leptokurtic distributions; also: the trunk tilt angle at right foot off for females, and the trunk tilt angles at right foot off, left foot off, and left foot down for males as having significantly platykurtic distributions. Descriptive statistics for all variables used in the statistical analyses are displayed in Table 2.

Hierarchical Stepwise Multiple Regression

A power analysis for the multiple regression with 10 IVs, power = 0.8, and alpha = 0.05 showed that 157 cases were required to detect a population $R^2 = 0.1$. The sample size of the current database may not be large enough, when split by gender, to detect the criterion R^2 with 80% probability.

A correlation matrix for official distance and the release characteristics for female discus throwers is displayed in Table 3. A correlation matrix for official distance and the release characteristics for male discus throwers is displayed in Table 4. The correlations of official distance with each technical parameter for both male and female discus throwers are shown in Table 5. These correlations, as well as theoretical links between the release characteristics and the technical parameters, were used to determine the order of entry of the different blocks of the technical parameters into the stepwise multiple regression equation for explaining variation in performance. The shoulder-arm separations were entered first, followed by the hip-shoulder separations second, followed by the throwing arm elevations third, followed by the trunk tilts fourth, followed by the absolute phase times fifth, followed by the relative phase times sixth.

A linear combination of: shoulder-arm separation at right foot down, hip-shoulder separation at left foot down, hip-shoulder separation at release, throwing arm elevation at maximum backswing, hip-shoulder separation at left foot off, throwing arm elevation at right foot off, trunk tilt at maximum backswing, trunk tilt at right foot down, the absolute second single support phase time, the absolute release phase time, and the absolute first double support phase time accounted for 41.2% of the variance in official distance for female discus throwers.

The shoulder-arm separation at right foot down accounted for a significant amount of the official distance variability ($R^2 = 0.030$, $F_{1,136} = 4.183$, $p = 0.043$). The hip-shoulder separation at left foot down accounted for a significant proportion of the official distance variance after controlling for the effects of shoulder-arm separation at right foot down (R^2 change = 0.083, $F_{1,135} = 12.614$, $p = 0.001$). The hip-shoulder separation at release accounted for a significant proportion of the official distance variance after controlling for the effects of shoulder-arm separation at right foot down and hip-shoulder separation at left foot down (R^2 change = 0.034, $F_{1,134} = 5.282$, $p = 0.023$). The hip-shoulder separation at left foot off accounted for a significant proportion of the official distance variance after controlling for the effects of shoulder-arm separation at right foot down, hip-shoulder separation at left foot down, and hip-shoulder separation at release (R^2 change = 0.032, $F_{1,133} = 5.194$, $p = 0.024$). The throwing-arm elevation at right foot off accounted for a significant proportion of the official distance variance after controlling for the effects of shoulder-arm separation at right foot down, hip-shoulder separation at left foot down, hip-shoulder separation at release, and hip-shoulder separation at left foot off (R^2 change = 0.055, $F_{1,132} = 9.520$, $p = 0.002$). The trunk tilt at maximum backswing accounted for a significant proportion of the official distance variance after controlling for the effects of shoulder-arm separation at right foot down, hip-shoulder separation at left foot down, hip-shoulder separation at release, hip-shoulder separation at left foot off, and throwing-arm elevation at right foot off (R^2 change = 0.053, $F_{1,131} = 9.693$, $p = 0.002$). The trunk tilt at right foot down accounted for a significant proportion of the official distance variance after controlling for the effects of shoulder-arm separation at right foot down, hip-shoulder separation at left foot down, hip-shoulder separation at release, hip-shoulder separation at left foot off, throwing-arm elevation at right foot off, and trunk tilt at maximum backswing (R^2 change = 0.027, $F_{1,130} = 5.186$, $p = 0.024$). The absolute second single support phase time accounted for a significant proportion of the official distance variance after controlling for the effects of shoulder-arm separation at right foot down, hip-shoulder separation at left foot down, hip-shoulder separation at release, hip-shoulder separation at left foot off, throwing-arm elevation at right foot off, trunk tilt at maximum backswing, and trunk tilt at right foot down (R^2 change = 0.042, $F_{1,129} = 8.487$, $p = 0.004$). The absolute release phase time accounted for a significant proportion of the official distance variance after controlling for the effects of shoulder-arm separation at right foot down, hip-shoulder separation at left foot down, hip-shoulder separation at release, hip-shoulder separation at left foot off, throwing-arm elevation at right foot off, trunk tilt at maximum backswing, trunk tilt at right foot down, and absolute second single support phase time (R^2 change = 0.036, $F_{1,128} = 7.522$, $p = 0.007$). The absolute first double support phase time accounted for a significant proportion of the official distance variance after controlling for the effects of shoulder-arm separation at right foot down, hip-shoulder separation at left foot down, hip-shoulder separation at release, hip-shoulder separation at left foot off, throwing-arm elevation at right foot off, trunk tilt at maximum backswing, trunk tilt at right foot down, absolute second single support phase time, and absolute release phase time (R^2 change = 0.020, $F_{1,127} = 4.399$, $p = 0.038$).

The shoulder-arm separation at right foot down ($t_{137} = 1.504$, p = 0.135), hip-shoulder separation at left foot off ($t_{134} = -1.784$, p = 0.077), and trunk tilt at right foot down ($t_{131} = -1.825$, p = 0.070) did not make significant individual contributions to the final regression equation. The decision was made to remove these independent variables and perform the multiple regression again, with the remaining predictor variables only. This new linear combination of: hip-shoulder separation at left foot down, throwing arm elevation at maximum backswing, trunk tilt at maximum backswing, trunk tilt at right foot down, the absolute second single support phase time, and the absolute release phase time accounted for 35.4% of the variance in official distance for female discus throwers. The hip-shoulder separation at left foot down and throwing arm elevation at maximum backswing were positively weighted. The trunk tilt at maximum backswing, trunk tilt at right foot down, the absolute second single support phase time, and the absolute release phase time were negatively weighted.

The hip-shoulder separation at left foot down accounted for a significant amount of the official distance variability ($R^2 = 0.066$, $F_{1,136} = 9.615$, $p = 0.002$). The throwing-arm elevation at right foot off accounted for a significant proportion of the official distance variance after controlling for the effects of hip-shoulder separation at left foot down (R^2 change = 0.064, $F_{1,135} = 9.924$, $p = 0.002$). The trunk tilt at maximum backswing accounted for a significant proportion of the official distance variance after controlling for the effects of hip-shoulder separation at left foot down and throwing-arm elevation at right foot off (R^2 change = 0.086, $F_{1,134} = 14.611$, $p < 0.001$). The trunk tilt at right foot down accounted for a significant proportion of the official distance variance after controlling for the effects of hip-shoulder separation at left foot down, throwing-arm elevation at right foot off, and trunk tilt at maximum backswing (R^2 change = 0.029, $F_{1,133} = 5.059$, $p = 0.026$). The absolute second single support phase time accounted for a significant proportion of the official distance variance after controlling for the effects of hip-shoulder separation at left foot down, throwing-arm elevation at right foot off, trunk tilt at maximum backswing, and trunk tilt at right foot down (R^2 change = 0.059, $F_{1,132} = 11.273$, $p = 0.001$). The absolute release phase time accounted for a significant proportion of the official distance variance after controlling for the effects of hip-shoulder separation at left foot down, throwing-arm elevation at right foot off, trunk tilt at maximum backswing, trunk tilt at right foot down, and absolute second single support phase time (R^2 change = 0.051, $F_{1,131} = 10.299$, $p = 0.002$). Each independent variable now made a significant individual contribution to the final regression equation. A summary of the final predictive equation for female discus throwers is presented in Table 6.

Bivariate correlations between the independent variables are displayed in the correlation matrix in Table 7. Two correlations between predictor variables were deemed suggestive of slight multi-colinearity. The zero-order bivariate correlation between hip-shoulder separation at left foot down and release phase time (-0.409) and the zero-order bivariate correlation between second single support phase time and release phase time (r = 0.322). However, both are below the criterion of r = 0.6, so were considered non-problematical. Individual cases were considered outliers if their Mahalanobis distance on the linear composite of the six independent variables was greater than $\chi^2_{(0.0001,\,6)} = 27.856$. No cases exerting undue influence on the model were identified.

A linear combination of: hip-shoulder separation at left foot off, hip-shoulder separation at release, throwing arm elevation at maximum backswing, and trunk tilt at right foot down accounted for 26.0% of the variance in official distance for male discus throwers. The hip-shoulder separation at release, throwing arm elevation at maximum backswing, and trunk tilt at right foot down were positively weighted. The hip-shoulder separation at left foot off was negatively weighted. The hip-shoulder separation at left foot off accounted for a significant amount of the official distance variability ($R^2 = 0.099$, $F_{1,142} = 15.665$, $p < 0.001$). The throwing-arm elevation at maximum backswing accounted for a significant proportion of the official distance variance after controlling for the effects of hip-shoulder separation at left foot off (R^2 change = 0.070, $F_{1,141} = 11.812$, $p = 0.001$). The trunk tilt at right foot down accounted for a significant proportion of the official distance variance after controlling for the effects of hip-shoulder separation at left foot off and throwing-arm elevation at maximum backswing (R^2 change = 0.058, $F_{1,140} = 10.471$, $p = 0.002$). The hip-shoulder separation at release accounted for a significant proportion of the official distance variance after controlling for the effects of hip-shoulder separation at left foot off, throwing-arm elevation at maximum backswing, and trunk tilt at right foot down (R^2 change = 0.034, $F_{1,141} = 6.305$, $p = 0.013$). Each independent variable made a significant individual contribution to the final regression equation. A summary of the full regression equation for male discus throwers is presented in Table 8, with the bivariate correlations between the independent variables shown in the correlation matrix in Table 9. No zero-order bivariate correlation between independent variables was deemed suggestive of multi-colinearity. Individual cases were considered outliers if their Mahalanobis distance on the linear composite of the four predictor variables was greater than $\chi^2_{(0.0001,\,4)} = 23.51$. No cases exerting undue influence on the model were identified.

Canonical Correlation

Two distinct correlations (Pillai's trace = 1.545, $p < 0.001$ for females; Pillai's trace = 1.528, $p < 0.001$ for males) of linear composites of the first group of release characteristics with linear composites of the technical parameters were found for both male and female discus throwers. The first canonical correlation was 0.920 ($F_{87,318} = 5.550$, $p < 0.001$) for females; and 0.912 ($F_{87,336} = 5.540$, $p < 0.001$) for males. The second canonical correlation was 0.675 ($F_{56,214} = 2.130$, $p < 0.001$) for females; and 0.669 ($F_{56,226} = 2.230$, $p < 0.001$) for males. The first canonical correlation was primarily between the height of release and a linear combination of: the throwing arm elevation at release and absolute release phase time (33.012% of variance) for females; and: the hip-shoulder separation at right foot touchdown, hip-shoulder separation at release, shoulder-arm separation at release, and throwing-arm elevation at release (39.558% of variance) for males. The second canonical correlation was primarily between a linear combination of the speed and angle of release and a linear combination of: the hip-shoulder separation at right foot down, hip-shoulder separation at left foot down, trunk tilt at right foot down, throwing-arm elevation at maximum backswing, and throwing-arm elevation at left foot down (33.247% of variance) for females; and: the shoulder-arm separation at right foot off, shoulder-arm separation at left foot down, trunk tilt at right foot down, and absolute second single support phase time (28.618% of variance) for males. The raw and standardized coefficients, and the correlations of the dependent variables and the variates with canonical variables one and two are displayed in Table 10.

Two distinct correlations (Pillai's trace = 1.555, $p < 0.001$ for females; Pillai's trace = 1.527, $p < 0.001$ for males) of linear composites of the second group of release characteristics with linear composites of the technical parameters were found for both male and female discus throwers. The third canonical correlation was 0.920 ($F_{87,318} = 5.593$, $p < 0.001$) for females; and 0.912 ($F_{87,336} = 5.534$, $p < 0.001$) for males. The fourth canonical correlation was 0.678 ($F_{56,214} = 2.175$, $p < 0.001$) for females; and 0.668 ($F_{56,226} = 2.220$, $p < 0.001$) for males. The first canonical correlation was primarily between the height of release and a linear combination of: throwing-arm elevation at release and absolute release phase time (33.120% of variance) for females; and: hip-shoulder separation at right foot down, hip-shoulder separation at release, shoulder-arm separation at release, and throwing-arm elevation at release (40.643% of variance) for males. The fourth canonical correlation was primarily between the vertical component of the discus release velocity, and a linear combination of: hip-shoulder separation at right foot down, hip-shoulder separation at left foot down, trunk tilt at right foot down, throwing-arm elevation at maximum backswing, and throwing-arm elevation at left foot down (34.524% of variance) for females; and: shoulder-arm separation at right foot off, shoulder-arm separation at left foot down, trunk tilt at right foot down, and absolute second single support phase time (28.731% of variance) for males. The raw and standardized coefficients, and the correlations of the dependent variables and the variates with canonical variables three and four are displayed in Table 11.

CHAPTER V

DISCUSSION

The results of the inter-digitizer reliability analysis indicates acceptable reliability when comparing two different digitizers, and that the selection of the critical instants is key when evaluating discus throwing performance at isolated times. The visual, qualitative determination of the critical instants seems to be significantly different for the two different digitizers. The largest differences in technical parameter values occur at the first and last critical instants which are qualitatively determined by visual inspection of the discus - that is maximum backswing and release. Large differences are also observed at right foot down, which is based on foot contact, but the foot is often occluded by the body in both camera views at this point.

The relatively small discrepancies between the values of the release characteristics, which are only calculated based on selection of the instant of release, indicate that there is good agreement between two different digitizers on where to digitize a critical landmark. The small discrepancies are especially impressive when one considers that the resolution of the system, the synchronizing of the 2-D video clips, and the digitizing of the calibration frame also affect the 3-D coordinates of the landmarks. The large mean relative difference for aerodynamic distance is due to its small numeric value (mean of 1.6 m) and its changeable nature based on the formula used in its calculation.

The greater discrepancies observed in the technical parameters highlight the difficulty of needing to twice select an exact critical instant at which to calculate a technical parameter. One determination is made during the synchronization process and one determination is made during the reduction process. The actual critical instant can vary by up to 0.2 seconds due to the sampling rate of 60 Hz. There are difficulties involved in selecting the exact body landmark necessary for digitization, since joint centers, and not points on the surface, were digitized. The absolute mean differences are similar in numeric value to the standard deviations. The greatest differences are found in the shoulder-arm separations. This is probably because the discus is furthest from the center of rotation and has a high velocity of movement, so any discrepancy in frame selection means the discus has traveled further than any other digitized landmark. The differences may be due to errors made during digitizing of the shoulder joint center and discus, which used in the technical parameter calculation. This is unlikely because the throwing-arm elevations have very low absolute differences and the same digitized landmarks were used for calculation of this technical parameter.

These relatively low absolute and relative differences suggest that there is acceptable agreement between the digitizing of two different researchers, and that the comparison of athlete’s techniques across different databases should not lead to any performance differences being observed due to digitizing discrepancy, but are likely to be real, observed differences. This enhances the justification of this method to analyze the real-life techniques of athletes in competition. The two digitizers who participated in this analysis were both using the same equipment for the digitizing and had the same digitizing training. It would be informative to compare the reliability of two digitizers using different equipment, and who had received different training before drawing any firm conclusions about justification. A method of comparing the entire digitizing procedure of two digitizers, possibly by comparing the CMC values of two characteristic curves of discus 3-D coordinates from the same trial, may better reveal any inherent differences.

The screening of the dataset indicated that there was a normal range of values for each technical parameter. The removal of a potentially outlying case raises a question about whether it truly deserved to be deleted, or whether it was in fact a special case the model did not predict well for. In this instance, the outlying values on certain technical parameters are most likely incorrect and not just special cases, since the outlier was often six times as large as the next largest value. It is also physically unlikely to be able to achieve a shoulder-arm separation of 170 degrees at maximum backswing. The deletion of one case in a set of 282 should not cause significant changes to any of the analyses.

The distributions of the technical parameters may suggest that there are a limited number of techniques for throwing the discus. A proportion of the technical parameters appeared to have non-normal distributions, especially in terms of skewness and kurtosis. This may be because in order to throw the discus an athlete must display certain characteristic body positions at specific critical instants. Without these body positions, the technique would simply not work. The relatively normal distributions of most release characteristics support this, since the technical parameters influence the release characteristics. A non-normal technical parameter distribution leading to a more normal release characteristic distribution suggests the range of values for the technical parameter is limited if the necessary release characteristic is to be achieved. The negatively skewed distribution of the speed of release for male discus throwers supports the assertion that the speed of release is critical to their performance. The positively skewed distribution of the speed of release for female discus throwers suggests they utilize other mechanisms to achieve long throws.

Female Regression Equation

The results of the multiple regression show that a linear combination of six key technical parameters can describe female discus throwing performance. Greater performance was associated with greater lead of the hips over the shoulders at left foot down, less throwing-arm elevation at right foot off, a more anterior lean of the trunk at maximum backswing and right foot down, and a shorter time from right foot down to release. A large hip-shoulder separation angle at the end of the flight phase and beginning of the second single support phase was also found by Sušanka *et al.* (1988). This was explained by Hay (1985) as a phenomenon necessary to stretch the trunk rotators to generate pre-delivery torsion. A greater lead of the hips over the shoulders after the flight phase leading to better performance is consistent with data reported by Schlüter and Nixdorf (1984). They found that poor throwers increase discus speed during this phase, and attributed this to a failure to maintain the hip-shoulder separation. The other technical parameters have not been quantitatively studied in previous research.

Each independent variable in the regression equation makes a unique contribution to the explanation of the variation in discus throwing performance. The most powerful independent variables are: hip-shoulder separation at left foot down, which uniquely explains about 40% of the total variation in performance explained by the model, and second single support phase time, which uniquely explains about 26% of the total variation in performance explained by the model. No variable artificially inflates the proportion of variance explained by the model, and no independent variable correlates significantly highly with any other independent variable for multi-colinearity to be a cause for concern. The strongest correlations are between the absolute release phase time, and the absolute second single support phase time and the hip-shoulder separation at left foot down, both of which occur immediately before the release phase, so the correlation is not surprising. The original regression equation included ten independent variables. More independent variables leads to greater redundancies in a model, and in the first model there were four incidents of multi-colinearity. This was reduced to two possible incidents in the second model, and shows that a decrease in the variance accounted for by the model was associated with a gain in parsimony and uniqueness.

Our data show that female discus throwers who maintain a greater lead of the line of their hips over the line of their shoulders to the end of the flight phase tend to throw further. Most female discus throwers release the discus when their arm has traveled past the line of their hips, as can be seen by inspecting the mean values for hip-shoulder and shoulder-arm separation at release. This reduction from a large to a small hip-shoulder separation increases the horizontal path traveled by the discus, increases the time for which force is transmitted from the athlete to the discus, and allows for large magnitude horizontal release velocities to be developed. The force applied to the discus by the athlete is due to the muscular strength of the individual athlete. The applied force can be increased by taking advantage of the elastic properties of muscles by generating pre-delivery torsion (Bartlett, 1992). An initially large hip-shoulder separation may be important to stretch the trunk rotators dynamically (Hay, 1985). Energy stored in the non-contractile element of these muscles can supplement the force applied to the discus and longer throws will be achieved. The critical instant of left foot down being important is indicative of the intuitive greater importance of technique closer to release of the discus.

Our data also show that female discus throwers who minimize the time spent in the power phase tend to throw further. Up to 73% (reported in Bartlett, 1992) of the discus's horizontal release velocity is obtained during the power phase. Athletes who minimize the time spent in this phase of the throwing procedure, who also display large hip-shoulder separations immediately before and who release the discus when their throwing arm has traveled past parallel with the line of their hips must have quickly made large movements to achieve their final body positioning. The short time spent in this phase coupled with the large movement of the throwing arm must be the result of large angular velocities of the throwing arm rotating about the center of the discus thrower. When the discus is released, a proportion of this large angular velocity is transferred to the discus in the form of a large horizontal release velocity. This will result in a large vacuum flight distance, and a long throw.

Our data further suggest that female discus throwers who orient their bodies so that the discus is initially held low at the back of the circle, and who have a more anterior trunk lean just before the flight phase and just before the power phase tend to throw further. The regression coefficient for throwing-arm elevation at right foot off is positively weighted, and the regression coefficients for the trunk tilts at maximum backswing and right foot down are negatively weighted. However, the mean values for the angles at these critical instants are all negative. This means that the athletes who throw furthest tend to hold the discus low at the back of the circle, and have a more anterior trunk lean when facing the back of the circle. This allows the discus to travel from low to high as it is moved from the back to the front of the circle, and for the athletes to progress from forward trunk lean as they face the back of the circle to backwards when they face the intended throwing direction. By doing this, the discus moves through a greater vertical distance during the flight phase and the power phase and will thereby gain greater vertical velocity and height at release. When this technique to increase the vertical release velocity is coupled with the technique to increase the horizontal release velocity, it is possible for elite female discus throwers to simultaneously increase the speed, angle and height of release through effective and efficient technique.

Male Regression Equation

The results of the multiple regression show that a linear combination of four key technical parameters accounts for variance in male discus throwing performance. Greater performance was associated with a smaller lead of the hips over the shoulders at left foot off, less throwing-arm elevation at maximum backswing, a more posterior lean of the trunk at right foot down, and a more parallel release of the discus. A smaller hip-shoulder separation angle at left foot off is consistent with Lindsay (1991) and Sušanka *et al.* (1988). These studies show large variations in hip-shoulder and shoulder-arm separation between athletes during the first double and single support phases, but that most athletes decreased separation during the first single support phase. Our data support the view of Johnson (1985) that large hip-shoulder and shoulder-arm separation is not necessary at this stage because it can be developed during the flight phase and second single support phase, which are closer to the instant of release and, therefore, more important to performance. A more parallel release is in agreement with conclusions drawn by Sušanka *et al.* (1988), Lindsay (1991), and Knicker (1990) who consider optimal technique to be a parallel release. Releases with positive hip-shoulder and shoulder-arm separations were considered to display insufficient utilization of trunk rotation, and releases past parallel to be a technical fault.

Each variable in the regression equation makes a unique contribution to the explanation of the variation in discus throwing performance. The most powerful independent variables are hip-shoulder separation at left foot off, which uniquely explains about 41% of the total variation in performance explained by the model, and throwing-arm elevation at maximum backswing, which uniquely explains about 36% of the total variation in performance explained by the model. No variable artificially inflates the proportion of variance explained by the model, and no independent variable correlates significantly highly with any other independent variable for multi-colinearity to be a cause for concern. The independent variables all appear to be independent of one another.

Our data show that male discus throwers who achieve a more neutral position before the flight phase, i.e. minimal rotation of the torso with the discus held straight out to the side, tend to throw further. This may be to allow them to achieve greater separation between the line of their hips and their throwing arm during the flight phase, which then subsequently decreases at release. The other alternative is that a neutral position during the flight phase is more advantageous to the generation of large release velocities for male discus throwers. By inspecting the mean values for the hip-shoulder and shoulder-arm separations at right foot down, left foot down, and release, the former supposition appears to be the case. This would enable them to supplement the force applied to the discus in the same manner as female discus throwers – by generating pre-delivery torsion. The strong influence of a small hip-shoulder angle at release confirms the importance of a parallel release to maximize the horizontal release velocity.

Our data also suggest that male discus throwers who keep the discus relatively low early in the throwing procedure, and who have a more posterior trunk lean just before the power phase tend to throw further. The regression coefficient for throwing-arm elevation at maximum back swing and for the trunk tilt at right foot down are positively weighted. However, the mean values for the angles at these critical instants are both negative. This means that the athletes who throw furthest tend to hold the discus low early in the throwing procedure, and have more posterior trunk lean after the flight phase. In a similar manner to the female discus throwers, this allows the discus to travel from low to high throughout the throwing procedure, thereby moving the discus through a greater vertical distance during the power phase and increasing the vertical velocity and height at release. However the more sophisticated progression of sequentially alternating the discus from low at the back of the circle to high at the front of the circle as demonstrated by the female discus throwers data does not seem to be as important for male discus throwers. In contrast to females, male discus throwers appear to have a much simpler technique to achieve the longest throws. This may be an indication of their greater reliance on strength than efficient technique to achieve high release speeds, with those males who are able to also incorporate effective body positions able to throw furthest. The fewer key independent variables in the regression equation for male discus throwers is also an indication of a much more standardized technique with small and inconsistent variations between performers.

Inspection of the regression coefficients and means for male and female discus throwers suggests that there is an optimum amount of trunk tilt at the critical instant of right foot down. This tilt is more anterior to that generally displayed by female discus throwers, and more posterior to that currently displayed by male discus throwers. Female discus throwers have an average trunk tilt of -26° at right foot down. However, the regression coefficient for this variable is negatively weighted; suggesting a more positive, or anterior, tilt is associated with better performance. At right foot down, male discus throwers have an average trunk tilt of -10°. Their regression coefficient is positively weighted; suggesting a more negative, or posterior, tilt is associated with better performance. Both regression equations include trunk tilt at right foot down, which indicates that it is a key factor in discus throwing performance. The optimal value is probably between 10° and 26° of posterior trunk tilt.

Female Canonical Correlation

The results of the canonical correlation show that a linear combination of two specific technical parameters are associated with the height of release, and a linear combination of five different technical parameters are associated with a linear combination of the speed and angle of release in general, and the vertical component of velocity specifically.

The linear combination of the throwing-arm elevation angle at release and the release phase time explain about 33% of the variation in the height of release for female discus throwers. The canonical weighting of the release characteristic is positive indicating an increase in this variable. The canonical weightings for the technical parameters are both positive with positive means, demonstrating that increasing either the throwing-arm elevation at release, or the time spent in the release phase of the throwing procedure, or a combination of both will allow females discus throwers to release the discus from a greater height. This makes intuitive sense, because the higher ones arm is and the longer you allow it to increase in elevation must increase the release height. This result is directly applicable, and the recommendation can be made that any athlete can achieve longer throws by increasing the height of release, since this is linearly related to the vacuum flight distance.

The linear combination of the hip-shoulder separation at right foot down and left foot down, the trunk tilt at right foot down, and the arm elevation at maximum backswing and left foot down explain about 33% of the variation in a linear combination of the speed and angle of release, and about 35% of the variation in the vertical component of the release velocity alone. The canonical weighting for the speed and angle of release is positive, indicating an increase in these release characteristics; whereas the canonical weighting for the vertical velocity is negative indicating a decrease in this release characteristic. The same technical parameters correlate with both the increase of speed and angle of release, and with the vertical release velocity, however the direction of the correlations of the technical parameters is opposite for the different release characteristics. The combination of these weightings and directions suggest that vertical release velocity is an important factor differentiating between long throws of female discus throwers. This could be explained by all discus throwers attempting to maximize the horizontal release velocity, since this is the primary determinant of long throws. However, those athletes that throw at a large angle to the horizontal, i.e. with a large vertical release velocity, also increase the angle of release, throw further and perform better. Female discus throwers should concentrate on throwing the discus at a higher angle of release, which should be achieved with a greater vertical release velocity to improve their performances.

The canonical weightings for the technical parameters with the performance improving canonical variate are positive with positive means for the hip-shoulder separations, negative with a negative mean for the trunk tilt, and positive with negative means for the throwing-arm elevation. This gives an indication of possible flaws in female discus throwers techniques, which are causing them to throw the discus at too low an angle of release. To improve performance, they should concentrate on increasing their hip-shoulder separations immediately after the flight phase, as well as increasing their anterior lean immediately after the flight phase, and lowering their throwing arm at the back of the circle.

Male Canonical Correlation

The results of the canonical correlation show that a linear combination of four of the technical parameters are associated with the height of release, and a linear combination of four different technical parameters are associated with a linear combination of the speed and angle of release in general, and the vertical component of velocity specifically.

The linear combination of the hip-shoulder separation at right foot down and release, shoulder-arm separation at release, and throwing-arm elevation angle at release explain about 40% of the variation in the height of release for male discus throwers. The canonical weighting of the release characteristic is positive indicating an increase in this variable. The canonical weightings for the technical parameters are negative with a positive mean for the hip-shoulder separation at right foot down, negative with negative means for the hip-shoulder and shoulder-arm separations at release, and positive with a positive mean for the throwing-arm elevation at release. Thus demonstrating that if male discus throwers wish to increase their height of release, they should decrease the amount trunk rotation at the end of the flight phase, increase the hip-shoulder and shoulder-arm separations at release, which in this case means releasing before the arm travels past parallel. Knicker (1990) and Lindsay (1991) both suggested that release of the discus when the throwing arm has traveled past parallel may be both a sign of flawed technique, and a reliance on arm strength. These results corroborate their findings. Male discus should also increase their throwing-arm elevation at release, which again makes intuitive sense, because the higher ones arm is the greater the release height is, and the recommendation can again be made that any athlete can achieve longer throws by increasing the height of release, since this is linearly related to the vacuum flight distance.

The linear combination of the shoulder-arm separation at right foot off and left foot down, the trunk tilt at right foot down, and the second single support phase time explain about 29% of the variation in a linear combination of the speed and angle of release, and about 29% of the variation in the vertical component of the release velocity alone. The canonical weighting for the speed and angle of release, and for the vertical release velocity is positive, indicating an increase in these release characteristics associated with the appropriate combination of technical parameters, which correlate with both the increase of speed and angle of release, and with the vertical release velocity. These weightings, correlations, and directions suggest that vertical release velocity is an important factor differentiating between long throws of male discus throwers. This can also be explained by male discus throwers attempting to maximize the horizontal release velocity, since this is the primary determinant of long throws. However, those athletes that throw at a large angle to the horizontal, i.e. with a large vertical release velocity, also increase the angle of release, throw further and perform better. Male discus throwers should concentrate on throwing the discus at a higher angle of release by achieving a greater vertical release velocity.

The canonical weightings for the technical parameters on the performance improving canonical variate are negative with a positive mean for the shoulder-arm separation at right foot off, negative with a negative mean for the shoulder-arm separation at left foot down, positive with a negative mean for the trunk tilt at right foot down, and negative with a positive mean for the second single support phase time. This indicates there are possible flaws in male discus throwers techniques, which cause them to throw the discus at too low an angle of release. To improve performance, they should concentrate on decreasing their shoulder-arm separations before the flight phase, then increase their posterior lean and increase their shoulder-arm separations immediately after the flight phase, and shorten the time they spend in the second single support phase time.

Limitations

The following limitations should be kept in mind when interpreting the results of this study. Although male and female discus throwers were analyzed separately in an attempt to limit the effects of the physical strength of the athletes on discus throwing performance, the individual strength of each athlete was a variable not controlled for, and is likely to be especially important for elite male throwers. The analyses performed were cross sectional in nature, however multiple trials from individual athletes were included in an effort to maintain the large sample size, which is a major advantage of this database. The effects of training and experience cannot be determined. The univariate distributions of the technical parameters and release characteristics were not normal, which may influence the results of this study, however the magnitude is difficult to determine. The statistical analyses performed investigated linear relationships between the technical parameters and discus throwing performance. No provision is included in them for any non-linear relationships that may be present between variables, so any non-linear correlations may go unnoticed. The canonical correlation analyses should be considered exploratory in nature, and results arising from them are open to different interpretations than the ones presented here. A line for future study is the use of structural equation modeling in a longitudinal study design to confirm or reject the proposed relationships between the technical parameters and allow a specific, directed training program to be developed for individuals, or groups of discus throwers.

Conclusions

The following conclusions can be drawn from the results of this study:

1. Specific techniques exist for throwing the discus, which can be described by combinations of technical parameters.
2. Key technical parameters can be used to explain variation in discus throwing performance.
3. Specific discus throwing techniques appear to be different for male and female discus throwers. Female discus throwers use a more sophisticated technique to simultaneously generate large vertical and horizontal release velocities, whereas male discus throwers seem to have a less variable technique and may place more reliance on physical strength to achieve long distances.
4. Vertical release velocity may be the primary determinant of the difference in performance of athletes with similar horizontal release velocities. To improve performance both male and female discus throwers should concentrate on generating large vertical release velocities, while maintaining their horizontal release velocities, however the mechanism to achieve this is different for male and female discus throwers.

Table 1: Reliability Statistics

Variable	Mean	S.D.	Mean Absolute Difference	Mean Relative Difference (%)
Official Distance (m)	61.36	1.67	0	0
Flight Distance (m)	60.1	2.8	5.7	9.39
Aerodynamic Distance (m)	1.6	3.2	5.5	234.18
Horizontal Discus Velocity at Release (m/s)	19.9	0.8	1.3	6.58
Vertical Discus Velocity at Release (m/s)	14.2	0.5	0.4	3.24
Resultant Discus Speed at Release (m/s)	24.5	0.6	1.4	5.52
Height of Discus at Release (m)	1.7	0.1	0.1	4.45
Angle of Release (°)	36	2	1	2.60
Hip-Shoulder Separation at Maximum Backswing (°)	105	5	16	15.02
Hip-Shoulder Separation at Right Foot Off (°)	21	4	6	18.83
Hip-Shoulder Separation at Left Foot Off (°)	29	7	4	14.71
Hip-Shoulder Separation at Right Foot Down (°)	51	11	8	14.76
Hip-Shoulder Separation at Left Foot Down (°)	62	28	0	0.17

Hip-Shoulder Separation at Release (°)	-14	3	3	14.11
Shoulder-Arm Separation at Maximum Backswing (°)	16	14	11	111.03
Shoulder-Arm Separation at Right Foot Off (°)	19	6	4	13.17
Shoulder-Arm Separation at Left Foot Off (°)	5	21	0	8.07
Shoulder-Arm Separation at Right Foot Down (°)	9	18	5	34.20
Shoulder-Arm Separation at Left Foot Down (°)	24	10	5	26.52
Shoulder-Arm Separation at Release (°)	-9	8	0	82.84
Trunk Tilt at Maximum Backswing (°)	5	-4	7	29.61
Trunk Tilt at Right Foot Off (°)	26	-5	3	18.81
Trunk Tilt at Left Foot Off (°)	6	3	2	11.65
Trunk Tilt at Right Foot Down (°)	11	2	13	201.06
Trunk Tilt at Left Foot Down (°)	4	-7	2	9.07
Trunk Tilt at Release (°)	10	-1	1	35.38
Arm Elevation at Maximum Backswing (°)	4	14	2	13.89
Arm Elevation at Right Foot Off (°)	-17	5	0	2.54

Arm Elevation at Left Foot Off (°)	-13	6	2	19.64
Arm Elevation at Right Foot Down (°)	-3	5	0	20.11
Arm Elevation at Left Foot Down (°)	-16	6	2	12.29
Arm Elevation at Release (°)	8	2	3	40.84
First Double Support Phase Time (s)	0.82	0.14	0.01	0.79
First Single Support Phase Time (s)	0.38	0.01	0.00	1.11
Flight Phase Time (s)	0.09	0.01	0.00	2.61
Second Single Support Phase Time (s)	0.16	0.03	0.01	5.47
Release Phase Time (s)	0.22	0.02	0.01	2.99

Table 2: Discus Throwing Descriptive Statistics

	Female			Male		
Variable	Range	Mean	S.D.	Range	Mean	S.D.
Official Distance (m)	26.53	57.13	5.03	18.49	59.86	3.90
Flight Distance (m)	32.2	54.5	5.66	30.7	58.1	4.9
Aerodynamic Distance (m)	31.3	2.9	5.41	26.2	2.0	4.1
Horizontal Discus Velocity at Release (m/s)	7.0	18.7	1.35	5.6	19.2	1.1
Vertical Discus Velocity at Release (m/s)	8.4	13.8	1.40	7.5	14.3	1.1
Resultant Discus Speed at Release (m/s)	6.6	23.3	1.19	5.9	23.9	1.0
Height of Discus at Release (m)	0.7	1.6	0.13	0.9	1.8	0.1
Angle of Release (°)	23	36	4	19	37	3
Hip-Shoulder Separation at Max Backswing (°)	122	77	23	126	95	23
Hip-Shoulder Separation at Right Foot Off (°)	93	26	15	80	29	15
Hip-Shoulder Separation at Left Foot Off (°)	109	31	16	73	37	16
Hip-Shoulder Separation at Right Foot Down (°)	89	44	15	95	50	17
Hip-Shoulder Separation at Left Foot Down (°)	93	47	18	91	54	18

Hip-Shoulder Separation at Release (°)	70	-12	14	76	-14	13
Shoulder-Arm Separation at Max Backswing (°)	116	54	17	88	36	18
Shoulder-Arm Separation at Right Foot Off (°)	105	35	16	72	35	14
Shoulder-Arm Separation at Left Foot Off (°)	86	22	19	93	25	20
Shoulder-Arm Separation at Right Foot Down (°)	82	26	17	94	25	17
Shoulder-Arm Separation at Left Foot Down (°)	70	43	12	65	36	13
Shoulder-Arm Separation at Release (°)	65	-7	14	68	-7	10
Trunk Tilt at Max Backswing (°)	52	-30	11	46	-20	9
Trunk Tilt at Right Foot Off (°)	68	-7	18	69	-7	20
Trunk Tilt at Left Foot Off (°)	92	13	22	73	3	23
Trunk Tilt at Right Foot Down (°)	91	-26	18	88	-10	28
Trunk Tilt at Left Foot Down (°)	50	11	9	48	13	11
Trunk Tilt at Release (°)	50	-5	9	44	-5	10
Arm Elevation at Max Backswing (°)	136	-1	15	81	-10	19
Arm Elevation at Right Foot Off (°)	72	-18	8	43	-18	7

Arm Elevation at Left Foot Off (°)	67	-10	11	42	-15	8
Arm Elevation at Right Foot Down (°)	53	5	11	46	-2	9
Arm Elevation at Left Foot Down (°)	76	-4	13	67	-13	12
Arm Elevation at Release (°)	39	7	7	41	9	7
First Double Support Phase Time (s)	0.49	0.53	0.10	0.62	0.60	0.13
First Single Support Phase Time (s)	0.31	0.44	0.05	0.21	0.38	0.04
Flight Phase Time (s)	0.17	0.09	0.03	0.18	0.09	0.04
Second Single Support Phase Time (s)	0.18	0.19	0.03	0.20	0.19	0.04
Release Phase Time (s)	0.13	0.18	0.03	0.16	0.20	0.03
Time for Throwing Procedure (s)	0.57	1.43	0.12	0.72	1.46	0.14
Relative First Double Support Phase Time (s)	0.22	0.37	0.04	0.24	0.41	0.05
Relative First Single Support Phase Time (s)	0.16	0.30	0.03	0.14	0.26	0.03
Relative Flight Phase Time (s)	0.13	0.06	0.02	0.15	0.06	0.03
Relative Second Single Support Phase Time (s)	0.14	0.14	0.02	0.15	0.13	0.03
Relative Release Phase Time (s)	0.09	0.13	0.02	0.12	0.13	0.02

Table 3: Female Discus Thrower’s Official Distance and Release Characteristics Correlation Matrix.

	Official Distance	Horizontal Discus Velocity at Release	Vertical Discus Velocity at Release	Resultant Discus Speed at Release	Height of Discus at Release	Angle of Release
Official Distance	1.000					
Horizontal Discus Velocity at Release	0.156	1.000				
Vertical Discus Velocity at Release	0.422	-0.255	1.000			
Resultant Discus Speed at Release	0.434	0.727	0.475	1.000		
Height of Discus at Release	-0.008	-0.192	0.164	-0.036	1.000	
Angle of Release	0.233	-0.701	0.867	-0.024	0.225	1.000

Table 4: Male Discus Thrower’s Official Distance and Release Characteristics Correlation Matrix.

	Official Distance	Horizontal Discus Velocity at Release	Vertical Discus Velocity at Release	Resultant Discus Speed at Release	Height of Discus at Release	Angle of Release
Official Distance	1.000					
Horizontal Discus Velocity at Release	0.287	1.000				
Vertical Discus Velocity at Release	0.443	-0.187	1.000			
Resultant Discus Speed at Release	0.534	0.776	0.472	1.000		
Height of Discus at Release	0.106	-0.211	0.296	-0.008	1.000	
Angle of Release	0.157	-0.700	0.831	-0.095	0.332	1.000

Table 5: Official Distance and Technical Parameters Bivariate Correlations.

Variable	Official Distance	
	Female	Male
Hip-Shoulder Separation at Max Backswing	-0.034	-0.020
Hip-Shoulder Separation at Right Foot Off	0.038	-0.105
Hip-Shoulder Separation at Left Foot Off	-0.089	**-0.324**
Hip-Shoulder Separation at Right Foot Down	-0.014	-0.042
Hip-Shoulder Separation at Left Foot Down	**0.257**	0.037
Hip-Shoulder Separation at Release	**0.205**	0.130
Shoulder-Arm Separation at Max Backswing	0.044	**-0.221**
Shoulder-Arm Separation at Right Foot Off	-0.096	-0.132
Shoulder-Arm Separation at Left Foot Off	0.161	0.046
Shoulder-Arm Separation at Right Foot Down	0.173	0.026
Shoulder-Arm Separation at Left Foot Down	0.157	0.009
Shoulder-Arm Separation at Release	0.163	0.086
Trunk Tilt at Max Backswing	**-0.272**	-0.187
Trunk Tilt at Right Foot Off	-0.114	-0.099
Trunk Tilt at Left Foot Off	0.051	-0.019
Trunk Tilt at Right Foot Down	**-0.232**	0.167
Trunk Tilt at Left Foot Down	0.002	-0.047
Trunk Tilt at Release	-0.198	-0.067
Arm Elevation at Max Backswing	**0.220**	**0.322**
Arm Elevation at Right Foot Off	**0.256**	0.037
Arm Elevation at Left Foot Off	0.028	0.019
Arm Elevation at Right Foot Down	0.126	0.010
Arm Elevation at Left Foot Down	0.134	-0.121
Arm Elevation at Release	-0.093	0.084
First Double Support Phase Time	0.155	0.107
First Single Support Phase Time	0.110	-0.118
Flight Phase Time	0.111	0.091
Second Single Support Phase Time	**-0.266**	-0.190
Release Phase Time	-0.120	-0.130
Time for Throwing Procedure	0.094	0.005
Relative First Double Support Phase Time	0.173	0.158
Relative First Single Support Phase Time	0.036	-0.086
Relative Flight Phase Time	0.086	0.095
Relative Second Single Support Phase Time	**-0.298**	-0.158
Relative Release Phase Time	-0.174	-0.147

Table 6: Female Discus Thrower’s Regression Equation.

Variable	Regression Coefficient	Standard Error	t	p	Partial Correlation	Part Correlation	Unique Explanation (%)	Tolerance
Constant	67.967	4.146	16.394	0.000				
Hip-Shoulder Separation at Left Foot Down	0.118	0.022	5.311	0.000	0.421	0.373	39.261	0.799
Arm Elevation Angle at Right Foot Off	0.096	0.046	2.057	0.042	0.177	0.144	5.887	0.916
Trunk Tilt Angle at Maximum Backswing	-0.094	0.035	-2.703	0.008	-0.230	-0.190	10.167	0.868
Trunk Tilt Angle at Right Foot Down	-0.043	0.021	-2.083	0.039	-0.179	-0.146	6.039	0.940
Second Single Support Phase Time	-49.508	11.455	-4.322	0.000	-0.353	-0.303	26.002	0.883
Release Phase Time	-49.638	15.467	-3.209	0.002	-0.270	-0.225	14.336	0.699

Table 7: Female Discus Thrower's Regression Equation Zero-Order, Bivariate Correlation Matrix.

	Hip-Shoulder Separation at Left Foot Down	Arm Elevation at Right Foot Off	Trunk Tilt at Max Backswing	Trunk Tilt at Right Foot Down	Second Single Support Phase Time	Release Phase Time
Hip-Shoulder Separation at Left Foot Down	1.000					
Arm Elevation at Right Foot Off	-0.141	1.000				
Trunk Tilt at Maximum Backswing	-0.099	0.090	1.000			
Trunk Tilt at Right Foot Down	0.069	-0.057	-0.220	1.000		
Second Single Support Phase Time	-0.183	0.123	-0.102	-0.066	1.000	
Release Phase Time	-0.409	0.250	-0.173	-0.042	0.322	1.000

Table 8: Male Discus Thrower’s Regression Equation.

Variable	Regression Coefficient	Standard Error	t	p	Partial Correlation	Part Correlation	Unique Explanation (%)	Tolerance
Constant	3.478	0.179	19.384	0.000				
Hip-Shoulder Separation at Left Foot Off	-0.017	0.004	-4.499	0.000	-0.356	-0.328	41.417	0.965
Arm Elevation at Maximum Backswing	0.014	0.003	4.199	0.000	0.335	0.306	36.078	0.963
Trunk Tilt at Right Foot Down	0.007	0.002	3.116	0.002	0.255	0.227	19.867	0.959
Hip-Shoulder Separation at Release	0.011	0.005	2.511	0.013	0.208	0.183	12.904	0.963

Table 9: Male Discus Thrower's Regression Equation Zero-Order, Bivariate Correlation Matrix.

	Hip-Shoulder Separation at Left Foot Off	Arm Elevation at Max Backswing	Trunk Tilt at Right Foot Down	Hip-Shoulder Separation at Release
Hip-Shoulder Separation at Left Foot Off	1.000			
Arm Elevation at Maximum Backswing	0.030	1.000		
Trunk Tilt at Right Foot Down	0.046	0.188	1.000	
Hip-Shoulder Separation at Release	-0.181	0.009	-0.069	1.000

Table 10: Canonical Correlations for Release Characteristic Set One with Technical Parameters.

Canonical Correlation	Female				Male			
Variable	Root 1 Raw Coeff.	Root 1 Corr.	Root 2 Raw Coeff.	Root 2 Corr.	Root 1 Raw Coeff.	Root 1 Corr.	Root 2 Raw Coeff.	Root 2 Corr.
Speed of Release	-0.037	-0.078	**0.491**	**0.567**	-0.090	-0.113	**0.761**	**0.719**
Angle of Release	-0.039	0.083	**0.217**	**0.810**	**0.042**	**0.445**	**0.256**	**0.584**
Height of Release	**7.410**	**0.989**	-0.168	0.142	**6.539**	**0.988**	-1.683	-0.005
Hip-Shoulder Separation at Max Backswing	0.004	0.155	0.011	-0.094	0.007	-0.058	0.003	-0.009
Hip-Shoulder Separation at Right Foot Off	0.000	0.141	-0.012	-0.026	-0.001	-0.110	-0.014	-0.033
Hip-Shoulder Separation at Left Foot Off	-0.005	0.031	-0.009	-0.121	0.002	-0.016	-0.015	-0.226
Hip-Shoulder Separation at Right Foot Down	-0.005	0.054	**0.017**	**0.337**	**-0.004**	**-0.329**	0.009	0.174
Hip-Shoulder Separation at Left Foot Down	-0.010	0.220	**0.019**	**0.298**	-0.011	-0.014	0.012	0.191
Hip-Shoulder Separation at Release	0.008	0.115	0.004	0.157	**0.004**	**-0.391**	0.018	0.248
Shoulder-Arm Separation at Max Backswing	0.009	0.055	0.009	-0.002	0.011	0.163	0.026	-0.022
Shoulder-Arm Separation at Right Foot Off	-0.002	-0.075	0.000	-0.102	-0.001	0.051	**-0.034**	**-0.370**
Shoulder-Arm Separation at Left Foot Off	-0.001	-0.224	0.002	0.040	-0.010	0.120	-0.014	-0.106
Shoulder-Arm Separation at Right Foot Down	-0.003	-0.185	-0.004	0.121	0.002	0.188	0.000	-0.212
Shoulder-Arm Separation at Left Foot Down	-0.013	-0.205	-0.003	0.134	0.002	0.151	**-0.011**	**-0.415**
Shoulder-Arm Separation at Release	0.002	-0.266	0.002	0.044	**0.005**	**-0.307**	0.016	0.233

Trunk Tilt Angle at Max Backswing	-0.003	0.177	0.030	-0.212	0.008	0.009	0.026	-0.051
Trunk Tilt at Angle Right Foot Off	-0.003	0.107	-0.016	-0.233	0.004	0.114	-0.014	-0.099
Trunk Tilt at Angle Left Foot Off	0.001	-0.023	-0.005	-0.066	-0.003	0.019	0.012	-0.079
Trunk Tilt at Angle Right Foot Down	0.005	-0.088	**-0.011**	**-0.332**	0.004	0.130	**0.016**	**0.328**
Trunk Tilt at Angle Left Foot Down	-0.029	-0.270	0.020	-0.039	-0.006	-0.035	0.030	0.218
Trunk Tilt at Angle Release	0.000	0.017	-0.054	-0.287	-0.010	-0.245	-0.013	-0.085
Arm Elevation Angle at Maximum Backswing	-0.006	-0.051	**0.025**	**0.402**	0.012	0.068	0.022	0.028
Arm Elevation Angle at Right Foot Off	0.019	0.012	-0.019	0.113	-0.012	-0.229	-0.012	-0.147
Arm Elevation Angle at Left Foot Off	-0.014	-0.074	0.005	-0.202	0.007	0.187	-0.055	-0.122
Arm Elevation Angle at Right Foot Down	-0.006	-0.078	-0.001	0.244	0.002	0.118	0.032	0.148
Arm Elevation Angle at Left Foot Down	-0.011	-0.173	**0.054**	**0.355**	0.012	0.072	-0.010	0.045
Arm Elevation Angle at Release	**0.109**	**0.870**	0.061	0.175	**0.136**	**0.932**	0.026	0.006
First Double Support Phase Time	-0.189	-0.008	2.462	0.156	0.721	-0.257	0.281	0.141
First Single Support Phase Time	2.459	-0.122	3.608	0.167	0.816	-0.265	-0.928	-0.277
Flight Phase Time	-2.608	-0.071	5.877	0.236	0.859	-0.039	-13.867	0.136
Second Single Support Phase Time	-7.487	-0.032	3.265	-0.176	1.394	-0.090	**-12.659**	**-0.417**
Release Phase Time	**19.460**	**0.351**	-34.711	-0.077	6.846	0.221	-15.420	-0.033

Table 11: Canonical Correlations for Release Characteristic Set Two with Technical Parameters.

Canonical Correlation	Female				Male			
Variable	Root 3 Raw Coeff.	Root 3 Corr.	Root 4 Raw Coeff.	Root 4 Corr.	Root 3 Raw Coeff.	Root 3 Corr.	Root 4 Raw Coeff.	Root 4 Corr.
Horizontal Discus Release Velocity	0.025	-0.126	-0.075	0.158	**-0.134**	**-0.359**	0.239	0.133
Vertical Discus Release Velocity	-0.100	0.017	**-0.726**	**-0.995**	**0.027**	**0.339**	**0.924**	**0.919**
Height of Release	**7.394**	**0.989**	0.034	-0.143	**6.537**	**0.988**	-1.792	-0.007
Hip-Shoulder Separation at Max Backswing	0.003	0.114	-0.011	0.091	0.007	-0.058	0.002	-0.011
Hip-Shoulder Separation at Right Foot Off	0.000	0.141	0.013	0.035	-0.001	-0.110	-0.015	-0.036
Hip-Shoulder Separation at Left Foot Off	-0.005	0.032	0.010	0.125	0.003	-0.016	-0.015	-0.224
Hip-Shoulder Separation at Right Foot Down	-0.005	0.055	**-0.017**	**-0.325**	**-0.005**	**-0.329**	0.008	0.173
Hip-Shoulder Separation at Left Foot Down	-0.010	0.220	**-0.018**	**-0.290**	-0.011	-0..14	0.012	0.194
Hip-Shoulder Separation at Release	0.008	0.115	-0.004	-0.148	**0.004**	**-0.391**	0.018	0.250
Shoulder-Arm Separation at Max Backswing	0.009	0.054	-0.009	-0.005	0.011	0.162	0.025	-0.025
Shoulder-Arm Separation at Right Foot Off	-0.002	-0.075	0.000	0.109	-0.001	0.052	**-0.034**	**-0.368**
Shoulder-Arm Separation at Left Foot Off	-0.001	-0.225	-0.004	-0.048	-0.010	0.119	-0.014	-0.105
Shoulder-Arm Separation at Right Foot Down	-0.003	-0.186	0.005	-0.123	0.002	0.188	0.000	-0.209
Shoulder-Arm Separation at Left Foot Down	-0.013	-0.206	0.004	-0.136	0.002	0.150	**-0.011**	**-0.415**
Shoulder-Arm Separation at Release	0.002	-0.265	0.000	-0.038	**0.005**	**-0.307**	0.018	0.243

Trunk Tilt at Max Backswing	-0.003	0.179	-0.028	0.223	0.007	0.008	0.026	-0.050
Trunk Tilt at Right Foot Off	-0.003	0.106	0.016	0.229	0.004	0.114	-0.014	-0.101
Trunk Tilt at Left Foot Off	0.001	-0.022	0.005	0.072	-0.003	0.019	0.013	-0.074
Trunk Tilt at Right Foot Down	0.005	-0.087	**0.013**	**0.353**	0.004	0.130	**0.016**	**0.327**
Trunk Tilt at Left Foot Down	-0.029	-0.270	-0.018	0.025	-0.006	-0.035	0.029	0.215
Trunk Tilt at Release	0.000	0.018	0.053	0.290	-0.010	-0.245	-0.014	-0.094
Arm Elevation Angle at Maximum Backswing	-0.006	-0.052	**-0.025**	**-0.412**	0.012	0.068	0.021	0.021
Arm Elevation Angle at Right Foot Off	0.018	0.011	0.017	-0.122	-0.012	-0.230	-0.009	-0.140
Arm Elevation Angle at Left Foot Off	-0.014	-0.075	-0.005	0.187	0.007	0.188	-0.057	-0.122
Arm Elevation Angle at Right Foot Down	-0.006	-0.078	0.002	-0.248	0.002	0.120	0.034	0.159
Arm Elevation Angle at Left Foot Down	-0.011	-0.174	**-0.055**	**-0.368**	0.012	0.072	-0.010	0.044
Arm Elevation Angle at Release	**0.110**	**0.870**	-0.059	-0.171	**0.137**	**0.932**	0.027	0.008
First Double Support Phase Time	-0.192	-0.008	-2.478	-0.155	0.732	-0.257	0.281	0.141
First Single Support Phase Time	2.454	-0.123	-3.686	-0.179	0.820	-0.266	-1.076	-0.277
Flight Phase Time	-2.587	0.071	-5.848	-0.232	0.853	-0.037	-13.647	0.149
Second Single Support Phase Time	-7.466	-0.031	-3.221	0.186	1.368	-0.091	**-12.596**	**-0.424**
Release Phase Time	**19.407**	**0.350**	33.542	0.063	6.784	0.220	-15.212	-0.033

Figure 1: Discus Throwing Distances.

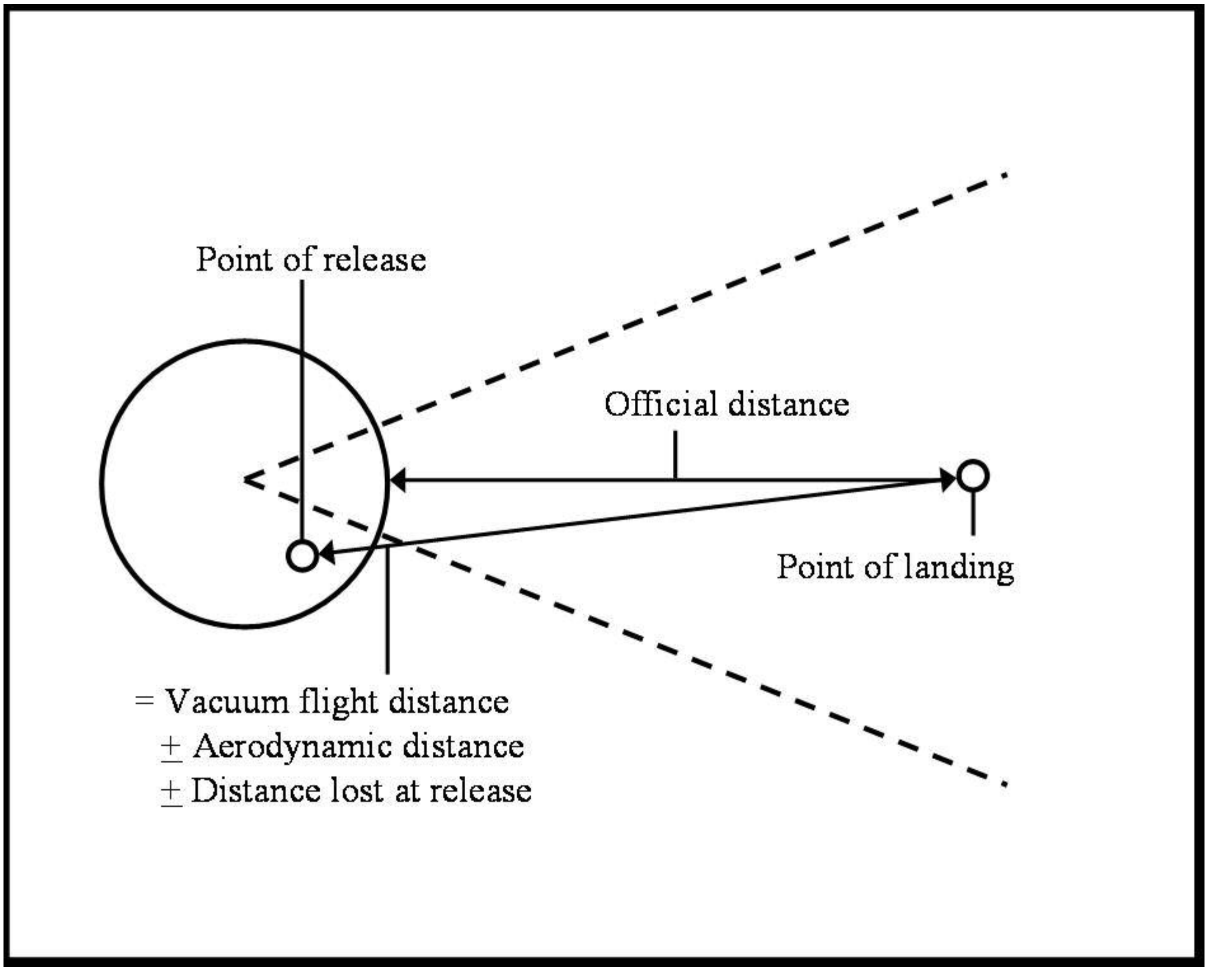


Figure 2: Angle of Attack. This is defined as the angle between the wind velocity vector and the discus's longitudinal-lateral plane.

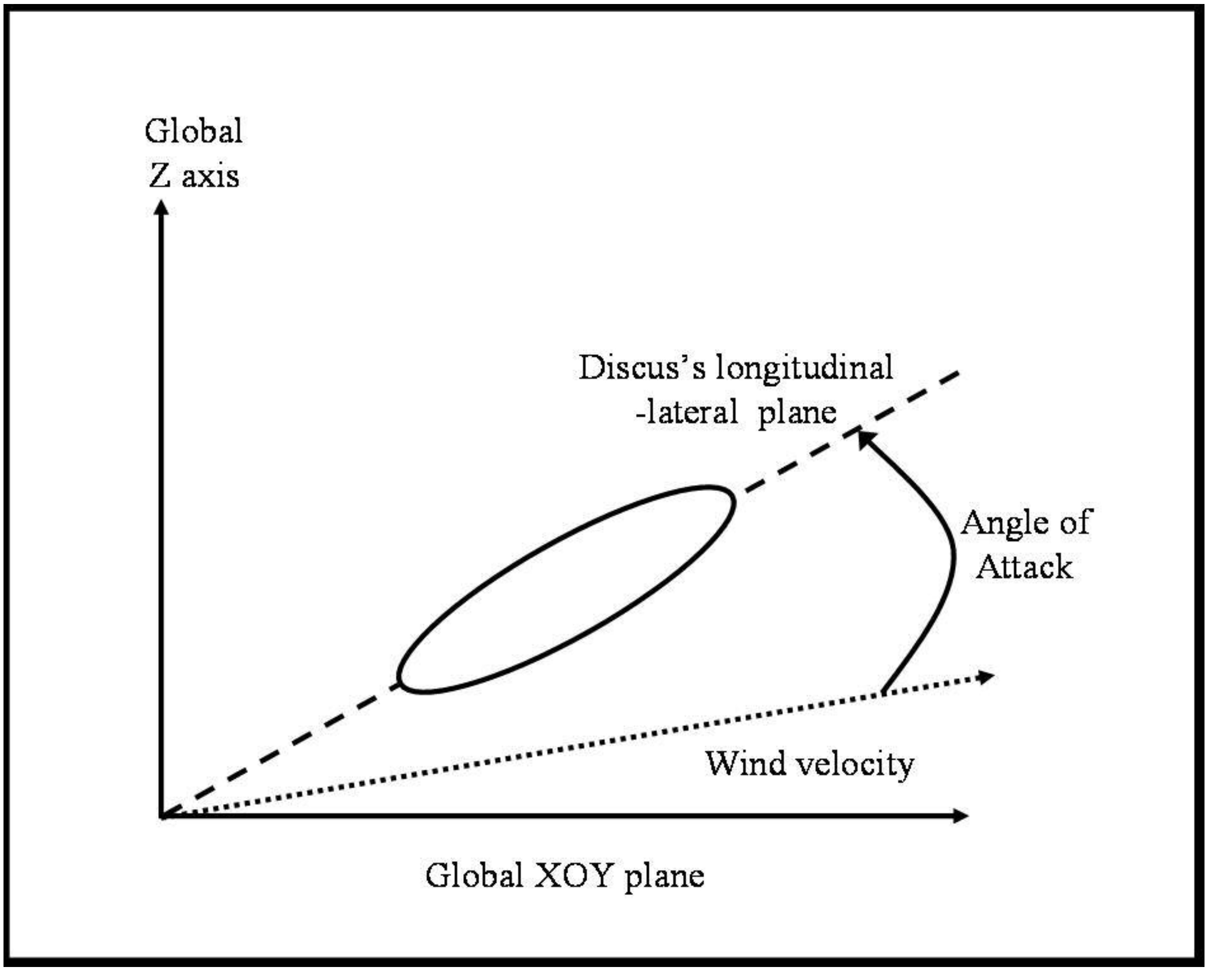


Figure 3: Discus in Cross-Section. Note the symmetry about a longitudinal-lateral plane through the centre of the discus.

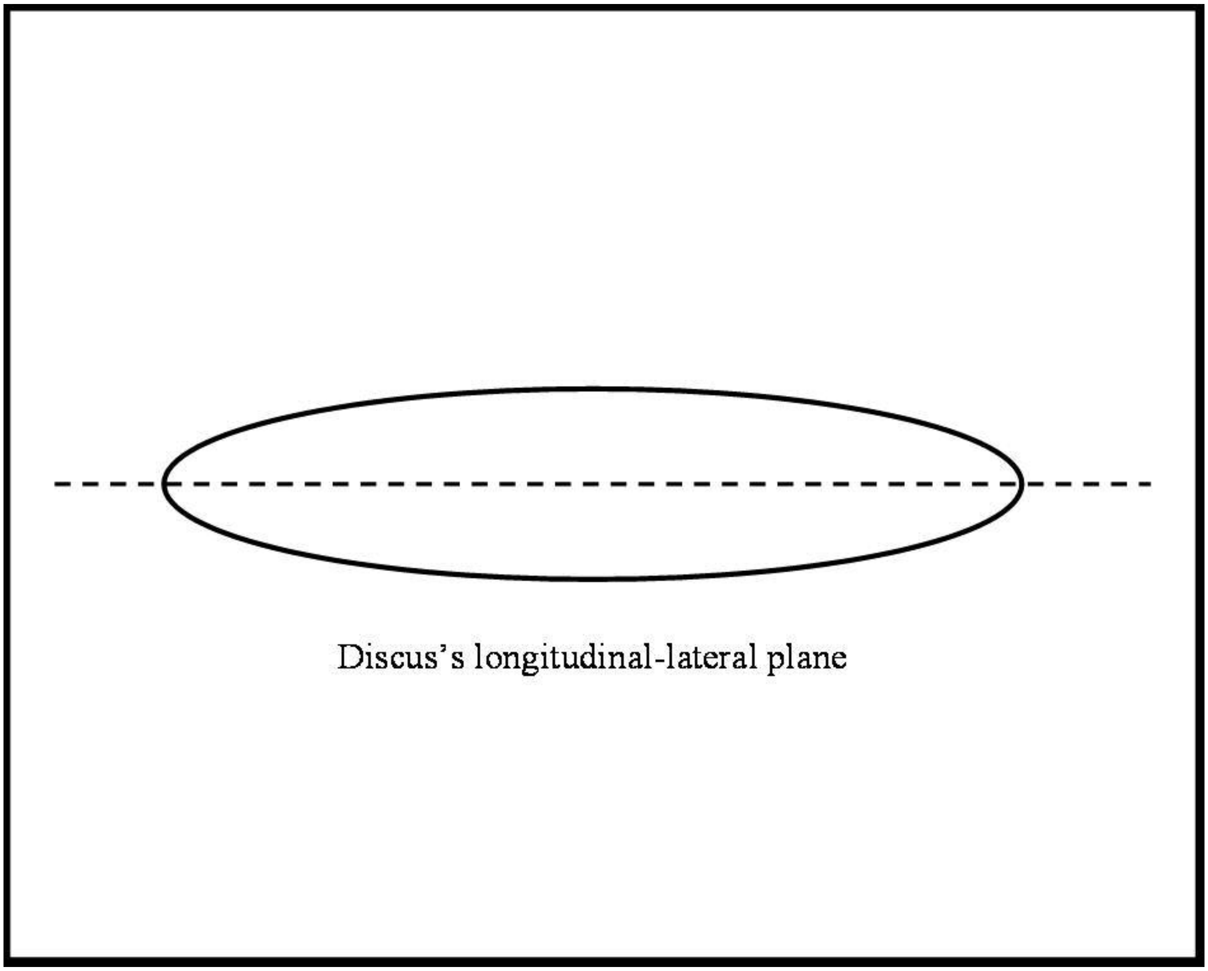


Figure 4: Definition of the Hip-Shoulder Separation Angle. This angle is calculated as the angle between the vector joining the right and left hip joint centers, and the vector joining the right and left shoulder joint centers in the XY plane of the trunk reference frame at each critical instant.

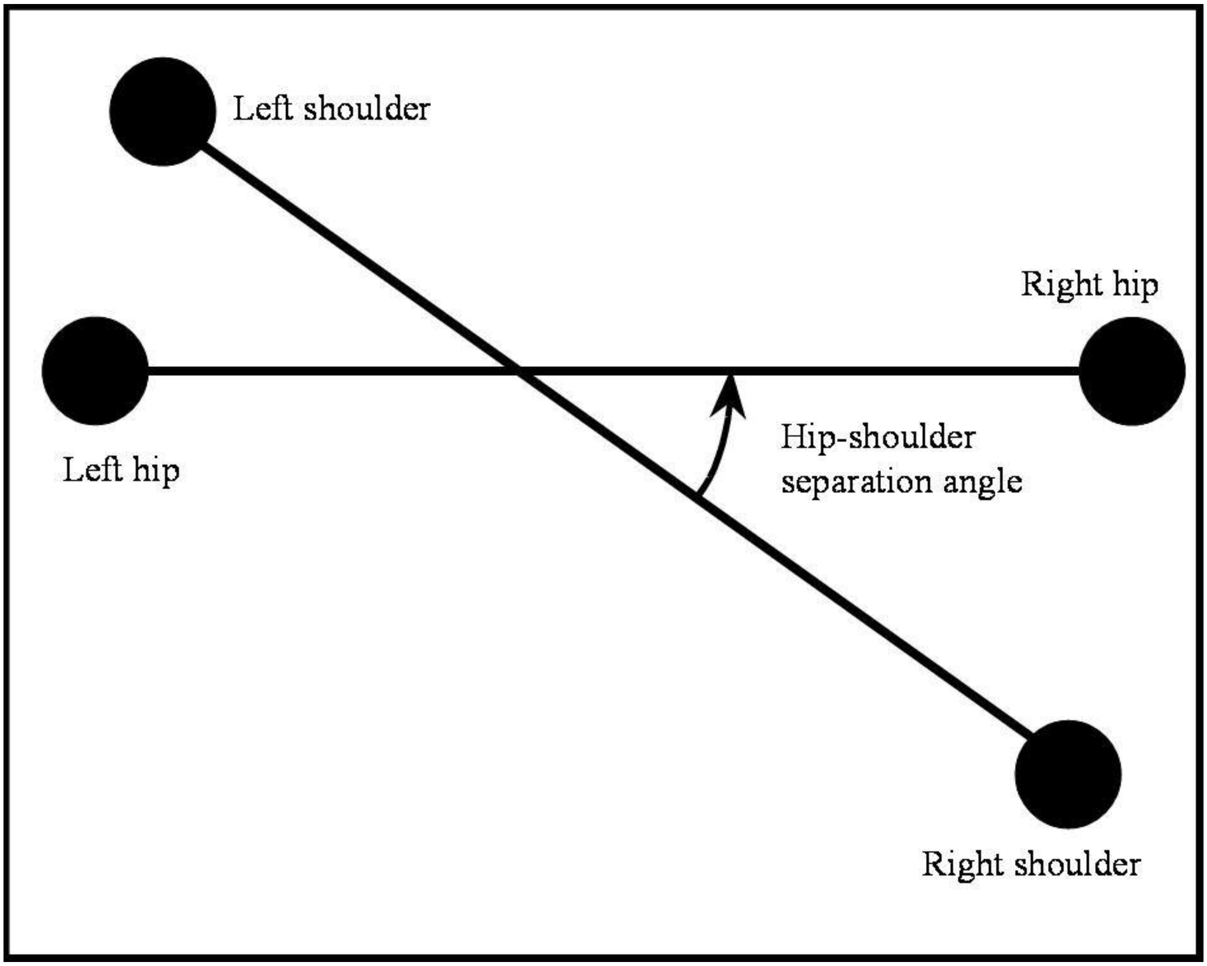


Figure 5: Definition of the Shoulder-Arm Separation Angle. This angle is calculated as the angle between the vector joining the right and left shoulder joint centers, and the vector joining the right shoulder joint center and the center of the discus in the XY plane of the trunk reference frame at each critical instant.

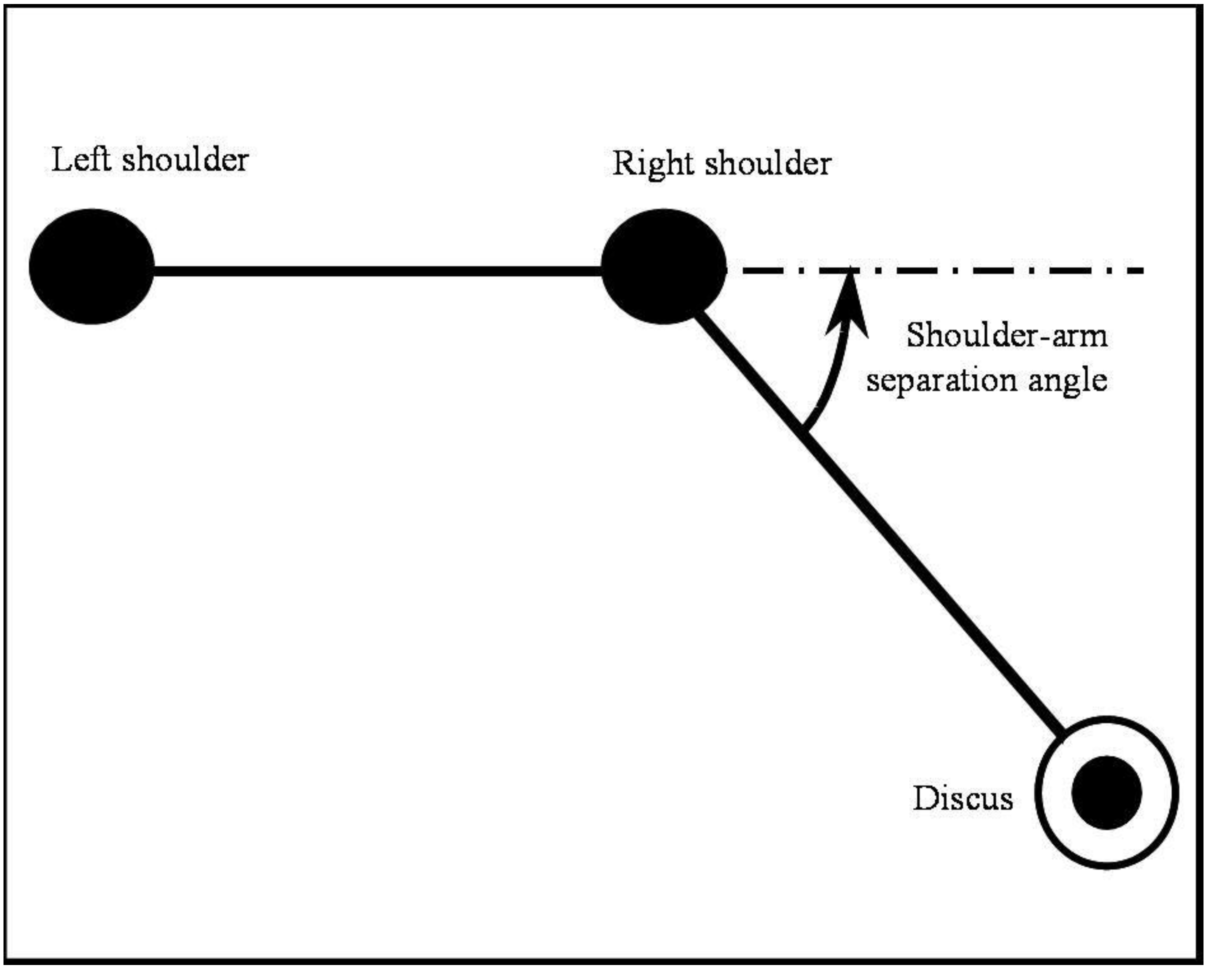


Figure 6: Definition of the Throwing Arm Elevation Angle. This angle is calculated as the angle between the vector joining the right shoulder joint center and the center of the discus, and the global XOY plane at each critical instant.

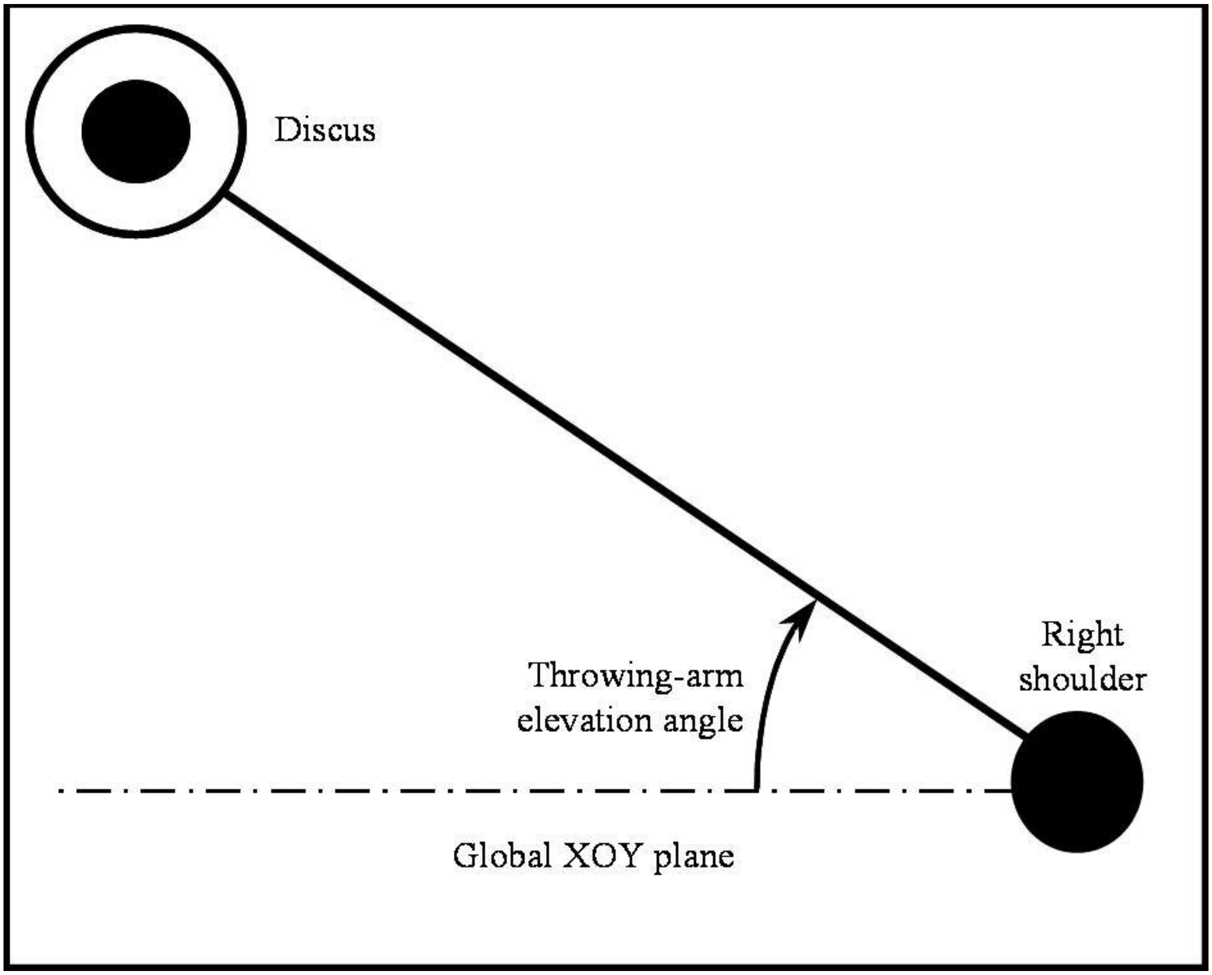


Figure 7: Definition of the Trunk Tilt Angle. This angle is calculated as the angle between the vector joining midpoint of the hip joint centers and the midpoint of the right and left shoulder joint centers, and the YZ axis of the hip reference frame in the hip reference frame at each critical instant.

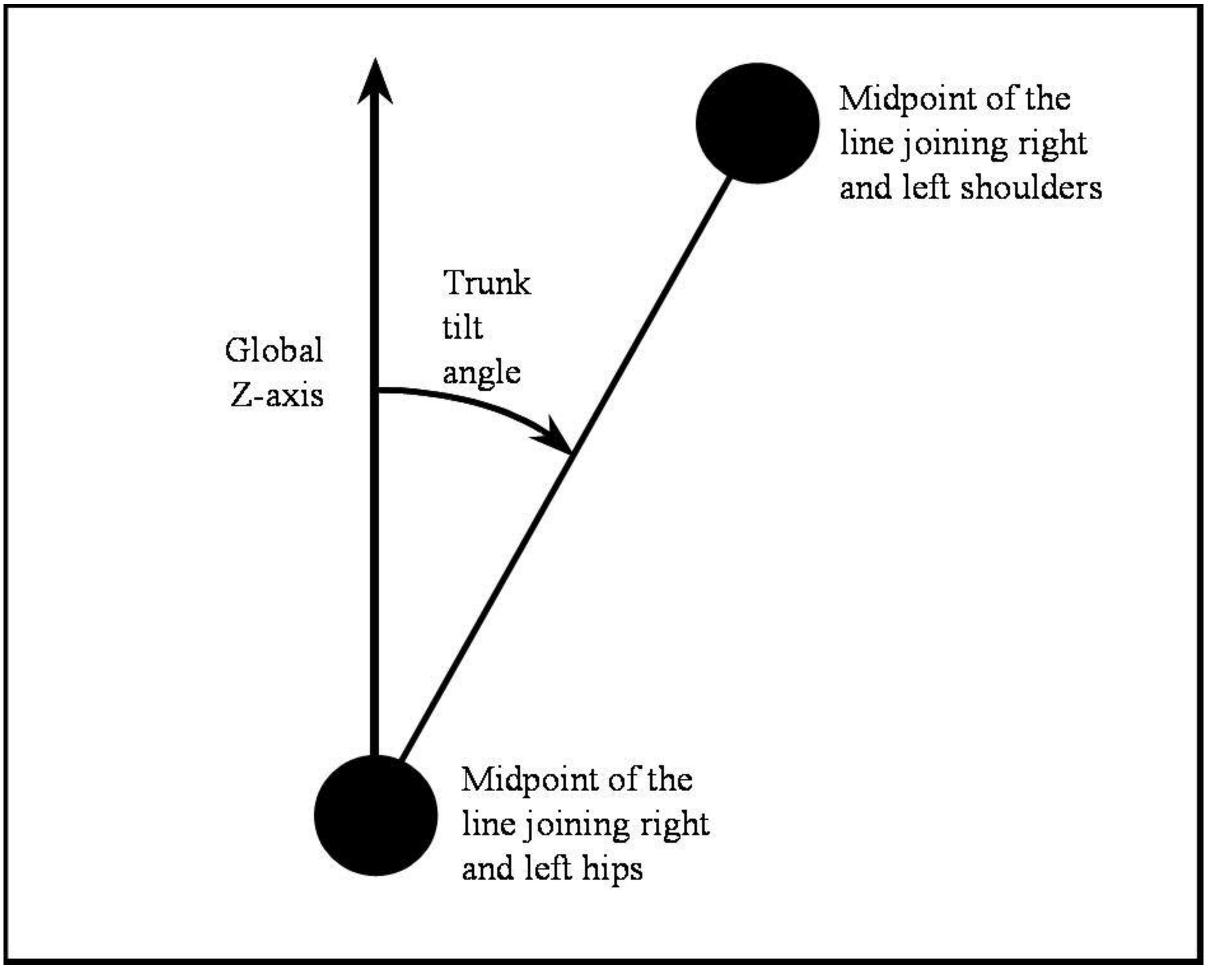


Figure 8: Deterministic Discus Throwing Performance Model.

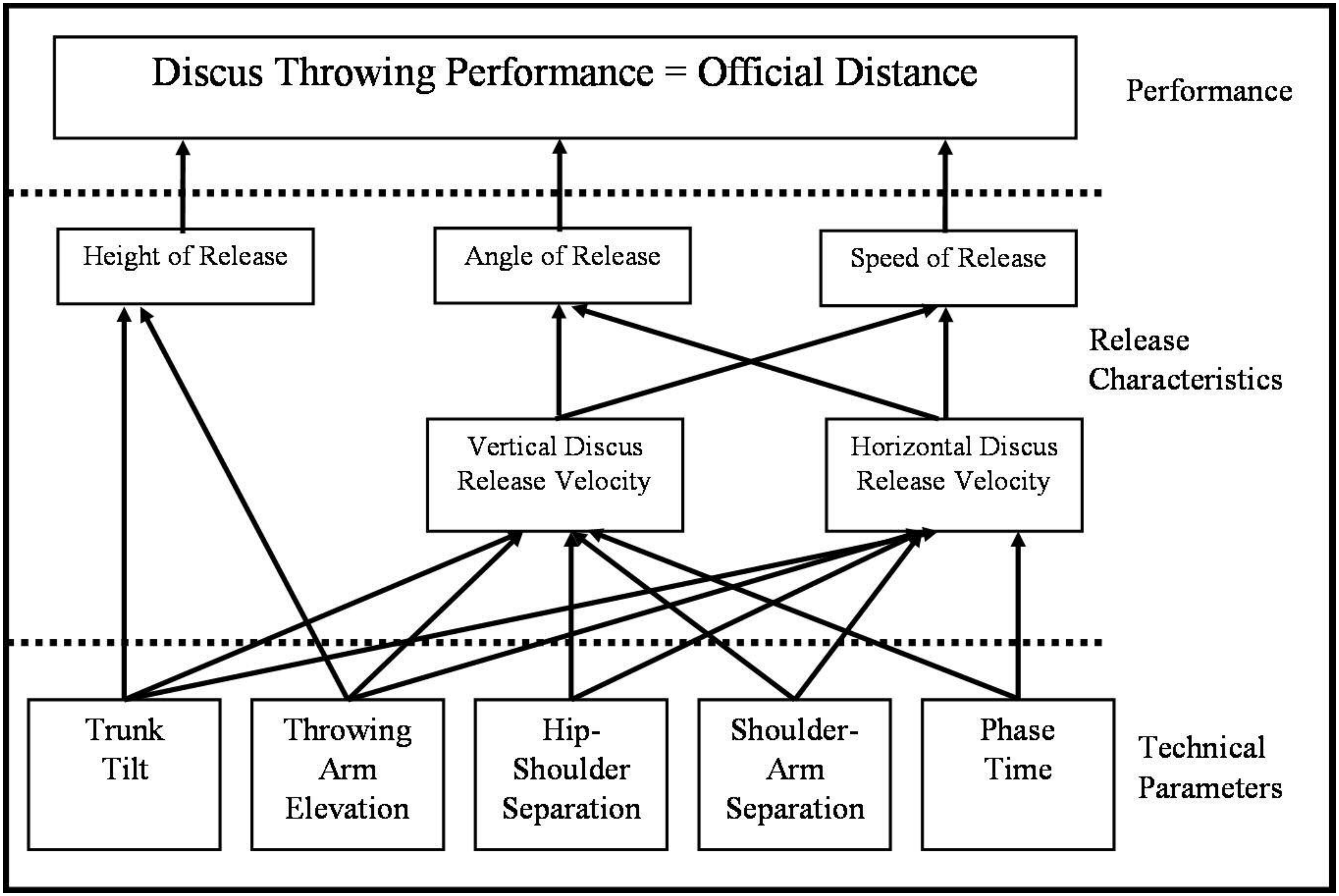


Figure 9: Positioning of Camcorders Relative to the Discus Throwing Circle and Global Reference Frame. The positive X-direction is the same as the intended throwing direction.

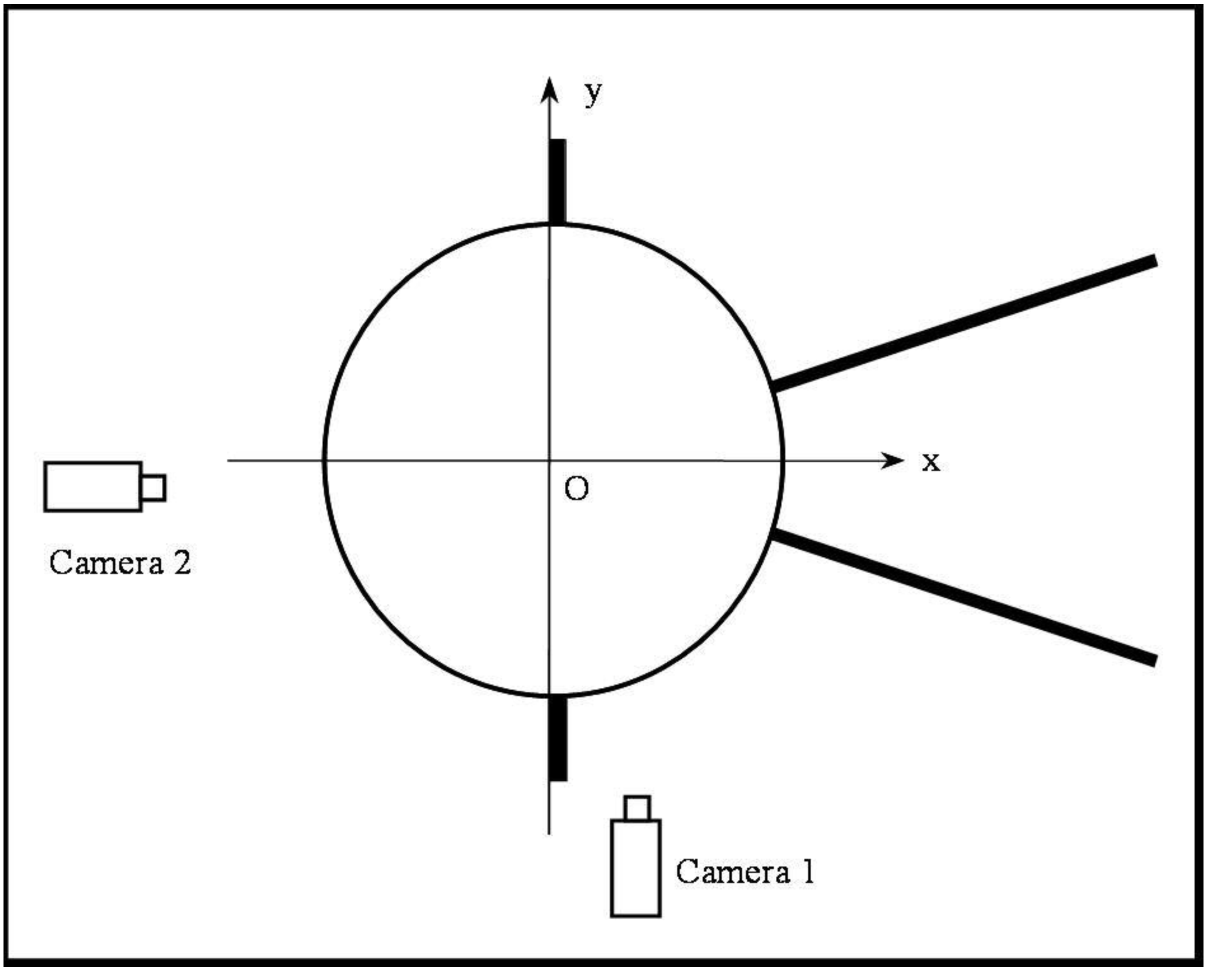


Figure 10: Twenty-Four Point Calibration Frame.

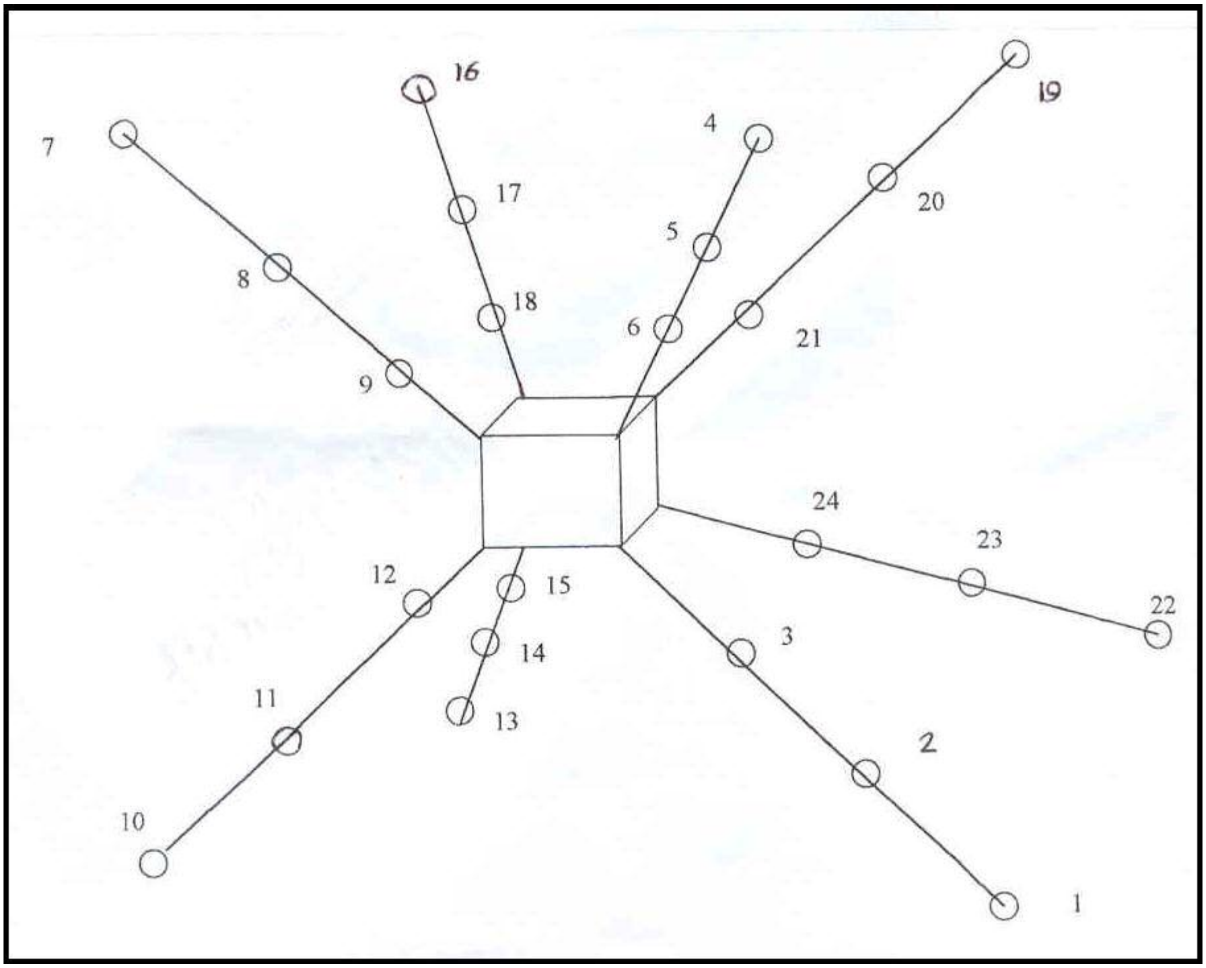
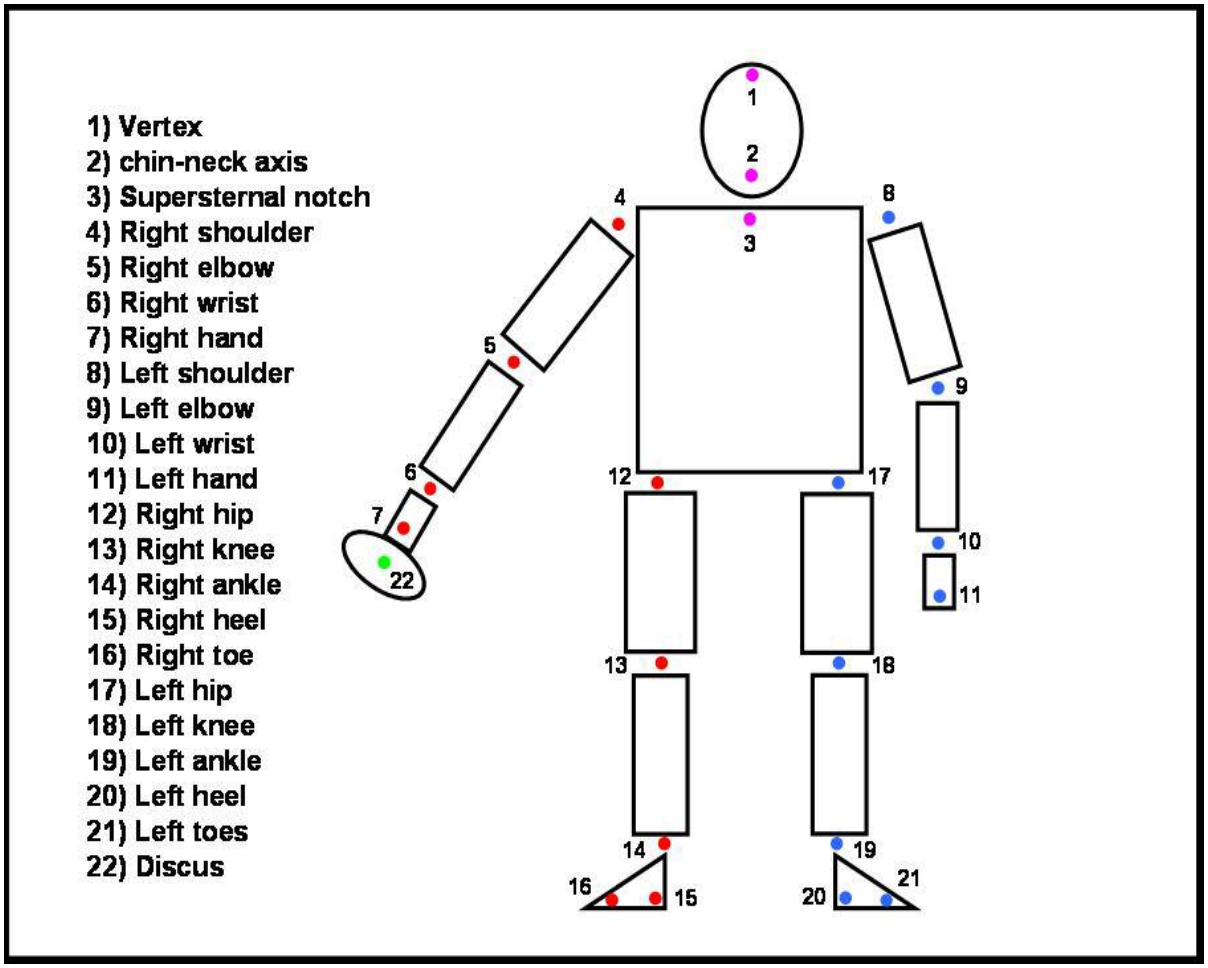


Figure 11: Critical Landmarks Digitized for each Throw.



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