A Kinetic Analysis of Discus-Throwing Techniques

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ABSTRACT

The purposes of this study were to investigate (1) the relationships between official distance and selected ground reaction measures during discus throwing; and (2) the relationships between selected ground reactions and selected lower extremity joint kinetics. Three high-speed video cameras and three force plates were used to collect three-dimensional videographic and force plate data in this study. An inverse dynamic model was used to determine the lower extremity kinetics. Multiple regression analyses were conducted to determine relationships of the selected kinematic and kinetic measures with the official distance. Official distance was significantly correlated with ground reaction forces on the left foot during the first single-support phase, on the right foot during the second single-support phase and delivery phase, and on the left foot during the delivery phase. Also, the right-hip extension and internal rotation moments and left-knee extension moment during the delivery phase were significantly correlated with official distance. These results suggest that discus throwers should drive vigorously forward during the first single-support phase and increase the landing impact force on the right foot after flight. Also they should increase forward and rightward ground reaction force on the right foot and backward and vertical force on the left foot by powerful right-hip extension and internal rotation and left-knee extension during the delivery phase. These results provide critical information regarding the training of discus-throwing techniques, and the direction of future biomechanical studies on this event.

INTRODUCTION

Discus throwing is one of the four throwing events in track and field (Figure 1). Complicated movements performed at high speed in a limited space make the discus throw technically and physically very demanding. Thus, the discus throw requires thorough biomechanical analysis to have a good understanding of the techniques and training of elite discus throwers. However, a recent extensive

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Figure 1 Discus throw. For a right-handed athlete, a discus throw has six critical instants: (1) maximum back swing, (2) right-foot takeoff, (3) left-foot takeoff, (4) right-foot touchdown, (5) left-foot touchdown, and (6) release. These six critical instants divided a discus throw into five critical phases: (1) initial double support, (2) first single support, (3) flight, (4) second single support, and (5) delivery.

A review of literature revealed that, although there are many debates on different aspects of the techniques of throwing the discus, the biomechanical studies on this topic are very limited. The primary reason for this is the lack of biomechanical studies appears to be the complexity of the technique of throwing the discus. Because of the complexity of the techniques, three-dimensional image analysis techniques are essential for kinematic analysis, multiple force plates are required for kinetic analysis, and sophisticated data reduction techniques are needed to obtain meaningful biomechanical parameters.

The ultimate goal of the technique in each throwing event is to obtain the maximum speed and optimum height and angle of release, which are key factors influencing the throwing distance. Several studies have been conducted to investigate the optimum release condition of the discus (Terauds, 1978; Gregor et al., 1985; McCoy et al., 1985; Stepanek and Susanka 1986; Hay and Yu, 1995a). The minimum measured speed of release of the discus for an official distance over 60 m was 23.5 m/s. The results of multiple regression analysis (Hay and Yu, 1995a) indicate that only the speed of release made a significant contribution to the prediction of the official distance. The possible reasons for the
lack of contribution of the release angle to the prediction of the official distance include a small range of the variation and possible non-linear relationship between official distance and selected kinematic variables. The lack of contribution of the release height to the prediction of the official distance is likely due to a lack of normalisation of the release height to the standing height.

To reveal the techniques used by elite discus throwers to obtain a high release speed, Hay and Yu (1995a) analysed the contributions of the increases in the speed of the discus during different phases to the official distance. Their results indicated that the increases in the speed of the discus during the initial double-support phase and delivery phase (Figure 1) have a significant influence on the official distance for male throwers, and that the increases in the speed of the discus during the flight phase and the delivery phase have a significant influence on the official distance for female throwers. Their results as well as those of other studies do not support the claim in coaching literature that there is a need for a smooth and continuous acceleration of the discus through the entire throwing procedure (Burke, 1988; Silvester, 1988).

In coaching literature, the foot placement and duration of foot contact with the ground during the delivery phase (Figure 1) are two technical considerations that are believed to have a significant influence on the official distance. However, Hay and Yu (1996) did not find any significant correlation between these two factors and the official distance. Their results do not support the correct foot placement described in textbooks nor maintaining foot contact with the ground during the second double-support phase as pre-requisites of success in throwing the discus.

In another study (Hay and Yu, 1995b), it was also found that a wide leg swing during the first single-support phase (Figure 1) significantly contributes to the angular momentum of the thrower-and-discus system at the takeoff to the flight phase, and thus to the official distance, especially for female throwers. These results support the use of wide leg swing techniques.

Ground reaction force data in the discus throw were collected in two studies (Bartlett et al., 1991; Hoffmann, 1990). The ground reaction force data collected by Hoffmann (1990) showed some differences in the ground reaction forces between model and flawed techniques. These results indicate a possibility to use force plate data as quick feedback to detect technical problems in throwing the discus. However, none of the two studies revealed the segment movements that caused the differences in the ground reaction forces. This lack of connection between the kinematics and kinetics limited the application of the results of those studies.

The purposes of this study were to investigate (1) the relationships between official distance and selected ground reaction measures during discus throwing; and (2) the relationships between selected ground reaction measures and selected lower extremity joint kinetics. An understanding of the relationship between official distance and ground reaction measures is essential for applications of force plates as a training tool in discus throw training. An understanding of the relationship between ground reaction measures and lower extremity joint kinetics may provide critical information for technical and physical training for discus throwers.
METHODS

Data Collection

Subjects
The subjects in this study were eight male discus throwers in a 1998 discus throw training camp held at the Olympic Training Center in San Diego. Standing height, body mass, and the personal record were obtained from each subject (Table 1).

Table 1 Subject Information and Trials Used for Analysis

<table>
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<tr>
<th>Subject No.</th>
<th>Body Mass (kg)</th>
<th>Standing Height (m)</th>
<th>Personal Record (m)</th>
<th>1st Single Support</th>
<th>2nd Single Support</th>
<th>Delivery</th>
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Videographic and Force Plate Data Collection

The Direct Linear Transformation (DLT) procedure (Abdel-Aziz and Karara, 1971) was used to collect three-dimensional (3-D) coordinates of 21 body landmarks and the centre of the discus for each subject in each trial. Three time-synchronised S-VHS video cameras were used to record the control object and the performances of the subjects at a frame rate of 60 frame/second. The cameras were placed around the discus circle a 120° angle between the optical axes of every two adjacent cameras (Figure 2). Three Kistler force plates (Model 9287) were placed in the discus circle in an I-formation (Figure 2) to collect ground reaction force data for the left foot during the first double-support phase, for the right foot during the second single-support phase, and both feet during the final delivery phase at a sampling frequency of 1000 Hz. Five reference marks were placed on the force plates to assist in translating the locations of the center of pressure to the global reference frame (Figure 2). The global reference was defined in such a way that the x-axis pointed in the throwing direction, the y-axis pointed in the left side of the thrower when the thrower was facing the throwing direction, and the z-axis pointed upwards (Figure 2). The force plates were time-synchronised with the video cameras using a manually controlled electric impulse.
Figure 2 Setups for video cameras, force plates, and global reference frame. Three force plates (FP-1, FP-2, and FP-3) were used to collect ground reaction force data. Five global reference markers (M-1, M-2, M-3, M-4, and M-5) were used to define the global reference frame.

Experiment Protocol

Each subject was instructed to throw the discus at maximal effort in each trial. The starting position was adjusted by having the subject move left or right from his usual starting position so that he can place his left foot on Force Plate 1 (Figure 2) to start throwing. Videographic and force plate data were collected for three trials with this starting position. The starting position was then adjusted again in a similar manner for each subject to place his right foot on Force Plate 2 and left foot on Force Plate 3 (Figure 2) after the flight. Videographic and force plate data were collected for three legal trials with the second starting position. Each subject had a total of six legal trials in which videographic and force plate data were successfully collected. Although every effort was made to have each subject place his feet on the desired force plates in each trial without changing
their usual techniques, only a few trials were obtained in which subjects placed their feet on more than one of the desired force plates (Table 2).

Data Reduction

The videotape records of the control object and each successful trial were digitised with the aid of a S-VHS videocassette recorder, a 14-inch color monitor, a micro-computer, and PEAK5 computer software (Peak Performance Technologies, Denver, CO). The DLT parameters for each camera were estimated from the digitised control object coordinates, and optimised using a MSDLT computer program package, version 4.0 (MotionSoft, Chapel Hill, NC). All real-life 3-D coordinates were converted from the control object reference frame to the global reference frame.

The record of each successful trial from each camera was digitised at a sampling rate of 60 frame/second from two fields before the maximum backward swing to two fields after the release of the discus. In each digitised field, 21 body landmarks defining a 14-segment model of the human body (Clauser et al., 1969) and the centre of the discus were digitised. The digitised 2-D video coordinate data from the two cameras and the ground reaction force data were mathematically synchronised using critical events such as the landing or takeoff of a foot. The real-life 3-D coordinates of the 21 body landmarks and the centre of the discus were estimated from the synchronised 2-D video coordinate data and DLT parameters. The estimated real-life 3-D coordinate data were smoothed using a second-order Butterworth digital filter (Winter et al., 1974). The optimum cut-off frequency was estimated from the sampling frequency (Yu et al., 1999). All data synchronisation, DLT transformation, and data smoothing were performed using the MSDLT computer program package, version 4.0 (MotionSoft, Chapel Hill, NC).

Ground Reaction Forces and Impulses

Digital data from the three force plates were time-synchronised with the videographic data and converted to ground reaction forces. Free moment and the locations of centre of pressure were estimated and transfer to the global reference frame. Peak forward-backward and left-right ground reaction forces were normalised to gravitational force and referred to as peak forward-backward and left-right ground reaction driving forces. Peak vertical ground reaction driving forces during the first single-support phase, landing after the flight, and the second single-support phase were determined by subtracting the gravitational forces and then normalised to gravitational force. The peak vertical ground reaction force on the left during the delivery phase was normalised to the gravitational force. Normalised ground reaction impulses were determined by integrating the corresponding normalised ground reaction forces over time. All ground reaction force data reduction and normalisation were performed using the MSFPT computer program package, version 2.0 (MotionSoft, Chapel Hill, NC).
Segment Models

Each upper extremity segment was defined as a single rigid body connecting its proximal joint centre to its distal joint centre. The trunk reference frame was defined using the two hip-joint centres and suprasternal notch with the x-axis pointing forward, y-axis pointing to the left, s-axis pointing from the mid-point between the hips to the suprasternal notch, and origin at the mid-point between the hip-joint centres. The thigh reference frame was defined using the hip-, knee-, and ankle-joint centres with the x-axis pointing forward, y-axis pointing to the left, z-axis pointing from the knee to the hip, and the origin at the knee. The shank reference frame was defined using the hip-, knee-, and ankle-joint centres with the x-axis pointing forward, y-axis pointing to the left, and z-axis pointing from the ankle to the knee, and the origin at the ankle. The foot reference frame was defined using the toe-, heel-, and ankle-joint centre with x-axis pointing from heel to the toe, y-axis pointing to the left, and z-axis pointing upwards.

The relative mass and relative location of the centre of mass of each segment were determined using the segment inertial data of Clauser et al. (1969) modified by Hinrichs (1990). The moments of inertia about the three principal axes of each segment were determined using the segment inertial data of Whitsett (1963). All the segment inertial data were corrected to total body mass and standing height (Dapena, 1978).

Linear Kinematics

The locations of the centre of mass of each segment, the whole body, and the body-plus-discus system in each field before the release were determined using the anthropometry data of Clauser et al. (1969). The velocity of the centre of mass of each segment, the centre of the discus, the whole body, and the body-plus-discus system before the release were determined using a central finite difference method.

Angular Momentum

The angular momentum of each segment, the whole body, the discus, and the body-plus-discus system in each field before the release were determined using a method described by Dapena (1978). The rotation of each non-trunk segment about its longitudinal axis was neglected in this calculation. The error in the estimated angular momentum due to this negligence is not significant (Dapena, 1978).

Joint Resultant Moments

The joint resultant moments at knees and hips during the first single-support, second single-support, and delivery phases were estimated using an inverse dynamic procedure (Greenwood, 1988) instrumented in the MSKin computer program package, version 4.0 (MotionSoft, Chapel Hill, NC). Segment angular
velocities used in this inverse dynamic procedure were estimated using a procedure described by Dapena (1978). The estimated joint resultant force vectors and moment vectors in the global reference frame were transformed to a lower extremity reference frame defined by the thigh and the lower leg. The component of a joint resultant moment vector perpendicular to the plane defined by the thigh and the lower leg was referred to as the flexion-extension moment. The component of a joint resultant moment vector parallel to the thigh or lower leg was referred to as the internal-external rotation moment. The component of a joint resultant moment vector perpendicular to both flexion-extension and internal-external rotation moment vectors was referred to as the abduction-adduction moment.

Data Normalisation

Ground reactions, joint resultants, and their impulses were normalised to fully reflect the technique characteristics, instead of anthropometric characteristics, represented by these parameters. Ground reaction forces were normalised to subject’s body weight. Angular momentum data were normalised to the product of each subject’s weight and height. Linear and angular impulses were also normalised to subject’s body weight and height.

Data Analysis

The trial with the longest official distance in which the subject placed one of his feet on the desired force plate was used in the analysis of the effects of the ground reactions from that force plate on official distance. A linear regression analysis was conducted to determine the relationships between selected kinetic measures and official distance with a regression model in the form:

\[ d_o = a_0 + a_1 x + e \]

Where \( d_o \) is the official distance; \( x \) is a given ground reaction measure; \( e \) is regression residual (error); and \( a_0 \) and \( a_1 \) are regression coefficients. The selected kinetic measures include normalised peak values and impulse of ground reaction forces, and knee- and hip-joint resultant moments during the first single-support, second single-support, and delivery phases. Eighteen regression analyses were performed for relationships between official distance and (1) peak ground reaction force and (2) ground reaction force impulse. A regression analysis was performed for relationships between official distance and peak vertical impact force on the right foot at right landing after the flight. Twelve regression analyses were performed for relationships between official distance and joint resultant moments. Additional regression analyses were performed for relationships between (a) ground reaction forces and impulses, (b) joint resultant moments and ground reaction forces, and (c) joint resultant moments and ground reaction impulses based on the outcome of the 31 initial regression analyses. A total of 51 regression analyses were actually performed. A Type I error rate of 0.1 was chosen to indicate statistical significance after considering the possible consequences of
Type I and Type II errors. All statistical analyses were conducted using the SYSTAT computer program package, version 5.0 (SYSTAT, Evanston, IL).

RESULTS
The Effects of Ground Reaction Forces on Performance

The normalised forward ground reaction impulse on the left foot during the first single-support phase also had significant correlation with the official distance (Figure 3a). This relationship indicates that the greater this impulse, the longer the official distance. The normalised peak forward ground reaction force and the normalised forward ground reaction impulse on the left foot during the first single-support phase were significantly correlated (Figure 3b). This relationship indicates that the greater the normalised peak forward ground reaction force, the greater the normalised ground reaction impulse.

![Graph](image)

**Figure 3** The relationships between (a) normalised forward ground driving impulse on the left foot and official distance, and (b) normalised peak forward ground reaction driving force on the left foot during the first single-support phase and its impulse.
The vertical ground reaction impulse on the left foot during the first single-support phase had significant correlation with the official distance (Figure 4). This relationship indicates that the greater the vertical ground reaction impulse on the left foot during the first single-support phase, the longer the official distance.

**Figure 4** The relationship between normalised vertical ground reaction driving impulse on the left foot during the first single-support phase and official distance.

The vertical ground reaction impulse on the right foot at landing after flight had significant correlation with the official distance (Figure 5). This relationship indicates that the greater the normalised peak vertical impact force on the right foot at landing after the flight, the longer the official distance.

**Figure 5** The relationship between normalised peak vertical impact force on the right foot at landing after the flight.
The normalised peak vertical impact force on the right foot at the landing after the flight also had a significant correlation with the official distance (Figure 5). This relationship indicates that the greater this normalised vertical impact force, the longer the official distance. This normalised peak impact force also had significant correlation with forward impulse and right impulse on the right foot during the second single-support and delivery phases (Figure 6), which also had significant correlation with official distance (Figure 7). These relationships indicate that the greater the normalised peak impact force on the right foot at the landing after the flight, the greater the forward impulse and rightward impulse during the second single-support phase and delivery phase, and the longer the official distance.

**Figure 6** The relationships between the normalised peak vertical impact force on the right foot after the flight and (a) the normalised forward-backward ground reaction driving impulse on the right foot during the second single-support and delivery phases, and (b) the normalised left-right ground reaction driving impulse on the right foot during the second single-support and delivery phases.
Figure 7 The relationships between the official distance and (a) the normalised forward-backward ground reaction driving impulse on the right foot, and (b) normalised left-right ground reaction driving impulse on the right foot during the second single-support and delivery phases.

The normalised peak backward and vertical ground reaction forces on the left foot during the delivery phase was significantly correlated with the official distance (Figure 8). These peak forces were also significantly correlated with corresponding ground reaction impulses (Figure 9), which was significantly correlated with official distance as well (Figure 10). These relationships indicate that the greater the backward and vertical ground reaction forces on the left foot during the delivery phase, the greater the corresponding impulses, and the longer the official distance.
The Effects of Lower Extremity Joint Resultant Moments on Ground Reaction Forces

The normalised right hip peak extension and internal rotation moments were significantly correlated with the normalised forward impulse on the right foot during the second single-support and delivery phases (Figure 11). These two hip moments were also significantly correlated with the official distance (Figure 12).

The normalised left-knee peak extension moment was significantly correlated with the normalised peak backward and vertical forces on the left foot during the delivery phase (Figure 13). This knee extension moment was also significantly correlated with the official distance (Figure 14).
Figure 9  The relationships between (a) normalised peak forward-backward ground reaction driving force on the left foot during the delivery phase and its impulse, and (b) the normalised peak vertical ground reaction force on the left foot during delivery phase and its impulse.

DISCUSSION

The results of this study provide a basic understanding of the roles of ground reaction forces during discus throwing. The results of this study suggest that the ground reaction forces on the left foot during the first single-support phase affect official distance by increasing the forward velocity of the thrower-plus-discus system during the first single-support phase and providing a vertical velocity necessary for takeoff into the flight. The forward ground reaction impulse on the left foot during the double-support phase was generally negligible. The forward
velocity of the thrower-plus-discus system at the takeoff into the flight was mainly due to the forward ground reaction impulse on the left foot during the first single-support phase. Therefore, the significant positive correlation of the forward ground reaction impulse on the left foot during the first single-support phase with the official distance indicates that the greater the forward velocity of the thrower-plus-discus system, the longer the official distance.

The significant positive correlation of the vertical ground reaction impulse on the left foot during the same phase indicates that the greater the increase in the vertical velocity of the thrower-plus-discus system during the first single-support phase.
phase, the longer the official distance. To a certain extent, this result supports our recent observation that there may be an optimum flight height of the thrower-plus-discus system during the flight phase. This result and our recent observations do not support the notion in some coaching literatures advocating a low flight of the thrower-plus-discus system during the flight phase.

The landing style appears to have significant effects on the performances during the second single-support and delivery phase and the official distance. A great vertical impact force on the right foot at the landing after the flight is associated with an increased forward ground reaction impulse and rightward
ground reaction driving impulse on the right foot, which are associated with long official distance. However, due to the limitations of this study, it is not clear if the increased vertical impact force on the right foot is a result of increased flight height of the thrower-plus-discus system, or thrower’s active movements after the landing.

The associations of peak ground reaction driving forces on the right foot during the second single-support phase and delivery phase with the official distance indicate that the major role of the right leg actions during these two phases is to provide a forward and right drive to the thrower-plus-discus system with a controlled vertical drive. The correlation of the forward and rightward ground reaction driving impulses on the right foot and the peak right-knee extension
Figure 13 The relationships between the normalised peak left knee extension moment and (a) normalised peak backward ground reaction driving force on the left foot, and (b) normalised peak vertical ground reaction force on the left foot during the delivery phase.

moment and right-hip internal rotation moment suggest that, to generate the forward and rightward driving force on the right foot, the right leg actions should be mainly a rotation of the entire leg to the throwing direction and a knee extension.

The significant correlation of the backward and vertical ground reaction forces and their impulses on the left foot during the delivery phase with official distance suggest that the major role of the left leg actions during the delivery phase is to generate a backward and vertical drive. The backward ground reaction force on the left foot coupled with the forward ground reaction force on
the right foot provides an external moment to accelerate the rotation of the thrower-plus-discus system about the vertical axis to the throwing direction.

The relationships of the right-hip extension and internal rotation moments during the second single-support phase and delivery phase with the forward ground reaction driving forces on the right foot and the official distance suggest that a strong right-hip extension and internal rotation during the delivery phase will increase the forward ground force and thus the official distance. The relationship of the left-knee extension moment with the backward and vertical ground forces during the delivery phase and official distance suggests that a strong left-knee extension will increase the backward and vertical ground reaction forces during the delivery phase and thus the official distance.

This study is limited by its small sample size, cross-sectional design, and discontinuous nature of the ground reaction data. Many kinetic measures were found not significantly correlated with performance measures in this study. One of the likely reasons for these non-significant results is the low power and high Type II error rate of the tests due to small sample size. Only cross-sectional analyses were conducted in this study due to the limited number of trials available for each subject. Although kinetic data were normalised to each subject’s body mass and standing height to eliminate the effects of these anthropometric characteristics on the results, many other detailed physical characteristics such as different strength characteristics and technical styles were not considered in data analysis. These physical characteristics and technical styles may have significant effects on the performance of individual athletes, and therefore threaten the external validity of this study when the results of this study are applied to individual athletes. In addition, ground reactions on different feet during different phases of discus throwing were collected in different trials because of the difficulty to have subjects land their feet on all desired force
plates in one trial. This discontinuous nature of the kinetic data prohibited the analysis of interactive effects of ground reactions of different feet on performance.

Despite the above-mentioned limitations, the results of this study suggest that force plates may be a quick feedback tool in discus-throwing training. The forward and vertical forces during the first single-support phase, the forward, rightward, and vertical forces on the right foot during the second single-support phase and delivery phase, and the backward and vertical forces on the left foot during the delivery phase may have significant effects on the performance of the discus throw. These ground reaction forces and their impulses may provide significant information in evaluating discus-throwing techniques.

Further studies with large sample sizes are needed to collect complete ground reaction forces on both feet during double-support, first single-support, second single-support, and delivery phases in each trial to have an understanding of the interactive effects of all ground reaction forces on the official distance. Optimum magnitudes of ground reaction forces and impulses on each foot during each phase and optimum ratios of ground reaction forces and impulses on different feet during different phases need to be determined if those optimum values exist.

APPLICATIONS AND IMPLICATIONS FOR COACHES AND ATHLETES

1. The combined results of this study have the following implications to coaches and athletes.
2. A discus thrower should drive his or her body-plus-discus system as vigorously as possible towards the throwing direction during the first single-support phase.
3. A discus thrower should also generate a certain amount of vertical thrust during the first single-support phase to have a certain height of flight. The concept that discus throwers should jump as low as possible for the flight is not supported by the results of this study.
4. A hard right-foot landing after the flight may assist discus throwers to generate ground reaction impulses on the right foot during the second single-support phase and delivery phase for long official distance.
5. A discus thrower should drive his or her right leg forward and rightward during the second single-support phase and delivery phase for long official distance. The knee-extension strength and hip internal rotation strength are critical for a vigorous right leg drive during the second single-support phase delivery phase.
6. A discus thrower should drive his or her left leg upwards and backwards as vigorously as possible to obtain maximal vertical thrust for long official distance. The knee- and hip-extension strengths are critical for a vigorous left-leg drive during the delivery phase.

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