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Development and application of an optimization model for elite level shot putting

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DEVELOPMENT AND APPLICATION OF AN OPTIMIZATION MODEL FOR ELITE LEVEL SHOT PUTTING

A Dissertation
Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

The Department of Kinesiology

by

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B.S., Ohio University, 2000
M.S.S., Ohio University, 2001
May, 2009
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ABSTRACT

Shot putting is one of the most ancient forms of athletic competition. Considerable research has been performed on the event. Despite this fact, research examining performance in the women’s shot put and using the spin technique is very limited. Also, only one attempt has been made to optimize the movement of elite shot putting and no attempts have been made to use the optimization model as a standard for technical training intervention. A series of three experiments were used to explore the development of an optimization model for shot putting and its application as a basis for technical intervention for elite athletes. Experiment 1 served as an exploratory study that explored the feasibility of developing an optimization model for shot putting. The results indicated that there are 8 variables that are highly linked with performance in the shot put and supported the notion that an optimization model for the shot put could be developed. Experiment 2 expanded on and validated the findings of the first study. Results of this study yielded a five variable optimization model for the shot put. Finally, Experiment 3 sought to apply the optimization model developed in Experiment 2 to elite athletes. The results indicated that a technical intervention based on an optimization model produces meaningful changes in performance that can be attributed to changes in optimization model parameters.
CHAPTER 1.
INTRODUCTION

Shot Putting

Rules

The current rules governing the event state that the shot must be spherical with a mass of 7.26 kg and 4 kg for men and women respectively. The concrete circle from which athletes throw must have a diameter of 2.135 m (± 5 mm) with a firmly fixed toe board attached to the ground outside of the front rim of the circle. The landing area for the put is marked with 5 cm wide white lines that extend at a 34.92 degree angle from the center of the circle.

Operational Terminology

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

Rear foot and front foot: defined as the foot furthest from and closest to the toe board when the athlete is in double support following the flight phase.

Takeoff: The moment at which the push off leg breaks contact with the surface of the throwing circle and the athlete enters the flight phase.

Flight phase: The period of time in which the athlete is moving towards the front of the throwing circle and has no contact with the throwing surface.

Rear foot touchdown (RFTD): The point at which the thrower’s rear foot makes contact with the throwing circle following the flight phase.
**Front foot touchdown (FFTD):** The point at which the thrower’s front foot makes contact with the throwing circle following the flight phase.

**Delivery phase:** The time between RFTD and release.

**Transition phase:** A subdivision of the delivery phase that begins with RFTD and ends at FFTD.

**Completion phase:** A subdivision of the delivery phase that begins with FFTD and ends with release.

**Peak vertical displacement of the athlete-plus-shot system’s center of mass:** The vertical displacement of the athlete-plus-shot system’s COM measured from the vertical position of the COM at the point of takeoff to its peak vertical position during flight.

**Prior Research**

There is considerable literature relating to the shot put (see reviews Lanka, 2000, Zatsiorsky et al., 1981). Precise and thoroughly documented data are available on only certain aspects of shot putting performance. Many variations in technique are based on personal opinions of athletes, coaches, and researchers. Although such personal opinions are not generally taken into consideration in scientific reviews, they will be included in this review in order to provide a systematic treatment of technique variations. The scientific merit of many of these views remains to be seen.

**Flight of the Shot**

Perhaps the most studied components of the shot put are the release parameters. When the implement is released, its horizontal displacement is dependent on its initial velocity, release angle, and release height. Among these parameters, the most important is the release velocity as the horizontal displacement of the projectile is proportional to
the release velocity squared. The horizontal displacement of a projectile is represented by
the following equation:

\[ L = \frac{V_0^2}{g} \cos \alpha_0 (\sin \alpha_0 + \sqrt{\sin^2 \alpha_0 + \frac{2gh_0}{V_0^2}}) \]

Where \( V_0 \) = release velocity; \( \alpha_0 \) = release angle and \( h_0 \) = release height. From this
equation, it is obvious that release velocity has the greatest impact on performance as it
has a quadratic relationship with the distance achieved.

**Parameter Observations**

The release parameters (Figure 1-1) of highly skilled shot putters have been
thoroughly studied. Previous research (Ariel et al., 2004; Luthanen, 1998; McCoy et al.,
1984; Tsirakos et al., 1995) has indicated that a release velocity in excess of 13.5 m/s is
necessary for a 21 m throw and 13 m/s for a 19 m throw (distances that typically win
medals in International competition for male and female throwers respectively). Release
heights for elite level athletes are typically between 2 and 2.2 m (Alexander et al., 1996;
McCoy et al., 1989; Tsirakos et al., 1995). As for release angle, it appears the large
majority of both elite and sub-elite level performers release the implement at an angle
considerably lower than 40° from the horizontal (e.g., Ariel et al., 2004; Bartonietz &
Felder, 1993; Maheras, 1995; McCoy, 1992a, 1992b), although some have observed
release angles greater than 40° (Ariel et al., 2004; Stepanek, 1986; Tsirakos et al., 1995).

A fourth release condition that is rarely considered is the horizontal release
distance with respect to the toe board. Greater horizontal release distances are beneficial
because they provide an advantageous release point relative to the point of measurement.
Lindsay (1994) reported similar horizontal release distances for both the glide and spin
techniques (ranging from 0.10 m behind the toe board to 0.25 m in front of the toe board).
Release Condition Relationships

All of the release parameters are affected by various factors ranging from interrelationships to anthropometry. Beyond the obvious ability of a given athlete to apply force to the implement, the release velocity appears to also be dependent on other factors as well. For example, several researchers have indicated that release velocity and angle are dependent on one another in an inverse relationship (de Mestre et al., 1998; Hubbard et al., 2001; Maheras, 1995). That is, as release angle increases, release velocity decreases. In fact, Hubbard and colleagues (2001) examined two collegiate level throwers and found that maximal attainable release velocity decreases with increasing release angle at about 1.7 (m/s)/rad.

While some authors (Dyson, 1986; Savidge, 1970) have speculated that height is relatively constant and cannot be changed, this is only partially true. The primary determinant of release height is an athlete’s anthropometry, specifically their height and the length of their throwing arm (Alexander et al., 1996; Hay, 1993, McCoy et al., 1984; Figure 1-1. Graphical representation of release parameters contributing to the total distance of the throw. The total distance is equal to the sum of the horizontal distance relative to the toe board (d1) and the projected distance (d2).
Pyka & Otrando, 1991). In this regard, release height may be more unchangeable than the other release parameters.

Release angle is largely influenced by the position of the athlete’s trunk and throwing arm. Both the inclination of an athlete’s trunk in the sagittal plane and the angle of throwing arm extension, relative to the trunk, affect the release angle. As indicated above, release angle has an inverse relationship with release velocity.

**Performer Kinematics**

The preceding portion of this review has focused primarily on the movements of the shot at the moment of release. It should be recognized, however, that the implement’s movement characteristics at release are largely the outcome of the performer’s movements prior to that point. The following section of the review will focus on the specific body segment kinematics of the performer throughout the course of the throw. Due to the unique differences between the glide and the spin, the review will begin with a brief comparison of the two techniques that will be followed by separate examination of some general mechanical principles that contribute to the outcome of the throw.

**Glide vs. Spin Technique Kinematics**

Recommendations that apply to both techniques have been made for efficient shot put technique. Several have suggested that efficient shot put technique is distinguished by movement of the implement through a large range of motion, minimal slowing of the implement in preliminary motions, attainment of optimal throwing position at the end of the preliminary motions, and correct sequencing of the body motions during the delivery (Dyson, 1986; Ecker, 1971; Hay, 1993).

In the glide, progression across the circle is dominated by linear motion with some rotation occurring during the delivery phase (Bosen, 1985). In contrast, movement
across the ring in the spin technique is primarily rotational in nature and linear force application is not a dominating factor other than in the final moments of the throw (Bosen, 1985).

**General Objectives**

While the glide and spin techniques are obviously different in many regards, research evidence suggests that the outcome of a throw is largely determined by what happens during the completion phase (Bartonietz, 1996, Young & Li, 2005a), the phase with the most shared characteristics between the two techniques. In fact, Turk (1997) suggested that 80-90% of the distance of the throw for gliders can be explained by what occurs in the period of time between FFTD and release.

The primary purpose of the completion phase is to maximize implement velocity while releasing at an angle, height and horizontal release distance that are suitable for high-level performance while still permitting a fair throw. Several mechanical and biological principles underlie the attainment of this goal: the length of the completion phase implement acceleration, the speed of the performer’s movement during the completion phase, the attainment of positions which allow the athlete to generate the greatest magnitude of force in the direction of the throw and development of conditions which allow the athlete to remain in the circle once the implement has been released.

**Criterion 1: Lengthen Trajectory**

Bartonietz (1994a; 1996) suggested that the length of the implement trajectory is one of the most important elements of the throw. Because of the great decelerations that occur prior to the final acceleration, one could surmise that lengthening the implement trajectory is of less importance than that of the completion phase implement trajectory where the implement has been observed to accelerate almost completely in the direction
of the throw (Ariel et al., 2004; Young, 2004a). Previous research has indicated that the
length of the implement trajectory in the completion phase ranges between 1.5 and 1.7 m
for elite male athletes using the glide technique (Bartonietz, 1996; Schpenke, 1973) with
greater throws typically having longer paths (Table 1.1). Slightly longer trajectories (1.7-
1.9 m) have been reported for the completion phase of athletes using the spin technique
(Bosen, 1985; Kerssenbrock, 1974).

<table>
<thead>
<tr>
<th>Athlete</th>
<th>Distance (m)</th>
<th>Completion Phase Duration (s)</th>
<th>Completion Phase Length (m)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.54</td>
<td>0.2</td>
<td>1.7</td>
<td>Schpenke (1973)</td>
</tr>
<tr>
<td>2</td>
<td>21.31</td>
<td>0.22</td>
<td>1.65</td>
<td>Bartonietz (1996)</td>
</tr>
<tr>
<td>3</td>
<td>21.07</td>
<td>0.25</td>
<td>1.78</td>
<td>Schpenke (1973)</td>
</tr>
<tr>
<td>4</td>
<td>20.09</td>
<td>0.18</td>
<td>1.55</td>
<td>Schpenke (1973)</td>
</tr>
<tr>
<td>5</td>
<td>20.27</td>
<td>0.26</td>
<td>1.7</td>
<td>Koutiev (1966)</td>
</tr>
<tr>
<td>6</td>
<td>19.08</td>
<td>0.26</td>
<td>1.5</td>
<td>Koutiev (1966)</td>
</tr>
<tr>
<td>7</td>
<td>19.00</td>
<td>0.28</td>
<td>1.55</td>
<td>Koutiev (1966)</td>
</tr>
<tr>
<td>8</td>
<td>18.98</td>
<td>0.27</td>
<td>1.48</td>
<td>Koutiev (1966)</td>
</tr>
</tbody>
</table>

**Criterion 2: Increase Speed of Movement**

The second factor that determines the effectiveness of the completion phase is the
performer’s speed of movement. Stepanek (1990) noted that the duration of the
completion phase is inversely directly related to performance. Dessureault (1978)
suggested that the best performers reduce the time of their completion phase. This is supported by data on athletes of varying skill levels. The duration of the completion phase for sub-elite athletes has been observed to be as great as 0.4 seconds (Alexander et al., 1996; Dessureault, 1976; 1978) while the duration for elite throwers typically falls in the range of 0.2-0.3s (Bartonietz, 1996; Grigalka & Papanov, 1988; Young, 2004a).
Perhaps, the most interesting point is that the best throwers not only move the implement over a greater distance, but they do so in a shorter period of time.

**Criterion 3: Optimal Positions and Movements**

The third criterion for an effective completion phase, one that certainly has a direct effect on the previous two factors, is the attainment of positions that allow the athlete to generate the greatest quantity of force in the direction of the throw. According to Tutevich (1955 as cited in Lanka, 2000), the effectiveness of the completion phase may be assessed by the degree to which the thrower’s force application is directed through the COM of the APSS in the direction of the throw. While other factors like muscle potentiation and efficient utilization of an athlete’s strength must also be considered, it is safe to say that Tuevich’s recommendation be one of the primary objectives.

**Criterion 4: Foul Prevention**

The final factor altering the effectiveness of the completion phase is the development of conditions that allow the athlete to remain in the circle once the implement has been released. In fact, all previously mentioned criterion should be thought of as subordinate to this final one. If the thrower is unable to remain in the ring following the release of the implement, it is of little consequence how well the previous three criteria were executed.

**Critical Parameters**

With the aforementioned points in mind, there are several areas of shot put technique that meet these criteria and have previously been indicated as beneficial to performance. The following section will examine three areas that meet the above
criterion and have been indicated by previous research as being beneficial to performance.

**Peak Height During Flight Phase**

The first technical component that we will examine is the PCOM. Increased PCOM has previously been indicated as being important for shot putting because of its ability to improve the positioning and physical capacity of an athlete to deliver the shot (Mileshin & Papanov, 1986; Young, 2004a; Young & Li, 2005b). More specifically, increased PCOM should theoretically produce two benefits. First, greater PCOM may elicit a greater stretch shortening cycle by eccentrically loading the lower extremities to a greater extent at RFTD. The second benefit is that a greater PCOM would be expected to increase flight time that in turn may permit the athlete to reposition the limbs under the body before RFTD. These two points have the potential to increase the speed of movement and enhance optimal positioning.

**Positions and Actions of the Lower Extremities**

The second technical area shown to affect the outcome of the throw is the position and action of the lower extremities following RFTD. The initial acceleration of the implement during the completion phase is primarily due to the actions of the lower extremity (Grigalka, 1972; Holmes, 1979). An effective completion phase is thus characterized by the most effective use of the lower extremity. Interestingly, considerable variability exists among recommendations on how to best accomplish this task.

Several suggestions have been made regarding the actions of the lower extremity. While many (Grigalka, 1972; Holmes, 1979; Palm, 1990; Ward, 1970) have suggested that the rear leg is the primary body part responsible for movement of the APSS in the direction of the throw, results of kinetic research do not support this view. Ground
reaction force data of the rear leg indicates that the rear leg primarily produces vertical forces during the completion phase (Ariel, 1979; Ward & McCoy et al., 1984; Zatsiorsky et al., 1981). Whatever the case, many have noted that a very active rear leg is one of the distinguishing characteristics between better and lesser performers using the glide technique (Bartonietz & Borgstöm, 1995; Bartonietz & Felder, 1993; Bell, 1979). Active rear leg extension has also been linked with upward movement of the trunk (Zatsiorsky et al., 1981) and increased S-H early in the completion phase (Holmes, 1979).

Previous research literature has indicated that it is beneficial to make RFTD with greater RK flexion although the range of motion of the RK differs little between the best and worst throws (Young & Li, 2005a). Therefore, greater RK flexion at release may also be associated with improved performance. Many have also suggested that the explosive extension of the RK is the initiation of the actions that follow in the S-H (Bartonietz & Borgstöm, 1995; Grigalka & Papanov, 1988; Mileshin & Papanov, 1986). This ties in closely with the third sub-group of parameters that has been linked to elite performance in the shot put – the positions and action of the S-H.

While the function of the rear leg is primarily to accelerate the APSS in the direction of the throw, the front leg has a dual role. During the initial moments of the completion phase, the front leg assists in accelerating the athlete. There is some debate as to whether this assist is passive or active in nature. Several authors (Holmes, 1979; Turk, 1997) suggested that the front leg should be bent slightly early on in the completion phase to allow for unimpeded forward movement of the hips. Brown (1985), however, suggested a more active role in which the front leg actually applies more explosive power than the rear leg.
Later in the completion phase, the front leg functions as a brace that applies braking forces to decelerate the athlete (Ariel, 1973a; Bartonietz, 1994b; Bosen, 1981). In this role, the front leg is said to act as a break and cause a “hinged moment” due to the quickly decelerated and minimized movement of the lower extremity causing increased acceleration of the more distal trunk and throwing arm (Mileshin & Papnov, 1986; Pearson, 1966). In support of this, Ariel (1973) reported minimized front leg movement among the best throwers during the final moments of the delivery and several have indicated that the front leg provides a high force impulse in the direction opposing the put (Ariel, 1979; Dessureault, 1978; McCoy et al., 1984; Mileshin & Papanov, 1986).

**Interaction of the Shoulders and Hips**

As with the actions of the lower extremity, the position and actions of the S-H has been discussed extensively in both coaching (Godina & Backes, 2000; McGill, 1983) and research literature (Bartonietz & Borgstöm, 1995; Young & Li, 2005b). Of particular interest is the interplay between the transverse axis of the hips and the transverse axis of the shoulders. When the S-H is large, it has the potential of increasing trunk whip. Trunk whip refers to the effect that occurs in distal segments as a result of the acceleration and sudden deceleration of a more proximal segment. In the case of trunk whip, the acceleration and deceleration of the hips can produce a whip effect in the shoulder segment. This position would also place the muscles of the trunk on stretch that should enhance the force (and speed) with which they are able to contract.

Ariel (1973) and Tschiene (1973 as cited in Lanka, 2000) found that the hips rotate 175°-220° during the completion phase. Powell (1960) claimed that the success of shot putting depends on the speed of this rotation. If the shoulders can be kept in a rear-facing position, the faster the hips rotate the greater the whip effect will be. Data from
Ariel (1973) indicated that among elite level throwers, the movement of the hips is linked to movement of other body parts. For instance, maximum rotational speed of the hips coincided with initiation of the throwing arm movement. Following attainment of maximum speed, rotational hip speed decelerated greatly and considerable momentum was transferred to the shoulders.

In addition to the points mentioned above, proximal segments must be decelerated just prior to release for the whip effect to be maximized. Several recommendations have been made on this point. For instance, Maltseva (1990) and McGill (1983) suggested that the non-throwing side should be anchored to speed up the rotation of the throwing side. Similarly, Irving (1980) suggested that the hips should rotate and stop prior to release to accelerate the shoulders and throwing arm. This is supported by data from Lanka (1976 as cited in Zatsiorsky et al., 1981) that indicated better performers display greater hip deceleration just prior to release.

**Optimization Modeling**

One of the overriding principles governing sports performance and all forms of human motion is the attempt of an individual or group of individuals to perform a task in the most optimal way possible. The desire of biomechanists to simulate and analyze human movement with the objective of better understanding and even enhancing the performance of that motion has led to a large amount of biomechanics research devoted to the modeling of human movement.

The focus of this review will be on optimization modeling and will begin with a review optimization modeling, examine some methodological issues concerning optimization modeling, and will conclude with a look at some examples of the use of optimization modeling in the field of athletics.
The field of optimization research is dependent on a single fundamental philosophical issue being true. That is, whether biological systems can in fact be optimized. There are two good reasons to believe that they can: natural selection theory and learning. Natural selection theory suggests that organisms tend to undergo changes that would increase their likelihood for survival (Darwin, 1979). Over time, this would account for an optimization effect on basic movements such as walking and running. The more complex motions used by humans, however, are far less likely to have been optimized by this process. This is particularly true for sports techniques because, in general, they are not essential to the survival of the person or the species and as a result are not likely to have evolved into an optimal form. On the other hand, they are much more likely to be influenced by individual learning processes aimed at performing the task in the best possible manner. That is, people may learn rather than inherit the movement patterns that maximize speed or minimize energy costs in “non-essential” movement patterns such as those commonly seen in sporting activities. Inherent in the belief that movement can be optimized through learning processes is the realization that this process is subject to human error. For this reason, optimal movement patterns are generally unknown. Because of this uncertainty, optimization models can be of great use in understanding “the best way” to perform a movement. An optimization model may provide an idealized or optimal template to accomplish a task objective or objectives.

Methodological Issues

Suitable Tasks for Optimization

At the current time, not all movements are suitable for optimization research. Tasks that are classified as discrete or continuous are ideal subjects for optimization research. A discrete task is one in which there is a recognizable beginning and end
Tasks such as lifting or throwing an object are examples of discrete tasks. In contrast to discrete tasks, continuous tasks have no recognizable beginning and end (Schmidt & Lee, 2005). Examples of continuous tasks include running and walking actions. In some cases, continuous tasks are partitioned in such a way that one “cycle” of the task is analyzed for optimization. An example would be examining one gait cycle in walking. In cases such as this, the continuous task is being analyzed in such a way that it is essentially a discrete activity.

**Elements of an Optimization Model**

**Objective Function**

Once a movement that meets the above requirements has been selected for optimization research, the process of optimization can begin. There are three fundamental elements in any optimization problem. They are the objective function, variables, and model constraints. Almost all optimization problems have a single objective function. An objective function is the task or movement goal that is being optimized. In most cases, models attempt to minimize or maximize the objective function. Some models attempt to minimize a given parameter, such as the stress in a hip prosthesis (Huiskes & Boeklagen, 1989). Others may have a goal of maximizing a parameter, such as the height of a jump (Hay et al., 1976). One interesting exception to this is when multiple objective functions are used. In such cases, the different objectives are not compatible; the variables that optimize one objective may be far from optimal for the others. Typically, problems with multiple objectives are reformulated as single-objective problems by either forming a weighted combination of the different objectives or by replacing some of the objectives by constraints.
**Variables of Interest**

The variables of interest are the second element of an optimization model. They are essential because without the variables, the objective function and the model constraints cannot be defined. These unknowns affect the value of the objective function. In other words, for the results of the optimization to truly reflect what it is supposed to, the parameters that are most important to the success of the movement must be included in the analysis. As such, in many cases it is important to review previous research so that all potentially relevant parameters are included.

**Model Constraints**

Model constraints are the final component of an optimization model. Constraints are often placed on the model to ensure results are within normal or realistic limits. Typically, a set of constraints permits the variables of interest to take on certain values but exclude others. It should be noted however that model constraints are not essential. In fact, it is quite possible for a model to produce reasonable results without putting constraints on the variables.

When all elements of the model are in place, the optimization problem then becomes an attempt to find the values of the variables that result in attainment of the objective function while satisfying the model constraints. Typically, this comes in the form of an algorithm that provides an analytical or numerical solution to the variable.

**Optimization Model Examples**

Many of the activities that have been the subject for optimization models have been sporting activities. A majority of these sports optimization activities have been either discrete or continuous tasks or movements performed in closed environments. This research has typically focused on movements in which performance is highly dependent
on technical skill rather than strategy or gamesmanship. Because of these issues, sports such as track and field, gymnastics, and diving have been the most frequently examined.

**Maximizing Range of Sports Projectiles**

Several studies have attempted to optimize initial projection parameters to maximize the range a projectile travels. Typically, determination of optimal projection angle is the goal of projection parameter optimization. The optimal initial projection angle is the angle that maximizes range. This is because when attempting to maximize range, higher projection velocities and heights will always result in greater displacement. Projection angle on the other hand does not have such a simple relationship with range and as such becomes the obvious choice for optimization.

At first glance, the process of determining optimal projection angles may appear to be a simple matter of calculation using the equation that governs projectile motion:

\[
R = \frac{V^2 \sin 2\theta}{2g} \left[ 1 + \left( 1 + \frac{2gh}{V^2 \sin^2 \theta} \right)^{\frac{1}{2}} \right]
\]

Indeed, early attempts at projectile parameter optimization took this approach (e.g., Lichtenburg & Wills, 1978; Soong, 1975). Despite the overwhelming number of recommendations based on the projectile motion equation, large discrepancies have been observed between the predicted optimal values and values observed in elite (Bartonietz & Borgstöm, 1995; Bartonietz & Felder, 1993; Luthanen, 1998; Tsirakos et al., 1995) and sub-elite (Dessureault, 1976; 1978) shot putters. This has led some authors to speculate that release angles should be lower than those determined using the projectile motion equation (Hubbard, 1988; Ward, 1975). Recent research supports this viewpoint. For instance, Linthorne (2001b, 2001c) examined university level shot putters and developed a model that related measurements to anthropometric and strength characteristics of the
athlete. Results indicated that release velocity and angle are not independent and that the optimal release angle is considerably lower (32-38°) than that determined using the projectile motion equation. Similar findings have been reported by other investigators for throwers using both the glide (de Mestre et al., 1998; Hubbard et al., 2001; Maheras, 1995; McWatt, 1982) and spin technique (Luthanen, 1998). Two mechanisms explaining this phenomenon have been proposed. First, as projection angle increases the performance is opposed by a greater effect of gravity (Hay, 1993; Linthorne, 2001b). This is due to the fact that the force of gravity acts perpendicular to the ground and as the release angle increases more force must be used to overcome the effect of gravity. Second, the structure of the human body may not be able to produce equal force (and as a result velocities) in every position (Linthorne, 2001b).

Because of these points, it is important to understand the relationship between the parameters for a given movement and possibly even for a particular athlete before attempting to determine the true optimal angle. Several methods may be used to establish these relationships. For example, Red and Zogaib (1977) determined the optimum release angle for throwing a 1.14kg ball by combining the equation which governs the range covered by a projectile in free flight with predetermined relationships between release speed, height and angle for an athlete. The predetermined relationships were established by obtaining measurements of the athlete’s release speed and height over a wide range of release angles above and below their preferred release angle. The values for release speed and height were then plotted as a function of release angle so that an algebraic expression could be determined for release speed and height as a function of release angle. These expressions were then substituted into the equation governing range of a projectile in free flight and the flight distance was plotted as a function of release angle. The release angle
that resulted in the greatest flight distance on the plotted curve was deemed the optimum release angle. Similar methods have been used in other studies to determine the optimal release parameters for the javelin throw (Viitasalo & Korjus, 1988) and the shot put (Maheras, 1995). In these studies, the optimal projection angles were considerably lower than predicted projection angles determined without taking into account the projectile parameter dependencies.

An alternative method to determine the mathematical expressions for the dependent release parameters was used by Linthorne (2001a) to optimize the release conditions for the shot put. In this study, Maheras’ (1995) measurements for release speed, height and angle for five shot putters was presented together with simple models that relate the measurements to the anthropometric and strength characteristics of the athlete. In this study, the expression for height was derived from an anthropometric model of the athlete at the instant of release. The expression for velocity was derived from a model of the forces acting on the shot during the delivery phase of the throw.

A final approach to determine the optimal release parameters for the shot put was used by Hubbard and colleagues (2001; see also de Mestre et al., 1998). In contrast to the previously mentioned research, Hubbard and colleagues optimized for release speed rather than angle. As in the previous studies, the relationship between the projection parameters was determined. 2D data that had been corrected for out-of-plane errors were used in a multivariate regression analysis to determine constraints on each of the projection parameters. As in the previously mentioned studies, the results indicated that achievable release speed has an inverse relationship with release angle and a positive relationship with release height. Release speed was shown to decrease with increasing release angle at about 1.7 (m/s)/rad and decreased with increasing release height at about
0.8 (m/s)/m with small deviation between throwers. Based off of these relationships, the authors suggested that the optimal release parameters for a particular athlete may be determined using similar constraints.

**Throwing**

In addition to the parameters associated with the flight of projectiles, the actual motion of throwing has also been a frequent subject of sports optimization modeling. Optimization techniques have been applied to general overhand throwing motions such as those seen in baseball (Alaways et al., 2001) and javelin throwing (LeBlanc & Dapena, 2002; Komi & Mero, 1985) but much of the research has focused on the less commonly seen motions of the track and field throwing events.

For example, Alexander (1996) examined 30 male and 31 female subjects in an attempt to determine the relative importance of selected anthropometric, strength, and technique parameters to their performance. They developed optimization models using multivariate analysis of variance with repeated measures for male and female sub-elite level shot putters and found that performance indicators in the event were gender specific. The critical parameters for female throwers included knee extension during the glide, elbow velocity during delivery, and a greater shoulder flexion angle at release. For male throwers, center of gravity velocity during glide, vertical acceleration of center of gravity during delivery, and trunk angle at the start of glide were the most important parameters to produce longer throws. This difference supports the notion that optimization models may need to be gender-specific.

Hay and Yu (1995) also reported differences between the optimal technique of men and women for the discus throw. In this study, an inverse optimization was used to determine the kinematic parameters of discus throwing that were most critical to the
distance of the throw. This study examined elite male and female throwers. Interestingly, differences in significant performance indicators were observed for each gender. For men, the results indicated that the change in speed of the discus during the second double support phase was more influential on the performance than the change in speed during any other phase of the throw. For females, changes in speed during the flight phase and during the second double support phase accounted for much of the distance of the throw.

The previously mentioned study examining the discus throw (Hay & Yu, 1995) was later expanded upon using an identical direct optimization method to determine the effect of selected kinetic and kinematic variables on performance in the men’s discus throw (Yu et al., 2002). A force plate embedded in the throwing ring was used to collect kinetic data at specific events. 3D kinematic data were also collected at specific events in the throw. Multiple regression analysis was performed using measured distance of the throw as the objective function. Results indicated that the kinetics and kinematics of the delivery phase of the discus throw are vitally important to performance. Right hip extension and internal rotation moments and left knee extension moment during the delivery phase were also significantly correlated with performance. In addition, GRFs on the left foot during the first single-support phase, on the right foot during the second single support phase and on both feet during the delivery phase were significant indicators of performance.

**Technical Intervention**

Although coaches and athletes have presumably used the results of sports research and even optimization modeling to enhance their performance; no known attempts have been used to quantify the effects of any changes that may have resulted. In fact, even guided technical interventions outside of athletics are quite rare. Optimization models
have been used in the training of other activities though. For example, a common movement model was successfully used in the training and rehabilitation of ACL reconstruction patients (Risberg et al., 2001). This training was shown to reduce female knee joint injury. Similar benefits may exist from a technical intervention using an optimization model for the shot put.

Despite the fact that the affect of a technical intervention based on an optimization model has not been quantitatively assessed in athletics, quantitative performance analysis has been used quite frequently. While this research has not produced mathematical optimization models per se, this research has nonetheless been valuable in a manner very similar manner to optimization models.

Performance analysis with the aim of performance enhancement research has typically used one of three methods: comparison, correlation, and critical review. Research using comparison involves comparison of selected parameters from two or more groups of different performance levels with the aim of determining which parameters are most likely to be responsible for the differences in performance. In an example of research using comparative means, Mann (1986) identified critical parameters for success in sprint races by comparing the results of kinematic data analysis of collegiate level and elite level athletes. Elite level sprinters were found to have lesser hip and knee extension during the support phase and shorter ground contact times.

Correlational studies attempt to determine performance-predicting parameters by correlating selecting parameters with a dependent variable. For example, Hay and Nohara (1990) analyzed the long jump technique of elite male and female long jumpers and correlated selected kinematic parameters with the distance of the jump. Similar methods had been used previously on the long jump (Hay & Miller, 1985a) as well to determine
the kinematic parameters that were most influential on the measured distance of a javelin throw (Kunz & Kaufmann, 1983) and triple jump (Hay & Miller, 1985b).

The critical review process involves analytically examining many research sources with the objective of determining which variables are most predictive of performance. An example of the use of critical review for performance enhancement is the review paper on javelin throwing by Barlett and Best (1988). Following a critical review of prior research, the authors provided suggestions for performance enhancement in the javelin.

References


Young, M., & Li, L. (2005b). Principal component analysis on the kinematic parameters of elite women shot putters. Oral presentation at the SEACSM Annual Meeting: Charlotte, NC.


CHAPTER 2.

EXPERIMENT 1: DETERMINATION OF CRITICAL PARAMETERS AMONG ELITE WOMEN SHOT PUTTERS

Introduction

Much research has been performed relating to the shot put (see review Zatsiorsky et al., 1981). Several of these studies have examined the theory and practice of determining optimal release conditions such as release velocity, release angle and release height (Hubbard et al., 2001; Lichtenberg & Willis, 1978; Linthorne, 2001c; Maheras, 1995; McWatt, 1982). Despite the fact that these parameters directly determine the projected distance of the throw, they do not give any indication of the events leading up to the instant of release. Consequently, they offer limited information to coaches seeking to improve the aspects of technique that will result in the best release parameters. Some other studies were descriptive in nature. They have ranged from quantitative (Ariel, 1979; Bartonietz, 1996; Dessurealt, 1978; Knudson, 1989; Liu et al., 2000; McCoy, 1990; Stepanek, 1990) to completely qualitative (Grigalka & Papanov, 1984; Ward, 1974; Wilt, 1982). While these studies do provide information regarding the kinematics associated with the performance; they too offered limited evidence as to which parameters were most influential on the performance.

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

Despite the shortage of work examining critical parameters in the shot put, attempting to determine critical parameters in sporting events is not unique. The most common method for identification is regression analysis. Hay (1978) and later Hay and colleagues (1981) developed a theoretical model for the standing vertical jump by describing the performance parameters in the skill and analyzing data from a large number of male athletes to evaluate the model. They calculated the correlation between each of the parameters in the model with the height jumped to determine which parameters might be most important, and then conducted a multiple regression analysis to determine which of the parameters contributed most to explaining the performance of each individual. The results suggested that the torques developed at the shoulder, hip, knee and ankle joints were important in the performance of male subjects. Triple jumping (Yu & Hay, 1996), sprinting and hurdling (Mann & Herman 1985a; Mann & Herman 1985b), discus throwing (Hay & Yu, 1995; Yu et al., 2002), and the acceleration phase in ice-skating (Marino, 1983) are other sporting techniques that have been analyzed in this manner. This research has provided insights into the technical parameters of these
events which were most closely related to success and which could best be used as predictors of performance.

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

Methods

**Operational Terminology**

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

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

**Shoulder-hip separation:** The orientation of the hips relative to the orientation of the shoulders. A neutral position (zero degrees of separation) occurs when the shoulders and hips are aligned with one another. A positive angle occurs when the throwing side shoulder is posterior to the throwing side hip. See Figure 2-1.

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

**Release velocity:** The magnitude of the shot velocity at the moment of release.

**Release angle:** The relative angle between the trajectory of the shot and the horizontal.
**Release height**: The height of the center of the shot above the surface of the ring at the moment of release.

**Horizontal release distance**: The horizontal distance between the center of the shot and the innermost edge of the toe board at the moment of release.

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

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**Figure 2-1.** Shoulder-hip separation for right handed thrower. The dashed line represents the orientation of the hips and the solid line represents the orientation of the shoulders. The small black circle represents the shot. The angle between the line of the shoulder and the line of the hip represents the shoulder-hip separation. For left handed throwers, these angles are reversed.

---

**Figure 2-2.** Definition of trunk angle. Trunk angle was defined as the angle formed between the shoulder-hip line and the horizontal plane. The dashed lines represent the shoulder-hip line and the horizontal plane formed by the ground.
**Projected distance:** The horizontal displacement of the shot beginning at the point of horizontal release distance and ending at the landing point of the shot.

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

**Subjects**

Seven of the top eight women who competed at the 2002 USA Track & Field National Championships in Palo Alto were used as participants in this study. Clothing was not standardized. Four of the athletes performed the glide technique and three performed the rotational technique. The method employed in this study to breakdown the throw into phases by predetermined events allowed for both techniques to be analyzed together based on the similar phases of support and flight (Figure 2-3).

**Video Data Collection**

The Direct Linear Transformation (DLT) procedure (Abdel-Aziz & Karara, 1971) was used to collect three-dimensional coordinates of 22 body landmarks and also the center of the shot for each trial. Two time-synchronized S-VHS Panasonic 60 Hz cameras were used to record the control object and the performances. The cameras were placed around the shot put throwing circle spaced approximately 90° apart. Video data were collected for the best trial of each subject. Following collection of the performance data, a Peak calibration spider was placed in the center of the throwing circle and was used to calibrate and synchronize the two fields of view.
Figure 2-3. Method of technical evaluation for each technique. Both techniques have similar instances of support and flight.
Data Reduction

The videotape records of the control and performance data were manually digitized and analyzed using a Peak Motus 3D motion analysis system (Englewood, Colorado, USA). The digitized control object coordinates were used to estimate the DLT parameters for each camera. The video record of the best throw for each athlete was manually digitized at a sampling rate of 60 Hz from two frames before the initiation of the throw to two frames after the release of the shot. In each digitized field, the following 23 points were manually digitized for model of the athlete-plus-shot system: forehead, chin, shoulder (L & R), elbow (L & R), wrist (L & R), hand (L & R), tip of index finger (L & R), hip (L & R), knee (L & R), ankle (L & R), heel (L & R), toe (L & R), and the shot. Some of these points were not included in the analysis of this study and were used only to provide additional information for athlete’s personal reports. The throwing circle was also digitized so that parameters relative to the diameter of the circle could be calculated. The digitized 2D data were time synced based on the release of the shot. A second event, front foot touchdown, was used to verify the accuracy of the synchronization. All analyzed clips met both synchronization criteria. The 3D coordinate data were smoothed using a second-order Butterworth digital filter with a cutoff frequency at 8 Hz (Winter et al., 1974). This smoothing method has previously been used for other throwing activities (Yu et al., 2002).

Parameter Selection

Thirty parameters were selected as independent variables and distance was used as the dependent variable. The independent variables were selected based on suggestions from coaching literature and results of descriptive biomechanical studies. The selected variables were sub-grouped into the categories of release parameters, athlete kinematics, implement velocities and accelerations, and temporal parameters. The parameters examined are presented in Table 2.1.
Data Analysis

Means and the range for all of the parameters were determined. Coefficients of Pearson Product correlation were examined to find which variables were correlated with measured distance. In addition, the correlation between each independent variable was examined. When independent parameters were closely related to one another – multi-collinearity, only one of the parameters was retained for further inclusion in the multiple regression analysis (Hay et al., 1981). An analysis of variance with stepwise selection was then performed. A stepwise procedure similar to that used by Alexander and colleagues (1996) eliminated parameters from the multiple regression equation that were not significant predictors of measured distance. Type I error of 0.10 was selected to indicate statistical significance as has been used by previous research examining similar activities (Yu et al., 2002). All statistical procedures were performed using SAS statistical software (Cary, North Carolina, USA).

Results

Stepwise Regression Analysis

Stepwise regression analysis indicated that five of the 30 independent parameters (Table 2.2) had a significant impact on the measured distance of the throw ($F = 738.7$, $r^2 = 1.0$, $p < 0.001$). The selected parameters were from either the release parameters or the athlete kinematics group. Greater release velocity, greater horizontal release distance, greater rear knee flexion at both rear foot touchdown (RFTD) and at release, as well as less shoulder-hip separation at release were strong predictors of greater measured distance. A summary of the release parameter and kinematic parameter data are presented in Tables 2.3 and 2.4 respectively.
Table 2.1. Parameters examined in the study and literature supporting their inclusion

<table>
<thead>
<tr>
<th>Sub-Group</th>
<th>Parameter</th>
<th>Event</th>
<th>Supporting literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Release Parameters</td>
<td></td>
<td></td>
<td>X* Hubbard et al., 2001</td>
</tr>
<tr>
<td></td>
<td>Resultant velocity (m/s)</td>
<td>TO</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal velocity (m/s)</td>
<td>RFTD</td>
<td>X Dessurealt, 1978</td>
</tr>
<tr>
<td></td>
<td>Vertical velocity (m/s)</td>
<td>FFTD</td>
<td>X Dessurealt, 1978</td>
</tr>
<tr>
<td></td>
<td>Lateral velocity (m/s)</td>
<td>RLS</td>
<td>X Dessurealt, 1978</td>
</tr>
<tr>
<td></td>
<td>Release angle (deg.)</td>
<td></td>
<td>X Hubbard et al., 2001</td>
</tr>
<tr>
<td></td>
<td>Release height (m)</td>
<td></td>
<td>X McCoy et al., 1984</td>
</tr>
<tr>
<td></td>
<td>Horizontal release distance (m)</td>
<td></td>
<td>X Hubbard et al., 2001</td>
</tr>
<tr>
<td>Athlete Kinematics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trunk angle (deg.)</td>
<td>TO</td>
<td>X Alexander, 1996</td>
</tr>
<tr>
<td></td>
<td>Shoulder-hip separation (deg.)</td>
<td>RFTD</td>
<td>X Schmolinsky, 2000</td>
</tr>
<tr>
<td></td>
<td>Rear knee angle (deg.)</td>
<td>FFTD</td>
<td>X Alexander, 1996</td>
</tr>
<tr>
<td></td>
<td>Front knee angle (deg.)</td>
<td>RLS</td>
<td>X Alexander, 1996</td>
</tr>
<tr>
<td></td>
<td>Push off knee angle (deg.)</td>
<td></td>
<td>X Alexander, 1996</td>
</tr>
<tr>
<td>Implement Parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Resultant velocity (m/s)</td>
<td>TO</td>
<td>X* Marhold, 1973</td>
</tr>
<tr>
<td></td>
<td>Resultant acceleration (m/s^2)</td>
<td>RFTD</td>
<td>X Marhold, 1973</td>
</tr>
<tr>
<td>Temporal Parameters</td>
<td></td>
<td>FFTD</td>
<td>X*</td>
</tr>
<tr>
<td></td>
<td>Time (seconds)</td>
<td>Deliv.</td>
<td>X Tsrakos et al., 1995</td>
</tr>
</tbody>
</table>

*Resultant velocity in the release parameters and resultant velocity at release of the implement parameters are the same parameter.

TO – Takeoff
RFTD – Rear foot touchdown
FFTD – Front foot touchdown
RLS – Release

Trans. – Transition phase
Comp. – Completion phase
Deliv. – Delivery phase
Table 2.2. Results of the stepwise regression analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter estimate</th>
<th>F Value</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>69.068</td>
<td>699.2</td>
<td>0.0241</td>
</tr>
<tr>
<td>Rear knee angle @ RFTD</td>
<td>-0.267</td>
<td>803.8</td>
<td>0.0224</td>
</tr>
<tr>
<td>Release velocity</td>
<td>-0.925</td>
<td>68.8</td>
<td>0.0764</td>
</tr>
<tr>
<td>Rear knee angle at release</td>
<td>-0.097</td>
<td>2457.3</td>
<td>0.0128</td>
</tr>
<tr>
<td>Shoulder-hip differential @ release</td>
<td>-0.899</td>
<td>2233.3</td>
<td>0.0135</td>
</tr>
<tr>
<td>Horizontal release distance</td>
<td>-0.255</td>
<td>121.6</td>
<td>0.0576</td>
</tr>
</tbody>
</table>

RFTD – Rear foot touchdown

None of the temporal parameters had any observable effect on the measured distance of the throw. Likewise, none of the implement velocities or accelerations at any of the events observed prior to the instant of release had an observable effect on the outcome of the throw. See Tables 2.5 and 2.6 for summaries of the implement velocities and accelerations and the temporal parameters at the selected events.

Correlation Analysis

Among the release parameters, the measured distance was positively influenced by the release velocity (R = 0.97, p < 0.0003, Figure 2-4A) and negatively influenced by the release angle (R = -0.74, p < 0.056, Figure 2-4B). Release angle and resultant velocity were also negatively correlated (R = -0.8467, p < 0.016, Figure 2-5).

Among the athlete kinematic parameters examined, the measured distance was inversely associated with rear knee angle at RFTD (R= -0.925, p < 0.003, Figure 2-6A) and rear knee angle at release (R= -0.761, p < 0.0472, Figure 2-6B). Also both push off leg angle at takeoff (R= -0.775, p < 0.04) and release angle (R = 0.836, p < 0.019) were also highly correlated with rear knee angle at RFTD. Shoulder-hip separation at release correlated with distance (R=0.724, p < 0.06, Figure 2-7).
Table 2.3. Mean of release parameters

<table>
<thead>
<tr>
<th></th>
<th>Group</th>
<th>Glide</th>
<th>Spin</th>
<th>Places 1-3</th>
<th>Places 5-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured distance (m)</td>
<td>17.26 ± 1.20</td>
<td>17.40 ± 1.33</td>
<td>17.07 ± 1.26</td>
<td>18.43 ± 0.81</td>
<td>16.38 ± 0.20</td>
</tr>
<tr>
<td>Release velocity (m/s)</td>
<td>12.40 ± 0.56</td>
<td>12.45 ± 0.56</td>
<td>12.33 ± 0.56</td>
<td>12.95 ± 0.32</td>
<td>11.99 ± 0.17</td>
</tr>
<tr>
<td>Release angle (degrees)</td>
<td>35.03 ± 2.47</td>
<td>34.50 ± 1.68</td>
<td>35.73 ± 3.57</td>
<td>32.73 ± 1.17</td>
<td>36.75 ± 1.44</td>
</tr>
<tr>
<td>Horizontal release distance (m)</td>
<td>0.17 ± 0.20</td>
<td>0.20 ± 0.25</td>
<td>0.13 ± 0.13</td>
<td>0.28 ± 0.09</td>
<td>0.08 ± 0.22</td>
</tr>
<tr>
<td>Release height (m)</td>
<td>1.97 ± 0.04</td>
<td>1.97 ± 0.03</td>
<td>1.98 ± 0.06</td>
<td>1.97 ± 0.05</td>
<td>1.97 ± 0.04</td>
</tr>
</tbody>
</table>

Table 2.4. Mean kinematic parameters at selected events

<table>
<thead>
<tr>
<th>Event</th>
<th>TO</th>
<th>RFTD</th>
<th>FFTD</th>
<th>Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push off knee angle (deg)</td>
<td>164.60 ± 11.36</td>
<td>***</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>Rear knee angle (deg)</td>
<td>***</td>
<td>104.43 ± 6.07</td>
<td>110.53 ± 5.27</td>
<td>146.83 ± 6.91</td>
</tr>
<tr>
<td>Front knee angle (deg)</td>
<td>***</td>
<td>***</td>
<td>122.34 ± 4.68</td>
<td>172.76 ± 3.97</td>
</tr>
<tr>
<td>Trunk angle (deg)</td>
<td>57.81 ± 6.77</td>
<td>49.48 ± 3.40</td>
<td>53.00 ± 4.93</td>
<td>77.06 ± 7.81</td>
</tr>
<tr>
<td>Shoulder-hip differential (deg)</td>
<td>***</td>
<td>56.94 ± 3.10</td>
<td>27.88 ± 3.99</td>
<td>-20.41 ± 5.75</td>
</tr>
</tbody>
</table>

TO – Takeoff
FFTĐ – Front foot touchdown
RFTĐ – Rear foot touchdown
Table 2.5. Mean instantaneous implement velocities and accelerations at selected events

<table>
<thead>
<tr>
<th>Event</th>
<th>TO (m/s)</th>
<th>RFTD (m/s)</th>
<th>FFTD (m/s)</th>
<th>Release (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>1.85 ± 0.83</td>
<td>1.99 ± 0.55</td>
<td>3.02 ± 0.59</td>
<td>12.40 ± 0.51</td>
</tr>
<tr>
<td>Acceleration</td>
<td>-2.57 ± 6.26</td>
<td>0.51 ± 4.05</td>
<td>15.56 ± 16.76</td>
<td>7.25 ± 9.07</td>
</tr>
</tbody>
</table>

TO – Takeoff
RFTD – Rear foot touchdown
FFTD – Front foot touchdown

Table 2.6. Mean temporal parameters (seconds) for selected phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Flight phase</th>
<th>Transition phase</th>
<th>Completion phase</th>
<th>Delivery phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
<td>0.16 ± 0.04</td>
<td>0.12 ± 0.10</td>
<td>0.14 ± 0.15</td>
<td>0.26 ± 0.06</td>
</tr>
<tr>
<td>Glide</td>
<td>0.18 ± 0.03</td>
<td>0.06 ± 0.05</td>
<td>0.23 ± 0.09</td>
<td>0.30 ± 0.05</td>
</tr>
<tr>
<td>Spin</td>
<td>0.12 ± 0.04</td>
<td>0.21 ± 0.09</td>
<td>0.02 ± 0.12</td>
<td>0.22 ± 0.04</td>
</tr>
</tbody>
</table>
Figure 2-4. Relationship between distance and release velocity (A) and angle (B). The solid diamonds are the raw data. The solid line is the regression line. The regression equation and the $R^2$ value of the regression are also presented in the graph.

Figure 2-5. Relationship between release velocity and release angle. The solid diamonds are the raw data. The solid line is the regression line. The regression equation and the $R^2$ value of the regression are also presented in the graph.
Figure 2-6. Relationship between distance and the rear knee angle at rear foot touchdown (A) and release (B). The solid diamonds are the raw data. The solid line is the regression line. The regression equation and the $R^2$ value of the regression are also presented in the graphs.

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

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

The mean release velocity observed in the present study was 12.40 m/s with a range of 11.91 to 13.15 m/s. These values are similar to those reported in studies of elite female athletes throwing similar distances as well as other studies examining males throwing the shot similar distances (Alexander et al., 1996; Bartonietz & Borgstrom, 1995; Dessureault, 1978; McCoy et al., 1984). The linear correlation observed in this study between release velocity and the projected distance is different from the prediction of the classical projection equation. Theory predicts a quadratic relationship between the two parameters. The very limited range of projection velocities observed in this study can explain the discrepancy. Varying release angles and heights may have also contributed to the linear approximation of this relationship. The release angles observed in this study ranged from 31.7° – 38.5° with a mean of 35.0°. These release angles were similar to those observed in studies on both elite and non-elite shot putters (Alexander et al., 1996;
The inter-dependency of release velocity and release angle observed here has been previously suggested by several authors (Dyson, 1986; Hay, 1993; Hubbard, 1988; McCoy et al., 1984) and is supported by the results of previous research (de Mestre, 1990; Hubbard, 2000; Hubbard et al., 2001; Linthorne, 2001c; Maheras, 1995). In fact, Hubbard and colleagues (2001) suggested that other than velocity, the optimal release parameters depend largely on their affect on release velocity. The mean release height observed in the present study was 1.97m and ranged from 1.92 – 2.04m. These values are close to those reported by other studies of female shot putters (Alexander et al. 1996; Bartonietz & Borgstrom, 1995; McCoy, 1990; McCoy et al. 1984). It has been suggested that the height of release is determined largely by the anthropometric parameters of the athlete, the body position at release and the angle of the arm at release (Hay, 1993; Stepanek, 1990). As a result, attempting to increase release height would likely have negligible results. The horizontal release distances observed in this study ranged from -0.17 to 0.39m with a mean of 0.17m. These results are similar with previously reported data (McCoy, 1990). This parameter may be significant for both its potential to create an advantageous (or disadvantageous) release point and as an indication of a greater range of force application to the implement. The latter has been suggested as being critical for success in the shot put (Schmolinsky, 2000; Stepanek, 1990).

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

The importance of shoulder-hip separation suggested in coaching literature was only partially supported by the results of this study. The results indicate that while shoulder-hip separation may not be critical at RFTD or front foot touchdown (FFTD), its magnitude at release was an important indicator of success (Figure 2-7). This position has been mentioned in the coaching literature as being indicative of a strong blocking action of the non-throwing side which may create a greater transfer of momentum to the implement (Bartonietz & Borgstrom, 1995; Godina & Backes, 2000; Schmolinsky, 2000).

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

Given the observations that there was no observable difference in the magnitude of the rear knee range of motion among the sample, and greater knee flexion at both RFTD and release was observed among the best throwers indicates that a shift in the range of motion of the rear knee may be advantageous. A proposed mechanism for this advantage is that shifting the range of motion of the rear knee joint would result in greater force output by placing the leg extensor muscles in a stronger contraction range due to the force-length relationship of muscle (Gordon et al., 1966, see Figure 2-8). At the greater muscle lengths that accompany a shifted range of motion, the muscle’s capacity to produce torque is enhanced because the muscular contraction coincides with the peak of the force-length curve. Without a shift in range of motion, the muscular contraction occurs prior to the peak of the force-length curve resulting in less force output. This proposed mechanism is supported by previous research indicating that knee extensor torques are greatest at angles which fall within the range of motion observed among the best throwers in this study (Pincivero et al., 2001, Tihanyi et al., 1982; Thorstensson et al., 1977).
The previously stated mechanism has several implications for the training of elite shot putters. The benefit of shifting the rear knee range of motion to one with greater knee flexion indicates that it may be advantageous to incorporate heavily loaded strength training exercises that enhance strength through this particular range of motion. Exercises such as deep squats, which develop leg extensor strength in similar ranges of motion observed in this study would likely be advantageous. It likewise might be beneficial to perform plyometric exercises with loads similar to those of the shot in order to mimic the load placed on the rear leg at RFTD so that athletes can learn how to use the strengthened muscles.

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

![Figure 2-8](image)

Figure 2-8. The curves illustrate the force-length relationship of knee extensor muscle. The shaded box represents the potential extensor torque the knee extensors are capable of producing through a shifted (A) and unshifted (B) range of motion. A shifted range of motion will stretch the leg extensors to a greater extent resulting in increased torque due to the muscular contraction coinciding with the peak of the force-length curve (A). Without a shift in range of motion, the muscular contraction occurs prior to the peak of the force-length curve (B).

Some of the differences in results between the present study and previous literature can be explained by the fact that this is one of the first studies to quantitatively examine female athletes. Research has indicated that the temporal and anthropometric parameters related to performance in females are different from those related to male performances (Alexander et al., 1996; Ballreich, 1983; McCoy, 1990; McCoy et al., 1984; Schulter, 1983; Stepanek, 1990). Alexander and colleagues (1996) also stated that there are important kinematic parameters that differentiate male and female shot put athletes. Another confounding factor is that it may be difficult to make comparisons of males and females due to the differences in equipment (Kentner, 1984) and their
anthropometry (Alexander et al., 1996; Atwater, 1988; Kentner, 1984; Komi & Mero, 1985). This suggests that the findings of research conducted on men may not be applicable to women.

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

Conclusion

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

References


CHAPTER 3.

EXPERIMENT 2: DEVELOPMENT OF AN OPTIMIZATION MODEL FOR ELITE WOMEN SHOT PUTTERS

Introduction

Considerable research has been performed on the task of shot putting (see reviews in Lanka, 2000; Zatsiorsky et al., 1981). Several studies (Alexander et al., 1996; Bartonietz, 1996; Hubbard et al., 2001; Linthorne, 2001c) have speculated on or made suggestions on important parameters to shot put performance but only two recent studies have quantitatively examined which parameters were most critical for elite level success in the women’s shot put (Young & Li, 2005a; 2005b). Both studies examined the performance of elite level women’s shot putters and determined that there were observable parameters that contributed to the performance of an athlete.

In the first study, Young and Li (2005a) analyzed the performance of seven of the top women shot putters competing at the 2002 USA Track and Field (USATF) National Championships. Video data were captured using two Panasonic 60 Hz cameras and the best throws of each athlete were digitized and analyzed using a Peak Motus 3D motion analysis system. A total of 30 variables were examined for their effect on the distance of the throw. Stepwise regression analysis indicated that release velocity, the orientation between shoulder-hip axes (S-H) at release, release angle, rear knee (RK) angle at rear foot touchdown (RFTD), and RK at front foot touchdown (FFTD) significantly contributed to the outcome of the throw. Correlation analysis indicated that measured distance was positively correlated with release velocity and S-H at release and negatively correlated with release angle, RK at RFTD and RK at release. Greater RK flexion at both
RFTD and release along with a neutral S-H at release were identified as the most critical parameters for success among this sample of elite women shot putters.

In the second of these studies, Young and Li (2005b) used principal component analysis on the kinematics of seven elite women shot putters competing in the 2003 USATF National Championships. Data collection was identical to the previous study. Principal component analysis was used to identify important features of data variation. Twenty-four previously cited parameters were included in the initial analysis. The correlation matrix of the original parameters was created and principal components (PCs) with eigenvalues greater than 1 were retained for further analysis. These PCs were given identities based on their correlations with the original parameters. Linear regression was performed using the case-wise PCs as independent variables and the corresponding measured distance of the throw as the dependent variable. The first six PCs accounted for approximately 90% of the dataset variance. Linear regression analysis indicated that three of the six PCs were significant contributors to the outcome of the throw. PCs representing peak center of mass vertical displacement of the athlete-plus-shot system during the flight phase (PCOM), S-H, and release angle were found to be significant contributors to performance.

When viewed together, the observations of the aforementioned studies can be summarized in to four areas that significantly affect the outcome of a throw: PCOM, the positions and action of the RK, the positions and action of the S-H, and release parameters.

Increased PCOM has previously been indicated as being important for shot putting because of its ability to improve the positioning and physical capacity of an athlete to deliver the shot (Mileshin & Papanov, 1986; Young, 2004b; Young & Li,
2005a). More specifically, increased PCOM should theoretically elicit a greater stretch shortening cycle by eccentrically loading the lower extremities to a greater extent at RFTD. This in turn would be expected to lead to a more powerful delivery of the implement.

The second sub-group shown to affect the outcome of the throw is the action of the RK. In addition to the two previously mentioned studies, the movements of the RK between RFTD and release has been discussed extensively in both research (McCoy et al., 1984) and coaching literature (Bartonietz & Borgstöm, 1995; Bosen, 1981; Grigalka, 1972; Irving, 1980). Previous research literature has indicated that it is beneficial to make RFTD with greater RK flexion although the range of motion of the RK differs little between the best and worst throws (Young & Li, 2005a). Therefore, greater RK flexion at release was may also be associated with improved performance.

Many have suggested that the explosive extension of the RK is the initiation of the actions that follow in the S-H (Bartonietz & Borgstöm, 1995; Grigalka & Papanov, 1988; Mileshin & Papanov, 1986). This ties in closely with the third sub-group of parameters that has been linked to elite performance in the shot put – the positions and action of the S-H. As with the RK, the position and actions of the S-H has been extensively discussed in both coaching (Godina & Backes, 2000; McGill, 1983) and research literature (Bartonietz & Borgstöm, 1995; Young & Li, 2005b). Of particular interest is the interplay between the transverse axis of the hips and the transverse axis of the shoulders. A greater angle between the axes can potentially generate trunk whip and beneficially stretch the trunk musculature. Trunk whip refers to the acceleration that occurs in the shoulder axis, elbow, and hand as a result of the preceding acceleration and sudden deceleration of the hip segment.
Several investigators have reported that both the speed and amplitude of the trunk whip is dependent on the S-H separation attained at RFTD or FFTD (Ariel, 1973; Delevan, 1973; Koltai, 1973; Nett, 1962). To increase S-H separation, the transverse plane of the hips must move ahead of the transverse plane of the shoulders. This position would also stretch the trunk muscles, which should enhance muscle contraction and produce greater force. In fact, Ariel (1973) found that the hips rotate 175°-220° following RFTD and that S-H separation coincided with the maximum speed of hip rotation among top performers maximum (100.3 ± 24.6 msec before release of the shot). Powell (1960) claimed that the success of shot putting depends on the speed of this rotation. If the shoulders can be kept in a rear-facing position, the faster the hips rotate the greater the whip effect will be.

Also important for maximization of trunk whip is the sudden deceleration of the hip segment prior to release in addition to increase S-H separation at RFTD. Irving (1980) suggested that the hips should rotate and stop prior to release. This would allow the shoulder segment to ‘catch up’ to the hip segment and the resulting whip effect would accelerate the shoulders and throwing arm.

Release parameters are the final sub-group. The release parameters consist of release angle, release velocity and release height. Of these, the release velocity and angle were indicated as being significant contributors to performance in the shot put (Young & Li, 2005a; 2005b). Previous research has indicated all three of these parameters are interdependent. The most important of these relationships is the one between release velocity and release angle, which share an inverse relationship (de Mestre et al., 1998; Hubbard et al., 2001; Linthorne, 2001c; Maheras, 1995). That is, as release increases, release velocity decreases.
The purpose of the present study was to further develop the optimization model for elite women’s shot putting. We have examined the parameters previously identified in the four previously discussed sub-categories with a greater number of performances and more vigorous statistical analysis.

**Methods**

**Operational Terminology**

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

**Shoulder-hip separation:** The angular relationship of the transverse axis of the hips relative to the transverse axis of the shoulders. S-H is neutral (zero degrees of separation) in anatomical reference position. A positive angle occurs when the throwing side shoulder is posterior to the throwing side hip (See Figure 3-1 for details).

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

**Peak center of mass vertical displacement of the athlete-plus-shot system:** measured from the vertical position of the COM at the point of takeoff to its peak vertical position during flight.

**Subjects**

Kinematic data from twenty elite women shot putters was used for this study. Video data were collected at the 2002, 2003, 2004, and 2005, and 2006 USATF National Championships. All of the participants were finalists at the National Championship meet. An athlete becomes a finalist if they achieve a throw that ranks amongst the top 8 in the
field after their first 3 attempts. Finalists are then given three additional attempts.

Athletes using both the glide and spin technique were included. One performer used the glide and the spin technique in different years. Due to the method of analysis employed in this study, this performer was counted as two individuals. Eighty-three throws from nineteen (with the aforementioned thrower counting twice) different performers were analyzed. Clothing was not standardized during a competition.

Figure 3-1. Shoulder-hip separation for right handed thrower. The solid white oval represents the orientation of the hips and the solid gray oval represents the orientation of the shoulders. The small black circle represents the shot. The angle between the line of the shoulder and the line of the hip represents the shoulder-hip separation. For left handed throwers, these angles were reversed.

Parameter Selection

Eight parameters were selected as independent variables and measured distance of the throw was used as the dependent variable. The parameters examined are presented in Table 3.1. The independent variables were identified from results of two previous studies (Young & Li, 2005a; 2005b). Although release velocity was indicated as a significant indicator for performance in the first of these studies, it was excluded from this study due to the fact that it does not reveal any applicable information to an athlete because all athletes are presumably trying to throw as hard and fast as possible during a competition. Likewise, because previous research (Young & Li, 2005a) has indicated that release
velocity explains so much of the variance of a throw by itself (90+%%) it was concluded that it could mask the importance of other parameters that may be more applicable to beneficially affecting a technical intervention due to multi-collinearity.

Table 3.1. Parameters examined in the study and literature supporting their inclusion

<table>
<thead>
<tr>
<th>Sub-Group</th>
<th>Parameter</th>
<th>Event / Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Release Parameters</td>
<td>Release angle</td>
<td>FLIGHT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RFTD</td>
</tr>
<tr>
<td>PCOM</td>
<td>B</td>
<td>FFTD</td>
</tr>
<tr>
<td>shoulder-hip separation</td>
<td>B</td>
<td>Release</td>
</tr>
<tr>
<td>Rear knee angle</td>
<td>AB</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>AB</td>
</tr>
<tr>
<td>Athlete Kinematics</td>
<td>RFTD – Rear foot touchdown</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FFTD – Front foot touchdown</td>
<td></td>
</tr>
<tr>
<td>PCOM</td>
<td>Vertical displacement of athlete-plus-shot system</td>
<td></td>
</tr>
<tr>
<td>A – Young and Li, 2005a</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>B – Young and Li, 2005b</td>
<td></td>
</tr>
</tbody>
</table>

Data Collection

Two time-synchronized video cameras were used to record a control object and the performances at a sampling rate of 60 Hz. The cameras were placed near the shot put throwing circle spaced approximately 90° apart. Following collection of the performance data, a calibration frame was placed in the center of the throwing circle and recorded so that the direct linear transformation (DLT) procedure could be performed.

Data Reduction

Video data were digitized using 4 different motion analysis packages: Peak Motus (2002), Hu-M-An (2003-2004), and MaxTraq (2005-2006). Discontinued availability of software and increased ease of use necessitated the changes in software. The same individual digitized all video data. The video record of each performance included for examination was manually digitized at a sampling rate of 60 frames per second from two frames before the initiation of the throw to two frames after the release of the shot. In each digitized field, 23 points were manually digitized to model the athlete-plus-shot
system (APSS, see Young & Li, 2005a for details). The digitized 2D data were time synced based on the release of the shot. A second event, FFTD, was used to verify the accuracy of the synchronization. All analyzed clips met both synchronization criteria.

The DLT procedure (Abdel-Aziz & Karara, 1971) was used to determine 3D coordinates of 22 body landmarks and also the center of the shot for each trial (see Figure 3-2 for details). The digitized control object coordinates were used to estimate the DLT parameters for each camera. The 3D coordinate data were smoothed using a fourth-order Zero-lag Butterworth low pass digital filter with a cutoff frequency at 8 Hz (Winter et al., 1974). This smoothing method has previously been used for the shot put (Young & Li 2005a) and other throwing activities (Yu et al., 2002).

**Data Analysis**

The method employed in this study to breakdown the throw into phases by predetermined events allowed for both techniques to be analyzed together based on the similar events (Figure 3-3). This method has been used previously to examine the shot put (Young & Li, 2005a; 2005b).

The data were analyzed using hierarchical linear modeling (HLM). Two HLM analyses were performed. Individuals were set up as level-1 units of study, and the groups into which they were arranged (glide or spin) were level-2 units. The first HLM analysis examined the effects of level-1 variables individually. A second HLM analysis considered the unique effects of the level-1 predictors in the context of a model containing all eight parameters. Stata software from StataCorp LP (Austin, TX) was used to perform the analysis. A significance level of 0.10 was used for the analysis. Previous
applied research on the shot put (Young & Li, 2005a; 2005b) and other track and field throwing events have used this significance level (Yu et al., 2002).

![Figure 3-2. 22 anatomical landmarks and the center of the shot put were manually digitized.](image)

**Results**

**Descriptive Statistics**

Mean and standard deviation for the eight parameters included in the HLM are presented in Table 3.2. These data are in agreement with previous literature on the shot put (Knudsen, 1989) indicating that the data collected for this study is comparable to those used in previous research on the event.
Hierarchical Linear Modeling

The first HLM analysis examined the affect of each independent variable on measured distance individually. Results indicated that seven of the eight variables had a significant impact on the measured distance of the throw. S-H at RFTD, FFTD, and release; RK at RFTD and FFTD, PCOM during the flight phase and the angle of release contribute to elite level success among women shot putters. RK at release did not significantly affect the measured distance (See Table 3.3 for details).

The second HLM analysis examined the unique effects of the level-1 predictors in the context of a model containing all independent variables. In this analysis, only release angle, PCOM during the flight phase, and S-H at RFTD were found to make unique...
contributions to the outcome of the throw (See Table 3.4 for details). A correlation matrix (Table 3.5) indicated that the partial discrepancy between the first and second HLM analysis was due to several of the level-1 predictors being highly correlated. The coefficients for predictor variables in HLM, like those in multiple regression analysis, reflect the unique contribution of each predictor variable, controlling for all of the other predictors in the equation. When variable A is the only predictor in the equation (as in the first HLM), the weight for variable A reflects all of the variance shared between variable A and the dependent variable. When additional variables are added to the equation as predictors (as in the second HLM), then the weight for variable A reflects the unique effect of variable A on the dependent variable, controlling for levels of all other variables input in to the equation. As such, when significant correlations exist between the dependent variables, discrepancies may occur between the results of single and multiple variable HLM analyses that are determined to be significant.

Table 3.2. Means and standard deviation for dependent and independent variables

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean (all)</th>
<th>Mean (glide)</th>
<th>Mean (spin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>83</td>
<td>53</td>
<td>30</td>
</tr>
<tr>
<td>Measured distance (m)</td>
<td>17.0 ± 1.1</td>
<td>17.3 ± 1.0</td>
<td>16.6 ± 1.1</td>
</tr>
<tr>
<td>Release angle (deg)</td>
<td>35 ± 2</td>
<td>36 ± 2</td>
<td>35 ± 2</td>
</tr>
<tr>
<td>PCOM (m)</td>
<td>0.18 ± 0.05</td>
<td>0.17 ± 0.05</td>
<td>0.21 ± 0.03</td>
</tr>
<tr>
<td>RK @ RFTD (deg)</td>
<td>116 ± 11</td>
<td>114 ± 9</td>
<td>121 ± 12</td>
</tr>
<tr>
<td>S-H @ RFTD (deg)</td>
<td>42 ± 20</td>
<td>50 ± 18</td>
<td>29 ± 17</td>
</tr>
<tr>
<td>RK @ FFTD (deg)</td>
<td>122 ± 12</td>
<td>119 ± 13</td>
<td>126 ± 10</td>
</tr>
<tr>
<td>S-H @ FFTD (deg)</td>
<td>25 ± 9</td>
<td>26 ± 9</td>
<td>23 ± 8</td>
</tr>
<tr>
<td>RK @ Release (deg)</td>
<td>147 ± 8</td>
<td>146 ± 8</td>
<td>149 ± 8</td>
</tr>
<tr>
<td>S-H @ Release (deg)</td>
<td>-15 ± 7</td>
<td>-16 ± 6</td>
<td>-14 ± 9</td>
</tr>
</tbody>
</table>

PCOM – Vertical displacement of athlete-plus-shot system
RK – Rear knee angle
S-H – Angle between transverse axes of shoulder and hip
RFTD – Rear foot touchdown
FFTD – Front foot touchdown
Table 3.3. Individual effects of level-1 variables from HLM analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Intercept Coefficient</th>
<th>Parameter Coefficient</th>
<th>Parameter Standard Error</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Release Angle</td>
<td>26.00</td>
<td>-0.26</td>
<td>0.05</td>
<td>0.00</td>
</tr>
<tr>
<td>PCOM</td>
<td>13.34</td>
<td>18.89</td>
<td>2.66</td>
<td>0.00</td>
</tr>
<tr>
<td>RK @ RFTD</td>
<td>22.62</td>
<td>-0.05</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>S-H @ RFTD</td>
<td>14.24</td>
<td>0.06</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>RK @ FFTD</td>
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<td>-0.04</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>S-H @ FFTD</td>
<td>16.17</td>
<td>0.03</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>RK @ Release</td>
<td>18.88</td>
<td>-0.01</td>
<td>0.01</td>
<td>0.32</td>
</tr>
<tr>
<td>S-H @ Release</td>
<td>17.92</td>
<td>0.07</td>
<td>0.02</td>
<td>0.00</td>
</tr>
</tbody>
</table>

PCOM – Vertical displacement of athlete-plus-shot system  
RK – Rear knee angle  
S-H – Angle between transverse axes of shoulder and hip

Table 3.4. Final estimation of fixed effects from HLM analysis

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Standard Error</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>18.057</td>
<td>2.171</td>
</tr>
<tr>
<td>Release Angle</td>
<td>-0.091</td>
<td>0.037</td>
</tr>
<tr>
<td>PCOM</td>
<td>14.648</td>
<td>2.396</td>
</tr>
<tr>
<td>RK @ RFTD</td>
<td>-0.008</td>
<td>0.008</td>
</tr>
<tr>
<td>S-H @ RFTD</td>
<td>0.037</td>
<td>0.008</td>
</tr>
<tr>
<td>RK @ FFTD</td>
<td>0.002</td>
<td>0.010</td>
</tr>
<tr>
<td>S-H @ FFTD</td>
<td>-0.006</td>
<td>0.010</td>
</tr>
<tr>
<td>RK @ Release</td>
<td>-0.010</td>
<td>0.008</td>
</tr>
<tr>
<td>S-H @ Release</td>
<td>-0.002</td>
<td>0.015</td>
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</table>

PCOM – Vertical displacement of athlete-plus-shot system  
RK – Rear knee angle  
S-H – Angle between transverse axes of shoulder and hip

Discussion

The study examined eight previously cited variables using two methods of HLM.

The first HLM analysis examined each parameter individually and the second observed

the unique effects of each parameter in a model containing all of the variables. The first
analysis indicated that seven variables significantly impacted performance: S-H at RFTD, FFTD, and release; RK at RFTD and FFTD, PCOM and the angle of release. The second HLM analysis indicated that release angle, PCOM and S-H at RFTD made unique, significant contributions to the performance. RK at release did not significantly affect the measured distance in either HLM analyses.

The dataset used for this study was unusual for a variety of reasons. Most obviously, the participants were among the best shot putters in the world and the data were captured in one of the most important competitions of their season. While this obviously makes for a very worthwhile research scenario, it also causes complications. Due to the nature of the data collection, we cannot control which throwers would show up to compete in a given year, which would make the finals, and how many fair (as opposed to illegal or foul) throws each would be credited with. As a result, the dataset is both highly variable by year and by performer. The dataset contains 83 different throws by 18 performers, only two of whom have data for every year. While the number of participants is relatively small, it represents a very large (90+%%) of the elite American shot put thrower population from 2002 to 2006. Some participants have only one throw examined. Others have as many as 12. The average trial per participant is 5.3 and the median is 4.5. The data are similarly not balanced by year or by technique. For example, in 2002, there are only data for 7 throws while in 2006 there and data for 24 throws. There are 53 glide throws with only 30 spin throws. With such an unbalanced dataset, controlling for bias (because the best performers tend to have the most data collected and the glide has a greater representation) was of utmost concern.

The chosen method of analysis provided a unique opportunity to examine this dataset while taking into account many of the previously mentioned challenges. It
addressed the unbalanced nature of the dataset as well as the individual characteristics (anthropometric, unique stylistic tendencies, etc) and technique employed (glide or spin) that could have affected the outcome of the analysis.

HLM is a form of multilevel modeling that can be effectively used to analyze data that are arranged in a hierarchy due to the observations being nested within clusters. HLMs were developed to permit the study of relationships at any level in a single analysis while still taking in to account the variability associated with each level of the hierarchy. The HLM procedure predicts the random effects associated with each sampling unit at every level and also estimates model coefficients at each level. This method was chosen for this particular set because it permitted the individual participants and techniques to be classified in to groups that could influence the study. Principal component analysis, stepwise regression analysis and econometric modeling were all considered for analysis but ultimately were not chosen because the author felt that they could not analyze the nested and highly unbalanced nature of the dataset.

The most important observation of the study was the identification of critical parameters for elite level performance among a population of elite level shot putters. Previous research has successfully identified critical parameters for other sporting events and this study indicates that the same may be done for shot putting. The observations indicate that there are specific parameters that are important for achieving elite level distances in the shot put that can be applied across both individual performers and the two prominently used techniques.

Seven of the parameters were found to have a significant impact on the measured distance of the throw either individually or as part of a model using all 8 parameters. This largely confirms and validates the previous observations of Young and Li (2005a; 2005b)
Table 3.5. Correlation matrix of independent variables

<table>
<thead>
<tr>
<th></th>
<th>Performance</th>
<th>Release Angle</th>
<th>PCOM</th>
<th>RK @ RFTD</th>
<th>S-H @ RFTD</th>
<th>RK @ FFTD</th>
<th>S-H @ FFTD</th>
<th>RK @ Release</th>
<th>S-H @ Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>---</td>
<td>-0.41</td>
<td>0.42</td>
<td>-0.59</td>
<td>0.11</td>
<td>-0.40</td>
<td>0.02</td>
<td>-0.11</td>
<td>0.27</td>
</tr>
<tr>
<td>Release Angle</td>
<td>-0.41</td>
<td>---</td>
<td>0.19</td>
<td>0.26</td>
<td>0.04</td>
<td>-0.19</td>
<td>0.04</td>
<td>0.10</td>
<td>-0.45</td>
</tr>
<tr>
<td>PCOM</td>
<td>0.42</td>
<td>-0.19</td>
<td>0.08</td>
<td>-0.40</td>
<td>0.23</td>
<td>-0.39</td>
<td>0.24</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>RK @ RFTD</td>
<td>-0.59</td>
<td>0.26</td>
<td>0.08</td>
<td>---</td>
<td>-0.39</td>
<td>0.68</td>
<td>-0.31</td>
<td>0.25</td>
<td>-0.01</td>
</tr>
<tr>
<td>S-H @ RFTD</td>
<td>0.11</td>
<td>0.04</td>
<td>-0.40</td>
<td>-0.39</td>
<td>---</td>
<td>-0.59</td>
<td>0.57</td>
<td>-0.33</td>
<td>-0.28</td>
</tr>
<tr>
<td>RK @ FFTD</td>
<td>-0.40</td>
<td>-0.19</td>
<td>0.23</td>
<td>0.68</td>
<td>-0.59</td>
<td>---</td>
<td>-0.32</td>
<td>0.20</td>
<td>0.25</td>
</tr>
<tr>
<td>S-H @ FFTD</td>
<td>0.02</td>
<td>0.04</td>
<td>-0.39</td>
<td>-0.31</td>
<td>0.57</td>
<td>-0.32</td>
<td>---</td>
<td>-0.43</td>
<td>-0.35</td>
</tr>
<tr>
<td>RK @ Release</td>
<td>-0.11</td>
<td>0.10</td>
<td>0.24</td>
<td>0.25</td>
<td>-0.33</td>
<td>0.20</td>
<td>-0.43</td>
<td>---</td>
<td>0.14</td>
</tr>
<tr>
<td>S-H @ Release</td>
<td>0.27</td>
<td>-0.45</td>
<td>0.22</td>
<td>-0.01</td>
<td>-0.28</td>
<td>0.25</td>
<td>-0.35</td>
<td>0.14</td>
<td>---</td>
</tr>
</tbody>
</table>

PCOM – Vertical displacement of athlete-plus-shot system
RK – Rear knee
S-H – Angle between transverse axes of shoulder and hip
RFTD – Rear foot touchdown
FFTD – Front foot touchdown

---

68
on the use of an optimization model for women’s shot putting. The HLM analysis revealed that release angle, PCOM during the flight phase, and S-H separation at RFTD made significant contributions to the outcome of the throw both as unique variables and when taking into account all other parameters.

That release angle has a large impact on performance was to be expected, as there is much literature that suggests that release angle is closely linked with the magnitude of release velocity (de Mestre et al., 1998; Hubbard et al., 2001; Linthorne, 2001c; Maheras, 1995). The release angles observed in this study ranged from 31.6° – 39.0° with a mean of 35° ± 2°. These release angles were similar to those observed in studies on both elite and non-elite shot putters (Alexander et al., 1996; Bartonietz & Borgstöm, 1995; Stepanek, 1990; Tsirakos et al., 1995). The current study indicated that performance improves as release angle decreases. This finding provides further support to the theory that performers benefit from releasing at an angle that is significantly lower than the mathematically predicted ‘optimal’ release angle of 41-42°. As noted above, this phenomenon is due to the interdependency of release angle and release velocity. Previous research has indicated that release angle and release velocity operate in an inverse relationship (de Mestre et al., 1998; Hubbard et al., 2001; Linthorne, 2001c; Maheras, 1995). And because release velocity is so influential to performance, it appears that it is beneficial to decrease release angle because of the accompanying increase in release velocity.

Similar to release angle, both HLM analyses revealed PCOM during the flight phase as being a significant indicator of performance in the shot put. The mean PCOM was 0.18 (± 0.05m). There is very little research on this parameter to compare these values to. Several authors (Mileshin & Papanov, 1986; Young, 2004b; Young & Li,
2005a) have suggested that the main benefit of the flight phase may be to elicit a stretch shortening cycle by eccentrically loading the lower extremities during rear foot touchdown for a more powerful delivery of the implement. More specifically, the stretch reflex of the knee extensors that occurs upon landing from the flight phase may increase their force producing capacity. If this theory were true, performance should increase with increased PCOM. The significance of this parameter along with its positive correlation with performance supports this notion.

As with previous studies on the subject, the position and action of the RK at various points of the throw was revealed to be very important to the outcome of the throw. While the observations of this study confirm this point, there remains much to understand about the exact relationship. The mean RK was 116 ± 11 degrees at RFTD, 122 ± 12 at FFTD and 147 ± 8 at release indicating that the knee joint was most flexed at RFTD and extended through release. These values are in line with previous research (Young & Li, 2005a).

The current research also verifies the observations of prior research (Young & Li, 2005a, 2005b) on the benefits of increased RK flexion at RFTD. Prior coaching literature also supports this point (Schmolinsky, 2000; Young, 2004b). While the mechanism of benefit is not fully understood, it has been proposed that increased RK flexion shifts the knee extensors in to a more advantageous position to produce force (Young & Li, 2005a). RK at FFTD appears to also be very important. As the correlation analysis of RK at RFTD and FFTD indicated a significant positive relationship, it is likely that the mechanism of benefit is the same.

Increased RK flexion at release was not linked with performance. It should be noted that although previous research has identified this relationship (Young & Li,
the present finding is in line with previous suggestions from coaching literature. These recommendations have implicated the importance of complete or near complete extension of the rear (Godina & Backes, 2000) or both legs (Schmolinsky, 2000; Stepanek, 1990) for achieving maximum distance.

The present study also examined the effect of S-H on performance. Previous research and coaching literature indicates that greater S-H separation is beneficial at RFTD and FFTD (Godina & Backes, 2000; Young & Li, 2005b); and a neutral orientation is beneficial at release (Young, 2004b; Young & Li, 2005a; 2005b). These positions are closely related to the concept of trunk whip. Increased trunk whip has been shown to greatly increase release velocity (Ariel, 1973; Bartonietz & Borgstöm, 1995; Johnson, 1992; McGill, 1983) that would in turn be expected to increase performance.

The positions observed in this study appear to bear this out. The mean S-H at RFTD, FFTD, and release were 42 ± 20, 25 ± 9, and -15 ± 7 respectively. Several investigators have reported that both the speed and amplitude of the trunk whip during the completion phase is dependent on the S-H separation attained immediately following RFTD and the sudden deceleration of the hips at release (Ariel, 1973; Koltai, 1973; Lanka, 2000) that causes the shoulder axis to catch up with the hips to assume a more neutral S-H. Such a movement pattern would be indicative of the proximal-to-distal (hips-to-shoulders) acceleration occurring in trunk whip and also place the trunk muscles on stretch which would enhance the force with which they are able to contract.

The observations of the present study only partially validated the trunk whip theory. As would be expected, S-H at RFTD was found to make a significant contribution to the measured distance of the throw in both HLM analyses. Correlation analysis indicated that greater S-H separation at RFTD is significantly associated with improved
performance. Similar observations were made for S-H at FFTD. At release, results were somewhat inconclusive as the first HLM analysis did not indicate a significant relationship with performance but the second HLM analysis did. Further complicating the issue is the fact that S-H at release showed a strong positive correlation with performance. It is suspected that these discrepancies are due to the fact that all three variables were significantly correlated and the previously noted weaknesses of the correlation analysis (unlike HLM analyses it is un-weighted). Further research is needed to fully understand whether a particular S-H at release is beneficial.

The results of this study should be useful for coaches and women shot putters attempting to improve performance because it provides quantitatively supported evidence for 8 key technical variables. Prior to this study, the majority of research on the shot put was conducted on men and was observational in nature. This research identified 8 parameters that could become the focus of an elite female’s technical training. Similarly, coaches who recognize the interdependence of technique and physical capacities (strength, speed, etc) may develop training methods to better enhance the athlete’s physical abilities to take advantage of the technical modifications.

**Conclusion**

The results of this study expanded the findings of previous optimization modeling attempts for elite women’s shot putting. Although the observations are not totally conclusive, they provide a large step forward towards a more complete optimization model for the task. The results of this study suggest that all 8 previously cited parameters play an important role in the performance of elite women’s shot putting. Further research on the topic is necessary to better understand all of the relationships both between these variables and with performance. The observations of this study provide useful
information for the technical development of women throwers and may provide insight on new training methods that should be devised that focus on the physical capabilities associated with the 8 parameters.

References


Young, M., & Li, L. (2005b). *Principal component analysis on the kinematic parameters of elite women shot putters*. Oral presentation at the SEACSM Annual Meeting: Charlotte, NC.


CHAPTER 4.

EXPERIMENT 3: APPLICATION OF AN OPTIMIZATION MODEL FOR ELITE WOMEN SHOT PUTTERS

Introduction

Considerable research has been performed on the task of shot putting (see reviews in Lanka, 2000; Zatsiorsky et al., 1981). Until recently, this research has been either qualitative or descriptive in nature. More recently, there have been several attempts to quantitatively determine the kinematic parameters that were most closely related to performance in the event (Young & Li, 2005a; 2005b).

In the first of these studies, the performance of seven of the top women shot putters competing at the 2002 USATF National Championships was analyzed (Young & Li, 2005a). Video data were captured using two Panasonic 60 Hz cameras and the best throws of each athlete were digitized and analyzed using a Peak Motus 3D motion analysis system. Thirty variables were examined for their effect on the measured distance of the throw (mark). Stepwise regression analysis indicated that release velocity, shoulder-hip orientation (S-H) at release, release angle, rear knee angle (RK) at rear foot touchdown (RFTD), and RK at front foot touchdown (FFTD) significantly contributed to the outcome of the throw. Correlation analysis indicated that mark was positively correlated with release velocity and S-H at release and negatively correlated with release angle, RK at RFTD and RK at release. Greater RK flexion at both RFTD and release along with a neutral S-H at release were identified as the most critical parameters for success among this sample of elite women shot putters.
In the second of these studies, principal component analysis was used on the kinematics of seven elite women shot putters competing in the 2003 USATF National Championships (Young & Li, 2005b). An identical data collection to the previous study was employed. Principal component analysis was used to identify important features of data variation. The initial analysis examined 24 previously cited parameters. The correlation matrix of the original parameters was created and principal components with eigenvalues greater than one were retained for further analysis. These retained principal components were given identities based on their correlations with the original parameters. Linear regression was performed using the case-wise principal components as independent variables and the corresponding mark as the dependent variable. The first six principal components accounted for approximately 90% of the dataset variance. Linear regression analysis indicated that three of the six principal components were significant contributors to the outcome of the throw. Principal components representing peak center of mass vertical displacement of the athlete-plus-shot system during the flight phase (PCOM), S-H, and release angle were found to be significant contributors to performance.

The latest study in this line of research used a larger population of participants and a more focused set of independent variables to verify the observations of the previous two studies. In this study, eight previously cited parameters were included for two analyses using hierarchical linear modeling (HLM). The first HLM analysis examined each parameter individually as independent variables and the second examined the unique effects of each parameter in a model containing all eight variables. Mark was used as the dependent variable. Results of the first analysis indicated that seven variables had a significant impact on the mark: S-H at RFTD, FFTD, and release; RK at RFTD and
FFT, PCOM and the angle of release contribute to elite level performance among women shot putters at the US national level. The second HLM analysis indicated that release angle, PCOM and S-H at RFTD made unique, significant contributions to the performance. RK at release was the only variable that neither HLM analysis indicated a significant impact on performance. Between the two analyses, seven of the eight variables were indicated as making significant contributions to the outcome of a throw and largely verified the observations of the previous research.

These three studies have provided insight as to which variables may be most critical to elite level performance in the women’s shot put. It remained to be seen, however, whether these observations could provide practical benefit for elite women shot putters. More specifically, could the results of the previous studies be used to beneficially guide the technical training of elite women shot putters?

Technical training based on optimization modeling is not altogether new. It has previously been used in several US Olympic Committee sport science programs for several decades (see Mann, 1986 for details). Despite this, there are no known research studies examining the effectiveness of a technical intervention using an optimization model as the basis for changing a performer’s kinematics. Optimization models have been used in the training of other activities though. For example, a common movement model was successfully used in the training and rehabilitation of ACL reconstruction patients (Risberg et al., 2001). This training was shown to reduce female knee joint injury. Similar benefits may exist from a technical intervention using an optimization model for the shot put.

The purpose of the present study was to test the effects of a technical intervention based on a previously developed optimization model on a female shot putter’s
competition performance. It was hypothesized that performance improvements of athletes receiving a technical intervention will be greater than those not receiving a technical intervention and any improvements in mark can be associated with corresponding changes in the optimization model parameters (OMPs).

**Methods**

**Operational Terminology**

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

**Shoulder-hip separation:** The orientation of the hips relative to the orientation of the shoulders. S-H orientation is neutral (zero degrees of separation) in anatomical reference position. A positive angle occurs when the throwing side shoulder is posterior to the throwing side hip. See Figure 4-1.

**Mark:** The horizontal displacement of the shot measured from the innermost edge of the toe-board and ending at the landing point of the shot. This is the distance recorded as the official result. More specifically, the mark is the sum of the projected distance and the horizontal release distance.

**Peak vertical displacement of the athlete-plus-shot system’s center of mass:** The vertical displacement of the athlete-plus-shot system’s COM measured from the vertical position of the COM at the point of takeoff to its peak vertical position during flight.

**Subjects**

Two groups of subjects were used for this study. The training intervention group (TI) consisted of the seven women shot putters who competed at both the 2006 and 2007 USATF National Championships and received a biomechanical report with kinematic feedback based on their individual results and the observations of the previous study.
This technical intervention was provided to both the athletes and their coaches nine months prior to the 2007 USATF National Championships at a USATF sponsored elite athlete summit via a 70 minute educational lecture to the entire group, a face-to-face meeting with each athlete and coach, and a multi-media biomechanical report in DVD format that the coaches and athletes were able to take home for future viewing. Technical intervention was presented using primarily an external focus of attention with an emphasis on movement effects. Previous research has indicated that this method enhances learning (Wulf et al., 2002, Wulf et al., 2001).

The no training intervention group (NTI) served as a control group and they received no technical intervention. This group was comprised of any female shot putter who competed in back-to-back USATF National Championships between 2002 and 2006 that did not receive a kinematic technical intervention report at any point during that time frame. This group consisted of eight athletes.

**Parameter Selection**

Eight kinematic parameters were used as independent variables and mark was used as the dependent variable. The independent variables were:

Positive  Neutral  Negative

Figure 4-1. Shoulder-hip separation for right handed thrower. The solid white oval represents the orientation of the hips and the solid gray oval represents the orientation of the shoulders. The small black circle represents the shot. The angle between the line of the shoulder and the line of the hip represents the shoulder-hip separation. For left handed throwers, these angles were reversed.
1. PCOM
2. RK at RFTD
3. S-H at RFTD
4. RK at FFTD
5. S-H at FFTD
6. RK at release
7. S-H at release
8. Release angle

These independent variables were identified from results of the two previous studies.

**Data Collection**

Two time-synchronized video cameras recorded a control object and the performances at a sampling rate of 60 Hz. Cameras were placed around the shot put throwing circle spaced approximately 90° apart. Following collection of the performance data, a calibration frame was placed in the center of the throwing circle and recorded so that the direct linear transformation (DLT) procedure could be performed.

**Data Reduction**

Video data were digitized using four different motion analysis packages: Peak Motus (2002), Hu-M-An (2003-2004), and MaxTraq (2005-2007). Discontinued availability of software and increased ease of use necessitated the changes in software. One individual digitized all video data. The video record of each performance included for examination was manually digitized at a sampling rate of 60 frames per second from two frames before the initiation of the throw to two frames after the release of the shot. In each digitized field, 23 points were manually digitized to model the athlete-plus-shot system (see Figure 4-2 for details). The digitized 2D data were time synced, based on the release of the shot. FFTD was used to verify the accuracy of the synchronization. All analyzed clips met both synchronization criteria. The DLT procedure (Abdel-Aziz & Karara, 1971) was used to determine 3D coordinates of 22 body landmarks and the center
of the shot for each trial. The digitized control object coordinates were used to estimate the DLT parameters for each camera. The 3D coordinate data were smoothed using a fourth-order zero-lag Butterworth low pass digital filter with a cutoff frequency at eight Hz (Winter et al., 1974). This smoothing method has previously been used for the shot put (Young & Li, 2005a) and other throwing activities (Yu et al., 2002).

Figure 4-2. 22 anatomical landmarks and the center of the shot put were manually digitized.

Data Analysis

The method employed in this study to breakdown the throw into phases by predetermined events allowed for both techniques to be analyzed together based on the similar events (Figure 4-3). This method has been used previously to examine the shot put (Young & Li, 2005a; 2005b).


**Statistical Analysis**

A simple statistical analysis providing mean and standard deviation for the eight OMPs and mark was performed for the TI and NTI groups for the first and second data collection. For the purposes of comparison with previous research, simple statistics for the three remaining release parameters was also performed. Additionally, individual inter-year performance differences (IIPD) were determined for each of the individual athlete’s mark and the eight previously mentioned parameters as well as the three remaining release parameters (velocity, height, and horizontal release distance). IIPD values represent the change, expressed as a percentage, of the given variable from one year to the subsequent year for a given athlete. This delta value was expressed as a positive value if the change from pre to post data collection for the given parameter was in the direction suggested in the technical intervention. Similarly, the IIPD value was expressed as a negative value if the change in the parameter from pre to post data collection was in the opposite direction from what was suggested in the technical intervention. Following determination of IIPD values, the mean group inter-year performance difference (IPD) for each parameter was determined. Note that because IPD values were determined using IIPD values first, that the direction (±) of the IPD may not necessarily correspond to the difference of the mean values of a given parameter from the pre to post data collection.

Using the raw data, IIPD, and IPD values, further analysis was performed. To determine whether the NTI and TI groups were significantly different a two part intra-group analysis was performed. The first analysis used a two-tailed multivariate t-test on the IIPDs of the two groups to determine whether the groups as a whole were significantly different. This analysis compared the IIPD values for mark and the eight
OMPs of both groups. Following the multivariate T-Test, individual t-tests were used to compare the IIPDs values for mark and the eight OMPs to determine whether a statistically significant difference exists between the IIPD values of the two groups. Significance level for both tests was set at 0.05.

To assess whether the technical intervention had any affect on the TI group’s performance a paired t-test was performed using the pre and post intervention data. Significance level was set at 0.05. The NTI group was used as a control. Finally, an observational analysis was performed to determine whether the IPD values of the TI group changed to a greater extent in the desired direction than the NTI group (as would be expected).

Figure 4-3. Method of technical evaluation for each technique. Both techniques had similar instances of single and double support.
Results

Descriptive Statistics

The mean and standard deviation for the eight parameters along with the release parameters of both groups is presented in Table 4.1. These data are in agreement with previous literature on the shot put (Knudsen, 1989; Young & Li, 2005a) indicating that the data collected for this study is comparable to those used in previous research on the event.

Examination of IPD values indicated that four of the five largest values were observed in the TI group. The IPD values observed in the TI group for PCOM (0.09 ± 0.18), S-H at RFTD (-0.26 ± 0.17), S-H at FFTD (0.30 ± 0.73) and S-H at release (-0.48 ± 1.77) were four of the largest IPD values observed in the study. The largest IPD value observed in the NTI group was S-H at RFTD (0.15 ± 0.46). The IPD values are presented in Table 4.2.

Analytical / Multivariate Statistics

The two-tailed multivariate t-test used for intra-group analysis indicated that the TI and NTI groups were significantly different ($F$ (9, 12) = 3.91, $p < .02$). The results are presented in Table 4.3.

The individual intra-group t-tests indicated five of eight IPD values were statistically different. RK at RFTD ($F$ (6, 14) = 5.11, $p < .03$) and FFTD ($F$ (6, 14) = 3.72, $p < .02$); and S-H at RFTD ($F$ (6, 14) = 7.34, $p < 0.01$), FFTD ($F$ (6, 14) = 10.94, $p < 0.01$), and release ($F$ (6, 14) = 62.48, $p < .01$) were indicated as being significantly different for the two groups. The complete results are presented in Table 4.4.
The two-tailed inter-group analysis indicated no significant changes in either the mark or any of the eight OMPs for the NTI group. In the TI group, significant changes were observed in RK ($T (6) = -2.95, p < .03$) and S-H at RFTD ($T (6) = 3.49, p < .01$). The results are presented in Table 4.5.

The two groups were deemed to be distinct and significantly different so an observational analysis was performed to determine whether the IPD values of the TI group made a greater positive change than the NTI group. The results of the observational analysis actually indicated that three of the five significantly different TI group IPD values changed in opposition to what was recommended in the technical intervention. See Table 4.6 for results of the observational analysis.

### Table 4.1. Mean and standard deviations of simple statistics both groups

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No Technical Intervention</th>
<th>Technical Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Pre</td>
<td>Mean Post</td>
</tr>
<tr>
<td>Mark</td>
<td>17.4 ± 1.0</td>
<td>17.6 ± 0.8</td>
</tr>
<tr>
<td>Release Velocity</td>
<td>12.5 ± 0.4</td>
<td>12.5 ± 0.3</td>
</tr>
<tr>
<td>Release Angle</td>
<td>35.2 ± 1.9</td>
<td>35.2 ± 1.5</td>
</tr>
<tr>
<td>Release Height</td>
<td>2.00 ± 0.1</td>
<td>2.00 ± 0.1</td>
</tr>
<tr>
<td>HRD</td>
<td>0.14 ± 0.11</td>
<td>0.17 ± 0.10</td>
</tr>
<tr>
<td>PCOM</td>
<td>0.17 ± 0.1</td>
<td>0.18 ± 0.1</td>
</tr>
<tr>
<td>RK @RFTD</td>
<td>113 ± 12</td>
<td>112 ± 9</td>
</tr>
<tr>
<td>S-H @ RFTD</td>
<td>51 ± 17</td>
<td>54 ± 17</td>
</tr>
<tr>
<td>RK @ FFTD</td>
<td>116 ± 13</td>
<td>117 ± 11</td>
</tr>
<tr>
<td>S-H @ FFTD</td>
<td>26 ± 9</td>
<td>27 ± 9</td>
</tr>
<tr>
<td>RK @ Release</td>
<td>146 ± 9</td>
<td>147 ± 8</td>
</tr>
<tr>
<td>S-H @ Release</td>
<td>-14 ± 6</td>
<td>-14 ± 5</td>
</tr>
</tbody>
</table>

IPD - Inter-year performance difference  
RFTD - Rear foot touchdown  
HRD - Horizontal release distance  
FFTD - Front foot touchdown  
PCOM - Vertical displacement of athlete-plus-shot system  
RK - Rear knee  
S-H - Angle between transverse axes of shoulder and hip
Table 4.2. IPD values by group for mark and eight optimization model parameters. IPD values for the mark, velocity, and the eight optimization model parameters reflect a % change in the desired direction of the IIPD. The IPD values for release height and horizontal release distance are represented in terms of absolute changes of the IIPDs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NTI IPD</th>
<th>TI IPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mark</td>
<td>0.01 ± 0.06</td>
<td>0.03 ± 0.08</td>
</tr>
<tr>
<td>Release Angle</td>
<td>0.00 ± 0.08</td>
<td>-0.01 ± 0.10</td>
</tr>
<tr>
<td>PCOM</td>
<td>0.08 ± 0.24</td>
<td>0.09 ± 0.18</td>
</tr>
<tr>
<td>RK @ RFTD</td>
<td>-0.01 ± 0.11</td>
<td>-0.05 ± 0.05</td>
</tr>
<tr>
<td>S-H @ RFTD</td>
<td>0.15 ± 0.46</td>
<td>-0.26 ± 0.17</td>
</tr>
<tr>
<td>RK @ FFTD</td>
<td>-0.01 ± 0.05</td>
<td>0.06 ± 0.10</td>
</tr>
<tr>
<td>S-H @ FFTD</td>
<td>0.06 ± 0.22</td>
<td>0.30 ± 0.73</td>
</tr>
<tr>
<td>RK @ Release</td>
<td>-0.01 ± 0.06</td>
<td>-0.01 ± 0.07</td>
</tr>
<tr>
<td>S-H @ Release</td>
<td>-0.02 ± 0.22</td>
<td>-0.48 ± 1.77</td>
</tr>
<tr>
<td>Group Mean*</td>
<td>0.03 ± 0.18</td>
<td>-0.05 ± 0.40</td>
</tr>
</tbody>
</table>

IPD - Inter-year performance difference
HRD - Horizontal release distance
PCOM - Vertical displacement of the athlete-plus-shot system
RK - Rear knee
S-H - Angle between transverse axes of shoulder and hip

*For the IPDs of the 8 parameters
Of the IPD values that were significantly different between the two groups, negative values (representing a change in opposition to technical intervention suggestions) were observed in the TI group for RK (-0.05 ± 0.05) and S-H (-0.26 ± 0.17) at RFTD and S-H at release (-0.48 ± 1.77). These IPD values represented mean pre-to-post technical intervention changes in the TI group of 115° ± 11 to 121° ± 10 for RK at RFTD; 43° ± 23 to 33° ± 20 for S-H at RFTD; and -15° ± 8 to -15° ± 12 for S-H at release. Positive IPD values were observed in RK at FFTD (0.06 ± 0.10) and S-H at FFTD (0.30 ± 0.73). These IPD values represented mean pre-to-post technical intervention changes in the TI group of 120° ± 9 to 112° ± 6 for RK at FFTD and 27° ± 9 to 35° ± 15 for S-H at FFTD.

For the significantly different IPD values in the NTI group, negative values were observed for RK at RFTD (-0.01 ± 0.11) and FFTD (-0.01 ± 0.05), and S-H at release (-0.01 ± 0.22). These IPD values represented mean pre-to-post data collection changes in the NTI group of 113° ± 12 to 112° ± 9 for RK at RFTD; 116° ± 13 to 117° ± 11 for RK at FFTD; and -14° ± 6 to -14° ± 5 for S-H at release. Positive IPD values were observed in S-H at RFTD (0.15 ± 0.46) and FFTD (0.06 ± 0.22). These IPD values represented mean pre-to-post data collection changes in the NTI group of 51° ± 17 to 54° ± 17 for S-H at RFTD and 26° ± 9 to 27° ± 9 for S-H at FFTD.

**Discussion**

The purpose of this study was to test the affects of an OMP-based technical intervention on an athlete’s competition performance. It was hypothesized that performance improvements of athletes receiving this technical intervention would be greater than those not receiving one and that any changes in mark could be associated
with corresponding changes in the OMPs. The results largely support the first hypothesis although a conclusion for the second hypothesis is less clear.

The most relevant result is that athletes in the TI group improved their mark more than twice as much; and their IPD value for mark almost three times as much as their counterparts in the NTI group. And although the individual t-test comparing the IPDs for mark between the two groups was insignificant; the result is meaningful because the mean difference separating the places of the eight finalists at the 2007 National Championship meet (0.17m) was less than the difference associated with the technical intervention.

The effect of the technical intervention was seen beyond improvements in the athlete’s mark. Indeed, the groups as a whole were shown to be significantly different, four of the five largest IPD values were observed in the TI group, and intra-group examination on the individual parameters further supported the benefits of the technical intervention and revealed the source of the significant difference. Five OMPs were shown to have significantly different IPD values between the two groups. And while three of these five IPD values were negative in the TI group, there appears to be a mechanical and physiological explanation that explains the results.

Although significant negative IPD values were observed for RK and S-H at RFTD in the TI group; the same group also exhibited very large positive IPD values for the same parameters on the subsequent event of the throw used in the analysis (FFTD). A single physiological phenomenon can explain this seemingly contradictory improvement in mark with concurrent mixed IPD values in the TI group.
Table 4.3. Two-tailed multivariate t-test for intra-group analysis

<table>
<thead>
<tr>
<th>Parameter Contrast</th>
<th>Ho. Diff</th>
<th>Actual Diff.</th>
<th>SE Diff.</th>
<th>$T^2$</th>
<th>DF for $T^2$</th>
<th>F</th>
<th>DF for F</th>
<th>P for F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mark</td>
<td>0.00</td>
<td>-0.02</td>
<td>0.01</td>
<td>58.70</td>
<td>9, 20</td>
<td>3.91</td>
<td>9, 12</td>
<td>0.02</td>
</tr>
<tr>
<td>Release Angle</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCOM</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RK @ RFTD</td>
<td>0.00</td>
<td>0.05</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-H @ RFTD</td>
<td>0.00</td>
<td>0.41</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RK @ FFTD</td>
<td>0.00</td>
<td>-0.07</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-H @ FFTD</td>
<td>0.00</td>
<td>-0.25</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RK @ Release</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-H @ Release</td>
<td>0.00</td>
<td>0.46</td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PCOM - Vertical displacement of the athlete-plus-shot system  
S-H - Angle between transverse axes of shoulder and hip  
RK - Rear knee  
RFTD - Rear foot touchdown  
FFTD - Front foot touchdown
Table 4.4. Individual t-tests for intra-group analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variance</th>
<th>F</th>
<th>DF 1</th>
<th>DF 2</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mark</td>
<td>0.00</td>
<td>1.95</td>
<td>6</td>
<td>14</td>
<td>0.14</td>
</tr>
<tr>
<td>Release Angle</td>
<td>0.01</td>
<td>1.61</td>
<td>6</td>
<td>14</td>
<td>0.22</td>
</tr>
<tr>
<td>PCOM</td>
<td>0.06</td>
<td>1.76</td>
<td>6</td>
<td>14</td>
<td>0.25</td>
</tr>
<tr>
<td>RK @ RFTD</td>
<td>0.01</td>
<td>5.11</td>
<td>6</td>
<td>14</td>
<td>0.03</td>
</tr>
<tr>
<td>S-H @ RFTD</td>
<td>0.21</td>
<td>7.34</td>
<td>6</td>
<td>14</td>
<td>0.01</td>
</tr>
<tr>
<td>RK @ FFTD</td>
<td>0.00</td>
<td>3.72</td>
<td>6</td>
<td>14</td>
<td>0.02</td>
</tr>
<tr>
<td>S-H @ FFTD</td>
<td>0.05</td>
<td>10.94</td>
<td>6</td>
<td>14</td>
<td>0.00</td>
</tr>
<tr>
<td>RK @ Release</td>
<td>0.00</td>
<td>1.06</td>
<td>6</td>
<td>14</td>
<td>0.43</td>
</tr>
<tr>
<td>S-H @ Release</td>
<td>0.05</td>
<td>62.48</td>
<td>6</td>
<td>14</td>
<td>0.00</td>
</tr>
</tbody>
</table>

PCOM - Vertical displacement of the athlete-plus-shot system
S-H - Angle between transverse axes of shoulder and hip
RK - Rear knee
RFTD - Rear foot touchdown
FFTD - Front foot touchdown
Table 4.5. Two-tailed multivariate T test for inter-group analysis

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Ho. Diff</th>
<th>Mean Diff.</th>
<th>SE Diff.</th>
<th>T</th>
<th>DF</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mark</td>
<td>0.00</td>
<td>-0.17</td>
<td>0.24</td>
<td>-0.72</td>
<td>14</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>Release Angle</td>
<td>0.00</td>
<td>0.01</td>
<td>0.68</td>
<td>0.01</td>
<td>14</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>PCOM</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.01</td>
<td>-1.10</td>
<td>14</td>
<td>0.29</td>
</tr>
<tr>
<td>NTI</td>
<td>RK @ RFTD</td>
<td>0.00</td>
<td>0.32</td>
<td>3.17</td>
<td>0.10</td>
<td>14</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>S-H @ RFTD</td>
<td>0.00</td>
<td>-2.52</td>
<td>2.31</td>
<td>-1.09</td>
<td>14</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>RK @ FFTD</td>
<td>0.00</td>
<td>-0.64</td>
<td>1.56</td>
<td>-0.41</td>
<td>14</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>S-H @ FFTD</td>
<td>0.00</td>
<td>-0.85</td>
<td>1.66</td>
<td>-0.51</td>
<td>14</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>RK @ Release</td>
<td>0.00</td>
<td>-1.30</td>
<td>2.43</td>
<td>-0.53</td>
<td>14</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>S-H @ Release</td>
<td>0.00</td>
<td>-0.24</td>
<td>0.88</td>
<td>-0.28</td>
<td>14</td>
<td>0.79</td>
</tr>
<tr>
<td>TI</td>
<td>Mark</td>
<td>0.00</td>
<td>-0.40</td>
<td>0.48</td>
<td>-0.84</td>
<td>6</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>Release Angle</td>
<td>0.00</td>
<td>-0.22</td>
<td>1.34</td>
<td>-0.17</td>
<td>6</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>PCOM</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.01</td>
<td>-1.11</td>
<td>6</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>RK @ RFTD</td>
<td>0.00</td>
<td>-6.13</td>
<td>2.08</td>
<td>-2.95</td>
<td>6</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>S-H @ RFTD</td>
<td>0.00</td>
<td>10.59</td>
<td>3.03</td>
<td>3.49</td>
<td>6</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>RK @ FFTD</td>
<td>0.00</td>
<td>8.06</td>
<td>4.69</td>
<td>1.72</td>
<td>6</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>S-H @ FFTD</td>
<td>0.00</td>
<td>-7.74</td>
<td>4.80</td>
<td>-1.61</td>
<td>6</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>RK @ Release</td>
<td>0.00</td>
<td>-0.87</td>
<td>4.07</td>
<td>-0.21</td>
<td>6</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>S-H @ Release</td>
<td>0.00</td>
<td>0.02</td>
<td>5.08</td>
<td>0.00</td>
<td>6</td>
<td>1.00</td>
</tr>
</tbody>
</table>

TI - Technical intervention  RFTD - Rear foot touchdown
NTI - No technical intervention  FFTD - Front foot touchdown
S-H - Angle between transverse axes of shoulder and hip  RK - Rear knee
PCOM - Vertical displacement of the athlete-plus-shot system
### Table 4.6. Mean IPD values presented with P-value from intra-group F-test and observational notes

<table>
<thead>
<tr>
<th>IPD (%)</th>
<th>NTI</th>
<th>TI</th>
<th>P</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mark</td>
<td>0.01</td>
<td>0.03</td>
<td>0.14</td>
<td>TI improves ~2.5 as much; statistically insignificant inter-group difference</td>
</tr>
<tr>
<td>Release Angle</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.22</td>
<td>No real change; no inter-group difference</td>
</tr>
<tr>
<td>PCOM</td>
<td>0.08</td>
<td>0.09</td>
<td>0.25</td>
<td>Both groups improved; no inter-group difference</td>
</tr>
<tr>
<td>RK @ RFTD</td>
<td>-0.01</td>
<td>-0.05</td>
<td>0.03</td>
<td>Both groups digressed; significant inter-group difference; TI actually digresses more</td>
</tr>
<tr>
<td>S-H @ RFTD</td>
<td>0.15</td>
<td>-0.26</td>
<td>0.01</td>
<td>NTI improves; TI digresses; significant inter-group difference</td>
</tr>
<tr>
<td>RK @ FFTD</td>
<td>-0.01</td>
<td>0.06</td>
<td>0.02</td>
<td>Significant inter-group difference; TI improves much more</td>
</tr>
<tr>
<td>S-H @ FFTD</td>
<td>0.06</td>
<td>0.30</td>
<td>0.00</td>
<td>Significant inter-group difference; TI improves much more</td>
</tr>
<tr>
<td>RK @ Release</td>
<td>-0.01</td>
<td>-0.01</td>
<td>0.43</td>
<td>Both groups digressed insignificantly; no inter-group difference</td>
</tr>
<tr>
<td>S-H @ Release</td>
<td>-0.02</td>
<td>-0.48</td>
<td>0.00</td>
<td>Both groups digressed; significant inter-group difference; TI actually digresses more</td>
</tr>
</tbody>
</table>

IPD – Inter-year performance difference  
NTI - No technical intervention  
TI - Technical intervention  
S-H- Angle between transverse axes of shoulder and hip  
RK - Rear knee  
RFTD - Rear foot touchdown  
FFTD - Front foot touchdown
The sudden shift from negative to positive IPD values between RFTD and FFTD is an expected characteristic of a phenomenon known as trunk whip. Trunk whip has been shown to be beneficial in a variety of throwing and striking tasks. It is the outcome of a proximal-to-distal movement strategy (PDMS) combined with a subsequent rapid deceleration of proximal segments to achieve maximal transfer of momentum from the system to the implement.

Several researchers have used computer simulations to show that a PDMS produces improved performance compared to simultaneous activation (Alexander, 1991; Herring & Chapman, 1992). Similar findings have been reported in baseball (Flesig et al., 1996) and javelin throwing (Morriss & Bartlett, 1996), as well as cricket bowling (Glazier et al., 2000; Stockill & Bartlett, 1994). Such a movement strategy takes advantage of the greater force producing capabilities of the more proximal muscles to overcome the system’s inertia, at which point the weaker, but faster, distal muscles can be employed more effectively (Kreighbaum & Barthels, 1990).

One of the characteristics expected to be observed as a result of a PDMS in the shot put is increased S-H values following RFTD. Because the throwing-side leg makes contact with the ground first, using a PDMS would accelerate the throwing-side hip in the direction of the throw, and, if the shoulders can maintain much of their rear-facing position, S-H values will increase. Indeed, Ariel (1973) found that the maximum S-H values coincided with the maximum speed of hip rotation (100.3 ± 24.6 msec before release of the shot).

With this in mind, S-H values should increase between RFTD and FFTD in performances exhibiting a PDMS. Increased S-H places the musculature of the trunk on stretch, which has been shown to enhance a muscle’s capacity for force production
(Cavagna et al., 1968; Ettema et al., 1990) and improve athletic performance (Bobbert et al., 1996). Of the four data collections (pre and post for both groups), the only one to show an increased S-H value from RFTD to FFTD was the post-technical intervention TI group. Following the technical intervention, the TI group actually increased their S-H value two degrees between RFTD and FFTD. Prior to the technical intervention, the same individuals S-H value decreased 16° in the same time frame meaning that there was a differential of 18° from pre-to-post data collection that was not observed in the NTI group (which actually increased S-H value 2 degrees from pre to post data collections).

This increase in S-H value between RFTD and FFTD indicates the technical intervention produced a more PDMS.

In addition to a PDMS, the other component of enhancing trunk whip is maximizing transfer of momentum to the implement via a rapid deceleration of proximal segments prior to release (Irving, 1980; Leblanc & Dapena, 1996). This allows the shoulder segment to ‘catch up’ to the hip segment and the resulting whip effect accelerates more distal segments, and transfers momentum of the system to the implement (Leblanc & Dapena, 1996). Although not directly examined, the data indicate that this was taking place to a greater extent in athletes who received the technical intervention.

The simple statistics indicate that the TI group’s S-H value changed approximately 120% more in the period between FFTD and release when compared to the same individual’s S-H value (50° vs 42°) prior to the technical intervention. No such change was observed in the NTI group (41° vs 40°). Because previous literature has indicated that the time between FFTD and release does not appreciably change within trials of a given athlete (Young & Li, 2004), this confirms that the post-TI group has
increased their shoulder rotational velocity in the moments immediately prior to release.
The fact that athletes in the TI group moved their shoulders through a larger range of
motion in what can be assumed to be the same time period indicates that trunk whip was
occurring. A more detailed analysis on the rotational velocities of the S-H in the moments
leading up to release are needed for confirmation.

Although enhanced trunk whip appears to explain the seemingly conflicting
relationship between the negative IPD values and improved mark; limitations of this
study should also be considered. First, the process of relaying the OMPs to the TI group
coaches and athletes is an imperfect science. And while fundamental motor learning
concepts were used, there is no way to be certain that the athlete and coach fully
understood or adhered to the recommendations. Similarly, there was no way to monitor
the method or extent of integration of the OMPs in the training plan other than the actual
competition day performances used in this study. Likewise, coaches and athletes may
misinterpret or choose to ignore some or all of the information presented in the technical
intervention and this would likely have an affect on any changes observed in the OMPs.
It is possible that the parameters with positive IPD values were more readily accepted,
understood or easier to integrate in to an athlete’s training than the parameters with
negative IPD values.

Finally, the study assumes that the OMPs used in this study are correct, complete,
and that all are equally important to all athletes. As previously indicated, the technical
model is not only incomplete but likely needs to be more individualized to the unique
characteristics of each athlete such as anthropometry and physical capabilities. Although
over the course of the preceding three studies approximately 40 parameters were
examined for inclusion in the OMPs, it would be unreasonable to think that the eight
selected OMPs are either the only eight kinematic parameters that have an affect on performance or are equally important to all athletes.

**Conclusion**

The purpose of this study was to test the affects of a technical intervention based on a previously developed optimization model on an athlete’s competition performance. The results indicate that a technical intervention produces meaningful changes in kinematics and performance not observed in a NTI group but the kinematic changes are not necessarily in agreement with the OMPs suggested in the technical intervention. This study provides important information to coaches and elite female shot putters and provides direction for future biomechanical research on this event. Future research should focus on both refining understanding of the current OMPs, individualizing the OMPs to each athlete, examining the trunk whip phenomenon in greater depth, and finding any parameters that may have been omitted. Continued research is also needed to determine the best means of disseminating information to coaches and athletes to most effectively produce beneficial change in the OMPs.

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CHAPTER 5.

GENERAL DISCUSSION

The purpose of this series of experiments, presented in Chapters 2, 3, and 4, was to determine whether an optimization model could be developed for the shot put that could be used to enhance competition performance in elite female shot putters. Most of the research performed on shot putting has ignored women making its application outside of men limited (Alexander et al., 1996). Furthermore, previous attempts to optimize the shot put have largely been confined to the release parameters rather than any examination of the athlete kinematics that preceded them. Only one previous study (Alexander et al., 1996) has attempted to optimize the kinematics associated with shot put performance and this study did not examine elite athletes. Optimization modeling of the shot put provides important information to coaches and shot putters and direction for future biomechanical studies on this event.

Because of the fact that no optimization models have been developed for elite shot putting, the effectiveness of any technical intervention based on one has yet to be examined. There is however a precedent for technical intervention based on optimization models. For example, a common movement model was successfully used in the training and rehabilitation of ACL reconstruction patients (Risberg et al., 2001). This training was shown to reduce female knee joint injury. Similarly, unpublished technical interventions have been performed on the discus throw and sprinting events as part of USA Track & Field’s (USATF) High Performance Project. While the effectiveness of these interventions remains quantitatively unproven, they have been successful by many
anecdotal accounts. If such a positive benefit exists for other track throwing events like the discus throw, one could expect that the shot put might similarly benefit.

**Overview of Results**

The initial study served as an exploratory study to determine whether optimization modeling techniques could be used on the shot put. While previous attempts had been made on other tasks such as running (Yanai & Hay, 2004), gymnastics backwards long swings on rings (Yeadon & Berwin, 2003) and triple jumping (Yu & Hay, 1996), it remained to be seen whether an optimization model could likewise be made for the shot put. The shot put is seemingly an ideal movement for optimization because it is a discrete task that takes place in a closed environment. While there were several methodological limitations in this study, the results provided strong support for the development of an optimization model for the shot put.

The most important observation of the study was the identification of critical parameters for elite level performance among a population of elite level shot putters. This addressed gaps in the research that had not been previously examined. The study was the first to examine critical parameters for success in the elite women shot put putters and it indicated that there are specific parameters that are critical to elite level performance. The results suggested that among high level shot putters, greater rear knee (RK) flexion at rear foot touchdown (RFTD) and release, increased release velocity, a more neutral shoulder-hip orientation (S-H) at release, and a greater horizontal release distance were the best predictors of mark. Although the observations were not conclusive due to the limited nature of the dataset, they provided sufficient support to suggest that development of an optimization model for the women’s shot put was viable.
The second study set out to validate the primary conclusion of the first study—that an optimization model for shot put could be developed. To address the primary shortcoming of the previous study, this study used a dataset that was larger in both participants and trials. Using the findings of the previous study as well as (Young & Li, 2005), this study used two hierarchical linear modeling analyses to determine that all eight examined parameters were significant contributors to elite level performance in the women’s shot put. The first analysis examined each parameter individually and indicated that seven of the variables had a significant impact on the measured distance of the throw: S-H at RFTD, front foot touchdown (FFTD), and release; RK at RFTD and FFTD, peak center of mass vertical displacement of the athlete-plus-shot system during the flight phase (PCOM) and the angle of release contribute to elite level success among women shot putters at the US national level. The second HLM analysis examined the unique effects of each parameter in a model containing all eight variables and indicated that release angle, PCOM and S-H at RFTD made unique, significant contributions to the performance. RK was the only variable that was not indicated as being a significant contributor to performance in either HLM analyses. These observations largely validated the findings of the previous study and established the first optimization model for elite female shot putting.

The final study tested the affect of a technical intervention based on the optimization model developed in the previous study. The two-tailed multivariate t-test indicated that the two groups were significantly different and individual t-tests on individual parameters indicated that the two groups differed on five of the eight examined variables. Inter-year performance differences (IPD) in mark were not statistically significant but are meaningful, as the TI group’s IPD for mark was more than twice that
of the NTI group. Although IPD values for the kinematic variables in the TI group did not fully explain their improved performances, putting the kinematic changes in the context of enhanced trunk whip reconciled any inconsistencies. The results indicate that the technical intervention produced beneficial changes in performance that were closely linked with the eight optimization model parameters. The study also pointed to the importance of the trunk whip phenomenon in shot putting.

**Overall Discussion**

The results of this series of research indicate that it is possible to develop an optimization model for the women’s shot put and administer it via a technical intervention with meaningfully beneficial effects on performance. In this section of the discussion the previously mentioned results will be examined in the context of related underlying mechanical, physiological, and learning mechanisms associated with them.

**Mechanical and Physiological Observations**

All improvements in performance can be attributed to either mechanical or physiological mechanisms. The results indicated that release angles considerably lower mathematical predicted optimal release angles are beneficial to performance. Release angle is primarily determined by the position of the athlete’s trunk and throwing arm and operates in an inverse relationship with release velocity. Although many authors (e.g., Bangerter, 1983; Townend, 1984; Trowbridge & Paish, 1981; Young, 1985) have suggested that the angle of release should be greater than 41°, these recommendations are based solely on the projectile motion equation presented in Chapter 1 rather than observation of elite athletes. Despite the number of recommendations, large discrepancies have been observed between the predicted optimal values and values observed in elite
Bartonietz & Borgstöm, 1995; Luthanen, 1998; Tsirakos et al., 1995) and sub-elite (Dessureault, 1976; 1978) shot putters. Recent research explains this discrepancy. Linthorne (2001b; 2001c) indicated that release velocity and angle are not independent and that the optimal release angle is considerably lower (32-38°) than that determined using the projectile motion equation. Similar findings have been reported by other investigators for throwers using both the glide (de Mestre, 1990; de Mestre et al., 1998; Hubbard et al., 2001; Maheras, 1995) and spin technique (Luthanen, 1998). Two mechanisms explain this discrepancy. First, as projection angle increases the performance is opposed by a greater effect of gravity (Hay, 1993; Linthorne, 2001b). This is due to the fact that the force of gravity acts perpendicular to the ground and as release angle increases more force must be used to overcome the effect of gravity. Second, the structure of the human body is likely not capable of producing force (and resulting velocities) equally across all positions (Linthorne, 2001b). On the latter point, it should be noted that this phenomenon may be due in part to a thrower’s exercise selection in weight training rather any anatomical limitations (McCoy et al., 1984).

The action of the rear leg was also indicated as being very important to the outcome of the throw. The results indicate that greater flexion of the rear knee at both RFTD and release was highly influential on greater measured distance. The benefit of greater flexion at RFTD is in agreement with coaching literature (Schmolinsky, 2000) but the same observation at release contradicts previous coaching literature (Bartonietz & Borgstrom, 1995; Godina & Backes, 2000; Schmolinsky, 2000). This discrepancy is reconciled by considering the active extension of the rear leg in a similar manner to what takes place in elite sprinting (Mann & Sprague, 1980) and weightlifting (Escamilla et al., 2000). In these cases, complete extension of the knee is not a critical parameter and is
perhaps even a marker of power deficiencies. That is, the initial force generated by the proximal-to-distal movement strategy (PMDS) of hip extension, knee extension, and plantar flexion accelerates the athlete and shot system with such rapidity that the shot is released prior to the complete extension of the more distal joints or the athlete breaks contact with the ground making further extension irrelevant. In such a case, while greater extension may not necessarily be harmful, lesser extension may be an indication of greater power and thus implement acceleration.

In light of the fact that there was no observable difference in the magnitude of the rear knee range of motion, and greater knee flexion at both RFTD and release was observed among the best performances, a shift in the starting point of rear knee extension may be advantageous. The advantage of a shift in the starting point of the RK extension would be that it places the leg extensor muscles in a stronger contraction range due to the force-length relationship of muscle (Gordon et al., 1966). At the greater muscle lengths that accompany a shifted range of motion, the muscle’s capacity to produce torque is enhanced because the muscular contraction coincides with the peak of the force-length curve. Without a shift in range of motion, the muscular contraction occurs prior to the peak of the force-length curve resulting in decreased force capacity. This proposed mechanism is supported by previous research indicating that knee extensor torques are greatest at angles which fall within the range of motion observed among the best throwers in this study (Pincivero et al., 2001; Tihanyi et al., 1982; Thorstensson et al., 1977).

Of all the results, those examining S-H values require the greatest inspection. Previous research had indicated that greater S-H values were better during the moments immediately following RFTD and more neutral S-H values were beneficial at the time of release. The results indicate that while this is partially true, the timing of peak S-H values
in the period following RFTD and the interaction of the shoulder and hip segments must be considered equally important. In fact, the final study indicates that S-H values must be examined in the context of the trunk whip phenomenon to be fully understood. More specifically, a PDMS combined with a subsequent rapid deceleration of proximal segments to achieve maximal transfer of momentum from the system to the implement is beneficial. Although this phenomenon has not been specifically examined in the shot put before, the benefits of such a movement strategy have been noted in several other throwing movements (Flesig et al., 1996; Morriss & Bartlett, 1996; Stockill & Bartlett, 1994) as well as computer simulation models (Alexander, 1991; Herring & Chapman, 1992).

PCOM was also indicated as being beneficial to shot put performance. The mechanism for benefit is improved positioning and enhanced physical capacity to deliver the shot (Mileshin & Papanov, 1986; Young, 2004a; Young & Li, 2005a). More specifically, increased PCOM should theoretically elicit a greater stretch shortening cycle by eccentrically loading the lower extremities to a greater extent at RFTD. This in turn would be expected to lead to a more powerful delivery of the implement.

Learning Observations

The most important and applicable finding of this series of research was that the performance of elite female shot putters could be improved via a technical intervention using the optimization model parameters (OMPs) indicated in the first two studies. In the grand scope of an athlete’s yearly training, the actual technical intervention was relatively small and questions remain about how coaches and athletes actually interpreted the findings and how many were able to successfully incorporate the suggestions into their technical training.
Although questions remain about the actual dissemination of information and how it was interpreted and incorporated, several statements can be made about the technical intervention. The means of presenting the information was novel but aimed to address several tenets of motor learning. The technical intervention was essentially a form of augmented feedback and was presented using an external focus of attention with an emphasis on movement effects. Previous research has indicated that this method enhances learning (Wulf et al., 2002; Wulf et al., 2001). And while the actual methodology of feedback delivery was somewhat novel, previous research indicates that the very fact that it provided clear movement goals and objectives may have been sufficient to explain the changes in kinematics and performance (Reid et al., 2007). Furthermore, because technical intervention was provided to the athletes and their coaches nine months prior to the final data collection it can safely be assumed that athletes had sufficient time to incorporate the technical modifications as their coaches saw fit.

**Relevance of the Observations to Coaching Application**

In light of the mechanical and physiological mechanisms explained above, several relevant observations can be made to enhance training for the shot put. Most of these are related to the theory of specificity of training. This theory states that adaptations to a training stimulus will be highly specific to the exact type of stimulus employed (Noakes, 1986; Zatsiorsky & Kraemer, 2006). Several studies have previously indicated that this theory holds true for shot putters (Egger et al., 1994; Judge et al., 2003; Kokkonen et al., 1988; Stone et al., 2003; Terzis et al., 2003; Uppal & Ray, 1986). And while no training studies exist examining whether specific training can either induce beneficial kinematic changes, there have been several studies that found that specific training can produce
observable and functional changes in a performer’s kinematics in other activities (Harris et al., 2007; Maglischo et al., 1985).

As noted above, there is a large discrepancy between optimal release angles determined using projectile motion equations (41-43°) and those predicted by the optimization model and other sources (32-36°). While this may largely be due to the anatomical constraints and limitations of the human body to produce force equally through all ranges of motion, the theory of specificity suggests that focused training may be able to shift an athlete’s strongest range of motion enough to actually allow them to throw at a higher angle without sacrificing release velocity. This strategy might be useful for athletes who were throwing below or on the low range optimum release angles (≤33°). Athletes who generally throw with release angles on the high range of those suggested by the optimization model may benefit more from attempting to increase the speed at which they are able to release. In such a case, an increased emphasis on high-velocity strength movements with a preceding fast eccentric phase might be appropriate as previous research has indicated that such an emphasis enhances performance in fast movements (Hori et al., 2008).

The specificity of training theory could also be applied to the positions and actions of the RK. In fact, several studies have already linked explosive leg strength to shot put performance (Terzis et al., 2003; Tschiene, 1988; Uppal & Ray, 1986). The preceding line of research suggested that it is beneficial for an athlete to have great knee flexion at RFTD and be so explosive that they actually release the implement prior to complete extension of the rear leg. In fact, results from chapters 2 and 3 indicated that all throwers move the knee joint through approximately the same angular displacement but that better performers begin their RK extension from a more flexed position. The benefit
of shifting the rear knee range of motion to one with greater knee flexion indicates that it may be advantageous to incorporate heavily loaded strength training exercises that enhance strength through this particular range of motion. Exercises such as deep squats, which develop leg extensor strength in similar ranges of motion observed in this study would likely be advantageous. It would likewise be beneficial to perform plyometric exercises through similar ranges of motion and with loads similar to those of the shot in order to mimic the load placed on the rear leg at RFTD.

In light of the findings regarding S-H positioning and its relationship with the trunk whip phenomenon, there are several areas that coaches and athletes should focus. First, athletes should strive to enhance dynamic mobility of their trunk musculature so that they are not inhibited and can more easily increase their S-H at and following RFTD. Increased S-H values at RFTD would allow an athlete to accelerate the implement through a longer angular trajectory which previous research has indicated as being beneficial to performance (Koltai, 1975; Pagani, 1981; Schpenke, 1973; Suskana, 1974). In addition to increasing mobility, gains in performance would also likely come from specific rotational trunk strength development. Several researchers have proven the benefits of specifically targeted strength development for the shot put (Egger et al., 1994; Kokkonen et al., 1988; Stone et al., 2003; Terzis et al., 2003; Uppal & Ray, 1986).

A final area in which coaches and athletes could benefit from this research is related to the findings on PCOM. The results suggested that a greater PCOM was beneficial to performance. The mechanism underlying this benefit is an increased eccentric loading of the knee extensors, especially of the rear leg. This is similar in nature to the enhanced jumping performance that occurs when a jump is preceded from a drop from elevation (Bobbert, 1990) or from a drop step (Brodt et al., 2008). With this in
mind, it would likely be beneficial to include explosive plyometric training as this has been shown to improve performance in jumping tasks (Chappell & Limpisvasti, 2008). One-legged jumping exercises using an external load similar to the implement would further the specificity of such training.

**Conclusions**

The series of studies presented here indicate that an optimization can be successfully developed for the shot put and that applying the optimization model through a technical intervention on elite female athletes can yield meaningful improvements in performance.

**Future Research**

Future research endeavors on shot put optimization and technical intervention should focus on four areas: re-examination and further validation of OMPs, investigation into the trunk whip phenomenon, expanding the breadth of the optimization model, and the application of technical interventions. The current OMPs should be refined and investigations to discover any potentially overlooked parameters should be made. Although all attempts were made to make the optimization model as comprehensive as possible, it is highly likely that the model is incomplete. This very issue was made clear in the third study by the seemingly contradictory results for S-H values and performance. Although these results were reconciled when placed in the context of trunk whip, little is known about this phenomenon with regards to the shot put. Future research is needed to clarify the exact relationship with performance and mechanisms of benefit that enhanced trunk whip provides. Also, the breadth of the optimization model should be expanded to take in to account gender, anthropometry, and physical capacities of the athlete. This
would allow for a more individualized optimization model with enhanced value to athletes and coaches. Continued research is also needed to determine the best means of disseminating information to coaches and athletes. Further study is need to identify the most effective means of relaying feedback that will produce beneficial changes in the OMPs. It is suggested that coaches and researchers work together closely for future research efforts.

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Chapter 1: Introduction & History of Shot Putting

History

Throwing heavy objects is one of the oldest forms of competitive sport. In fact, Homer makes mention of rock throwing between soldiers during the siege of Troy (Homer, 1984). In the Iliad, Homer documents that throwing stones and rocks were an integral part of Achaean sport. From Homer’s use of the term κατωμαδίῳ, meaning “thrown from the shoulder,” Gardiner (1910) suggests that the Acheans may have been practicing an early form of shot putting. This may be the earliest documentation of a shot put competition. In addition to the Greeks, Quercetani (1964) reports of shot put-like events being practiced in ancient Scotland and Ireland as tests of strength.

The invention of the cannon in the 14th century revolutionized the sport of heavy object throwing as the cast iron ball, the precursor to today’s shot, became the implement of choice (Quercetani, 1964). In fact, Oxford and Cambridge universities adopted this type of ball for intercollegiate competitions in the middle of the 19th century (Quercetani, 1964). Shortly after this time, the implement weight and size were standardized and competition rules began appearing for the first time (Encyclopedia of Track & Field, 1986). In the 1904 Olympics, the square platform that was previously used for a surface in shot put competitions was replaced by a circular ring (Quercetani, 1964); and in 1909, a wooden toe-board was added to the front edge of the throwing circle (Encyclopedia of Track & Field, 1986).
Olympic Games

The men’s shot put has been a part of the Summer Olympic Games since their inception in 1896. In three of these games, St. Louis in 1904, Stockholm in 1912, and Paris in 1920, hybrid shot put events were also contested. At the St. Louis Games of 1904, there was a “heavy” shot competition where the implement weighed 25.4 kg as opposed to the standard 7.26 kg shot (Encyclopedia of Track & Field, 1986). In the 1912 Stockholm and 1920 Paris Olympic Games, shot put competitions were held as a combined left and right hand event, with athletes putting first with one hand, then with the other and summing the best throw for each side to determine the winner (Encyclopedia of Track & Field, 1986). The first documented women’s shot put competition was held in France in 1917 and it has been included in the Olympic Games program since 1948 (Quercetani, 1964).

Record Performances

The first recognized world record in the men’s shot put was 15.54 m, set by American Ralph Rose in 1909 (Butler, 2003). Today, the world record in the men’s shot put stands at 23.12 m set by American Randy Barnes in 1990 (Butler, 2003). The current women’s world record of 22.63 m was set by Natalya Lisovskaya of the former USSR in 1987 (Butler, 2003). This is over 8 m further than the first recognized women’s world record, Gisela Mauermayer’s 14.38 m put for Germany in 1934 (Butler, 2003). Despite the huge improvements in performance over the past century, competitive marks for both men and women have decreased since the late 1980s. This is likely due to increased anti-doping efforts (Hilton, 2004). In light of this it is important to note that the outstanding shot put performances achieved between 1970 and the early 1990s may more reflect
widespread drug use than advances in technique or training. While this notion has not been verified, continued research on shot put technique may lessen or eliminate the gap between current and past performances.

Rules

The objective of the event is to put a shot as far as possible without breaking any of the rules governing the event. The action of a “put” is an overhand throw or cast with a pushing motion from the shoulder (Merriam-Webster's dictionary, 1993). The International Amateur Athletic Federation (IAAF) rulebook adds that a put is a throw initiated with the implement between the neck and shoulder performed with a pushing motion (IAAF competition rules, 2003).

Previous Rules

In the early days of putting, rocks and stones were likely the most convenient objects to throw during competition and no widely accepted rules existed for the event (Gardiner, 1910). This left little for standardization and made the comparison of results difficult. The first rules governing shot put competition were not established until 1860 (Gardiner, 1910). These early rules focused mainly on the performance of the throw and the throwing surface (Gardiner, 1910). Since then, additional rules have been added and old ones have evolved as track and field gained popularity. Despite this, the women’s event did not reach the same level of standardization until 1927 with the most notable difference being the use of various weight implements (Encyclopedia of Track & Field, 1986).
Current Rules

Implement

The current rules governing the event are established by the IAAF and are laid out in their rulebook (IAAF competition rules, 2003). These rules state that the shot must be spherical and made of a metal no softer than copper or a shell of such metal filled with lead or another material. For indoor throwing, the shot may also be made of plastic or enveloped in rubber. The shot must be smooth and without irregularities on its surface. For men, the weight of the shot must be 7.26 kg with a diameter between 110 and 130 mm. For women, the shot must have a mass of 4 kg with a diameter between 95 and 110 mm.

Equipment

The IAAF rulebook (IAAF competition rules, 2003) also states that any form of assistance that could aid an athlete to throw the shot is forbidden. Back belts and wrist wraps are however allowed to help prevent injury of the back and wrist. Athletes are allowed to smudge a sticky substance onto their hands and neck so that they can improve their grip but are not permitted to wear gloves. In most competitions, athletes may use their own implements, provided they are checked and marked as approved by the competition's organizing committee before the contest and made available to all competing athletes. No modifications can be made to any implements during the competition.

Throwing Ring

The IAAF rulebook (IAAF competition rules, 2003) also regulates the throwing environment. The throwing circle itself has a diameter of 2.135 m (± 5 mm) and is
submerged 1.4 to 2.6 cm below the surface of the ground outside of the circle. A rim made of steel or iron must surround the submerged throwing surface and be flush with the ground outside of the circle. The surface of the circle itself must be made of a non-slippery material such as concrete or asphalt. Athletes may not spray nor spread any substance in the circle or on their shoes to enhance their grip. A white toe board made of wood or other suitable materials must be firmly fixed to the ground outside of the front rim of the circle. The toe board must be 11.2 to 30 cm wide, with a chord of 1.15 m (± 10 mm) for an arc equal to that of the circle and 10 cm (±0.2) high in relation to the level of the inside of the circle (Figure 1).

**Landing Area**

The landing area for the put is marked with 5 cm wide white lines that, if extended, would extend at a 34.92 degree angle from the center of the circle (Figure 1). The landing plane must be level and made of a material that permits the implement to make an imprint upon landing. Grass or cinder is typically used.

**Competition**

Throws are considered legal when the shot lands within the lines of the field and the athlete completes the throw without touching anything outside of the circle before the shot hits the ground. Athletes are allowed to touch the inside of the toe board but not the top or any of the sides that do not face the center of the ring. All throwing attempts in the shot put must be initiated from a stationary position inside the circle and the shot must be put from the shoulder with one hand only. The implement must touch or stay in close proximity to the neck or chin until the athlete is ready to release. The shot should not drop below this position during the putting motion nor should it move behind the line of
the shoulders. An attempt is considered a failure if the athlete improperly releases the shot or touches any part of the ground outside of the circle between the time they have stepped inside the ring to begin the throw and the moment the implement lands after the completion of the throw.

Figure 1. Shot put throwing environment specifications.

In a competition, each athlete typically gets an equal number of throws, usually three or six. In some cases, all competitors are given three throws with only the top 8-10 athletes given the opportunity for three more throws. Even when the shot is released at the wrong moment, it is still counted as an attempt. The winner of the competition is the athlete with the furthest legal throw. Measurements are made in m and are rounded off downwards on whole cm.

Technique

Glide

Little is known about the putting technique used in Homeric times (Gardiner, 1910). It is however known that a sidestep action in the circle was invented in the United States in 1876 which greatly assisted in throwing the shot (Quercetani, 1964).
Technique was still not standardized though and most athletes failed to take advantage of the many benefits of modern throwing technique (Encyclopedia of Track & Field, 1986). Not until 1951 did a dominant shot putting technique come into use. In 1951, American athlete Parry O’Brien refined the sidestep technique to one which is now known as the glide. In the glide, O’Brien started from a position facing the back of the circle rather than the side. O'Brien then jumped across the ring, landed in a position that still faced the rear of the circle, and then rotated 180 degrees before making the final release (Quercetani, 1964). This technique helped him become the first athlete to break the 18 m (and subsequently the 19 m) barrier.

**Spin**

In 1976, another new technique was developed by Aleksandr Baryshnikov of the former USSR (Encyclopedia of Track & Field, 1986). Baryshnikov developed a technique similar to that used by discus throwers and used it to become the first athlete to throw the shot beyond 22 m. This technique later became known as the spin or rotational technique. The proportion of finalists using each technique in the Olympic and World Championships over the past 10 years has seen a growing number of male athletes use the spin technique to the point that it is now the most popular technique. Over the same period of time the glide technique has remained the most prevalent technique in elite female shot putters. Use of the spin technique among elite women has however begun to grow slightly. Despite the current shift towards the use of the spin technique, both techniques have produced similar results (Butler, 2003) and the glide remains the more popular technique at the amateur level. This may be due to the belief that the glide technique is easier to master (Bosen, 1985).
Chapter 2: Methods of Evaluation

Body movement in the shot put has been measured using several methods. In general, these methods can be grouped into either the study of shot put kinematics or shot put kinetics.

**Kinematics**

Kinematics refers to the branch of mechanics that studies the motion of a body or a system of bodies without consideration given to its mass or the forces acting on it. Kinematics considers movement in terms of position, displacement, velocities and accelerations. Kinematic assessment provides information on the relationship of body parts to one another as well as to the environment.

**Spatial and Joint Reference Systems**

Kinematic research must involve a spatial reference system and a standardized joint coordinate system to facilitate interpretation of the data. The spatial reference system allows coordinates to be assigned to a given location. Typically a Cartesian coordinate system is used to provide a reference for movement and to measure the position of a point from a defined origin along three perpendicular axes (Winter, 1990). The three axes are defined as follows:

\[ Y = \text{vertical component or direction} \]
\[ X = \text{anterior posterior component or direction} \]
\[ Z = \text{medial lateral component or direction} \]

Definitions of the joint coordinate system are considerably more complex and beyond the scope of this paper. The International Society of Biomechanics Standardization and
Terminology Committee has made recommendations on definitions of joint coordinate system of various joints (Wu et al., 2002; Wu et al., 2005).

**Types of Analysis**

**Qualitative**

Shot put kinematics refers to the study of the action of throwing the shot without considering the system’s mass or the forces acting on it. Several methods have been used to assess the kinematics of shot putting. Perhaps the simplest method of assessment and evaluation is by qualitative analysis. This method has been frequently used to examine the shot put (e.g., Grigalka & Papanov, 1984; Ivanov & Maksimov, 1973; Mileshin & Papanov, 1986; Svendsen, 1973; Terauds, 1984; Ward, 1974; Webb, 1975). Qualitative analysis involves the systematic observation and introspective judgment on the quality rather than the quantity of the movement. Qualitative kinematic assessment may either be performed by visual observation or slow-motion video review.

Visual observation offers the greatest ease of use but has many drawbacks. While experienced observers may be able to obtain substantial information about the movement, it is largely subjective and does not provide accurate measurements for future comparisons. Another drawback of using visual observation is that the unassisted eye functions at the equivalent of $1/30^{th}$ of data capture and as a result the amount of detail actually observed may be limited (Trew & Everett, 2001, p. 144). Qualitative kinematic analysis using film or video review helps to address these shortcomings.

**Quantitative**

Quantitative kinematic research on the shot put involves describing the action in numerical terms. Several methods have been employed to quantitatively examine shot put kinematics. The most common of these techniques is motion analysis through the
The digitization of the performer (e.g., Alexander et al., 1996; Bartonietz & Borgstöm, 1995, Marhold, 1973; McCoy et al., 1984). In this method, a pre-recorded video image of a movement is converted to digital form so that the movement can be quantified. The process of digitizing film may be done either automatically by a computer or manually. The digitizing process involves the identification and storage of the desired body and background landmark coordinates. The stored coordinates can then be recalled for future calculations. Automatic digitization is considerably faster than manual digitization but is typically only possible when the video recording of the participant has been made under controlled lab environments. While far more time-consuming, manual digitization is often necessary when controlled recording environments are not possible. Manual digitization has been shown to be a reliable tool for quantifying data (Sullivan et al., 2002) with comparable results to automatic digitization (Wilson et al., 1999).

Data Collection

Camera Selection

Regardless of the type (qualitative or quantitative) of analysis or digitization method, great care must be taken in selecting appropriate camera(s). The first factor that must be considered in camera selection is sampling rate. The sampling rate refers to the frequency of images taken within a second and is measured in hertz (Hz). Some authorities (Winter, 1990) have stated that a sampling rate of 50 or greater is acceptable for all but the fastest athletic movements. Previous research on the shot put has used sampling rates ranging from 50 (Tsirakos et al., 1995) to 100 (McCoy et al., 1984).

Shutter speed is another important factor when considering a camera. Shutter speed refers to the duration of exposure for the image. Blur occurs with slow shutter
speed as a result of movement of the body or object through the field of view during the time of exposure.

**Dimensionality**

**2D Analysis**

Beyond camera selection, the number of cameras and subsequent dimensionality of the analysis is also important. Two-dimensional (2D) (e.g., Tsirakos et al., 1995) and three-dimensional (3D) (e.g., McCoy et al., 1984) motion analysis has been used to study the shot put. Many researchers have used 2D motion analysis to examine the shot put under the assumption that the event is largely planar. The accuracy of the results of a 2D analysis are dependent on the perpendicular alignment of the moving body with the video or filming plane. This requirement is not completely met in the shot put due to rotational components present in both the glide and spin techniques. As a result, Knudson (1989) questioned the use of 2D motion capture for the shot put.

In addition to the previous problem, 2D motion analysis may also introduce perspective error (Li et al., 1990; Miller et al., 1980; Orosz et al., 1994). Perspective error occurs when a planar system's orientation is not parallel to the calibration plane of the camera. In other words, 2D analysis makes the assumption that the motion occurs in a calibrated plane perpendicular to the camera axes. Out-of-plane movement can be minimized if the ratio of out-of-plane distance to the camera is small (Sih et al., 2001). Often times though, researchers take this condition for granted despite the existence of known equations (Martin & Pongratz, 1974a, 1974b; Nigg & Cole, 1994) that can be used to estimate the magnitude of the out-of-plane error. In doing so they may violate the assumptions of 2D analysis.
Despite the issues commonly associated with 2D analysis, it is possible to correct for out-of-plane errors. For instance, out-of-plane errors have been corrected for elbow flexion angle (Li et al., 1990) and the embryonic movements of chicks (Orosz et al., 1994) using known segment length and location to calculate the perspective error. In addition to this method, Miller and colleagues (1980) have also described a technique using a single camera in which three points of known location on a rigid body can be used to determine the 3D location of that body. However, these methods are only applicable where one or more points are of known location and where the segments or linked segments have known lengths. Consequently, these methods cannot be applied to single points or non-rigid bodies. To address these limitations, Sih and colleagues (2001) described a method to determine out-of-plane distance from other, non-image related information. Sih and colleagues presented two examples, one of which focused on the shot put, and their method was found to dramatically improve the accuracy of the 2D kinematic data. The use of perspective-corrected 2D motion analysis techniques is particularly relevant to capturing and analyzing the competition performances of elite track and field competitors. This is because capturing these performances generally requires manual digitization and reducing the number of cameras required to obtain accurate data would permit greater sample sizes with the same time commitment.

3D Analysis

Despite the relatively recent ability to correct perspective error in 2D data, 3D motion analysis remains the gold-standard for motion analysis. 3D motion analysis involves the transformation of two or more sets of 2D data into a single set of 3D data. The Direct Linear Transformation (DLT) (Abdel-Aziz & Karara, 1971; Marzan & Karara, 1975; Shapiro, 1978; Walton 1981) and its revisions (Gazzani, 1993; Hatze,
allow the determination of the 3D coordinates of a point from two or more 2D views of the point. The DLT procedure uses two or more 2D views of an accurately surveyed control object to create camera parameters that relate the image space to the object space. The 3D coordinates of the control object are then used to define both the reference frame and the units of measurement.

An alternative to the DLT procedure is the non-linear transformation (NLT) method proposed by Dapena and colleagues (1982). The NLT also uses a control object of known size, but the precise 3D coordinates of points on the control object are not necessary for the transformation. A typical NLT procedure involves moving a control object with points of a known distance within the activity volume. A reconstruction algorithm uses the known dimensions of the control object and approximate information about the camera arrangement to solve for one camera’s orientation relative to the other camera(s) using an iterative approach. The calibration is used to define both a scaling factor and reference frame transformation external to the cameras. This effectively permits the calibration algorithm to “build” the desired size control object.

When using the DLT procedure, the use of 2D data captured outside of the physical space of the control object should be limited to ensure accuracy of transformed data (Chen et al., 1994; Wood & Marshall, 1986). In fact, research has indicated that the accuracy of the DLT procedure decreases as the extrapolation from the control volume increases (Hinrichs & McLean, 1995). This criterion may make calibration of large areas impractical. In such cases, the use of NLT may be desirable. Because the control object used for the NLT procedure can be relatively small and does not need to be surveyed, it is less costly and may be easier to implement than the DLT for large control volumes.
Accuracy of the NLT procedure has been shown to be comparable in calibration accuracy to the DLT procedure (Dapena, 1985b; Hinrichs & McLean, 1995).

Regardless of whether the DLT or NLT procedure is used, the accuracy of the data is highly dependent on the time synchronization of the cameras (Yeadon, 1999). One method of achieving this synchronization involves using phase-synchronized cameras. Such cameras are 10 to 20 times more expensive than standard video cameras (Pourcelot et al., 2000). Consequently, researchers have attempted to find ways to accurately synchronize the video from two or more non-phase-locked cameras. In an attempt to synchronize cine film, Rome (1995) described a system in which the cameras’ output shutter pulses to a computer recording system where they were recorded and counted, and to a digital device which counted the pulses and illuminated the count on an LED device which was filmed with the subject. Synchronization was performed by using the rising edge of the shutter pulse and by comparing the frame number imprinted on the film to the frame number recorded by the computer system. To synchronize video, a light source has been used by both Miller and colleagues (1980) and Deguerce and colleagues (1996) to mark the synchronization point. Yeadon used the digitized location of the ankle at the beginning and end of a trampoline movement to synchronize the video of two cameras (1984). Yu and colleagues (2002) later used a similar method, using events within the discus throw, to synchronize video from three cameras. None of these methods took into account the time offset between the cameras that may be a source of inaccuracy to the 3D kinematic data (Yeadon, 1989).

There have been attempts to address the inaccuracy brought about by ignoring the time offset of the cameras used. Yeadon (1989) proposed a method for synchronizing digitized video of a ski jumper at takeoff and landing. This method required knowing the
location of the athlete’s center of mass at takeoff in the vertical plane. Yeadon (1990) has also used a timing device placed in the view of each camera to synchronize two views. Later, both Yeadon and colleagues (1999) and Pourcelot and colleagues (2000) used the DLT procedure to estimate the time offset between cameras by minimizing the DLT error calculated for a moving marker(s).

**Kinetics**

Although most of the research performed on the shot put has focused on the kinematics of the event, the kinetics of shot putting has also received considerable attention. Kinetics is the description of movement in terms of force. These forces can be either external or internal. External forces include ground reaction forces (GRFs) that are forces generated by external loads or the environment. Internal forces include those resulting from muscle activity, a force generated by the stretch of passive tissues and internal friction (Zajac, 1989).

**External Forces**

The external forces associated with shot putting have been obtained both directly and indirectly. Most of the attempts to indirectly determine force application have focused on the forces applied to the implement. Force measurements of the implement can be estimated using known relationships between energy, work, and acceleration with force. Examining these relationships, Zatsiorsky and Matveev (as cited in Zatsiorsky et al., 1981) used the work-energy relationship to point out that that the work performed by an athlete to move the shot is made of two components. The first component is to cause a change in the vertical position of the implement, resulting in a change in its potential energy. The second component is to change the velocity of the shot that results in a change in the kinetic energy of the implement. The equation for such a relationship is:
\[ W = m_a g h + \frac{1}{2} m v^2 \]

Where \( W \) is work done by the athlete; \( m \) is the mass of the shot; \( a_g \) is gravitational acceleration; \( h \) is change of height of the implement; and \( v \) is the implement velocity. For example, the total energy of a shot at the moment of release is equal to the sum of its kinetic and potential energies, which is equal to the mechanical work performed by the athlete to accelerate and elevate the implement.

**Forces Applied to the Shot**

Force application to the shot can also be indirectly assessed through its relationship with mass and acceleration. That is, force may be estimated by multiplying the mass of the shot by its observed acceleration. The obvious assumption in such a method is that the examined parts of the shot path are linear. This assumption is safe when high sampling rates are used. This method has been used to estimate the force application to the shot by both Kristev and colleagues (as cited in Lanka, 2000) and Tutevich (1955 as cited in Zatsiorsky et al., 1981). In a similar method, Knudson (1989) used the mass and velocities of the athlete-plus-shot system (APSS) to determine the linear momentums of shot putters.

In addition to indirect measurement of forces, direct means have also been used to examine the kinetics of the event. For instance, Machabeli (as cited in Zatsiorsky et al., 1981) used a shot instrumented with an accelerometer. This permitted measurement of horizontal (radial and tangential) and vertical acceleration that could be used to calculate force application to the implement. Yuan and colleagues (2004) developed a similar instrument that used a sensor inside of the implement to measure three-axis force application in real time. The sensor was made from an elastic body based on chaff embedded in the center of the shot.
**Forces Applied to the Ground**

Although the previous methods have been used to examine forces applied to the implement it is far more typical for shot put kinetic research to examine GRFs. GRF is typically measured with small rectangular metal plates known as force platforms. These platforms are equipped with piezoelectric or strain gauge transducers embedded in the corners of the plate which produce an electrical output that is proportional to the force on the plate (Linthorne, 2001a). Force platforms can be used to measure vertical as well as shear forces in the horizontal plane. In the horizontal plane, forces may be measured in both an anterior-posterior direction as well as a medial-lateral direction. A single resultant force vector can be determined from these three force vectors. The acquired force data is usually plotted against time so that changes in force can be observed over time.

The use of force platforms offers several advantages over indirect methods when examining the kinetics of the shot put. One advantage of force platforms is that they can be used to measure sheer forces. Force platforms also permit the examination of the forces applied by each foot individually when two force platforms are placed in the throwing circle at appropriate positions. This can be especially important when attempting to determine the specific role of each leg over the course of the throw.

**Internal Forces**

**Electromyography**

In addition to direct and indirect measurement of forces, the kinetics of shot putting has also been examined using electromyography (EMG) (e.g. Herman, 1962; Marhold, 1985). According to Basmajian and DeLuca (1985) EMG can be used to determine which movements develop tension within a particular muscle group and also to
clinically assess nerve conduction velocities and muscle response as a means of
diagnosing or tracking pathological conditions of the neuromuscular system.

EMG involves the use of electrodes to sense myoelectric activity present at a
particular site over time. The electrodes used to measure myoelectric activity come in the
form of surface electrodes or fine wire electrodes. There is some evidence that surface
electrodes may be more reliable and because they are non-invasive they may be
preferable (Arokoski et al., 1999; Winter, 1990). Regardless of the electrode type, the
output signal should be free from distortion, artifacts, and noise and amplified to achieve
best results (Winter 1990). EMG can be used to examine the timing and magnitude of
muscle contractions that can provide useful insight on which movement patterns are most
important to performance.
Chapter 3: Shot Put Review

There is considerable literature relating to the shot put (see reviews Lanka, 2000, Zatsiorsky et al., 1981). The purpose for this section of the review is to summarize the results of experimental investigation on the biomechanics of shot putting. Precise and thoroughly documented data are available on only certain aspects of shot putting performance. Many variations in technique are based on personal opinions of athletes, coaches, and researchers. Although such personal opinions are not generally taken into consideration in scientific reviews, they will be included in this review in order to provide a systematic treatment of technique variations. The scientific merit of many of these views remains to be seen.

Research performed on the shot put has been both qualitative and quantitative in nature. Most of the research that has been performed on the event has used male participants employing the glide technique. This is likely due to the fact that the spin has only recently come in to common usage in the past decade and also due to the simplicity in analyzing the more linear movement of the glide as opposed to the spin. Men have generally been used as the participants in studies largely because until recently more funding has been available to sponsor research on men’s athletics than women’s. The applicability of research performed on one gender to another remains to be seen however there is some evidence (Alexander et al., 1996) to suggest that male and female athletes may perform the task quite differently.
Motor Task Classification

Division Systems

To better understand the movement of shot putting this review will start with an overview of previously used approaches to studying the movement as well as discussing some operational terminology for the movement. Several approaches have been taken to examine the shot put. The purpose of these various approaches has been to subdivide the performance so that the movements of one throw (or athlete) may be compared to others regardless of the specific time-history of the throw (or athlete). Zasiorsky and colleagues (1981) noted that as many as eight approaches have been taken to subdividing shot put performance (Table 1). Ironically, while each individual division system has facilitated and enhanced analysis of the movement, the large number of division systems has made comparing the data and results of different researchers difficult. For example, Suskana (1974) reported that the final portion of the shot put movement takes approximately one second. In contrast, Tsirakos and colleagues (1995) estimated a time of 0.3 seconds. This discrepancy is due to the fact that the authors used different starting positions for their analysis. Several authors have suggested that the final delivery of the implement begins the moment the rear foot contacts the ground after the flight phase (e.g. Hay, 1993; Jones, 1948). Others have suggested that it does not begin until the front foot touches the ground (e.g. Bresnahan et al., 1960). A third alternative was used by Markov (as cited in Zatsiorsky et al., 1981) who suggested that it occurs after the rear foot touches down but before the front foot touches down. Obviously such varied methods of subdivision accounts for much of the differences observed between results of various studies.

Researchers have divided the throw into as few as four (Hay, 1993) and as many as eleven (Simonyi, 1973) phases. Various methods have been used for division of the
movement. Hay (1993) for instance divided the throw into various motor tasks such as the initial stance, glide, delivery, and reverse. Other studies (e.g. McCoy et al., 1984b) have used the phases of support for dividing the throw. All of the subdivisions have used external qualities of the movement rather than accelerations of the implement or kinetics of the performance to classify the throw. This results in difficulty when comparing the results of various investigators. For this reason, a standardized set of terminology will be used for this review to facilitate interpretation of previous research.

Table 1: Shot put movement classification

<table>
<thead>
<tr>
<th>Division principle</th>
<th>Phase Designation</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Task</td>
<td>Wind up, push-off, final putting effort</td>
<td>Hay (1993)</td>
</tr>
<tr>
<td>Nature and location of the final putting effort</td>
<td>Initiation and completion of the final putting effort</td>
<td>Tutevich (1969 as cited in Lanka, 2000)</td>
</tr>
<tr>
<td>Temporal and spatial characteristics</td>
<td>Glide, push-off, rotation, etc.</td>
<td>Marhold (1970)</td>
</tr>
<tr>
<td>Support</td>
<td>Single support, double support, no support</td>
<td>McCoy et al. (1984b)</td>
</tr>
<tr>
<td>Character of acceleration of the implement</td>
<td>Active, passive</td>
<td>Tutevich (1955 as cited in Lanka, 2000)</td>
</tr>
<tr>
<td>Body position</td>
<td>First and second tucked position, T-position, etc.</td>
<td>Grigalka (1974)</td>
</tr>
<tr>
<td>Subordination</td>
<td>Main, secondary</td>
<td>Grigalka (1967)</td>
</tr>
<tr>
<td>Function</td>
<td>Starting, gliding, etc.</td>
<td>Marhold (1974)</td>
</tr>
</tbody>
</table>

**Operational Terminology**

The following terms were chosen to best simplify discussion and will be used wherever possible. The push off leg will be defined as the leg that is last in contact with the throwing circle prior to the flight phase. For right-handed gliders, this is their right
leg; for right-handed throwers using the spin technique this is their left leg. The rear foot will be defined as the foot that is towards the rear of the circle when the athlete touches down following the flight phase. For right handed throwers using both the glide and spin technique this would be the right foot. Likewise, the front foot is the one that is closest to the toe board when the athlete is in double support following the flight phase. This is the left foot for a right-handed thrower using both the glide and spin technique.

In addition to the performer terminology defined above, the following terms will be used to define various events and phases in the throw. The preparatory phase begins with the initiation of the throwing movement and is concluded at the moment of takeoff. Takeoff will be defined as the moment at which the push off leg breaks contact with the surface of the throwing circle and the athlete enters the flight phase. The period of time in which the athlete is moving towards the front of the throwing circle and has no contact with the throwing surface will be called the flight phase. Rear foot touchdown (RFTD) is the point at which the thrower’s rear foot makes contact with the throwing circle following the flight phase. Likewise, front foot touchdown (FFTD) is the point at which the thrower’s front foot makes contact with the throwing circle following the flight phase. The time between RFTD and release will be referred to as the delivery phase. The delivery phase will be further subdivided with the time between RFTD and FFTD being referred to as the transition phase and the time between RFTD and release the completion phase. See Figure 2 for a visual breakdown of the events and phases of the throw to be used in this review.
Implement Kinematics

Prior to Release

**Velocity**

Much research has been devoted to examining both the magnitude of the speed of the shot as well as its movement trajectory prior to release. Results of this research have varied greatly. The following section will be devoted first to examining the magnitude of the implement’s speed prior to release and then to the trajectory of the implement prior to release. Because these two subjects are closely intertwined, they will first be discussed independently and a concluding examination of their relationship will follow.

**Speed Dynamics**

One commonality in the research examining speed magnitude is that results are typically reported for only the sagittal plane, ignoring the effect of speed in the transverse
plane. This is most likely due to the fact that transverse plane speed has the smallest contribution to the projected distance of the implement. Additionally, previous research was limited by motion capture requiring the use of 2D techniques. As such, unless otherwise preceded by ‘resultant’, the term speed used in the following section will refer to the speed value of the implement resulting from the horizontal and vertical speed components only.

**Undulating**

Several speed profiles have been discussed in the literature. The most commonly observed speed profile for both the glide (Ariel et al., 2004; Lindsay, 1994; Marhold, 1974; McCoy et al., 1984a, 1984b; Suskana & Stepanek, 1988) and spin technique (Ariel et al., 2004; Bartonietz, 1994a; Lindsay, 1994; Luthanen, 1998; McCoy et al., 1984a, 1984b; Palm, 1990) is one in which the speed of the implement fluctuates throughout the duration of the throw. In all such cases, implement speed was observed to increase, decrease, and then increase again prior to release. In more detail, the initial increase in speed corresponds with the initial push-off phase through the takeoff. The implement then decelerates slightly during the flight phase and greatly at RFTD. The final acceleration takes place in the period of time leading up to release. An undulating speed profile is not unique to the shot put. In fact, Atwater (1979) examined other throwing movements and found that in most cases speed decreases to values approaching zero before dramatically increasing in the final portion of the throw. Luthanen (1998) examined several elite throwers using the spin technique and reported the following implement velocities over the course of the throw: 2.75 m/s (preflight), 2.48 m/s (takeoff), 1.02 m/s (flight), 2.88 m/s (RFTD), 12.20 m/s (FFTD); 13.19 m/s (release).
Despite the common undulating speed pattern for the glide and spin techniques there is considerable difference in the specific dynamics (magnitudes and specific timings) of the speed profiles of the two techniques. For the glide, implement velocities reach maximums of 2.0-4.0 m/s during the preparatory and flight phases (Bosen, 1985; McCoy, 1992a, 1992b; McCoy et al., 1984a; McCoy & Koprowski, 1989; McCoy et al., 1989; Suskana, 1974). Upon RFTD the implement decelerates to around 1.5 to 3.5 m/s (Bosen, 1985; Fidelus & Ziencowicz as cited in Lanka, 2000; McCoy, 1992a, 1992b; McCoy et al., 1984a; McCoy & Koprowski, 1989; McCoy et al., 1989; Suskana, 1974). Following RFTD, the implement speed increases slightly during the transition phase (to around 4.0 m/s) after which point there is a sharp increase in speed until just prior to the moment of release (Bosen, 1985; McCoy, 1992a, 1992b; McCoy et al., 1984a; McCoy & Koprowski, 1989; McCoy et al., 1989). Some have suggested that the greatest acceleration of the implement coincides with the initiation of the throwing-side shoulder rotation (Fidelus & Ziencowicz as cited in Lanka, 2000; Grigalka, 1980 as cited in Lanka, 2000) and extension of the throwing arm (Grigalka, 1980 as cited in Lanka, 2000). Results of this research suggested that shoulder girdle rotation accounted for 70-85% of this acceleration.

In the spin, Kerssenbrock (1974a, 1974b; 1981 as cited in Lanka, 2000) noted that during the preparatory phase weight shift from double to single support the resultant speed of the shot can reach almost 4 m/s. This is more than twice as fast as preparatory phase implement speeds observed in the glide technique. Following takeoff, implement speeds have been observed to be 3.75-4 m/s (Bosen, 1985; McCoy & Koprowski, 1989). This is considerably higher than the implement speed achieved at the same point during the glide. This advantage however appears to be short-lived as Kerssenbrock (1974a,
1974b) observed a 65% loss of this initial speed at RFTD in his examination of an elite shot putter using the spin technique. Indeed, several researchers reported the implement speed during the spin transition phase is between 0.6 and 1.2 m/s (Bartonietz, 1983 as cited in Lanka, 2000, McCoy & Koprowski, 1989; Palm, 1990, Stepanek, 1987, 1990). This is approximately half the value observed for elite gliders (Bosen, 1985; McCoy & Koprowski, 1989). On this point, Johnson (1992) suggested that a weakness of the spin technique is that there is a limit to the speed which the athlete is capable of accepting and utilizing upon making FFTD and that the threshold of this utilization may lay below that of the glide. This viewpoint is not widely held however and the mechanism of this deceleration may be more related to the method of data capture than the actual resultant speed of the implement. That is, in the spin technique the implement is likely traveling in a small loop during the transition phase (Lanka, 2000; Zatsiorsky et al., 1981) and this rotational movement is not adequately reflected by the 2D techniques used by the majority of previously cited authors.

In theory an undulating implement speed would appear to be a drawback because the speed of the implement is actually allowed to decrease prior to release. Many authors, however, have suggested that an undulating implement speed may be beneficial to performance (Bartonietz, 1994a; Fidelus & Ziencowicz as cited in Zatsiorsky et al., 1981; Marhold, 1974; McCoy et al., 1984b; Suskana, 1974; Suskana & Stepanek, 1988). Most proponents suggest that an undulating speed profile is representative of an efficient takeoff and allows an athlete to better use the strength of their legs upon landing.

**Fast the Whole Way or Gradual Increase**

In spite of the suggestions in its support and its prevalence among elite throwers, alternatives to the undulating speed profile have been suggested. For instance, some have
suggested that athletes attempt to maximize the speed of the implement upon initiating the throw (Doherty, 1950; Simonyi, 1973). No experimental data exists to substantiate this viewpoint. Others have suggested that to maximize performance, the speed of the implement should increase gradually. Several authors have written in support of this speed profile (Alexander et al., 1996; Ariel, 1979; Fidelus & Ziencowicz as cited in Lanka, 2000; Francis, 1948; Grigalka, 1970 as cited in Lanka, 2000; Pagani, 1981; Schpenke, 1973; Ward, 1985). Experimental data from Suskana and Stepanek (1988) and Lanka and Shalmanov (as cited in Lanka, 2000) suggest that while attaining such a speed profile may be unlikely, it may be beneficial to strive for it. Both sets of authors indicated that although the speed of the implement inevitably undulates, smaller changes in speed with a more gradually increasing trend are observed in athletes with better performances. Furthermore, they found that the technique of the most highly skilled performers is distinguished by a higher speed at the beginning of the delivery phase. Additional support to this point was provided by Marhold (1974) and Pearson (1963a), whose data indicated that achieving a high implement speed at FFTD is very important to performance in the event. Marhold (1974) suggested that for a performance to exceed 21 m, the implement must reach 25-27% of the release speed prior to the start of the delivery. Marhold (1974) and Pearson (1963a) both suggested that the deceleration that is observed at RFTD is dependent on the strength and speed of the thrower and found that in highly skilled athletes the speed can actually increase at the beginning of delivery. Others (Fidelus & Ziencowicz as cited in Lanka, 2000; Suskana & Stepanek, 1988) have suggested that this deceleration is dependent on the speed and direction of the implement motion and the movements of the athlete’s center of mass (COM). All of the literature supporting a gradual increase in implement speed was specifically written for the glide technique and
it remains to be seen whether a similar recommendation can be made for the spin technique as well.

**What is Optimum?**

With each of the three previously mentioned speed profiles being supported by various authors, the optimal speed pattern of the implement remains to be seen. Previous research however has provided insight into the mechanisms producing speed fluctuation that may be useful in determining if one speed profile is superior. Many of the best shot putters in the world are able to throw the shot a distance of 19-20 m from a standing position (Grigalka, 1971; Lanka, 2000). This corresponds to a release velocity of approximately 13 m/s. At the end of a glide, implement speeds in the range of 1.5-3.5 m/s have been observed (Fidelus & Ziencowicz as cited in Lanka, 2000; Suskana, 1974). If the velocities achieved in throws from a standing position could somehow be summed with those just prior to RFTD, release speeds would be 15-15.5 m/s. Such release speeds would correspond to a throw greater than 3 m in excess of the world record. The nonlinearity of the shot speeds at various phases of the throw does not however permit such summation. In fact, losses of up to 60-70% in initial speed have been reported for both gliders (Koltai, 1973) and spinners (Kerssenbrock, 1974a, 1974b) at RFTD. As such, it would appear that while it may be beneficial to strive for a gradual increase of the resultant speed throughout the duration of the throw actually attaining it may be impossible.

**Direction**

As noted above, large changes in the resultant speed of the implement have been observed in the shot put. As might be expected, these changes in resultant speed are highly correlated with changes in the trajectory of the shot. In other words, the changes
in the speed of the implement are closely linked to nonlinearity in the trajectory of implement’s path. The following section will examine the trajectory of the implement over the course of the throw.

Theoretically, one would expect that the ideal trajectory of the implement would be linear in all three planes throughout the duration of the throw. Such a trajectory would ensure linearity of all speed components. Lanka (2000) pointed out that because the shot’s release velocity is equal to the sum of speeds that are achieved at prior phases of the movement, such linearity of the speed components would maximize the resultant release velocity. This geometric summing can be illustrated graphically according to the parallelogram principle (Figure 3). This principle states that the magnitude of the resultant vector in any plane will be equivalent to the sum of all vectors in that plane. In light of this concept, several authors have suggested that ideal shot put technique would permit a linear trajectory throughout the throw (Koltai, 1973; Pearson, 1966a; Tutevich, 1969 as cited in Lanka, 2000). And while this
theoretically optimal trajectory has been observed (Zatsiorsky et al., 1981) its true value has not been confirmed. To better understand the relationship between implement speed and trajectory and for an in-depth investigation of implement trajectory, the movement path of the implement in each plane will be examined separately. As is the case with most research on the shot put, the focus on this topic has been on the glide technique. Unless otherwise noted, the following section on implement trajectory will refer to the movement of the implement in the glide technique.

**Sagittal Plane**

Suggestions vary widely on the most efficient sagittal plane trajectory for the implement to travel during the course of the throw. As noted in the review on speed magnitude prior to release, large losses in speed are often observed at RFTD. Such losses in speed appear to greatly correspond with changes in the implement trajectory. More specifically, decreases in horizontal and vertical implement speed roughly correspond with the implement height during the flight phase and RFTD. Likewise, the final rapid acceleration of the implement corresponds with a change in implement trajectory. Based on this relationship, three different sagittal plane implement trajectories (SPIT) have been suggested as optimal for performance in the shot put: inclined and linear, straight and linear, and undulating.

**Linear Trajectory**

Perhaps the most widely suggested SPIT is the inclined linear trajectory (Alexander et al., 1996; Bell, 1979; Furlong, 1972; Marhold, 1974; Pagani, 1981; Pearson, 1963a; 1966a, 1966b; Powell, 1960; Staff of Modern Athlete and Coach, 1974). Such a trajectory would be expected to produce higher release speeds because the speeds of each preceding phase would be collinear with the trajectory of the release and also
allow the athlete to release the implement at a great enough angle to maximize the
distance. Despite the many suggestions and the theoretical benefits, this trajectory has
only rarely been observed (Baert, 1984). Several researchers have however observed
nearly linear trajectories in one or more of their examined subjects (Bartonietz &
Borgstöm, 1995; Dessureault, 1976; 1978; Grigalka, 1971; Grigalka & Papanov, 1988;
Knudson, 1989; Marhold, 1974). For example, Marhold (1974) divided the implement
trajectory into two phases and found a tendency for the trajectory to approximate a
straight line in each of the two parts, and a tendency for the angle between the two parts
to approach 180˚ (Figure 4a). Other investigators have observed similar trajectories in
one or more of their examined subjects (Baert, 1984; Bartonietz & Borgstöm, 1995;

One way to enhance the linearity of an inclined SPIT may be to decrease the
height of the shot in the starting position (Figure 4d). In doing this, the shot trajectory
will be more linear in the vertical direction and thus the loss of speed may be minimized.
This technique has been observed (Bartonietz, 1994b; Bartonietz & Borgstöm, 1995;
Bartonietz & Felder; 1993; Dessureault, 1978; Grigalka & Papanov, 1988; Knudson,
1989; Mileshin & Papanov, 1986; Ward, 1974) and suggested (Bartonietz, 1994b;
Delevan, 1973; Pearson, 1966a, 1966b; Schpenke, 1974) by several authors to enhance
the linearity of the SPIT. In fact, a majority of the leading shot putters using the spin
technique employ this method. They assume a low starting position by flexing their knees
and leaning their upper body forward (Bartonietz, 1994b). Bartonietz (1994b) pointed out
that such a technique produces a smooth and controlled starting movement with a wide
amplitude; a more linear rise of the APSS COM; and a flat movement path during the
non-support phase without dropping the upper body onto the rear foot. For gliders, it has
been suggested that the hip angle should be 40-45 degrees during the preparatory phase and increase to 55-65 degrees at the moment of takeoff to ensure a low starting position and gradual rise of the implement (Staff of Modern Athlete and Coach, 1974). While some of the current top shot putters produce a straight, low and long SPIT (Lanka, 2000) there is still some debate whether it is indeed the optimal trajectory.

Perhaps because of the difficulty in achieving an inclined linear SPIT, Lanka (2000) suggested that a more flat but still linear trajectory could be an acceptable alternative to the inclined linear trajectory. Such a trajectory may provide a more easily attainable linear trajectory than the inclined linear trajectory. A flat linear trajectory is distinguished by having a linear trajectory that starts and ends at approximately the same point on the vertical axis (Figure 4c). Lanka (2000) provided two means by which a straight and linear trajectory might be achieved. First, he suggested that pushing the shot at a lower angle during the delivery phase (and thus releasing at a lower angle) might increase the linearity of the SPIT. Lanka (2000) also suggested that straightening the legs and body more actively at the beginning of the throw might create a more flat and linear path. This technique however would only be beneficial to athletes who are already very upright at RFTD. Otherwise, the athlete’s legs may be too extended to fully use the strength of their legs. In light of these points, it
should be noted that the flat and linear trajectory likely limits acceleration in the vertical direction and may restrict release angles to ones lower than optimal. No studies have examined whether the potential benefits of a flat linear SPIT outweigh these drawbacks. Overall, it appears that while achieving a completely linear (whether inclined or straight) SPIT may be difficult there are potential benefits. Some authors have suggested that while attainment of a completely linear SPIT may be unlikely, striving for it may still be beneficial (Grigalka, 1972; Jarver, 1976).

**Undulating Trajectory**

An alternative to a linear SPIT is an undulating path. This trajectory is characterized by a wave-like movement of the implement leading up to the release with high points corresponding with mid-flight and release and low points corresponding to the initiation of the throw and RFTD (Figure 4b). This trajectory has been observed by many researchers (Bartonietz & Borgstöm, 1995; Dessureault, 1976; 1978; Grigalka, 1971; Grigalka & Papanov, 1988; Knudson, 1989; Lindsay, 1994; McCoy, 1992a, 1992b; McCoy et al., 1984a; McCoy & Koprowski, 1989; McCoy et al., 1989) and while it obviously lacks the advantage of greater linearity of force and subsequent speed vectors, several authors (Grigalka, 1974 as cited in Lanka, 2000; Mileshin & Papanov, 1986; Ward & McCoy, 1984; Young, 2004a; Young & Li, 2005) have suggested that it may improve the positioning and physical capacity of an athlete to deliver the shot. This benefit is attributed to an enhanced stretch-reflex. These authors suggested that an athlete would not be able to efficiently use their strength if they were to attempt to achieve a completely linear SPIT from the start to the release of the throw. These authors conceded that while a linear SPIT may be optimal in a purely mechanical sense, it might be less than ideal in practice. It was proposed that an undulating SPIT is indicative of a higher
flight phase which allows an athlete to plyometrically load the lower extremities upon landing, thus resulting in greater power output during the delivery phase.

**Horizontal Plane**

Like the sagittal plane, many (IAAF, 1987; Pearson, 1963a; 1966a, 1966b; Powell, 1960) have suggested that the horizontal plane implement trajectory (HPIT) be as linear as possible (Figure 5b). In spite of these recommendations, a linear HPIT is rarely observed in either the glide or spin techniques (Lanka, 2000). This is likely because the shot is carried in a position (the throwing side shoulder) that is not centrally located on the vertical axis of the APSS (Jarver, 1976; Lanka, 2000). As a result, when the athlete begins to rotate their shoulders from a back facing position to a forward facing position, deviation from a linear trajectory is likely to occur (Figure 5a-R1). Some authors have suggested that HPIT linearity is only likely to occur when the athlete’s shoulders are inclined too far to the non-throwing side during delivery (Grigalka, 1967; Lanka, 2000; Zatsiorsky et al., 1981). And while this deviation from a linear trajectory theoretically reduces the resultant speed at release, it is likely an inevitable byproduct of proper throwing technique and attempting to achieve a more linear HPIT would likely have drawbacks that outweigh the benefits. In fact, Lanka (2000) suggested that a larger deviation from a linear HPIT might actually be beneficial because it is representative of the implement traveling around a larger radius. If this rotation were to occur with the same angular velocity a higher linear velocity would result when compared to a more linear trajectory with a smaller radius. Increasing the implement’s movement radius will increase the load on the athlete’s muscles and will likely necessitate a higher level of strength (Tutevich, 1969 as cited in Lanka, 2000). If the radius of rotation becomes too
great, Lanka (2000) cautioned that it might actually hinder the speed at which the throwing arm can be extended and can potentially affect the linearity of the release.

**Glide**

In light of the above discussion, it should be noted that great differences have been observed in the HPIT of athletes using the glide and spin techniques (Baronietz, 1995; Lanka 2000; Lindsay, 1994; McCoy et al., 1984a; McCoy & Koprowski, 1989; McCoy et al., 1989). In the glide technique, the HPIT of the implement typically follows an “S-shaped” path (Figure 5a-R₁). As was stated previously, this non-linear trajectory in the horizontal plane is likely inevitable due to the fact that the implement is placed to one side of the athlete’s neck and as a result is not on the central axis of the APSS. Grigalka (1974 as cited in Lanka, 2000) observed that the HPIT of highly skilled throwers tends to deviate from linearity as the shoulders rotate in the early delivery with the implement trajectory then returning to a relatively linear path leading up to the point of release (Figure 5a-R₁). In contrast, the HPIT of less skilled athletes had a greater deviation during the early delivery and was less likely to return to a linear path prior to release (Figure 5a-R₂).
Spin

Many of the issues associated with the HPIT over the course of the throw may be solved by the spin technique. That is, a rotational technique in which the implement path loops in the middle of the ring may address the problem of non-collinearity of the initial and final speed directions and theoretically make it possible to considerably increase the path of force application during the final part of the movement (Ihring as cited in Lanka, 2000; Bosen, 1985).

Although Lindsay (1994) noted considerable similarity between the HPIT of gliders and spinners, this is not typically the case. While the HPIT observed in athletes using the glide technique is relatively consistent across athletes there appears to be considerable variability in the HPIT of athletes using the spin technique. Two main HPIT for the spin technique have been observed: looping and non-looping.

Figure 6. Horizontal plane implement trajectory (spin). The top figure (A) represents an implement trajectory where the implement rotates around the athlete. The bottom figure (B) represents an implement trajectory where the athlete rotates around the implement.
Several investigators have observed a looping HPIT for athletes using the spin technique (Barotnietz, 1994b; Bartonietz & Borgstöm, 1995; Bosen, 1985; Hay, 1993; Lanka, 2000; McCoy & Koprowski, 1989). In such a trajectory the implement actually moves in the opposite direction of the throw for a short period of time (Figure 6a). The magnitude of this loop is directly related to the aforementioned radius of rotation. Within those athletes displaying a looping HPIT Lanka (2000) reported radii ranging from 7-20cm. In all cases the loop appears to coincide with the transition phase. For a looping trajectory to occur, the implement almost certainly needs to rotate around the athlete’s movement. The backwards movement and looping trajectory is likely a result of the implement being carried in a position which is not centrally located with respect to the axis of rotation. The radius of rotation is likely influenced by the width of the shoulder axis, length of the trunk, and magnitude of inclination of the trunk during the transition phase. A wider shoulder axis upon which the implement is being carried would be expected to increase the radius of rotation. Likewise, the length and inclination of the trunk would greatly affect the magnitude of the loop. For a given trunk inclination, a longer length trunk segment would be expected to increase the radius of rotation. Similarly, greater trunk inclination during the transition phase would also be expected to increase the radius of rotation. Males tend to have a wider shoulder axis and a longer trunk (Fuster et al., 1998) and this may at least partially explain why the looping HPIT is more prevalent among male throwers using the spin technique than their female counterparts.

The second HPIT observed in athletes using the spin technique is the non-looping path. In this HPIT the radius of rotation is 0 during the transition phase. Several researchers have observed the non-looping HPIT among elite level throwers (Bartonietz,
This type of HPIT is typically characterized by a point where the movement of the implement toward the front of the circle appears to come to a momentary pause (see Figure 6b). Similar to the looping HPIT, this momentary pause generally coincides with the transition phase. In such a HPIT, it is likely that the athlete is rotating around the implement rather than the implement rotating around the athlete (Lanka, 2000).

The radius of the HPIT can have a considerable affect on the centripetal forces developed in the spin technique. The quantity of centripetal force developed is influenced by the velocity of the implement and the radius of rotation as indicated in the following equation:

\[ F = \frac{mv^2}{r} \]

Where \( F \) = centripetal force component (N); \( m \) = mass of the implement (kg); \( v \) = velocity of the implement (m/s); and \( r \) = radius of the implement movement (m). From the equation it is clear that velocity has a squared influence on the centripetal force. Bartonietz (1994b) noted that the average centripetal force component of the shot can reach values in excess of 300N. As a result of the large centripetal forces in throws with a wide looping implement trajectory, Lanka (2000) cautioned that a high initial velocity may cause fouling problems due to the implement being thrown to the throwing side of the boundary. This problem has often been observed for the spin technique (Egger et al., 1994). It should however be noted that with all else being equal, a greater radius of rotation would also generate larger linear velocity at the moment of release. In fact, Koltai (1975) suggested that athletes should strive to move the implement through the greatest radius possible to achieve a greater speed in the final phase of the put. With this
in mind the optimal radius of rotation is likely one that allows the largest radius of rotation possible without resulting in so much centripetal force that the athlete has difficulty with keeping the implement within the fair throw sector.

**Length of Path**

Despite the differences between the various implement trajectories one recommendation appears to be common for both techniques as well as all planes. That is that the implement trajectory path should be as long as possible. Several authors have suggested that a longer movement path would increase the distance over which an athlete can exert force on the implement (Booysen, 1971; Furlong, 1972; Grigalka, 1971; Pearson, 1963a, 1963b; 1966a, 1966b; Schpenke, 1973; Staff of Modern Athlete and Coach, 1974). While theoretically true, no known data substantiates the benefit of a longer resultant implement trajectory.

For male throwers, Bosen (1985) noted that the resultant length of implement trajectory is about 2.4 m for athletes using the glide technique and 4.8 m for those using the spin technique. The large difference between the two techniques is due to primarily rotational path of the spin technique compared to the primarily linear path of the glide technique. Thinking that a longer resultant implement trajectory provides an advantage, several authors have suggested that throwers using both techniques should lower the trunk in the preparatory phase so that the implement is as low as possible and is outside of the throwing circle at the initiation of the throw (Booysen, 1971; Dessureault, 1978; Hay, 1993; Pagani, 1981; Pearson, 1963a; 1966b). This would lengthen both the horizontal and vertical displacement of the implement. In a similar vain, other authors have suggested that the horizontal release distance in front of the toe board be as great as possible (Young, 2004a; Young & Li, 2005).
Not all authors think that the resultant length of the implement trajectory is vitally important. Several authors have actually suggested that the resultant distance the implement covers during the delivery phase is more important than the length of the entire trajectory (Grigalka, 1971; Schpeneke, 1973; Staff of Modern Athlete and Coach, 1974; Pagani, 1981; 1985; Pearson, 1963a). Authors supporting this viewpoint cite the substantial deceleration of the implement at RFTD and the fact that accelerative forces cannot be applied to the implement during the flight phase as indicators that the trajectory of the implement prior to the delivery phase is of relative unimportance when compared to the length of the final acceleration. Research substantiates this point as the length of the resultant implement trajectory during the delivery phase of highly skilled throwers has been observed to be between 1.60-1.80 m with longer delivery paths being advantageous (Pagani, 1981; Schpenke, 1973; Suskana, 1974).

**Flight of the Shot**

When the implement is released, its horizontal displacement is dependent on its initial velocity, release angle, and release height. Among these parameters, the most important is the release velocity, as the horizontal displacement of the projectile is proportional to the release velocity squared. The horizontal displacement of a projectile is represented by the following equation:

\[
L = \frac{V_0^2}{g} \cos \alpha_0 (\sin \alpha_0 + \sqrt{\sin^2 \alpha_0 + \frac{2gh_0}{V_0^2}})
\]

Where \(V_0\) = release velocity; \(\alpha_0\) = release angle and \(h_0\) = release height. From this equation, it is obvious that release velocity has the greatest impact on performance as it has a quadratic relationship with the distance achieved. Although two studies (Smith &
Snow, 1990, 1992) examined elite level decathletes putting the shot and found no relationship between any of the release parameters and performance. The data upon which these analyses are based appears flawed, as the reported release parameters are not comparable to other research on elite or sub-elitishot putters. In contrast, Alexander and colleagues (1996) examined university level athletes and found that of the release parameters, only velocity was a significant predictor of distance. Given the equation above, this relationship seems far more plausible.

**Parameter Observations**

The release parameters (Figure 7) of highly skilled shot putters have been the subject of much research. Previous research (Ariel et al., 2004; Luthanen, 1998; McCoy et al., 1984b; Tsirakos et al., 1995) has indicated that a release velocity in excess of 13.5 m/s is necessary for a 21 m throw and 13 m/s for a 19 m throw (distances which typically win medals in International competition for male and female throwers respectively). Release heights for elite level athletes are typically between 2 and 2.2 m (Alexander et al., 1996; Dessureault, 1976, 1978; Luthanen, 1998; McCoy, 1992a, 1992b; McCoy et al., 1984a, 1984b; McCoy & Koprowski, 1989; McCoy et al., 1989; Stepanek, 1990; Tsirakos et al., 1995) although Ariel and colleagues (2004) observed release heights in excess of 2.3 m among elite male athletes. The results of this research are questionable however as other studies examining the same athletes have observed considerably lower release heights (Young, 2004b). As for release angle, it appears the large majority of both elite and sub-elite level performers release the implement at an angle considerably lower than 40° from the horizontal (e.g., Ariel et al., 2004; Bartonietz & Felder, 1993; Cureton, 1939; Lindsay, 1994; Luthanen, 1998; Maheras, 1995; McCoy, 1992a, 1992b; McCoy et al., 1984a, 1984b; McCoy & Koprowski, 1989; McCoy et al., 1989) although some have
observed release angles greater than 40° (Ariel et al., 2004; Marhold, 1974; Smith & Snow, 1990, 1992; Stepanek et al., 1986; Tsirakos et al., 1995).

A fourth release condition that is rarely considered is the horizontal release distance with respect to the toe board. Greater horizontal release distances are beneficial because they provide an advantageous release point relative to the point of measurement. Lindsay (1994) reported similar horizontal release distances for both the glide and spin techniques (ranging from 0.10 m behind the toe board to 0.25 m in front of the toe board). In contrast, Kerssenbrock (1974a) reported significantly greater horizontal release distances for athletes using the spin technique (0.4 m vs. 0.1 m).

Perhaps because of the relatively short distance thrown and the lack of any significant aerodynamic properties of the implement, previous research has indicated that air resistance does not have a significant effect on the flight of the shot (de Mestre, 1990;
de Mestre et al., 1998; Hubbard, 1988; Hubbard et al., 2001; Linthorne, 2001b, 2001c; Maheras, 1995; Tutevich, 1969 as cited in Lanka, 2000). It should be noted that Mizera and Horváth (2002) found that environmental factors such as air resistance, wind, air pressure and temperature, altitude, and ground obliquity can have an effect on the distance of the throw which can be actually be substantially larger than the smallest increases in world record performances acknowledged by the IAAF.

**Release Condition Relationships**

All of the release parameters are affected by various factors ranging from interrelationships to anthropometry. Beyond the obvious ability of a given athlete to apply force to the implement, the release velocity appears to also be dependent on other factors as well. For example, several researchers have indicated that release velocity and angle are dependent on one another in an inverse relationship (de Mestre, 1990; de Mestre et al., 1998; Hubbard, 2000; Hubbard et al., 2001; Linthorne, 2001b; 2001c; Maheras, 1995; McWatt, 1982). That is, as release angle increases, release velocity decreases. In fact Hubbard and colleagues (2001) examined two collegiate level throwers and found that maximal attainable release velocity decreases with increasing release angle at about 1.7 (m/s)/rad. Their data also indicated that maximal attainable release speed decreases with increasing release height at 0.8 (m/s)/m. This relationship is likely more a function of the relationship between release angle and release height (as release angle increases so does release height) than it is anything directly associated with release height.

While some authors (Dyson, 1986; Grigalka, 1974 as cited in Lanka, 2000; Savidge, 1970) have speculated that height is relatively constant and cannot be changed this is only partially true. The primary determinant of release height is an athlete’s
anthropometry, specifically their height and the length of their throwing arm (Alexander et al., 1996; Hay, 1993, Marhold, 1974; McCoy et al., 1984b; Pyka & Otrando, 1991; Stepanek et al., 1986). In this regards, release height may be more unchangeable than the other release parameters. There are, however, other factors that can produce small but observable changes in release height. For instance, the position of the thrower at the moment of release affects release height. For example, if all else is equal a thrower who propelled themselves into the air just prior to release would have a greater release height than one who remained in contact with the ground at release. Similarly, an athlete can increase release height simply by increasing their release angle and keeping all other body positions constant (Hubbard et al., 2001).

Release angle is largely influenced by the position of the athlete’s trunk and throwing arm. Both the inclination of an athlete’s trunk in the sagittal plane and the angle of throwing arm extension relative to the trunk affect the release angle. As indicated above release angle has an inverse relationship with release velocity. In addition to this relationship changes in release angle will also produce changes in release height (as mentioned above) and horizontal release distance. Horizontal release distance is primarily determined by the athlete’s body position, arm position, and the athlete’s unique anthropometry (Hay, 1993). Hubbard and colleagues (2001) reported that horizontal release distance decreases with increasing release angle at about 1.7 m/rad and increases with increasing release height at about 1.3 m/m.

**Optimization of Initial Release Parameters**

In an attempt to further projectile motion theory and perhaps also enhance performance of shot put athletes, much research has attempted to optimize the release parameters of the shot put. Projectile motion theory focuses on the release parameters that
result in the projection of an object or body, the flight patterns of projected objects or bodies, and the interaction between the release parameters. In the case of the shot put, most projectile motion research has focused on determining the release angle that would maximize the projected distance. There is no shortage of authors who suggest that the angle of release should be greater than 41° (e.g., Bangerter, 1983; Bashian et al., 1982; Bosen, 1966; Burghes et al., 1982; Furlong, 1973; Sharpley, 1964; Townend, 1984; Trowbridge & Paish, 1981; Ward, 1970, 1985; Young, 1985). These recommendations are supported by several researchers (Bose, 1983; Hooper, 1979; Lichtenberg & Willis, 1978; Muhoray & Balzarini, 1982; Trowbridge, 1980) who determined optimal release angles using the projectile motion equation given above.

Despite the overwhelming number of recommendations, large discrepancies have been observed between the predicted optimal values and values observed in elite (Bartonietz & Borgstöm, 1994; Bartonietz & Felder, 1993; Luthanen, 1998; McCoy, 1992a, 1992b; McCoy et al., 1984a, 1984b; McCoy & Koprowski, 1989; McCoy et al., 1989; Tsirakos et al., 1995) and sub-elite (Dessureault, 1976, 1978) shot putters. This has led some authors to speculate that release angles should be lower than those determined using the projectile motion equation (Hubbard, 1988; Ward, 1975). Recent research supports this viewpoint. For instance, Linthorne (2001b, 2001c) examined university level shot putters and developed a model that related measurements to anthropometric and strength characteristics of the athlete. Results indicated that release velocity and angle are not independent and that the optimal release angle is considerably lower (32-38°) than that determined using the projectile motion equation. Similar findings have been reported by other investigators for throwers using both the glide (de Mestre, 1990; de Mestre et al., 1998; Hubbard, 2000; Hubbard et al., 2001; Maheras, 1995; McWatt,
1982) and spin technique (Luthanen, 1998). Two mechanisms explaining this phenomenon have been proposed. First, as projection angle increases the performance is opposed by a greater effect of gravity (Hay, 1993; Linthorne, 2001b; Zatsiorsky & Matveev as cited in Zatsiorsky et al., 1981). This is due the fact that the force of gravity acts perpendicular to the ground and as the release angle increases more force must be used to overcome the effect of gravity. Second, the structure of the human body may not be able to produce equal force (and as a result velocities) in every position (Linthorne, 2001b). On the latter point, it should be noted that this phenomenon may be due in part to a thrower’s exercise selection in weight training rather any anatomical limitations (McCoy et al., 1984b).

**Performer Kinematics**

The preceding portion of this review has focused primarily on the movement characteristics of the implement. The implement’s movement characteristics however are largely the outcome of the movements of the performer. Unfortunately, despite several authors noting the importance of the coordination and timing of muscle sequences for shot putting (Ariel, 1973b, 1979; Cureton, 1985; Grigalka & Papanov, 1978; Hay, 1993; Maltseva, 1990; Pagani, 1981; Ward, 1975) only a few attempts (Christmann, 1937 as cited in Zatsiorsky et al., 1981; Doherty, 1950; Vasiliev as cited in Zatsiorsky et al., 1981) have been made to study the interaction of body segments and how they affect the movement characteristics of the shot.

**Coordination Patterns**

Lanka (2000) pointed out that each body segment takes part in two movements: turning around the proximal joint axis and movement together with a joint. For instance, the velocity of the hand and shot is equivalent to the vector sum of the velocity of the
shoulder joint and the arm. This then begs the question of how each individual segment movement should be coordinated to maximize the speed of the hand (and thus the shot) at the moment of release. Further complicating matters is the complex requirements of the movement itself.

Broer (1960) identified three different types of coordination patterns for enhancement of movement efficiency depending on the purpose of the movement:

1. When speed of movement is the primary objective, proximal segments should be engaged first with distal segments only engaged when the more proximal segments have reached maximal speed.

2. When maximum force development is the primary objective, weaker segments should not be engaged and the strongest body segments should act simultaneously.

3. When one or more segments are engaged in the activity, the lower segments should be fixed, providing a stable base for a more effective performance by the upper segments.

As shot putting would seem to require all three aforementioned criteria, no single movement strategy would appear to be an obvious choice.

To maximize the speed of movement, Broer (1960) suggested a proximal-to-distal activation sequence. Other authors have also suggested this coordination pattern for the shot put. For instance, Dyson (1986) and Ward (1985) suggested that the movement should be initiated by the strong musculature of the trunk and finished by the extremities. The rationale for this coordination pattern was explained by Pagani (1981) and Ward (1975) who suggested that to most effectively throw the shot, the larger slower muscle groups should be engaged first and followed by the smaller and weaker contractions of
the more distal muscles. This coordination pattern would allow an athlete to use the strongest muscles when the greatest force (and acceleration) was necessary (at the start of the delivery) and the fastest (but weakest) muscles when the inertia of the implement had largely been overcome (in the final stage of the release). A variation on this theme has also been suggested where movement is initiated by the muscles of the thigh, followed by the muscles of the trunk, and then the throwing arm (Bartonietz & Borgstöm, 1995; Brown, 1985; Holmes, 1979; Maltseva, 1990; McGill, 1984; Mileshin, 1984; Pearson, 1966a, 1966b; 1967; Tschiene, 1969; Vigars, 1979). While research on this subject is sparse, there is some evidence to suggest that the proximal-to-distal firing order is the most effective for throwing the shot (Christmann, 1937 as cited in Zatsiorsky et al., 1981; Vasiliev as cited in Zatsiorsky et al., 1981).

In the shot put, maximum force production is also essential to performance. The second possible coordination pattern proposed by Broer (1960) is aimed at achieving this goal. This coordination pattern is characterized by maximal and simultaneous contraction of the strongest segments. Proponents of this viewpoint claim that that maximum force can only be generated when the speed of all body segments is maximal (Marhold, 1964 as cited in Lanka, 2000). The rationale behind this theory is based on Hochmuth’s (as cited in Lanka, 2000) biomechanical principle of “particular impulse coordination.” This principle states that maximal velocity is achieved when the temporal coincidence of the maximum speed of all body segments is achieved. In the case of the shot put the speed of the implement consists of two components: the resulting speed from the extension of the lower extremities and trunk and the resulting speed from the extension of the throwing arm. Thus according to Hochmuth’s principle, temporal coincidence of the maximum speed of lower extremity, trunk and arm speeds should lead to an increase in release...
velocity. While previous data (Grigalka, 1970 as cited in Lanka, 2000; Schpenke, 1973) has suggested that all joints should extend simultaneously during the delivery of the shot, the validity of this theory has yet to be verified.

Broer’s (1960) third coordination pattern suggests that the lower body should be fixed to provide a stable base from which the upper extremity, especially the throwing arm in the case of the shot put, may exert force against. This suggestion and several variations of it are quite common. For instance, many authors have suggested that both legs should remain in contact with the ground during the delivery of the shot all the way through the point of release (Booysen, 1971; Fitness and Amateur Sport Directorate, 1966; Furlong, 1972; Grigalka, 1970 as cited in Lanka, 2000; Grigalka & Papanov, 1978; Maltseva, 1990; Pagani, 1981; Pearson, 1966a, 1966b; Powell, 1960; Tsirakos et al., 1995; Ward, 1970, 1975, 1985; Woicik, 1983). A variation of this suggestion is that athlete’s should maintain ground contact as long as possible while still permitting takeoff if necessary (Pagani, 1976; Ward, 1975). Despite the widespread recommendation to maintain ground contact through the point of release, several investigators have noted that most top level shot putters actually break contact with the surface of the ring prior to release with one (Pagani, 1981; Ward, 1975) or both feet (Bartonietz & Borgstöm, 1995; Grigalka & Papanov, 1978; McCoy et al., 1984b; Palm, 1990; Wilt, 1982). Several authors have suggested that the discrepancy between recommendation and practice is that the detrimental effects of being off the ground are outweighed by the additional velocity added to the APSS by an explosive takeoff prior to release (McCoy et al., 1984b; McGill, 1983; Staff of Modern Athlete and Coach, 1974; Sullivan, 1962). Under this premise, McGill (1983) suggested that athletes should actually attempt to jump off the ground
while delivering the implement. Others have suggested that only the front foot need remain in contact with the ground (Paish, 1980).

In light of the arguments in support of each coordination pattern, it appears that the best option may not be one individual movement strategy but some combination of the three. This is because in the shot put, maximum speed is necessary to achieve the highest possible release velocity, maximum force is necessary to effectively accelerate the implement, and the implement is thrown with only one arm. Grigalka (1970 as cited in Lanka, 2000) suggested that in such a situation, all three types of interaction may be combined to utilize the greatest “explosive power capacity” of the athlete during the delivery phase.

Grigalka (1967, 1970 as cited in Lanka, 2000) proposed an optimal coordination pattern in which each segment is brought into action at a different time, but the cessation of their movements should be simultaneous and occur as close as possible to the moment of release (Figure 8). This proposed optimum movement pattern is not supported by research however. A study by Lanka (1978 as cited in Lanka, 2000) indicated that when throwing the shot, body segments do not cease motion simultaneously as Grigalka suggested. In this study, 50 shot putters of various skill levels were examined using goniometers to measure changes in joint angles during the completion phase of the throw. Two different segmental interaction patterns during the latter moments of the delivery of the shot were observed:

1. Rear knee extension is followed by a change in the angle of the throwing side hip which is followed by front knee and throwing side elbow extension; and

2. Extension of the front knee precedes extension of the throwing side hip while the sequence of the other segments remains unchanged.
In no cases were body segments found to cease movement simultaneously as Grigalka proposed.

Figure 8. Proposed optimal coordination pattern. The lines represent the proposed optimal activations for the (1) lower extremities, (2) hip musculature, (3) trunk, and (4) arms and shoulder up to release. The hatched area represents the duration of time in which all segments are engaged simultaneously. (From Grigalka, 1970).

In light of the above discussion, what then is the optimal movement coordination pattern? While many of the body segment interactions offered above may be rational from a mechanical standpoint they may all fail to describe the optimal coordination pattern for the shot put. This may result of not taking in to account the many difficult to define characteristics of the human organism. Variations in such factors as the mass of each body segment, the force generating capacity of each muscle, and the structural limitations of each joint make optimizing human coordination patterns very difficult. Other factors such as rate of force development and the effect of the force-velocity relationship of muscle are also very important factors that should not be overlooked. Because of these factors and the complexity of the movement, it appears the most
efficient coordination pattern cannot be determined simply on the basis of mechanical principles.

Experimental data on a variety of throwing activities indicates that a proximal-to-distal segment activation pattern is crucial to attaining maximal speed (Zatsiorsky, 1997). Studies on baseball pitching (Atwater, 1979; Dillman et al., 1993; Elliot et al., 1986; Escamilla et al., 2001; Feltner & Dapena, 1986; Fleisig et al., 1996), javelin throwing (Best et al., 1993), American football throwing (Fleisig et al., 1996; Rash & Shapiro, 1995) and water-polo (Elliot & Armour, 1988) have noted that the fastest throwing action is accomplished with a proximal-to-distal progression of body segments. These findings have been further supported by simulation studies. Alexander (1991) used simple mathematical models to investigate the consequences of sequential contraction. Results indicated that there is an optimum delay between activation of the more proximal muscle and of the more distal one that maximizes the release velocity. When the delay is shorter than optimal, the throw is completed sooner and less time is available for contraction of the more proximal muscle. If the delay is too long, less time is available for contraction of the distal muscle and it is not able to perform maximal work. Similar results have been produced using computer simulations (Bath & Kearney, 1996; Herring & Chapman, 1992; Kearney et al., 1993). Overall, a proximal-to-distal sequence is generally accepted as the most efficient coordination pattern for achieving maximum release velocity in throwing activities (Putnam, 1993; Zatsiorsky, 1997).

A second recommendation for efficient movement coordination in the shot put is consecutive acceleration and deceleration of the main body segments. Lanka (1978 & 1996 as cited in Lanka, 2000) used 3D motion analysis to investigate the glide shot put technique and found that during the delivery phase, body segments are accelerated and
then immediately decelerated. As might be expected, more highly skilled throwers were observed to have greater body segment maximum speed values than less skilled throwers. Other authors have reported similar results. For instance, Tutevich (1969 as cited in Lanka, 2000) suggested that during the preparatory and flight phase the entire APSS accelerates. Then in the time period lasting between RFTD through the first half of the completion phase the implement is accelerated by contraction of the trunk musculature and through a transfer of momentum to the upper body by deceleration of the translation and rotational movement of the lower extremities. The final portion of the throw begins with extension of the throwing arm where the forces are directed towards accelerating the shot. Results indicated that release velocity is maximized if there is a gradual deceleration of all body segments following the preliminary acceleration of the APSS. At the moment of release, the speed of the lower extremities and trunk should approach zero.

When considering the beneficial effects of proximal-to-distal and acceleration-deceleration coordination patterns it is important to note that much of the benefits from each coordination pattern may in fact be a shared effect of a common point. One of the proposed benefits of a proximal-to-distal coordination pattern is that it generates a whip-like motion (Bath & Kearney, 1996; Kearney et al., 1993). That is because when the upper leg and trunk musculature are the first to contract greater separation is developed between the shoulders and hips. This results in a whip effect as the hips are decelerated and the shoulders accelerate as they uncoil and the implement is released. This deceleration of the hip is one of the very things that have been indicated as being critical in an acceleration-deceleration coordination pattern. In fact, Lanka (2000) suggested that the effectiveness of body segment deceleration is primarily a product of deceleration of the hip. Overall, it would appear that an optimal coordination pattern is one in which
muscle activation (and segment acceleration) occurs in a proximal-to-distal manner with an optimally timed deceleration of body segments leading up to the moment of release.

**Trajectory of the Center of Mass of the Athlete-Plus-Shot System**

Following the discussion of implement movement characteristics and athlete coordination patterns a discussion of the trajectory of the COM of the APSS is in order. Previous research on male athletes using the glide technique indicated that the COM of the APSS undulates in a manner paralleling that of the implement trajectory (Ariel, 1973b, 1979). McCoy (McCoy, 1992a, 1992b; McCoy et al., 1984a; McCoy & Koprowski, 1989; McCoy et al., 1989) observed a similar relationship for female athletes using the glide technique but found that the trajectory of the COM of the APSS differed from the implement trajectory for athletes using the spin technique and men using the glide technique. This research indicates that following FFTD the COM of the APSS in the above mentioned groups, experiences a rapid vertical movement far greater than that of the implement. In the only known research directly comparing the COM trajectory of the APSS for both the glide and spin technique, Lindsay (1994) found that throwers of both techniques maintained a significant forward velocity of the COM together with a progressive rise in vertical velocity of COM up until the point of release. Ariel (1973b) reported similar findings. His data indicated that the COM displacement for the APSS accelerates from the initiation of the throw to the point of release. One notable conclusion from these findings relates to the previously mentioned deceleration of the hip. Remembering a well-timed hip deceleration is vitally important to the success of a throw, it should be noted that the hip deceleration must occur, as the COM of the APSS is moving in the direction of the throw. This means that the speed of the hip likely never reaches zero due to the movement of the APSS. Another interesting observation from
research on this subject is that the COM trajectory of the APSS is significantly different between men and women. Alexander and colleagues (1996) examined male and female throwers using the glide technique and found that peak horizontal velocity of the COM during the throw was higher for men, resultant velocity was higher for men and peak vertical velocity was equal for both genders.

**Performer Movements**

The following section of the review will focus on the specific body segment kinematics of the performer throughout the course of the throw. Because the glide and the spin are quite different, the review will begin with a brief comparison of the two techniques that will be followed by separate in-depth examinations of each technique. This examination will break down each particular technique and examine each phase or event in the order that it occurs in the actual throw.

**Glide vs. Spin Technique Kinematics**

Recommendations that apply to both techniques have been made for efficient shot put technique. Several have suggested that efficient shot put technique is distinguished by movement of the implement through a large range of motion, minimal slowing of the implement in preliminary motions, attainment of optimal throwing position at the end of the preliminary motions, and correct sequencing of the body motions during the delivery (Dyson, 1986; Ecker, 1971; Hay, 1993).

In the glide, progression across the circle is dominated by linear motion with some rotation occurring during the delivery phase (Bosen, 1985). In contrast, movement across the ring in the spin technique is primarily rotational in nature and linear force application is not a dominating factor other than in the final moments of the throw (Bosen, 1985). Besides this obvious difference others have been observed. For example,
the total time to complete the throw is considerably longer in the spin (McCoy et al., 1984b) and temporal parameters throughout the course of the throw are considerably different (Young & Li, 2005). Despite these differences however, neither technique has a clear edge in performance.

As might be surmised from the similar distances achieved with both techniques, the release parameters of both techniques are quite similar (Lindsay, 1994; McCoy et al., 1984b; Young & Li, 2005). It appears however that the spin technique may provide a greater benefit to an athlete’s standing throw performance than the glide. A standing throw is made over what is otherwise known as the completion phase without being preceded by a preparatory, flight or transition phase. The glide has been said to increase standing throw performance by 1.5-2.0 m (McGill, 1983) or 7-10% (Bosen, 1985). Holmes (1979) suggested that this enhancement is a result of the action of the glide, which allow the athlete to gain momentum but also enables the athlete to elicit a stretch reflex that would not otherwise be attained in a throw from a standing position.

The benefits noted for the glide likely also apply for the spin technique however the spin is said to provide a considerably greater advantage (12-24%) over a performer’s best standing throw when compared to the glide (Bosen, 1985). World Champion and Olympic Medalist Adam Nelson claimed to increase his standing throw by up to 8 m using the spin technique (Thompson, 2000). In addition to the benefits that Holmes (1979) noted for the glide, it has also been suggested that the spin technique’s better rhythmic qualities facilitate greater generation of torque and storage of kinetic energy from preceding actions (Johnson, 1992) and produces greater angular momentum and preserves previously developed kinetic energy (Palm, 1990). If this is indeed the case, two questions arise: 1). Why are the performances achieved with both techniques so
similar and 2). Why don’t all athletes use the spin technique? It would appear that either the techniques require distinct physical characteristics, different skills, or standing throw performance is not as closely related to spin performance as it is to glide performance.

Enhancement Discrepancy Explained by Physical Characteristics?

There seems to be a consensus that the glide technique is better suited to athletes who are especially strong and massive (Bosen, 1985; Egger et al., 1994; Oesterreich et al., 1997). No such consensus exists in regards to the spin. In fact, despite Booth's (1985) suggestion that taller athletes have an advantage regardless of the technique used, both he and others (Egger et al., 1994) have conceded that if a smaller athlete has the necessary qualities the spin technique may allow them to compete at a higher level than the glide would otherwise permit.

Several authors have claimed that the spin technique may be better suited to shorter athletes (Heger, 1974; Oesterreich et al., 1997). This claim is based on the assumption that the relatively small throwing circle (when compared to the discus ring) makes the spin technique difficult for larger individuals. Turk (1997) and Alexeev (1972) however pointed out that the first competitor to use the spin technique at the elite level did so because he felt the size of the throwing circle restricted his ability to use the glide technique. Finally, Durant and Ellyn (1977) suggested that women are better suited to the spin technique due to their lower center of mass and lighter implement. He argued that these factors would facilitate rotational movement. It remains to be seen whether a particular body type is better suited to the spin technique.

Enhancement Discrepancy Explained by Skill?

Beyond physical characteristics, distinct motor abilities may also help to answer the questions posed above. There appears to be a common notion that the glide technique
is more dependent on strength than skill (Bosen, 1985; Egger et al., 1994) while the spin is a more complex movement more heavily dependent on skill and speed (Booth, 1985; Egger et al., 1994; Johnson, 1992; Oesterreich et al., 1997). Presumably, if development in the spin technique were more dependent on skill, beginners would likely perform better with the glide technique. Research on this very subject is inconclusive. Two studies have examined whether one technique is superior for novices. A study by Wilkinson (1975) indicated that while novice athletes perform better with the glide technique, body size and strength had no significant correlation with either technique. Another study by Jolly and Crowder (1982) found no such difference on the effect of technique variation on novice performance. More research on this subject is needed however it is likely better to say that the skills necessary for success with each technique are distinct rather than one necessarily being more complex. Suggestions from practitioners indicate that the most important characteristics to be successful in the glide technique are size (both height and weight) and strength (Bosen, 1985; Egger et al., 1994; Oesterreich et al., 1997). Similarly it has been suggested that athletes using the spin technique possess good balance, coordination, flexibility and speed (Pagani, 1985; Paish, 2005; Turk, 1997).

Results of a study by Lindsay (1994) provide considerable insight on this issue. This study compared the differences between throwers using the glide and spin techniques using 3D data obtained at major competitions in 1992-1993. The study examined the path of the shot, release parameters, temporal aspects, velocity of the shot, size of the completion phase base, angular hips and shoulders displacements, absolute knee angles, velocity of the athlete’s COM and the angular velocity of the athlete’s COM and angular velocity of the athlete’s hips and shoulders. Results indicated that although throwers using the spin technique reached the center of the circle faster there resultant
implement velocity was significantly lower than those using the glide technique. The author concluded that spinners arrive in a more advantageous position at RFTD but lose most of this advantage because of the significantly longer duration of the transition phase. Top-level athletes using the spin technique generate greater angular velocity of hips and shoulders than glide throwers and use their legs more efficiently to provide significantly increased vertical velocity of the COM of the APSS. The author concluded that only athletes who are capable of capitalizing on these factors would benefit from an adoption of the spin technique. Johnson (1992) reported similar benefits and likewise concluded that the spin can provide improved performance only for those athletes with the necessary abilities.

Is the Standing Throw Unimportant?

A final explanation for the discrepancy in performance enhancement of the two techniques over standing throw performance is that the standing throw is a skill that is more closely related to the glide technique than to the spin technique. Standing throws are typically taken using a wide stance with a great inclination of the trunk toward the rear of the circle (Godina & Backes, 2000). This position more closely resembles the position attained for the completion phase in the glide technique. Whatever the case, the exact relationship between standing throw performance and the full throw (whether spin or glide) performance remains to be seen.

Glide Kinematics

The following section will examine the specific kinematics of the glide technique. As described above the shot put throw has been broken down into its various phases, beginning with the preparatory phase, by events within the throw to better facilitate interpretation of the data. The preparatory phase is important for establishing a good
position from which to start the throw (Babbitt, 2000). Several authors have suggested that starting rhythm and balance are critical because of their effect on the entire throw (Bosen, 1985; Powell, 1960; Turk, 1997). In general, preparatory phase movements should be simple yet effective while minimizing movements that do not contribute to the objectives of the phase (Mileshin, 1984; Mileshin & Papanov, 1986).

**Preparatory Phase**

Two starting strategies have been employed for the glide technique: static and dynamic. The static start strategy is characterized by the athlete beginning the push-off from a stationary position. Using this starting strategy, throwers typically begin in single support with the athlete flexed at the hip such that their trunk is lowered towards the ground (Schmolinsky, 2000).

Several starting positions have been observed for the static start. The first is the more traditional “T-position.” This starting position is characterized by the athlete balanced in single support on the rear leg with the non-support leg and trunk held close to parallel with the throwing circle to form a position resembling a “T” (Hay, 1993). In the alternative static starting start position athletes assume a crouched position. This position differs from the traditional “T-position” start in that the chest is lowered closer to the support leg and the non-support leg is tucked under the body close to the support leg. Regardless of the specific technique, the free arm should be relaxed (McGill, 1983; Pearson, 1967; Ward, 1985) and used in conjunction with the non-support leg to maintain balance (Schmolinsky, 2000).

Several authors have stressed the importance of a low starting position (Hay, 1993; Marhold, 1974; McGill, 1983; Pagani, 1981; Powell, 1960; 1961; Ward, 1975) with the shoulders facing the rear of the circle (McGill, 1983). And while the crouch
position may permit a lower starting position, Holmes (1979) believed that there is no true advantage to either technique. One thing that should be noted however is that an athlete’s individual strength levels may play an important role in determining which starting position is best for a given athlete. Judge (1991) and Powell (1961) suggested that lack of strength may make the preparatory phase particularly difficult to execute proficiently and that starting in a position that is too low may have detrimental effects on all subsequent phases of the throw.

The alternative starting technique to the static start is the dynamic start. Athlete’s using the dynamic start technique initiate movement from an upright position; they then aggressively drop down into a low position from which the initial push-off is made (Judge, 1991). Some (Judge, 1991) have claimed that a dynamic start can increase the range over which the implement may be accelerated as well as increase the momentum of the APSS. The validity of these statements has not been verified and both the static (Knudson, 1989; McCoy & Koprowski, 1989; McCoy et al., 1989) and dynamic (Bartonietz & Felder, 1993; Knudson, 1989; McCoy & Koprowski, 1989; McCoy et al., 1989) starts have been observed in elite shot putters.

As hinted above, the dynamic start concludes with the athlete in a position very similar to the starting position of the static start. That is, following the aggressive drop from the upright position, the athlete’s trunk will be lowered close to the flexed support leg. This shared position provides the advantage of both lowering the starting position of the implement and also placing it outside of the ring (Hay, 1993). As discussed previously, this theoretically permits a greater range over which the implement can be accelerated. This position is also thought to place the support leg in a position from which it is better able to accelerate the APSS into the takeoff as well as place the trunk
musculature in a position from which it will be able to greatly contribute to the final delivery of the shot (Hay, 1993).

Just prior to the initial push-off, throwers flex their knee and hip of the non-support leg so that it comes underneath the body. Combined with the aforementioned trunk and support leg flexion this puts the athlete into a low and compact position. It is from this position that the athlete begins the drive across the circle. This drive consists of a combination of several well-coordinated but separate movements (Hay, 1993):

1. A backwards shift of the athlete’s COM beyond the limit of their base of support. This shift is brought about by the downward and forward swing of the non-support leg and an accompanying backward falling action of the thrower’s hips. This action is referred to as “unseating.”

2. Active extension of the non-support leg toward the front of the circle.

3. Extension of the support leg.

Ward (1970, 1975) suggested that the athlete should unseat (allow their weight to shift backwards) and then push with the support leg without emphasizing the action of the non-support leg. Others have claimed the non-support leg plays a crucial role in the push-off portion of the preparatory phase. Some (Schmolinsky, 2000) suggest that both legs should extend simultaneously for optimal effect. Others (Hay, 1993; Mileshin, 1984) suggest that it is best to first unseat, then actively drive the non-support leg towards the toe board, and then push with the support leg. Experimental data from Mileshin (1984) confirmed that the latter movement strategy is the most common in elite throwers. These data indicated that most elite throwers complete extension of the non-support leg prior to extension of the push-off from the support leg.
Opinions on the action and function of the action of the non-support leg differ. One use of the non-support leg is to increase propulsive forces at takeoff (Brown, 1985; Pagani, 1981; Paish, 1980; Ward, 1975). As attainment of maximum velocity of the APSS at takeoff is likely not beneficial and the push-off is primarily achieved by the support leg, the benefit of this use of the non-support leg is questionable. Another role suggested for the non-support leg is to help direct the trajectory of the APSS push-off. In this role, some suggest (Grigalka, 1967; Mortensen, 1952; Tutevich, 1955 as cited in Lanka, 2000) that the non-support leg should assist in generating both horizontal and vertical velocity of the APSS. These authors claimed that the non-support leg should be both forward and upward rather than directly to the toe board. On the other hand, others (Hay, 1993; Kristev as cited in Lanka, 2000; Schpenke, 1973; Simonyi, 1973) have claimed that the non-support leg should be directed towards the toe board to enhance horizontal movement. The coordination of such an action is said to be simpler and also facilitates correct foot contact with the ground (Zatsiorsky et al., 1981). It has also been cautioned that if extension of the non-support leg is directed too high it makes it difficult for the thrower to keep their upper body in the desired position (Grigalka & Papanova, 1978; McGill, 1983).

In addition to the lower body kinematics, several recommendations have also been made for the positions and movement of the upper body during the preparatory phase of the glide technique. Most of these suggestions are related to the orientation of the shoulders. Several authors (Grigalka & Papanova, 1978; McGill, 1983) have suggested that the shoulders should face the rear of the throwing circle throughout the preparatory phase. Other authors have suggested that a relaxed and extended free arm
during the preparatory phase may assist in orienting the thrower’s shoulders in the appropriate direction (McGill, 1983; Pearson, 1967; Ward, 1985).

**Takeoff**

The final moment of the preparatory phase is the takeoff. This is the instant at which the athlete’s support foot breaks contact with the ground and the athlete enters a period of flight. Intuitively it may seem as if athletes should strive for a maximal takeoff velocity. This however is not necessarily the case. Several authors (Grigalka, 1972; McCoy et al., 1984b; Young, 2004a; Young & Li, 2005) have suggested that all movements prior to RFTD are subordinate movements whose main purpose is to create favorable positions for the delivery. As such, a successful takeoff may be more characterized by the effect it has on the positions an athlete is able to attain later in the throw than by the attainment of maximal linear velocity. This is supported by the findings of Tsirakos and colleagues (1995) who compared the flight phase durations of skilled and highly skilled shot putters using the glide technique and found no significant difference (0.13s vs. 0.14s). In light of this, recommendations for the takeoff position have been focused more at influencing body position for the subsequent delivery than on the magnitude of the final push-off. For instance, some authors have suggested that some shoulder-hip separation should be evident by takeoff (Holmes, 1979; Pagani, 1981; Ward, 1975). Shoulder-hip separation refers to the differential angle formed between the plane of the shoulders and the plane of the hips in the transverse axis (Figure 9). Holmes (1979) suggested that this separation may be aided by the action of the non-support leg which should encourage the hips to turn sideways while the shoulders remained facing the rear of the circle.
Two foot positions have been observed for the final push-off in the glide technique: takeoff made from the heel with a dorsiflexed ankle and takeoff from the toe with a plantarflexed ankle (Hay, 1993; Zatsiorsky et al., 1981). Grigalka (1967) stated that short athletes typically push-off from the heel while taller athletes push off from the toe without fully extending the knee. Although Turk (1997) and others have suggested that the heel should be the last contact point before takeoff there is no known research indicating that one technique is superior. In fact, some have suggested that this matter is of little importance with the preferred technique being dependent on the individual athlete (Nett, 1969 as cited in Zatsiorsky et al., 1981).

**Flight Phase**

As soon as the push-off has been completed, the athlete enters the flight phase. Following takeoff in the glide technique the push-off leg should travel close to the ground and land close to the center of the circle (Schmolinsky, 2000). During the flight phase several authors have recommended that the push-off leg be actively and rapidly be
brought underneath the COM of the APSS (Ariel, 1979; Hay, 1993; Zatsiorsky et al., 1981) and the free arm used to counter the movement of the legs to keep the shoulders facing the rear of the circle (Bartonietz & Borgstöm, 1995; McGill, 1983).

Most of the implement speed present during the flight phase is lost at RFTD (Koltai, 1973; McCoy et al., 1984a; 1984b; McCoy & Koprowski, 1989; McCoy et al., 1989; Young, 2004b). For this reason, several authors (Grigalka, 1974 as cited in Lanka, 2000; Mileshin & Papanov, 1986; Young, 2004a; Young & Li, 2005) have suggested that the primary benefit of the flight phase may be to elicit a stretch shortening cycle by plyometrically loading the lower extremities for a more powerful delivery of the implement. If this is indeed true, greater vertical displacement of the APSS during flight may be more beneficial than attempting to maximize horizontal velocity of the APSS.

Previous research has reported a wide range of durations for the flight phase. Some researchers (Alexander et al., 1996; Knudson, 1989) have reported durations of 0.4-0.5s while others (Dessurault, 1976; 1978; Tsirakos et al., 1995; Young & Li, 2005) have reported significantly shorter durations (< 0.2s). It is unclear why the difference in results is so large however some of the variance may be explained by different throwing styles.

Large variation has also been reported for the length of the flight phase (as indicated by the displacement of the foot from takeoff to RFTD). According to Hay (1993) the linear displacement of the push-off foot during the flight phase varies greatly from athlete to athlete with the stature of the athlete being the primary determinant. For an effective delivery the RFTD must be made somewhere within reasonable distance of the center of the throwing circle. Hay (1993) speculated that taller athletes who require a slightly wider completion phase stance due to their size often restrict the length of their
glide to less than 1.05 m and thus place the rear foot either on the center line or just
behind it in the rear half of the throwing circle. Likewise, shorter athletes who benefit
from a narrower completion phase stance must travel more than 1.05 m during the flight
phase and typically make RFTD in the front half of the ring (Hay, 1993). These claims
are supported by a study by Alexander and colleagues (1996) which examined the
displacement of the push-off foot for sub-elite male and female throwers during the flight
phase and found that it was highly correlated with the athlete’s height.

Despite the findings above, height alone does not fully explain the variances
observed in flight phase length and it is likely that other factors may also be responsible.
For instance, Stepanek (1990) examined male and female shot putters and found that
females tend to have shorter glides (0.15 m) than their male counterparts. As females are
typically shorter in stature than their male counterparts this would necessitate that women
takeoff deeper into the circle for Hay’s (1993) observations to be completely true. Such a
starting position has not been previously noted. Other research (Knudson, 1989)
examined elite male and female athletes using the glide technique and found only two
athletes with flight phases longer than 1.05 m and many considerably lower than Hay
(1993) stated (with the shortest female flight phase being 0.74 m and the shortest male
0.79 m).

A final factor that certainly plays a role in the length of the flight phase is the
specific technique employed by the athlete. That is, two distinct variations of the glide
 technique have been observed. The first technique is likely the one which Hay (1993)
described where the throwers generally make RFTD somewhere close to the center of the
circle. This is referred to as the long-short technique because it is characterized by a
longer flight phase and a shorter completion phase stance (Dunn, 1989; Turk, 1997). The
second variation of the glide technique was first popularized by the East German’s and is characterized by a shorter glide and a wider stance (Dunn, 1989; Modern Athlete and Coach, 1974; Spenke & Ariel, 1974; Turk, 1997). Predictably, it has been named the short-long technique. Although some have advocated one technique over the other (Marhold, 1974; Staff of Modern Athlete and Coach, 1974; Turk, 1997) both the long-short (Ariel, 1979; Bartonietz & Felder, 1993; Knudson, 1989; Mileshin & Papanov, 1986) and short-long (Ariel, 1979; Bartonietz & Borgstöm, 1995; Bartonietz & Felder, 1993; Farrally et al., 1977; Grigalka & Papanov, 1978; Knudson, 1989; Mileshin & Papanov, 1986) techniques have been observed among elite athletes of both genders. Previous literature has indicated that the optimal technique may be specific to the individual characteristics of a given athlete. According to Alexander and colleagues (1996) the narrower stance observed in the long-short technique may be better for less powerful athletes. In contrast, the wider stance of the short-long technique allows for a longer delivery path but likely requires greater strength and power (Dunn, 1989).

**Rear Foot Touchdown**

Following the flight phase in which the push-off foot travels close to the ground, the push-off foot lands near the center of the circle otherwise known as RFTD. Much has been written about the orientation, position, and location of the foot at RFTD. Hay (1993) noted that the orientation of the foot at RFTD varies greatly from athlete to athlete. Despite this, several authors have suggested that the foot should be turned 45°-90° from the direction of the throw (Delevan, 1973; Farrally et al., 1977; Pagani, 1981; Simonyi, 1973; Tschiene, 1969). Others have suggested that the foot be oriented much more (80°-135°) towards the rear of the circle (Bell, 1979; Schmolinsky, 2000). No known research has examined whether one orientation is superior to the other. Indeed, the problem may
be more complex than simply having a universally superior foot orientation. The optimal foot position may be related to whether an athlete employs a long-short technique or a short-long variation of the glide (Judge, 1991). More specifically, the delivery of an athlete using the narrower stance associated with the long-short technique may require a more forward facing orientation than an athlete using the short-long technique. The reason for this difference is the dissimilar action and function of the rear leg during the delivery phase of each glide technique variant.

Much has been written on the position of the rear foot at RFTD also. Several authors have suggested that RFTD should be made flat footed (Fidelus & Zienkowicz as cited in Lanka, 2000; Fitness and Amateur Sport Directorate, 1966; Pearson, 1966a). This suggestion has largely been made on the grounds that extension of the rear ankle could then begin immediately without the necessary delay of first having to flex the ankle and lower the heel. An alternative reasoning is that the ankle joint is the weakest joint in the lower extremity and as a result, complete contact between the foot and the ground may be a more effective technique when athletes are attempting to apply maximum force to the ground (Zatsiorsky et al., 1981). While this may be true in theory many have made suggestions to the contrary (Brown, 1985; McGill, 1984; Grigalka, 1967; Kristev as cited in Lanka, 2000). Of these authors, Grigalka (1967) and Kristev (as cited in Lanka, 2000) further suggested that an upward movement should immediately follow ground contact. Hay (1993) noted that a forefoot landing at RFTD is far more common among elite throwers than a flat-footed landing. It is obvious that more research is necessary to determine the relationship between foot position and overall technique (short-long vs. long-short) as whether one foot position is superior.
Location of the foot position at RFTD has also been discussed. Most are in agreement that RFTD should be made directly under the athlete’s COM (Alexander et al., 1996; Bell, 1979; Holmes, 1979; Ward, 1970). Mechanically however there may be some advantage to RFTD being made slightly behind the athlete’s COM. Such a position would likely be a better position from which to accelerate the upper body during the delivery phase. There will also be some variation dependent on whether the athlete is using a short-long or long-short technique but most authors (Bresnahan et al., 1960; Kristev as cited in Lanka, 2000; Tutevich, 1955 as cited in Lanka, 2000) have recommended that RFTD be made near the center of the circle.

Several other recommendations have been made for the position of the thrower at RFTD. As was the case during the preparatory and flight phases, many have written that the trunk should face the rear of the circle (Alexander et al., 1996; Bell, 1979; Dalrymple, 1962; Huyck, 1967; McGill, 1983; 1984). It has also been widely suggested that the rear leg knee be flexed at RFTD (Alexander et al., 1996; Bartonietz & Borgstöm, 1995; Bell, 1979; Grigalka & Papanov, 1978; Holmes, 1979; McGill, 1983; Ward, 1970; Young, 2004a; Young & Li, 2005). In fact a study by Young and Li (2005) indicated that among elite female shot putters rear knee flexion at RFTD has a strong positive relationship with performance.

**Transition Phase**

The period of time between RFTD and FFTD is the transition phase. Many authors are in agreement to the importance of this phase of the throw (Ariel, 1979; Schmolinsky, 2000; Stepanek, 1990). In fact, Ariel (1979) claimed that this phase is the primary distinguishing factor between good and elite athletes using the glide technique. The importance of this phase is likely due to the effect it can have on the acceleration.
pattern of the implement. A poorly executed transition phase will result in great
deceleration of the implement. Bosen (1985) observed decelerations ranging from 1-2.75
m/s during this phase. Conversely, a well-executed transition phase will experience a
significant acceleration of the implement during the transition phase (Lindsay, 1994;
McCoy et al., 1984b). A well-executed transition phase has also been said to be the initial
condition for a long completion phase trajectory (Stepanek, 1990). Furthermore, Ariel
(1979) stated that the primary objective of this phase should be to minimize deceleration
of the COM of the APSS and allow transfer of energy to the delivery (Ariel, 1979).

Achieving these objectives appears to be largely a matter of timing. Previously
reported transition phase durations for athletes using the glide technique range from near
simultaneous rear foot and front foot touchdown to 0.37 seconds (Dessureault, 1976;
1978; Grigalka & Papanov, 1984; Knudson, 1989; Tsirakos et al., 1995). Many authors
have suggested that shorter transition times are better for athletes using the glide
technique (Ariel, 1979; Bell, 1979; Dessureault, 1978; Heger, 1974; Kristev as cited in
Lanka, 2000; McGill, 1984; Pearson, 1967; Tschiene, 1969; Tsirakos et al., 1995;
supports this point (Ariel, 1979; Heger, 1974; McGill, 1984; Tsirakos et al., 1995; Ward,
1970). It should be cautioned however that a simultaneous rear and front foot touchdown
(making transition phase duration = 0.0 seconds) is likely not advisable. While some
(Judge, 1991; Turk, 1997) have suggested a simultaneous landing of the rear and front
foot, most authors agree that the rear foot should land prior to the front foot (Bresnahan et
al., 1960; Christmann, 1937 as cited in Zatsiorsky et al., 1981; Fitness and Amateur Sport
Directorate, 1966; Grigalka & Papanov, 1988; Hay, 1993; Jones, 1948; Oesterreich et al.,

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time is beneficial, some authors (Pearson, 1963a, 1967; Simonyi, 1973) have suggested a simultaneous rear and FFTD may be detrimental because it may halt the forward momentum of the APSS.

**Front Foot Touchdown**

Two different techniques for FFTD have been described in the literature (Nett, 1969 as cited in Zatsiorsky et al., 1981): a forward-downward drive of the foot into the toe board; and a downward “raking” movement with the front foot toe turned somewhat in the direction of the throw. In the first case, the foot initially contacts the ground with the toe and then flatly contacts the ground. In the second method, the landing is flat-footed permitting an earlier active extension of the limb (Nett, 1969 as cited in Zatsiorsky et al., 1981). Whatever the case, observations of elite throwers indicate a more active placement of the front leg at FFTD is beneficial (Bakarinov & Oserov, 1985). In other words, top athletes using the glide technique appear to actively direct the front foot towards the ground rather than passively waiting for ground contact to occur.

As with the RFTD, recommendations for FFTD generally focus on the orientation and location of the feet. Tschiene (1969) suggested that both feet be oriented approximately 90° from the direction of the throw. It is generally recommended that FFTD be made near the toe board (Bell, 1979; Bresnahan et al., 1960; Brown, 1985; Kristev as cited in Lanka, 2000; Tutevich, 1955 as cited in Lanka, 2000) and because this is typically the case, considerably less variation is observed in FFTD location when compared to RFTD location. There is however still considerable variability in the width of the completion phase stance (distance between RFTD and FFTD) as a result of the variation in RFTD location.
Several researchers (Alexander et al., 1996; Knudson, 1989; Stepanek, 1990) have reported stance widths ranging from less than 0.8 to over 1.1 m. The simple explanation of this variance is that it is a result of throwers intentionally using a short-long or long-short technique. Athletes using a short-long glide technique shorten their flight phase and make RFTD closer to the rear of the ring with the intention of having a wider stance from which to deliver the shot. Conversely, athletes using the long-short technique cover greater distance during their flight phase, make RFTD closer to the front of the circle and subsequently have a narrower completion phase stance at FFTD.

There are pros and cons for both variations of the glide. Authors advocating the narrower stance (< 1.0 m) of the long-short technique assume that such a position provides a greater opportunity to apply force from the lower extremity because of a longer period of knee extension (Booysen, 1971; Powell, 1960). A narrow stance however has the disadvantage of decreased balance during the completion phase and a potentially shorter completion phase implement trajectory (Tutevich, 1955 as cited in Lanka, 2000). A wider completion phase stance (1.0-1.2 m) reduces the amount of force that can be applied by the rear leg (Tschiene, 1973b as cited in Lanka, 2000) but lengthens the path over which the implement travels during the all-important completion phase (Schpenke, 1973). Analysis has shown that the advantages of increasing the length of the completion phase path outweigh the loss from incomplete use of the strength of the rear leg provided that the strength of the rear leg is sufficiently high (Schpenke, 1973).

Interestingly, both Stepanek (1990) and Knudson (1989) reported slightly wider completion phase stances for elite women than elite men. Stepanek (1990) speculated that this was because of women’s shorter flight distances. Among a sub-elite population,
Alexander and colleagues reported opposite results with the average width of stance for women and men being 1.01 m and 1.13 m respectively. It thus appears that elite women either have shorter flight distances than their sub-elite counterparts or sub-elite women begin their preparatory phase motions with their support-foot placed closer to the center of the circle. Further research is necessary to fully understand this relationship.

In addition to the width of the completion phase stance recommendations for the fore-aft positioning of the feet have also been made. It is generally recommended that the toe of the rear foot and the heel of the front foot should straddle the mid-line of the throwing circle (Bartonietz & Borgstöm, 1995; Fitness and Amateur Sport Directorate, 1966; Furlong, 1972; Pearson, 1963a; Tschiene, 1969; Ward, 1970). Research data indicates the front foot contacts the ground 0.15-0.20 m (Ward, 1970) or 0.20-0.35 m (Lanka, 1996 as cited in Lanka, 2000) behind the rear leg. Lanka (2000) suggested that the distance of separation is dependent on the variation of glide technique used by the thrower. If emphasis is placed on rotation during the delivery as is typically the case in the long-short technique the front foot should be placed more posterior to the rear foot (Lanka, 2000).

Additional recommendations have also been made on the positions of the shoulders at FFTD. Several authors (Hay, 1993; Holmes, 1979; Mileshin, 1984) claimed that the shoulders should remain facing the rear of the circle at FFTD because of the lengthening effect it will have on the completion phase trajectory path. Ward (1970) however suggested that the hips and shoulders should be slightly turned from the initial rear-facing position to enhance continuity of the implement’s movement. Perhaps more importantly considerable discussion has been made on shoulder-hip separation at this point of the throw. While some have claimed that the axes of the shoulders and hips
should be parallel to each other and facing the rear of the circle at FFTD it is difficult to achieve this position. In fact, Zatsiorsky and colleagues (1981) pointed out that the hips are more likely to be aligned in the direction of the throw due to the fact that the backwards movement of the non-support (front) leg at takeoff tends to turn the hips and because the feet are placed at least 1 m apart. Perhaps because of this, some authors no longer consider this position to be incorrect, provided that the transverse plane of the shoulders is perpendicular to the direction of the throw (Delevan, 1973; Nett, 1969 as cited in Zatsiorsky et al., 1981). This is because the “open” hip position has the advantage of placing the muscles of the trunk on greater stretch (Koltai, 1973) and permits an earlier initiation of the put (Delevan, 1973; Nett, 1969 as cited in Zatsiorsky et al., 1981).

**Completion Phase**

The final phase of the throw is the completion phase. The outcome of a throw is largely determined by what happens during this phase (Bartonietz, 1996a). In fact, Turk (1997) suggested that 80-90% of the distance of the throw for gliders could be explained by what occurs in the period of time between FFTD and release. Most authors (Grigalka & Papanov, 1988; Pagani, 1981; Pearson, 1963a, 1967; Schmolinsky, 2000; Stepanek, 1990; Tschiene, 1969) consider FFTD the beginning of the completion phase and for the purposes of this review it will likewise be seen as such. It should be noted however that others have defined the completion phase as the final coordinated sequence of movements that culminates in the release of the shot. Using this less-precise definition of the completion phase some have suggested that the completion begins at RFTD (Grigalka & Papanov, 1998; Hay, 1993). Booysen (1971), noting that the shoulders and hips begin to turn prior to RFTD actually thought that the delivery of the implement began while the athlete was still in flight that would mean that the completion phase begins prior to
RFTD. Any debate however may be moot with an examination of both implement and COM of the APSS velocity profiles for the glide technique. These profiles indicate that a rapid acceleration occurs only after FFTD is made (Ariel, 1979; Fidelus & Zienkowicz as cited in Lanka, 2000). Others have refined this definition to suggest that the completion phase begins with the weight shift from the rear to the front leg (Maltseva, 1990; McGill, 1984; Pearson, 1967; Staff of Modern Athlete and Coach, 1974; Tschiene, 1969; Vigars, 1979; Ward, 1970, 1975). As stated above, this review will consider the completion phase to be the time between FFTD and release.

**General Objectives**

The primary purpose of the completion phase is to maximize implement velocity while releasing at an angle, height and horizontal release distance that are suitable for high-level performance while still permitting a fair throw. Several mechanical and biological principles underlie the attainment of this goal: the length of the completion phase implement acceleration, the speed of the performer’s movement during the completion phase, the attainment of positions which allow the athlete to generate the greatest magnitude of force in the direction of the throw and development of conditions which allow the athlete to remain in the circle once the implement has been released.

**Criterion 1: Lengthen Trajectory**

While the length that the implement travels over the entire throw was discussed previously, Bartonietz (1994b; 1996) has suggested that consideration of the completion trajectory is far more important. Because of the great decelerations that occur prior to the final acceleration, one could surmise that lengthening the implement trajectory is of less importance than that of the completion phase implement trajectory where the implement has been observed to accelerate almost completely in the direction of the throw (Ariel et
al., 2004; Young, 2004b). Previous research has indicated that the length of the implement trajectory in the completion phase ranges between 1.5 and 1.7 m for elite male athletes using the glide technique (Bartonietz, 1996a; Koutiev as cited in Lanka, 2000; Schpenke, 1973) with greater throws typically having longer paths (Table 2). Slightly longer trajectories (1.7-1.9 m) have been reported for the completion phase of athletes using the spin technique (Bosen, 1985; Kerssenbrock, 1974a). Stepanek (1990) noted that the length of the completion phase implement trajectory is directly related to performance and that women typically have shorter completion paths likely due to their shorter stature.

Table 2: Completion phase data

<table>
<thead>
<tr>
<th>Athlete</th>
<th>Distance</th>
<th>Completion Phase Duration (s)</th>
<th>Completion Phase Length (m)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.54</td>
<td>0.2</td>
<td>1.7</td>
<td>Schpenke (1973)</td>
</tr>
<tr>
<td>2</td>
<td>21.31</td>
<td>0.22</td>
<td>1.65</td>
<td>Bartonietz (1996a)</td>
</tr>
<tr>
<td>3</td>
<td>21.07</td>
<td>0.25</td>
<td>1.78</td>
<td>Schpenke (1973)</td>
</tr>
<tr>
<td>4</td>
<td>20.09</td>
<td>0.18</td>
<td>1.55</td>
<td>Schpenke (1973)</td>
</tr>
<tr>
<td>5</td>
<td>20.27</td>
<td>0.26</td>
<td>1.7</td>
<td>Koutiev (1966)</td>
</tr>
<tr>
<td>6</td>
<td>19.08</td>
<td>0.26</td>
<td>1.5</td>
<td>Koutiev (1966)</td>
</tr>
<tr>
<td>7</td>
<td>19.00</td>
<td>0.28</td>
<td>1.55</td>
<td>Koutiev (1966)</td>
</tr>
<tr>
<td>8</td>
<td>18.98</td>
<td>0.27</td>
<td>1.48</td>
<td>Koutiev (1966)</td>
</tr>
</tbody>
</table>

The implement trajectory of the completion phase is comprised of two components that can both be optimized to enhance performance: horizontal and vertical. Both of these components can be increased from the starting position and finishing position of the completion phase. It should be noted however that the optimum length completion path may not necessarily be equivalent to a maximum length completion phase path due to the constraints of the human body and potential technical drawbacks associated with producing a throw with a maximized completion phase implement trajectory path.

The length of the completion phase path can be increased by having the implement start from a low position that is as close to the rear of the circle as possible.
One way in which this may be accomplished is through greater trunk inclination towards the rear of the circle. Such a position will move the starting position of the implement lower and further back in the circle. Powell (1960) suggested that the trunk should begin the completion phase from a low position and gradually rise from the moment FFTD occurs. Likewise, Alexander and colleagues (1996) claimed that the completion phase should begin with shoulders facing the rear of the circle from which point the trunk should rotate 180° and extend 90°.

A second way in which the completion phase path may be lengthened at the start of the completion phase is increased knee flexion at FFTD. Young and Li (2005) found rear knee angle to be a significant predictor of performance and suggested that greater rear knee flexion may be beneficial not only for its effects on the length of the completion phase implement trajectory path but also because it may place the knee extensors in a more advantageous position from which to extend.

Finally, the stance that the thrower assumes for the completion phase will have a great impact on the starting position of the implement during the completion phase. Some (Bosen, 1981; Schpenke, 1973; Staff of Modern Athlete and Coach, 1974; Turk, 1997) have suggested that the wider stance observed in the short-long technique may increase the range over which force can be applied to the implement during the completion phase.

The positioning of release can also increase the distance that the implement travels during the completion phase. A release point that is both high and as forward as possible will result in a lengthened completion path. As discussed previously the height of release is largely governed by the stature of the athlete however the athlete’s position at the moment of release can also play a significant role (Hay, 1993). Several authors (Bartonietz & Borgstöm, 1995; Pagani, 1981; Powell, 1960; Ward, 1970, 1975) have
suggested that the front leg should be almost completely extended at the moment of release to both increase the height of release and also to serve as a braking mechanism, which results in transfer of momentum from the APSS to the implement. Furthermore, a qualitative analysis on elite shot putters indicated that complete extension of the front leg helps produce higher release angles (Bartonietz & Borgstöm, 1995). Research (Lanka, 1976 as cited in Zatsiorsky et al., 1981; Shalmanov, 1977 as cited in Lanka, 2000) and anecdotal reports (Fitness and Amateur Sport Directorate, 1966; Tutevich, 1955 as cited in Lanka, 2000) have also indicated that full extension of the arm may be beneficial.

Other suggestions to increase the length of force application are focused more on the specific location of the release. For instance, Grigalka (1972) suggested that the release should occur over the non-throwing side foot while others (Ward, 1970) claimed that release should occur as far in front of the plane of the toe board as possible. Data from Young and Li (2005) supports the latter point. Furthermore, several authorities (Fitness and Amateur Sport Directorate, 1966; Lanka, 1976 as cited in Zatsiorsky et al., 1981; Shalmanov, 1977 as cited in Lanka, 2000; Tutevich, 1955 as cited in Lanka, 2000) have indicated that release should occur with full extension of the arm, with the throwing side shoulder facing the direction of the throw and the implement being propelled by a final flip of the wrist and fingers. This wrist and finger extension at the moment of release has been suggested to add approximately 1 m to the performance (Pearson, 1967).

One highly debated issue that has a large effect on the release position of the implement is whether an athlete should be in contact with the ground during the final moments of the delivery. If an athlete were to remain in contact with the ground through the point of release, they would theoretically be expected to have a lower release position but would have the benefit of having a stable base off of which to apply forces. Various
recommendations have been made regarding this topic. The most common suggestion by practitioners and researchers is for both feet to remain in contact with the ground for the duration of the delivery (e.g., Fitness and Amateur Sport Directorate, 1966; Furlong, 1972; Grigalka, 1970 as cited in Lanka, 2000, 19; Grigalka & Papanov, 1978; Maltseva, 1990; Powell, 1960; Smith & Snow, 2005). Glushenko (as cited in Zatsiorsky et al., 1981) suggested a “sliding contact” in which the rear foot slides along the ground in order to maintain contact with the circle while moving forward. Those suggesting release from double-support typically argue that it is only in support that the athlete could efficiently handle the forces that the implement imparts back on the athlete during the delivery.

Contrary to what has been suggested, complete double support during the final stages of delivery is rarely observed (Zatsiorsky et al., 1981). In fact, McGill (1983) and others actually suggested that athletes should attempt to jump off of the ground during the completion phase. Proponents of this method of delivery argue that any potential detrimental effect of being off the ground during the delivery is more than adequately compensated for by the additional velocity added to the shot by the explosive lifting prior to release (McCoy et al., 1984b; McGill, 1983; Staff of Modern Athlete and Coach, 1974; Sullivan, 1962). An added benefit of such a release would be a potentially higher release position and thus longer completion phase implement trajectory path. Paish (1980) suggested that single support on the front foot at the moment of release offers a compromise between the benefits of a fully grounded release and an unrestrained takeoff at release. Such a position could potentially allow for greater horizontal release distance but would offer little benefit on the vertical component of the completion phase implement trajectory.
Results of previous research are inconclusive as to whether one support strategy at release is more beneficial than another. Zatsiorsky and colleagues (1981) indicated that the best performers tended to maintain ground contact with the front foot until the implement was released. Other research (Tsirakos et al., 1995) reported no significant difference in contact times with results. Film and video observation have produced equally inconclusive results as some have indicated that the best performers tended to maintain ground contact with the front foot until the implement was released (Pagani, 1981; Ward, 1975) while others have observed that most top throwers break contact with the ground prior to release (Bartonietz & Borgstöm, 1995; Grigalka & Papanov, 1978; McCoy et al., 1984b; Nett, 1962; Palm, 1990; Wilt, 1982). Although there does not appear to be an objective answer to this question, the empirically derived techniques of the top shot putters would seem to suggest that an athlete must reduce the vertical forces they exert to remain in contact with the ground and that the resulting loss in release speed of the shot is probably greater than that due to being in flight during the final moments of the delivery.

**Criterion 2: Increase Speed of Movement**

The second factor that determines the effectiveness of the completion phase is the performer’s speed of movement. Stepanek (1990) noted that the duration of the completion phase is inversely directly related with performance. Dessureault (1978) suggested that the best performers reduce the time of their completion phase. This is supported by data on athletes of varying skill levels. The duration of the completion phase for sub-elite athletes has been observed to be as great as 0.4 seconds (Alexander et al., 1996; Dessureault, 1976; 1978) while the duration for elite throwers typically falls in the range of 0.2-0.3s (Bartonietz, 1996a; Grigalka & Papanov, 1984; Koutiev as cited in
Lanka, 2000; Schpenke, 1973; Young, 2004b). Perhaps the most interesting point is that the best throwers not only move the implement over a greater distance but they do so in a shorter period of time.

**Criterion 3: Optimal Positions and Movements**

The third criterion for an effective completion phase and one that certainly has a direct effect on the previous two factors is the attainment of positions that allow the athlete to generate the greatest quantity of force in the direction of the throw. According to Tutevich (1955 as cited in Lanka, 2000) the effectiveness of the completion phase may be assessed by the degree to which the thrower’s force application is directed through the COM of the APSS in the direction of the throw. While other factors like muscle potentiation and efficient utilization of an athlete’s strength must also be considered it is certainly safe to say that Tuevich’s recommendation be one of the primary objectives.

During the completion phase, much has been written on the actions of the performer. Due to the quantity of research and coaching literature on the completion phase this section will examine the actions of each body part in the completion phase independently. Lanka (2000) identified two mechanisms that will ensure maximal release speed: 1) the use of a whip technique and 2) elicitation of a stretch reflex. Rotation of a distal segment is a result of the moment of force acting at the proximal joint and accelerated movement of the joint itself. When the joint’s axis accelerates the segment will turn around this axis. Both mechanisms are widely applied in throwing and striking movements. Coordinated translational movement of the proximal joint that involves consecutive acceleration and deceleration of the joint has been termed a “whip technique” (Bath & Kearney, 1996; Kearney et al., 1993). At the beginning of the movement the proximal joints move quickly in the direction of the throw, but afterwards they are
actively decelerated. This movement pattern produces a quick rotation of the distal segment.

When a linear motion of a rigid object is constrained at one end, the result is forward rotation. The other end of the object continues to move ahead and rotation begins, and consequently the velocity of the end can increase. When a shot putter plants the front foot prior to releasing the shot, the speed of the upper body and arm increases and as a result the shot’s release speed increases. The axis of rotation passes through the point where the foot meets the ground. For instance, it has been proven that in the high jump and long jump (Shalmanov, 1986 as cited in Lanka, 2000) this inverted pendulum mechanism contributes considerably to the speed of the body’s COM. Though this mechanism has not been investigated for shot putting, it may be safe to assume that when the COM of the APSS is moving at a high speed and the front leg applies a sufficiently large braking force its contribution could be similarly beneficial.

As long as external forces do not act on the system and internal forces do not change its movement, the velocity of the system’s COM has to be constant. However, in the system itself it is possible to redistribute momentum (momentum is the product of the velocity of the body’s COM and the body’s mass). Hence, by means of internal forces it is possible to increase the velocity of some body parts by decelerating other parts of the system. In shot putting, of course, this principle does not act alone because external forces (ground reaction) affect the shot putter and the momentum of the APSS is not constant. Still, the described mechanism may increase the speed of the hand and shot. In fact, Ariel (1973a) observed redistribution of momentum between segments. His data indicated that immediately before and at the beginning of the throwing arm extension, the
consecutive deceleration of the body segments in an upward direction takes place resulting in an increased speed of the upper body as well as the hand and shot.

The initial acceleration of the implement during the completion phase is due primarily to the actions of the lower extremity (Grigalka, 1972; Holmes, 1979). An effective completion phase is thus characterized by the most effective use of the lower extremity. Interestingly, considerable variability exists among recommendations on how to best accomplish this task. While some of these differences stem simply from a lack of consensus among authorities others can be explained by differences in the most efficient actions of the lower extremity for the two variations of the glide technique. That is, the lower extremity actions that are optimal for the short-long technique are not the same as those of the long-short technique.

The function of the front and rear leg during the completion phase differ considerably based on individual differences as well as the glide variation employed by the athlete. While many (Grigalka, 1970 as cited in Lanka, 2000; 1972; Holmes, 1979; Lanka, 1976 as cited in Zatsiorsky et al., 1981; Palm, 1990; Shalmanov, 1977 as cited in Lanka, 2000; Ward, 1970) have suggested that the rear leg is the primary body part responsible for movement of the APSS in the direction of the throw, results of kinetic research do not support this view. Ground reaction force data of the rear leg indicates that the rear leg primarily produces vertical forces during the completion phase (Ariel, 1979; Ward & McCoy, 1984; Zatsiorsky et al., 1981). Whatever the case, many have noted that a very active rear leg is one of the distinguishing characteristics between better and lesser performers using the glide technique (Bartonietz & Borgstöm, 1995; Bartonietz & Felder, 1993; Bell, 1979). In fact, Ariel (1973a) suggested that the rear leg should extend all the way through the moment of release. Active rear leg extension has also been linked with
upward movement of the trunk (Zatsiorsky et al., 1981) and increased shoulder-hip separation early in the completion phase (Holmes, 1979).

While the function of the rear leg is primarily to accelerate the APSS in the direction of the throw, the front leg has a dual role. During the initial moments of the completion phase, the front leg assists in accelerating the athlete. There is some debate as to whether this assist is passive or active in nature. For instance, several authors (Holmes, 1979; Turk, 1997) suggested that the front leg should be bent slightly early on in the completion phase to allow for unimpeded forward movement of the hips. Brown (1985) however suggested a more active role in which the front leg actually applies more explosive power than the rear leg. This however would only be possible once the COM of the APSS had shifted from a position over the rear leg to a position more equally balanced over the front and rear leg.

Later in the completion phase, the front leg functions as a brace that applies braking forces to decelerate the athlete (Ariel, 1973a; Bartonietz, 1994c; Bosen, 1981). In this role the front leg is said to act as a break and cause a “hinged moment” due to the quickly decelerated and minimized movement of the lower extremity causing increased acceleration of the more distal trunk and throwing arm (Mileshin & Papanov, 1986; Pearson, 1966a). In support of this, Ariel (1973a) reported minimized front leg movement among the best throwers during the final moments of the delivery and several have indicated that the front leg provides a high force impulse in the direction opposing the put (Ariel, 1979; Dessureault, 1978; Fidelus & Zienowicz as cited in Lanka, 2000; Lanka, 1976 as cited in Zatsiorsky et al., 1981; McCoy et al., 1984b; Mileshin & Papanov, 1986; Salmanov, 1977 as cited in Lanka, 2000).
There remains some debate as to what the best means is to generate braking forces. Christmann (1937 as cited in Zatsiorsky et al., 1981) and Vigars (1979) suggested that the front leg should be fully extended at release to best decelerate the lower extremity and facilitate transfer of momentum to the implement. Others have recommended that it is more advantageous for the front leg to remain slightly flexed (Bartonietz & Borgstöm, 1995; Pagani, 1981; Paish, 1980; Powell, 1960; Turk, 1997; Ward, 1970, 1975). Paish (1980) suggested that such a front leg position at the moment of release still creates an adequate brace for the rear leg to push against without causing piking at the hips or excessive resistance to movement in the direction of the throw that accompanies a completely extended front leg. It remains to be seen whether one technique is more beneficial.

Several recommendations have been made regarding the combined actions of the lower extremity. For instance, Grigalka and Papanov (1983) suggested that the resultant force vector of the lower extremity should be aligned with the direction of the throwing arm extension to maximize linearity of force application (Grigalka & Papanov, 1983). While no experimental data has examined this point it is unlikely that the force application of the lower extremities could be aligned with that of the throwing arm given their very different orientations of their points of contact with the ground and implement respectively. Lundberg offered a more reasonable suggestion (1947a, 1947b, 1947c as cited in Zatsiorsky et al., 1981). He recommended that the rear leg should not extend until the COM of the APSS passes over the rear foot. In theory, the further the COM of the APSS is in front the rear foot at RFTD, the more force the thrower will be able to apply in the direction of the throw with minimal braking forces and subsequent loss of the horizontal velocity achieved during the glide.
Three lower extremity movement strategies have been observed during the completion phase of the glide technique. While the actions described for the rear and front leg are evident in all three strategies the magnitude and timing of the actions can differ considerably. Predictably each of the movement strategies is associated with one of the glide variations.

The first of these movement strategies is characterized by active extension of the rear knee and hip following FFTD, a strongly braced front leg and a large transfer of weight toward the non-throwing side. This movement pattern is most commonly observed in the short-long technique (Bosen, 1981). Combined with the wider stance of the short-long technique the strongly braced front leg serves create a large ‘hinged moment.’

The second lower extremity movement strategy is characterized by rotation of the lower extremity prior to extension. This movement pattern is most commonly observed in athletes using the long-short variation of the glide. The purpose of the rotation is to position the legs in a better position to generate large forces in the direction of the throw by positioning the thrower under and behind the implement. The rotation also helps to enhance shoulder-hip separation in the early moments of the completion phase.

Suggestions for both foot rotation (Grigalka, 1972; Irving, 1980) and entire leg rotation (Brown, 1985; McGill, 1983; Paish, 1980; Ward, 1975) can be found in the literature. Many have advised that rotation should initiate from the rear foot and continue to the thigh, pelvis and shoulder (Bartonietz & Borgstöm, 1995; Grigalka & Papanov, 1978, 1988; Mileshin & Papanov, 1986).

The final movement pattern observed in the lower extremity of gliders during the completion phase is the so-called “rotational leg lift” (Bosen, 1981; Zatsiorsky et al., 1986).
Similar to the rotation-extension movement pattern, the rotational leg lift is observed only in athletes using the long-short glide variant and is characterized by rotation and extension of the lower extremities. Unlike the rotation-extension movement pattern the rotational leg lift is characterized by rotation and extension of the rear leg during the transition phase during which time weight is transferred to a balanced position on both legs at FFD. From this position the athlete actively and simultaneously rotates and extends both legs for a more balanced double leg push. Several authorities have recommended this method (Bakarinov & Oserov, 1985; Bartonietz & Borgstöm, 1995; Brown, 1985; Grigalka & Papanov, 1978, 1988; Mileshin & Papanov, 1986; McGill, 1983; Paish, 1980; Ward, 1975). The benefit of this movement pattern is that it allows the athlete to use the strength of both legs during the completion phase. Several authors (Alekseyev, 1974; Grigalka & Papanov, 1988; Holmes, 1979; Marhold, 1964 as cited in Lanka, 2000; McCoy et al., 1984b) have suggested that both legs should be completely extended at the moment of release, something that is not often observed in the athletes using the short-long variation of the glide.

The explosive lifting and rotating actions of the lower extremity are closely mirrored in the movement of the hips. As with the legs, the hips both rotate and extend during the completion phase. There is however considerable variation in both the timing and range of motion of hip extension and rotation among shot-putters of different skills levels. Zatsiorsky and colleagues (1981) noted that the hip movement of top shot putters is characterized by successive hip extension and rotation. In contrast, athletes of lower skill level typically rotated their hips prior to extension.

In elite level shot putters the Ariel (1973a) and Tschiene (1973b as cited in Lanka, 2000) found that the hips rotate 175°-220° during the completion phase. Powell (1960)
claimed that the success of shot putting depends on the speed of this rotation. If the shoulders can be kept in a rear-facing position, the faster the hips rotate the greater the whip effect will be. Data from Ariel (1973a) indicated that among elite level throwers the movement of the hips is linked to movement of other body parts. For instance, maximum rotational speed of the hips coincided with initiation of the throwing arm movement. Following attainment of maximum speed, rotational hip speed decelerated greatly and considerable momentum was transferred to the shoulders. At the moment of release, some have suggested that the throwing side hip should be over the non-throwing side foot (Staff of Modern Athlete and Coach, 1974).

The movement of the trunk during the completion phase has received much discussion. As a general statement Alexander and colleagues (1996) suggested that the trunk should rotate 180° and extend 90° during the completion phase. Two variations have been observed that both fit this suggestion. According to Tutevich (1955 as cited in Lanka, 2000) the first variation is characterized by trunk rotation followed by trunk extension. In this variation, the trunk is moved in a forward and upward direction after the initiation of the rear leg (Tutevich, 1955 as cited in Lanka, 2000). Trunk rotation begins only when the trunk is perpendicular to the ground. This variation is likely to place a greater load on the muscles of the lower back. The second variation is characterized by the trunk rotating around two movable axes simultaneously (Grigalka, 1970 as cited in Lanka, 2000). That is, the trunk extends and rotates at the same time. It remains to be seen whether one technique is superior to the other.

Much of the discussion regarding the trunk relates to the positioning of the trunk, specifically the shoulders, with respect to that of the hips during the completion phase. Of particular interest is the interplay between the transverse axis of the hips and the
transverse axis of the shoulders because of both the trunk whip that can potentially be generated as well as the beneficial stretch that it can place on the trunk musculature. Trunk whip refers to the aforementioned effect that occurs in distal segments as a result of the acceleration and sudden deceleration of a more proximal segment. In the case of trunk whip, the acceleration and deceleration of the hips can produce a whip effect in the shoulder segment. Several investigators have reported that both the speed and amplitude of the trunk whip during the completion phase is dependent on the shoulder-hip separation attained in the early delivery phase (Ariel, 1973a; Delevan, 1973; Koltai, Lanka, 1976 as cited in Zatsiorsky et al., 1981; Lasarev as cited in Zatsiorsky et al., 1981; Nett, 1962; Shalmanov, 1977 as cited in Lanka, 2000). For this to occur, the transverse plane of the hips must move ahead of the transverse plane of the shoulders. This position would also place the muscles of the trunk on stretch that should enhance the force with which they are able to contract.

Several authors have suggested that it is beneficial for the throwers hips to rotate prior to the shoulders in order to create greater separation between the shoulder-hip axes (Grigalka, 1970 as cited in Lanka, 2000; Grigalka & Papanova, 1978; McGill, 1983; Mileshin & Papanov, 1986; Pearson, 1967; Sullivan, 1962; Ward, 1985). If the shoulders can be kept in a rear-facing position, the faster the hips rotate the greater the greater the whip effect will be. Research on the kinematics of throwers of various skill levels supports this viewpoint (Ariel, 1973a; Bartonietz & Borgstöm, 1995; Grigalka, 1971; Grigalka & Papanov, 1983; 1988; Johnson, 1992; McGill, 1983; Tschiene, 1969). In fact, Ariel (1973a) used 3D motion analysis techniques and found that among top performers maximum shoulder-hip separation coincided with the maximum speed of hip rotation (100.3 ± 24.6 msec before release of the shot). Other investigators have used
accelerometers to investigate the relationship of the shoulders and hips during the completion phase and found that the duration of hip movement was greater than that of the shoulders and that the best throwers were distinguished by greater shoulder-hip separation early in the completion phase (Lanka, 1976 as cited in Zatsiorsky et al., 1981; Lasarev as cited in Zatsiorsky et al., 1981; Shalmanov, 1977 as cited in Lanka, 2000).

For the whip effect to be maximized, proximal segments must be decelerated just prior to release. Several recommendations have been made on this point. For instance, Maltseva (1990) and McGill (1983) suggested that the non-throwing side should be anchored to speed up the rotation of the throwing side. Similarly, Irving (1980) suggested that the hips should rotate and stop prior to release to accelerate the shoulders and throwing arm. This is supported by data from Lanka (1976 as cited in Zatsiorsky et al., 1981) that indicated that better performers display greater hip deceleration just prior to release.

Although the free arm cannot actively or directly impart force to the implement, Ariel (1973a) found that the free arm could indirectly help to accelerate the implement. One way in which the non-throwing side arm may assist in the throw is by developing a pre-stretch on the upper body musculature of the throwing side. Several authors (Irving, 1980; Pagani, 1981; Ward, 1970, 1975) have stated that the action of the free arm may put the muscles of the throwing side chest and shoulder girdle on stretch prior to being engaged. This would likely enhance force output from the stretched musculature. To accomplish this objective some authorities have recommended that the free arm should be swung wide and then brought in tight to the body (Irving, 1980; Pagani, 1981; Ward, 1975). Other authors (Grigalka & Papanov, 1983) have suggested that the free arm should actually move overhead during the completion phase to help the trunk to rotate
around a vertical axis. Whatever the case, experimental data (Ariel, 1973a) and anecdotal reports (Booth, 1985) have both indicated that in better throws the free arm should accelerate early in the completion phase and decelerate as the moment of release approaches. Such a movement pattern would facilitate a whip effect around the vertical axis by decelerating the non-throwing side.

As the throwing arm and hand in particular are the medium by which the force generated by all other body parts is imparted to the implement it is with good reason that they have been the subject of much discussion. Indeed, previous research has indicated that 65% and 80% of the total release velocity of the implement is achieved during the completion phase after the initiation of the throwing arm extension (Fidelus & Ziencowicz as cited in Lanka, 2000; Markov as cited in Zatsiorsky et al., 1981).

Furthermore, Maltseva (1990) pointed out that the speed of movement of the throwing arm is very important because the implement can only travel as fast as the arm is capable of moving. Both the timing and the movement pattern of the throwing arm have both been widely discussed.

Experimental data from Ariel (1973a) indicated that the coordinated action of the shoulder musculature is extremely important in generating force. Ariel (1973a) speculated that proper relaxation and facilitation of different muscle fibers within the shoulder muscle group is essential to performance. As stated previously, the weaker but faster throwing arm should only be engaged after the stronger but slower lower extremity and trunk has accelerated the implement. While there seems to be a general agreement that throwing arm extension should be delayed as long as possible (Grigalka, 1967; 1970 as cited in Lanka, 2000; Lundberg 1947a, 1947b, 1947c as cited in Zatsiorsky et al.,
1981; Pearson, 1966b; Powell, 1960; Vigars, 1979) the exact timing of initiation is still under considerable debate.

Many recommendations have been made associating the initiation of arm extension with various body movements or positions. For instance, Lundberg (1947a, 1947b, 1947c as cited in Zatsiorsky et al., 1981) recommended initiating throwing arm extension only after extension and rotation of the lower extremity and trunk had been completed. He claimed that if the arm strike were initiated earlier, the transfer of force from the lower body to the implement would be reduced because arm strength may not be sufficient to transfer forces generated by the lower extremity and trunk. Observation of elite throwers has provided some support to this viewpoint. For example, research on elite throwers has linked initiation of the throwing arm extension with both rear (Mortensen, 1952) and front leg extension (Christmann, 1937 as cited in Zatsiorsky et al., 1981; Zatsiorsky et al., 1981). Christmann (1937 as cited in Zatsiorsky et al., 1981) actually suggested that the throwing arm and front leg should extend simultaneously such that their initiation and completion (marked by maximal front leg extension and release for the leg and throwing arm respectively) coincide. Others have linked the arm strike with various other body movements such as shoulder orientation (Christmann, 1940 as cited in Zatsiorsky et al., 1981; Rider as cited in Zatsiorsky et al., 1981; Simonyi, 1973; Tutevich, 1955 as cited in Lanka, 2000; Ward, 1970) and hip rotation (Ariel, 1973a). Data from Ariel (1973a) revealed that the initiation of arm extension in the most skilled throwers was closely related to the maximum rotational speed of their hips and maximum shoulder-hip separation (125.8 ± 24.6 msec before release of the shot). In less skilled putters, there was a longer time between the maximum shoulder-hip separation and the beginning of arm extension (78.2 ± 35.4 msec and 142.4 ± 34.4 msec before release of
the shot). As there is considerable experimental support for several of the throwing arm initiation points discussed above, it is unclear whether one is in fact optimal or whether the timing of the arm strike is actually associated with several body actions.

In addition to the timing of the arm strike, it is also important that the forces generated are applied behind the implement in the direction of the throw. To accomplish this Bell (1979) suggested that the throwing-side elbow should be kept behind the implement during the arm strike while others (Pagani, 1981; Vigars, 1979; Ward, 1975) have recommended that the arm be held at a 90° angle to the body. The latter position is suggested to put the athlete in the strongest position to produce force but also position the throwing arm in a position in which the force would be applied directly behind the implement in the direction of the throw. Ward (1970) also recommended that the implement should break contact with the shoulder and neck during the final 90% of shoulder rotation thereby increasing the radius of rotation of the implement and also moving it into a position from which the throwers force can be aligned directly behind the implement.

**Criterion 4: Foul Prevention**

The final factor affecting the effectiveness of the completion phase is the development of conditions that allow the athlete to remain in the circle once the implement has been released. In fact all previously mentioned criterion should actually be thought of as subordinate to this final one because if the thrower is unable to remain in the ring following the release of the implement it is of little consequence how well the previous three criterion were executed.

Several recommendations have been made to set up such a scenario. One recommendation is to ensure maximum transfer of momentum from the APSS to the
implement during the final moments of the delivery. Such a transfer of momentum would not only be beneficial with regards to the legality of the throw (whether it is fair or foul) but also to projected distance (McCoy et al., 1984b). Several recommendations have been made on how best to produce this transfer of momentum. Ariel (1973a) for instance suggested that deceleration of the hips greatly contributes to the force applied to the implement and the transfer of momentum. Additionally, blocking the non-throwing side has also been indicated as beneficial because it accelerated the throwing side and allows for greater transfer of momentum to the implement (Godina & Backes, 2000).

Another way in which the athlete can preserve a throw is by stopping their own momentum following the release. In fact, several authors have suggested that this is one of the primary benefits of the glide technique (Bosen, 1985; Fitness and Amateur Sport Directorate, 1966; Heger, 1974; Oesterreich et al., 1997; Smith, 2005). The performer’s final movements of the delivery as well as those immediately following release may be effectively used to stop the thrower’s forward momentum and preserve a fair throw. As momentum is the product of mass and velocity, and the mass of the athlete is certainly not going to change, it becomes clear that the horizontal velocity of the athlete needs to be halted. To do so, braking forces in the opposite direction of the throw must be applied. Bartonietz (1983 as cited in Lanka, 2000, 1995) claimed that the wide stance observed in the short-long technique can improve conditions for braking action of the front leg and also helps to stabilize the body. Besides this however, there is still considerable debate over what is the most efficient way and time to apply this braking force.

In general, three movement strategies have been observed to preserve a legal throw. In the first option the athlete stops their forward momentum by applying braking forces in the final moments of the delivery phase and immediately following release.
Knudson (1989) referred to this method as the non-reverse because unlike the other two methods, the athlete does not switch the position of their feet following release. Although Ward (1975) suggested this method to be optimal it has rarely seen observed among elite level shot putters.

As indicated above the two other methods of preserving a throw involve an exchange in the position of the front and rear feet. The first such technique is called the step-reverse or delayed reverse (Knudson, 1989). Using this method, the forward momentum of the athlete is adequately stopped so as not to require a full exchange of foot positioning but the athlete does step forward with the rear foot after a considerable delay from the release (Knudson, 1989). The delayed reverse has been said to allow time for increased range of motion at the hip to take place and when combined with a violent blocking action can be very effective in stopping the athlete’s forward momentum (Irving, 1980).

The final method used to preserve a legal throw is the so-called reverse. This technique is characterized by the athlete exchanging the front and rear foot positions so that the rear foot can be used to stop the forward momentum of the APSS (Knudson, 1989). Several authors (Holmes, 1979; Matson, 1983; Pearson, 1966b) have advocated this method as best for stopping momentum and preventing foul throws without being detrimental to the projected distance of the throw. Whatever the case, several (Bell, 1979; Furlong, 1972; Judge, 1991) have suggested that the reverse should not begin before release and should only result from an explosive extension of the lower extremity rather than being thought of as an action unto itself (Judge, 1991). The validity of this statement remains in question, as it appears to contradict the overwhelming use of a jumping release observed in elite throwers.
Spin Kinematics

The following section will examine the specific body segment kinematics for the spin technique. Much like the preceding section on the glide, this examination will break down the spin technique and examine each phase or event in the order that it occurs in the actual throw. Special attention will be given when significant differences exist between the objectives or the methods of the spin technique and those discussed previously for the glide.

Preparatory Phase

As was the case in the glide technique the preparation phase of the spin technique is important because it establishes a good position from which to start the throw (Godina & Backes, 2000). Several authors have suggested that starting rhythm and balance are critical because balance and timing can affect the entire throw (Bosen, 1985; Jones, 1987; Powell, 1960; Turk, 1997).

Starting Position

The starting position for the spin differs greatly from the glide technique. Unlike the glide, little has been written on the starting position of the spin technique. Several authors have suggested that it should be much like that of the discus throw (Paish, 2005; Pyka & Ortando, 1991). In the discus throw, athletes begin in a balanced position in double support (Babbitt, 2000). Pagani (1985) made the same suggestions for the spin technique. Jones (1987) suggested that shot putters using the spin technique should begin the throw in a well-balanced position with their feet placed slightly wider than shoulder width. Several researchers (Bartonietz, 1994b; Bartonietz & Borgstöm, 1995) have observed elite spinners starting from a low position with great knee (90-120°) and trunk flexion. Bartonietz (1994b) suggested that such a position allows athletes using the spin
technique to have a smooth and controlled preparatory movement with a wide swing leg; a continuously increasing rise of the COM of the system; and a flat movement path of the implement during the non-support phase without dropping the upper body onto the rear foot.

**Initial Movements**

Despite the limited recommendations for the starting position of the spin shot put technique, much has been suggested for the movements of the preparatory phase. As would be expected, the initial movements of the glide and spin technique differ greatly. During the spin technique the athlete moves from a position of double support to a position of single support by lifting what will become the rear foot and rotating on what will become the front foot. Several authors (Booth, 1985; Oesterreich et al., 1997) have suggested that the turn and move toward single support should be initiated by turning the foot and knee rather than the upper body. In so doing the thrower may be able to establish separation between the shoulders and hips early in the throw.

Before proceeding to any in-depth discussion of the spin technique it is important to first note that there are two variations of the spin technique whose differences become evident very early in the throw (Paish, 2005; Turk, 1997). The first of these variations has the seemingly paradoxical name of “linear” spin technique (LST). The primary characteristics of this technique are shorter durations in single support and flight and an attempt to keep the implement moving in a linear horizontal trajectory (Smith, 2005). While Smith (2005) advocated this variation for its greater reliability under the pressure of championship conditions, others (Paish, 2005; Turk, 1997) have stated that it is inferior to the more commonly observed second variation of the spin technique.
In contrast to the more linear variation, the second variation of the spin technique is referred to as the rotational spin technique (RST) and is characterized by longer periods in single support and flight and a less linear HPIT. The primary factors that distinguish the two variations of the spin technique during the preparatory phase are the use of the non-support leg and the degree of rotation prior to takeoff. In the LST, athletes rotate more than 180° from their initial starting position prior to pushing off. As a result, they are typically facing the direction of the throw at the end of the preparatory phase (Smith, 2005). Athletes using the LST also tend to have a much less active non-support leg that is swung close to the body (Turk, 1997). In contrast, spinners using the more conventional technique are likely to have rotated considerably less and have a much wider sweeping action of the non-support leg (Paish, 2005; Turk, 1997). A long sweeping non-support leg is said to increase the angular velocity and momentum of the APSS (Oesterreich et al., 1997; Young, 2004a) as well as increase shoulder-hip separation at RFTD (Turk, 1997; Young, 2004a). Similar relationships have been observed for the swing leg of discus throwers (Hay & Yu, 1995).

**Takeoff**

As with the glide technique, the takeoff concludes the preparatory phase. Unlike the glide technique however, the athlete takes off from a more forward-facing position as opposed to the rear-facing position of the glide. Despite this difference, one of the primary benefits of the takeoff and subsequent flight phase of the spin technique is to create favorable positions for the delivery upon landing much like in the takeoff and flight phase of the glide technique (Young, 2004a, Young & Li, 2005). In fact, Oesterreich and colleagues (1997) suggested that beneficial shoulder-hip separation should be evident by takeoff in athletes using the spin technique. In the LST, athletes
may actually step without breaking contact with the ground. For athletes using the RST, the above-mentioned long sweep of the non-support leg should gradually shorten leading up to the moment of takeoff such that the hip and knee are flexed at the moment of takeoff (Turk, 1997). Athletes using the RST thus assume a takeoff position resembling a “sprint” position (Turk, 1997).

**Flight Phase**

At the completion of the push-off the athlete enters a period of flight. While some of the velocity developed in the flight phase is carried over to the delivery of the implement most is lost at RFTD. In fact, Koltai (1973) and Kerssenbrock (1974a; 1974b) reported 60-70% losses in flight velocity at RFTD. This may be of little concern however as Young and Li (2005) speculated that the primary benefit of the flight phase is to plyometrically load the lower extremities for a more powerful delivery of the implement. If this explanation is true, greater vertical displacement of the APSS during the flight phase may be more beneficial than linear or perhaps even rotational speed.

The two styles of the spin technique differ greatly during the flight phase. The LST is characterized by a shorter (in some cases nonexistent) flight phase with greater rotation of the body prior to RFTD and little to no shoulder-hip separation at RFTD (Turk, 1997; Paish, 2005). In contrast, the flight phase of athletes using the RST is characterized by an active swing leg, and a high-knee sprint position during the takeoff and flight phase (Turk, 1997).

**Rear Foot Touchdown**

As is the case in many of the preceding actions, the body positions at RFTD observed in athletes using the RST and those using the LST are considerably different. Little to no shoulder-hip separation is evident at RFTD in athletes using the LST (Paish,
In contrast, athletes using the RST make RFTD with the upper body greatly wrapped and pointing down the non-throwing side sector line (Paish, 2005; Turk, 1997). From this position they then grind the rear foot in the middle of the circle and continue rotation about the support leg (Paish, 2005; Turk, 1997). To enhance this rotation Pyka and Ortando (1991) recommended drawing in all extremities close to the body.

At RFTD, Oesterreich and colleagues (1997) suggested that the trunk should be more erect than for throwers using the glide technique. This position provides the advantage of a shorter radius of rotation that allows the athlete to continue spinning more easily. This advantage however comes at a cost. In theory this position shortens the horizontal and vertical trajectory along which the implement could be accelerated during the completion phase. It appears that this disadvantage may be offset by two other factors that increase the angular and vertical trajectory of the implement at RFTD, greater shoulder-hip separation and greater rear knee flexion at RFTD.

Lindsay (1994) compared gliders and spinners (likely RST) and found that while athletes using the spin tended to have lower absolute velocity of the implement at RFTD they arrive in a more advantageous throwing position. He reported that athletes using the spin technique have much greater (15°) shoulder-hip separation at RFTD with the implement placed a greater lateral distance from the direction of the throw. This would in theory allow the athlete to increase the angular trajectory of the implement from RFTD to the point of release. Several authors (Jarver, 1976; Pagani, 1985) claimed that this position also generates a secondary benefit of increased pre-tension in the muscles of the trunk. Jarver (1976) noted that the shoulder axis of athletes using the spin technique slows down more than the hip axis, creating a favorable torqued position.
In addition to greater shoulder-hip separation, athletes using the spin technique may also offset the potential loss in horizontal trajectory at RFTD associated with a more upright trunk position by having greater flexion at the knee joint. Lindsay (1994) found that athletes using the spin technique had significantly greater rear knee flexion (28°) at RFTD than their counterparts using the glide technique. Greater rear knee flexion at RFTD was identified by Young and Li (2005) to have a positive effect on performance. It should however be noted that the results of another study actually indicated that better throwers have less rear knee angle at RFTD (Goss-Sampson & Chapman, 2003).

**Transition Phase**

In contrast to athletes using the glide technique, research has indicated that the implement actually decelerates during the transition phase of throwers using the spin technique (Lindsay, 1994; McCoy et al., 1984b). In light of this, some authors (Bartonietz & Borgstöm, 1995; Oesterreich et al., 1997) have suggested that turning on the support foot is vitally important because it keeps both the athlete and the implement moving.

While no known research has examined the cause of the deceleration during the transition phase, it may be due to the longer transition times that have been observed in the spin technique (Heger, 1974; Lindsay, 1994; McCoy et al., 1984b). Lindsay (1994) reported that the transition times of spinners are twice as long gliders. It should be noted however that much of this research likely examined throwers using the RST rather than those using the less conventional LST. Athletes using the LST would be expected to have considerably shorter transition times. Whatever the case, shorter transition times appear to be associated with longer throws in the spin technique (Goss-Sampson & Chapman, 2003; Young, 2004b) much like in the glide. Jones (1987) suggested that the benefit of shorter transition times might lie in its causal effect on greater shoulder-hip separation.
Experimental data from Goss-Sampson and Chapman (2003) support this explanation. These data indicated that longer transition times, smaller maximal shoulder-hip separation during the transition phase and reduced shoulder-hip separation at the end of the transition phase were associated with shorter throws. Another possible explanation was offered by Heger (1974). He suggested that shorter transition times minimize deceleration of the implement before the athlete enters a period of double support. He stated that this was one of the primary disadvantages of the spin technique.

Some have suggested that the implement should move around the athlete (Bartonietz & Borgstöm, 1995; Bosen, 1985; Hay, 1993) in which case it would actually move backwards in the ring. Others have suggested that the athlete should move around the shot (Bartonietz, 1994a; Oesterreich et al., 1997). Johnson (1992) suggested that backward movement of the implement would negate any positive effect of all preceding movements. There is not a consensus of opinions, as some have suggested that athletes should actually attempt to move the implement through a greater radius to increase the radius of rotation and thus reach a greater linear speed in the final moments of the throw (Koltai, 1975).

Front Foot Touchdown

There is considerable difference in the stance at FFTD of athletes using the spin and glide techniques. Several researchers have noted that athletes using the spin technique have a narrower stance than their counterparts using the glide technique (Bartonietz, 1994a; Heger, 1974; Jones, 1987; Johnson, 1992; Pagani, 1985). In fact, previous research has indicated that the completion phase stance of athletes using the spin technique is between 0.2 and 0.5 m narrower than those using the glide (Bartonietz, 1994a; Bartonietz & Borgstöm, 1995; Bosen, 1985; Lindsay, 1994; Oesterreich et al.,
1997; Pagani, 1985). Heger (1974) suggested that this narrower stance is a disadvantage during the completion phase and increases the likelihood of fouling. Likewise, Brown (1985) suggested that a narrower stance was disadvantageous and suggested that the stance width of spinners should be as wide as the glide. Others however (Johnson, 1992; Jones, 1987; Pagani, 1985), claim that the narrower stance is actually advantageous because it facilitates a beneficial vertically directed double-leg lift.

In addition to differences in the stance of the two techniques (and as might be assumed from the previous discussion on trunk position at RFTD) Bosen (1985) also noted that spinners display a more upright trunk position at FFTD. Also, much of the shoulder-hip separation that athletes using the spin technique achieved at RFTD is actually gone at FFTD (Lindsay, 1994). This may indicate that unlike their glide counterparts, athletes using the spin technique are accelerating the implement to a greater extent prior during the transition phase by ‘uncoiling’ their shoulder-hip axis prior to FFTD. In fact, Oesterreich and colleagues (1997) referred to this as rotational pre-acceleration and claimed that it was one of the primary advantages of the spin technique.

Completion Phase

As in the glide technique, the action of the rear leg should be very active during the completion phase (Bartonietz & Borgstöm, 1995; Booth, 1985; Oesterreich et al., 1997; Palm, 1990). Likewise, Bartonietz and Borgstöm (1995) suggested that the front leg should extend almost completely at the moment of release just as has been suggested for the glide technique. The timing of initiation and the magnitude of action of the lower extremity does however differ considerably between the two techniques. Unlike the glide technique, the workload of the lower extremity in the delivery of the implement is more evenly distributed between both legs (Jones, 1987; Larsen, 1992). That is, instead of an
initial push with the rear leg and a weight transfer to the front leg, spinners push more simultaneously with both legs.

While some have suggested that the narrow stance, minimal weight shift, and simultaneous leg push observed in the completion phase of the spin technique is inferior to that of the glide (Heger, 1974), others (Oesterreich et al., 1997) argued that the spin technique actually creates a more favorable working condition for the completion phase than the glide technique. They stated that this advantage comes from rotational pre-acceleration of the athlete and shot and highly efficient redistribution of the rotational energy in the athlete’s body. More succinctly, athletes using the spin technique are able to begin rotational acceleration of the implement while still in single support (during the transition phase) and continue it through release and are able to accelerate the implement more efficiently in the final moments of the delivery. On the latter, it appears that in the spin technique, vertical acceleration is primarily developed by the action of the lower extremity while horizontal acceleration is a result of the arm strike and the horizontal component of the rotational acceleration.

Regarding the function of the legs, several authorities have suggested that their aggressive extension, especially that of the front leg, helps to block the hips and transfer the momentum of the hips and trunk to the implement at the moment of release (Bartonietz & Borgstöm, 1995; Larsen, 1992; McCoy et al., 1984b; Oesterreich et al., 1997). Likewise, Jones (1987) suggested that the direction of the final leg thrust should be more vertically oriented when compared to the glide and Oesterreich and colleagues (1997) suggested that athletes using the spin technique should attempt to jump up during the final moments of the delivery phase in order to maximize their performance. To achieve this objective, the close stance, minimal weight shift, and near simultaneous
double-leg push observed in the completion phase of the spin technique may be better suited than the wider stance observed in the glide. Indeed, Pagani (1985) made this very point and pointed to the fact that spinners jump higher (20 cm vs. 15 cm) than gliders at the moment of release from a much narrower completion phase stance. To facilitate the efficiency of this vertical jump, Bartonietz and Borgstöm (1995) suggested that the rear foot should turn on the ball of the foot to place the implement directly over the rear thigh, pelvis and shoulder so that the most direct application of force can be transmitted to the implement.

Release

As in the glide technique, the actions of the legs in the moments leading up to and including release are vitally important in the spin technique (Oesterreich et al., 1997). The final leg extension determines whether the completion phase movement can take place about a stable throwing side, whether the rotational movement of the athlete can be partly converted into a translational component in the putting direction, whether the optimal release angle can be achieved, and whether the throw is fair.

Several authorities have commented that it is considerably more difficult to block (decelerate) the non-throwing side prior to release in the spin technique when compared to the glide (Goss-Sampson & Chapman, 2003; Heger, 1974; Larsen, 1992). Some actually suggested that athletes should actually attempt to maintain non-throwing side trunk rotational velocity through the point of release instead of attempting to decelerate it (Goss-Sampson & Chapman, 2003). Heger (1974) suggested that the difficulty in blocking the non-throwing side is actually a disadvantage of the spin technique because it limits the stretch on the upper extremity and may cause forward movement of the trunk to
be stopped prematurely. If this is indeed the case, results appear to indicate that it is adequately compensated by other technical advantages.

Unlike the glide technique there is little debate over the question of whether an athlete using the spin technique should remain in contact with the ground or not during the final moments of the delivery phase. Only one author (Smith, 2005) has suggested that the feet of athletes using the spin technique remain on the ground and this recommendation was specifically made for athletes using the LST. Most authorities are in agreement that throwers using the spin technique should jump during the completion phase (Bartonietz & Borgstöm, 1995; Booth, 1985; Oesterreich et al., 1997; Pagani, 1985). A jumping delivery is also the most commonly observed in elite athletes using the spin technique (Bartonietz & Borgstöm, 1995; Grigalka & Papanov, 1978; McCoy et al., 1984b; Pagani, 1985; Palm, 1990; Wilt, 1982). In fact, Oesterreich and colleagues (1997) suggested that a jumping delivery is absolutely necessary to maximize performance when using the spin technique. The close stance, minimal weight shift, and near simultaneous double-leg push during the final moments of the spin completion phase lends itself to a jumping release. In fact, the front foot breaks contact with the ground prior to and reaches a higher position above the ground than the rear leg in many top spinners (Bartonietz & Borgstöm, 1995; Oesterreich et al., 1997). This provides evidence of the explosive bracing and lever function of the rear leg that causes the athlete to quickly accelerate in the vertical direction.

An added benefit of the closed stance, double-leg push of the spin technique is a more forward hip position at release. Data reported in Kerssenbrock (1974a) indicated that athletes using the spin tend to release the shot with the hips directly over the front foot. This position allowed throwers to release the shot 0.4 m in front of the toe board.
This is in contrast to gliders who tend to release the shot with their hips well behind the front foot to maximize horizontal braking forces. Kerssenbrock (1974a) reported that this forward hip position allowed athletes using the spin technique to increase their horizontal release distance by approximately 0.3 m.

**Kinetics**

**Forces Applied to Implement**

No review of a sporting event would be complete without examination of the forces that produce the motion. The following section will both examine the kinetics of the shot put and attempt to relate their dynamics with the kinematics discussed previously. In the case of the shot put, kinetics research is quite limited when compared to kinematic research. This research has primarily examined force dynamics as well as work and energy relationships in the shot put. In fact, most of the available research originates from decades old unpublished Eastern Bloc research. Unfortunately, research on the kinetics of shot putting has been limited to the glide technique and primarily male athletes.

Several attempts have been made to measure the application of force to the shot. In all known cases however, measurements have been indirect estimations using known relationships between force and energy, work, and acceleration. For instance, research from Zatsiorsky and Matveev (as cited in Zatsiorsky et al., 1981) using the work-energy relationship indicated that that the work performed by an athlete to move the shot is comprised of two components. The first component produces a change in the vertical position of the implement resulting in a change in its potential energy. The second component produces a change in the velocity of the shot that results in a change in the kinetic energy of the implement. The equation for such a relationship is:
\[ W = ma_g h + \frac{1}{2} mv^2 \]

Where \( W \) is work done by the athlete; \( m \) is the mass of the shot; \( a_g \) is gravitational acceleration; \( h \) is change of height of the implement; and \( v \) is the implement velocity.

The total energy of the shot at the moment of release is equal to the sum of its kinetic and potential energies, which is equivalent to the mechanical work performed by the athlete to accelerate and elevate the implement. Samotsvetov (1961) used this relationship to examine an 18.19 m throw and found that 80% of the 732 N.m of work performed in the delivery of the shot was used to accelerate the implement horizontally with the remaining 20% responsible for elevating it. The brief duration of the completion phase (0.2-0.3 seconds) combined with the quantity of work performed in this short time produced power outputs in the neighborhood of 7 horsepower.

Force application to the shot has also been indirectly assessed via its relationship with the implement’s known mass and observed acceleration. Force can be estimated by multiplying the mass of the shot by its recorded acceleration. The obvious assumption in such a method is that the examined parts of the shot path are linear. This method has been used by several researchers (Fidelus & Ziencowicz as cited in Lanka, 2000; Kristev et al., as cited in Lanka, 2000; Tutevich, 1955 as cited in Lanka, 2000) to estimate the force application to the shot. In most attempts, only the tangential component of acceleration is measured with the radial component considered to be equal to zero. In a similar method, Knudson (1989) used the mass and velocities of the APSS to determine the linear momentums of shot putters.

Various force-time records have been mentioned for the force application to the implement during the glide shot put. The force-time record of the throw has been divided by two (Lebedev as cited in Zatsiorsky et al., 1981), three (Kristev as cited in Lanka, 2000)
2000), and four (Tutevich, 1955 as cited in Lanka, 2000) different phases. Differences in these results may be explained by the use of different starting points for the throw along with potentially flawed methodology.

Lebedev (as cited in Zatsiorsky et al., 1981) examined the force-time history to the forces applied to the implement during the completion phase. He reported two distinct phases of force application. The first phase of the curve was characterized by a small increasing slope with the second phase having a sharp increase leading up to the moment of release. Lebedev indicated that acceleration decreased as arm extension was initiated and then again just prior to release. When examining the acceleration curve of a novice thrower, Lebedev found that the acceleration fluctuated to a much greater extent, was much less steep, and had a longer duration than the expert shot putter.

Without collecting experimental data, Kristev (as cited in Lanka, 2000) proposed a force-time model for the delivery phase of the glide shot put. This theoretical model had three distinct phases of force application to the implement, each of which corresponded with the various phases of support following RFTD. The first phase, which corresponded with RFTD and the transition phase, was the longest in duration and was characterized by moderate force output. Greater force output was proposed during the second phase that encompassed the period of time between FFTD through the moment the rear foot broke contact with the ground. The final phase, which was also the shortest, took place when the thrower was in single support on the front leg.

Likewise, Fidelus and Zienkowicz (as cited in Lanka, 2000) reported two distinct phases of force application. Unlike the previous studies, they examined the entire throw rather than just the completion phase. They reported an initial force peak at takeoff with the force applied to the implement approaching zero at RFTD. The second phase began
with FFTD at which point force application to the implement was reported to increase abruptly. Fidelus and Zienkowicz reported force applications as high as 465 N during the delivery phase with maximum vertical and horizontal components of 298 N and 381 N respectively. Undulations in the vertical and horizontal force curves throughout the course of the throw were also reported. Horizontal acceleration dropped at the beginning of the flight phase and increased at the end due to trunk extension. A steep horizontal acceleration was also observed at FFTD. The authors suggested that a short transition time may facilitate horizontal deceleration.

Like the study mentioned above, Tutevich (1955 as cited in Lanka, 2000) examined the force-time history for the entire throw and observed four distinct phases of force application. The first peak in the force-time record coincided with the take-off, the second peak with RFTD, and the third peak occurred when the throwing arm began the throwing movement. This peak was found to be very short in duration and the author claimed that the sudden fall of the third peak was caused by weakness in the throwing side wrist and deceleration of the throwing side shoulder, which resulted in the athlete’s chest coming forward and the shot being delayed. The fourth and final peak had the greatest magnitude and coincided with completion of the extension of the front ankle, when the throwing side elbow was approximately 90°.

In the only known attempt to measure forces directly applied to the implement, Machabeli (as cited in Lanka, 2000) reported considerable fluctuations in all directions. A shot with a built-in accelerometer was used to examine horizontal (radial and tangential) and vertical acceleration. Considerable fluctuations were observed in all directions. Vertical acceleration fluctuated between 0 and 1 G prior to the delivery phase but from that point on, it increased rapidly, reaching 5.4 Gs. Radial horizontal acceleration started
at the moment of takeoff. Midway through flight, it became negative, and at rear foot touch down, the shot positively accelerated to a value of 5.8 Gs. At the beginning of the throw, the tangential component of horizontal acceleration was near zero but gradually increased with values reaching 7.8 Gs just prior to release.

As seen above, more research is needed to truly understand the forces that a shot putter applies to the implement over the course of the throw. Previous research attempts have yielded inconclusive results. The studies appear to have contradictory results on such elements as force and acceleration patterns, the nature of force development, and the number and location of force peaks. Differences may come from the varied methodologies employed to examine force application to the implement. The film analysis used by some of the researchers has been shown to produce inaccurate velocity and acceleration data for the shot put (Fidelus & Zienkowicz as cited in Lanka, 2000; Zatsiorsky et al., 1973 as cited in Zatsiorsky et al., 1981). Furthermore, the accelerometers of the time were plagued by imprecision (Miller & Nelson, 1973) bringing in to question the results of Machabeli (as cited in Lanka, 2000).

**Ground Reaction Forces for Glide Technique**

Several researchers have examined GRFs during the throw. Some have used force platforms to measure the magnitude and direction of the GRFs while others have used an inverse dynamics approach. This research has provided useful insight on the forces generated by the athlete at various points in the throw. When examining the kinematics of any movement, the timing, magnitude and direction of the force application can be examined. As might be expected, researchers have observed considerable differences in the force profiles of athletes of varying levels of performance. Experimental data has
indicated that the horizontal and vertical GRFs of athletes of different performance levels vary in magnitude, direction and duration.

**Preparation Phase**

**Duration of Push**

Using force platforms, Lanka (1978 as cited in Lanka, 2000) found a low but statistically significant ($r = 0.29$) correlation between the performance of elite men and the duration of force application by the support leg prior to takeoff. Seliverstov (as cited in Zatsiorsky et al., 1981) observed a similar relationship in women shot putters. Both authors concluded that more highly skilled athletes used a slower initial acceleration than their less skilled counterparts and that an abrupt change in GRFs prior to takeoff had a detrimental effect on subsequent actions of the throw.

**Magnitude and Direction of Push**

The duration of force application is not the only differing characteristic in the preparatory phase GRF profiles of elite and sub-elite athletes. Experimental data from Ariel (1979) and Lanka (1978 as cited in Lanka, 2000) indicate that elite level throwers exert between 500 and 900 N of horizontal force prior to takeoff. Others (Marhold, 1970 as cited in Lanka, 2000; Fidelus & Ziencowicz as cited in Lanka, 2000) reported similar values and also found that performance improved as the direction of the resultant push-off vector became more horizontally directed. Fidelus and Ziencowicz (as cited in Lanka, 2000) claimed that a more horizontally directed takeoff was beneficial and suggested that top throwers apply forces in such a manner to minimize the height of the glide and maximize horizontal velocity of the implement. Their data also indicated that the horizontal component of the GRF of elite athletes is characterized by a gradual but steep increase to a maximum value followed by a sharp decrease to zero as they broke contact.
with the ground. In less skilled shot putters, a more gradual increase with a sharper drop in force was observed. The true value of horizontal GRFs remains to be seen as others have observed larger vertical than horizontal GRF values in elite throwers (Ariel, 1979; Ward & McCoy, 1984). In fact, Ariel (1979) reported vertical GRFs close to double the athlete’s body weight prior to takeoff. Whatever the case, data from Marhold (1970 as cited in Lanka, 2000) indicated a link between the magnitude of the resultant force application and the specific manner of force application (take off from the heel as opposed to the toe was found to be most beneficial) and improved performance.

**Delivery Phase**

In the glide shot put an athlete is in single support at RFTD through the transition phase, double support at FFTD through the transition phase, and in single, double or no support during the completion phase. As a result of any difficulty this might produce, the following portion of this review will first consider the GRFs applied by each foot separately and then the interaction between the two.

**Rear Foot**

**Vertical Force Following Rear Foot Touchdown**

Experimental GRF data on shot putters of various skill levels has indicated that the vertical and horizontal GRFs exerted against the rear foot undulates in a complex manner with athletes of different performance levels displaying distinct force records (Zatsiorsky et al., 1981). Regardless of skill level, the vertical component of the GRFs has two major peaks followed by a gradual decrease in magnitude until the foot breaks contact with the ring (Ward & McCoy, 1984; Zatsiorsky et al., 1981). As might be expected due the initial impact of landing from the flight phase, considerable GRFs are
generated at RFTD. In some athletes, the vertical GRF reaches three to four times the athlete’s body weight (Zatsiorsky et al., 1981).

Zatsiorsky and colleagues (1981) reported that the size of the initial force peak at RFTD is related to the specific variation of the glide used (long-short v. short-long) and the position and subsequent movement of the rear foot at touchdown. Results indicated that the actions and force-records of sub-elite athletes could be grouped into two main categories. The first group contacts the ground following a high glide and as a result, produces high maximum vertical forces. The second group is characterized by a softer rear foot contact followed by a rapid weight shift to the front foot. In athletes with better performances are a more rapid and forceful contact of the rear foot with the ground has been observed (Zatsiorsky et al., 1981).

After the initial vertical force peak, the vertical GRF decreases to a relative minimum before increasing again. The second peak coincides with the initiation of rear knee extension (Payne et al., 1968; Zatsiorsky et al., 1981). In athletes with better performances, the magnitude of the second peak is greater than their less skilled counterparts reaching between 1.66 and 2 times (up to 2500 N) the athlete’s body weight (Ariel, 1979; Ward & McCoy, 1984; Zatsiorsky et al., 1981). As a result of their more forceful ground contact, the initial slope of the force-time curve is steeper among athletes with better performances. Zatsiorsky and colleagues (1981) concluded that the rate of increase in vertical GRFs better reflects an athlete’s skill level than the magnitude of force exerted.

**Horizontal Force Following Rear Foot Touchdown**

According to some reports, the horizontal GRF in the direction of the put against the rear foot changes direction three times (Lanka, 2000; Lanka & Shalmanov as cited in
Lanka, 2000; Zatsiorsky et al., 1981). At RFTD, the GRF is directed towards the rear of the circle (shown as a negative deflection). In some athletes these “blocking” forces reached 700-800 N, resulting in considerable horizontal deceleration. Because these blocking forces hinder movement of the athlete in the direction of the throw, athletes would likely benefit from minimizing these forces. Indeed, experimental data indicates that shorter durations and smaller maximum values of the second horizontal GRF peak were characteristic of the best performers (Ariel, 1979; Ward & McCoy, 1984; Zatsiorsky et al., 1981).

Following this initial negative deflection, the force exerted against the rear foot switches in direction to help accelerate the APSS in the direction of the throw. Lanka (2000) reported maximal values of 500-600 N for elite shot putters during this portion of the throw. The magnitude of this force was found to have a negative correlation with the maximum value of the aforementioned negative deflection.

The third and final change in direction of the horizontal GRF exerted by the rear foot coincides with the rear foot breaking contact with the ground just prior to release. At this point, the horizontal component of the GRF under the rear foot reverses to face toward the rear of the circle (Dessureault, 1976, 1978; Lanka & Shalmanov as cited in Lanka, 2000). More specifically, 70-80 ms before the rear foot leaves the ground, the horizontal force became negative reaching values of 200-300 N in the best throwers (Zatsiorsky et al., 1981). The force developed as a result of sliding the rear foot across the ground from the center of the circle toward the stop board. This action is a byproduct of the athlete’s failed attempt to maintain contact with the ground while moving forward (Zatsiorsky et al., 1981). Several researchers (Dessureault, 1976, 1978; Lanka, 2000)
have noted a positive correlation between this force and the distance of the put, suggesting the importance of the rear leg in exerting breaking forces prior to release.

**Front Foot**

Like the rear foot, complex force curves have also been reported for the front foot in the period of time between FFTD and release (Dessureault, 1976; 1978; Lanka, 2000; Zatsiorksy et al., 1981). At FFTD, Lanka (2000) reported that the front foot exerts a braking force that decelerates forward movement and facilitates the elevation of the COM of the APSS. Better performers exhibit are distinguished by higher force magnitudes and steeper slopes in the vertical and horizontal direction (Lanka, 2000; Zatsiorsky et al., 1981). As the front leg bends immediately following FFTD, better throwers also tend to minimize decreases in force (Lanka, 2000) providing evidence of the importance of the front leg. In fact, Lanka (2000) reported that the blocking impulse generated by the front leg is considerably greater than that generated by the rear leg. This is in agreement with anecdotal claims that the decelerating role of the front leg requires more force than the rear leg (Ionesku, 1992; Lanka & Shalmanov as cited in Lanka, 2000; Payne, 1974; Simonyi, 1973).

**Interaction**

From the data presented above, it appears that the GRF profiles of top athletes following RFTD are characterized as such: the rear leg performs a two-fold task and the front leg primarily exerts breaking forces which help to decelerate the lower body and accelerate the upper body. In its dual role, the rear leg first accelerates the APSS and then along with the front foot, it decelerates the movement of the lower extremities of the athlete, thereby increasing the speed of the upper body segments and increasing the velocity of the shot. Specifically, experimental data has indicated that the rear leg
contributes up to 61% of the total vertical impulse generated by both feet (Dessureault, 1976; 1978). With regards to horizontal GRFs, the breaking forces generated by the front leg exceed any breaking forces generated by the rear leg by up to 75% (Desureault, 1976; 1978). Furthermore, this same research indicated that when the total horizontal impulse exerted by both feet is considered, all shot putters achieve a greater horizontal braking impulse compared with the total thrusting impulse.

**Ground Reaction Forces for Spin Technique**

While kinetic research on the spin is even more limited than that of the glide technique, there are some data to suggest that the GRF profiles of athletes using both techniques show a similar pattern of interaction between the feet and the ground in the period between RFTD and release (Bartonietz, 1994a; Palm, 1990). However, these data did indicate that athletes using the spin technique are distinguished by a higher vertical component of the GRF during the completion phase and a steeper rise in both the horizontal and vertical forces just prior to release. Pagani (1985) indicated that the front leg of athletes using the spin technique exerts up to three times as much force as the rear leg. This greatly exceeds the force contribution of the front leg in athletes using the glide technique and indicates that the role of the role of the front leg in particular may be quite different between the two techniques.

**Muscle Activity**

While it appears clear from much of the discussion above that the action of putting the shot is a full body movement demanding the powerful contraction of practically every muscle in the athlete’s body, quantitative evaluation of the contribution, timing and magnitude of each muscle’s activation patterns over the course of the throw are very limited. Previous EMG studies indicate that at the very least all major muscle
upper (Hermann, 1962; Peng et al., 2005) and lower (Ohyama et al., 1995) extremity muscle groups are activated during the shot put.

A study by Hermann (1962) examined the muscle activation patterns during the delivery phase of eight upper extremity muscles from athletes of varying performance levels. In average and good performers the pectoralis major (PM), lateral, medial and long head of the triceps brachii (TB_lats, TB_med, TB_long) and the anterior (D_ant) and lateral (D_lat) heads of the deltoid produced the strongest action potentials during the delivery of the shot. In lesser skilled performers, muscle activation tended to peak after the shot had either already been released or after they would be able to significantly contribute to the outcome of the throw. EMG records indicated that the best throwers were distinguished by greater activation of the PM, TB_lats, TB_med, TB_long, and D_lat during the early moments of the completion phase.

A later study by Peng and colleagues (2005) used three different weight shots (3.64kg, 5.45kg, 7.26kg) to examine the effect of varying implement weight on the muscle activation pattern of thirteen upper extremity muscle groups during the standing throw. Interestingly of all the muscle groups examined, the lower (TR_low), middle (TR_mid) and upper trapezius (TR_up) and D_ant and D_lat showed substantially stronger activity than the other muscle groups. This is considerably different than the results of the previous study and contrary to what most would assume are the primary movers in shot putting. Of the muscles examined only the forearm flexor (FA_flex) demonstrated a statistically significant increase in muscle activation with increasing implement weight. It should be noted however that a non-significant but increasing trend was observed for the serratus anterior (SA), FA_flex, forearm extensor (FA_ext), triceps brachii (TB), sternal pectoralis major (PM_stern), clavicular pectoralis major (PM_clav), D_lat, D_ant, and TR_mid.
Early in the throw, EMG records indicated strong activation of the D_{lat}, F_{ext}, F_{flex}, PM_{clav}, and TB. These results are largely in agreement with the results of Hermann (1962). In general, peak muscle activation was achieved in the latter part of the standing throw. Midway through the throw the bicep brachii (BB), D_{ant}, F_{ext}, F_{flex}, PM_{clav}, PM_{sternal} and TR_{mid} became highly active. Immediately prior to release, SA, F_{flex} and D_{post} reached peak EMG leading the authors to conclude that these muscles are critical in the final moments of the completion phase. This sequence of peak muscle activation does not follow the previously mentioned recommendation for a proximal-to-distal firing pattern. It is unclear whether this discrepancy is due to the skill level of the participants (sub-elite), the influence of the varied weight implements, or simply because the proximal-to-distal activation pattern is not the most optimal. Interestingly they also reported co-activation of the F_{ext} and F_{flex} and BB and TB. While such co-activation of antagonist muscles may appear to be detrimental to performance, previous research has indicated that such co-activation may be beneficial for very fast motions or when movement stability is required (Deluca & Mambrito, 1987).

In addition to these two studies on the upper extremity, another study examined the EMG activity of five muscles in the rear leg of three skilled shot putters (Ohyama et al., 1995). Muscle activity was examined from preparatory phase through release of the glide throw. Results indicated that early in the preparatory phase the larger muscles of the support thigh (biceps femoris (BF), rectus femoris (RF) and vastus lateralis (VL)) are very active but in the moments immediately preceding takeoff these muscles interestingly become silent and the tibialis anterior (TA) becomes very active. The authors suggested that this indicates that athletes use a ‘heel kick’ to quickly switch from kicking (knee extension prior to takeoff) to pulling (knee flexion following takeoff to prepare for
RFTD). The TA continued to be very active through RFTD that the authors concluded helped facilitate knee flexion of the rear leg through the tendinous action of the gastrocnemius muscle (GAS). During the midpoint of the flight phase the BF resumes activity, suggesting that it is acting to flex the knee prior to RFTD and possibly also pre-tense the leg prior to impact. During the delivery of the shot the BF, GAS, RF, and VL are all extremely active all the way through the moment of release while the TA becomes inactive.

**Performer Attributes**

**Strength**

As the above section indicates, shot putting places a premium on being able to produce very large forces over a relatively short period of time. Strength is the ability to produce force (Siff, 2000; Stone et al., 2002) and as might be expected, several practitioners have noted its importance to shot putting (Bakarinov & Oserov, 1985; Bartonietz, 1994; Marks, 1985; Poprawski, 1988; Tschiene, 1973a). Several researchers support the value of maximum strength to shot put performance (Egger et al., 1994; Kokkonen et al., 1988; Stone et al., 2003; Terzis et al., 2003; Uppal & Ray, 1986). For instance, one intervention study found that shot put performance is improved by strengthening the flexor muscles of the toes and fingers (Kokkonen et al., 1988). Uppal and Ray (1986) reported similar findings on the importance of hand and arm strength to shot put performance.

**Power**

While the value of strength to shot putting appears irrefutable, several authors have suggested that explosive power is actually a more important physical characteristic
(Bakarinov & Oserov, 1985; Bartonietz, 1994; 1996b; Billeter et al., 2003; Jesse, 1964; Jones, 1998; Marks, 1985). A study by Poprawski (1989) provided support for this notion. This study examined ten elite shot putters and found that shot put performance is more closely related to tests of speed and power than maximum strength. Other studies have also linked explosive leg strength to shot put performance (Terzis et al., 2003; Tschiene, 1988; Uppal & Ray, 1986).

**Strength-Power Relationship**

From a practical standpoint, the preceding section begs the question of whether training should be more focused towards the development of maximal strength or maximal power output. This question however may be addressed by an understanding of the relationship between maximal strength and power output. Because force is a vector quantity, the display of strength will have a magnitude and direction. Power is the product of force and velocity and as a result, changes in force produce changes in power output. Schmidtbleicher (1992) suggested that maximum strength is the primary influencing factor on power output. Consequently, maximum strength could potentially affect peak power because a given load would represent a smaller percentage of the athlete’s maximum, thus making the load easier to accelerate. It is possible that a person with a higher maximum strength level would have a greater percentage or greater cross-sectional area of type II fibers, which strongly contribute to high power outputs. Results from a study by Stone and colleagues (2003) confirmed the relationship between maximum strength and power and also provided insight to their effect on shot put performance. This study examined the relationship between strength and power indicators for 11 well-trained collegiate shot putters and found that maximum strength was strongly associated with peak power output, even with lighter loads such as the shot.
Another study by Reis and Ferreira (2003) evaluated the validity of several strength and power tests to predict performance in the shot put. The study provided mixed results as some tests of power (such as a variety of jumping tests) did not correlate with performance while throwing tests (power) and weight lifting tests (strength) showed a significant association with performance.

**Anthropometry**

In light of the above discussion on strength and power, it should be noted that absolute strength and power is likely more important to shot put performance than their relative counterparts. As the name indicates, absolute strength and power refers to the maximal strength and power output of an individual regardless of bodyweight. Relative strength and power refers to the strength and power output of an individual relative to the performer’s own body weight. Absolute strength and power tend to increase proportionally with body weight while relative strength and power tend to peak at lower body weights (Siff, 2000; Zatsiorsky, 1995). Because acceleration of a relatively light implement is the primary objective of shot putting (as opposed to simply accelerating one’s own body as in running or jumping), greater body mass is likely beneficial. While only one known study has directly linked body size with shot put performance (Johnson, 1932 as cited in Cureton, 1985), the results of several studies have indirectly provided support for it. For instance, one anthropometric study examined athletes from a variety of sports and found that shot putters are the largest sportsmen in both body mass and stature (Ruff, 2000). Likewise, Pietraszewska (2004) found that shot putters are distinguished from all other track and field athletes by having the heaviest of all builds of athletes. Interestingly, an earlier study (Uppal & Ray, 1986) found that body density, lean
body weight, and percentage of body fat were not significantly related to shot put performance.

**Muscle Physiology**

In addition to an athlete’s anthropometry, other factors such as muscle physiology and training likely influence strength and power and consequently shot put performance. Previous research has shown that having a high percentage of fast twitch (Type II) muscle fibers is strongly related to muscle strength (Gregor et al., 1979; Thorstensson et al., 1977). Similar research has indicated there is a link between strength and muscle cross-sectional area (Hakkinen, 1994; Maughan et al., 1983; Schantz et al., 1983). As such, it would be expected that top-level shot putters should be characterized by greater proportions of Type II muscle fibers and greater muscle cross-sectional area. Costill and colleagues (1976) took muscle biopsies from track and field athletes competing in a variety of events and found a 63% fast twitch fiber composition in the medial vastus lateralis from four shot putters and discus throwers. Another study examined the relationship between shot put performance and triceps brachii fiber type composition and found that fiber type composition and the functional capacity (e.g., isokinetic torque) of the triceps brachii muscle explain a part of shot put performance. Another study by Billeter and colleagues (2003) examined the fiber type and cross-sectional area of the medial vastus lateralis of three subjects. Two of the subjects were retired elite shot putters, the first a former World Champion and Olympic shot putter (shot putter 1) and the other was his training partner (shot putter 2). The third subject was the brother of shot putter 1. Examination of muscle biopsies from each participant showed that shot putter 2 had a predominance of type II fibers (67%) and distinct hypertrophy of both type I and type II fibers. In shot putter 1, type II fibers amounted to only 40% but because of
selective hypertrophy, they accounted for 67% of the total cross-sectional area. The type I fibers in shot putter 1 were similar in size to his untrained brother. After 3 years of retirement from competitive throwing, the type II fibers of shot putter 1 had reduced in size to values closer to those of his brother. Based on the large difference between type I and type II fiber size for the two brothers, the authors concluded that genetic predisposition to selectively hypertrophy type II fibers may be a key element in shot put performance.

**Effects of Training**

Research has indicated that strength training results in several adaptations to skeletal muscle that in turn enhance power output. These adaptations include such changes as hypertrophy of type II fibers, increased in the Type II/I cross-sectional ratio, and alterations in motor unit activation (Hakkinen, 1994). As might be surmised, it is difficult to precisely determine the extent to which a thrower’s anthropometry (especially body mass) and muscle physiology characteristics are due to genetics and which are due to training. Ultimately it may be safe to say that the physical characteristics of elite level shot putters are likely affected by both training and genetics.
Chapter 4: Optimization Model Review

One of the overriding principles governing sports performance and all forms of human motion is the attempt of an individual or group of individuals to perform a task in the most optimal way possible. The desire of biomechanists to simulate and analyze human movement with the objective of better understanding and even enhancing the performance of that motion has led to a large amount of biomechanics research devoted to the modeling of human movement.

The focus of this review will be on optimization modeling but space will also be given to provide a broader scope of modeling in general for the study of human movement. This overview of modeling will begin with a review of the various types of models that are commonly used in biomechanics research, with an emphasis on optimization modeling. Issues relating to the methodology and objectives of optimization will then be discussed. Finally, selected examples on a wide variety of topics will be used to demonstrate that biomechanics in general and optimization modeling in particular can offer significant contributions to the solution of a large variety of problems including sporting techniques. The examples will cover topics ranging from prostheses design to sport technique optimization. Emphasis will be placed on the objective and methodology of the study, scope of results, and validity of such models. Some thoughts on the need for a shot put optimization model will conclude this overview.

Types of Models

Conceptual

Three general categories of modeling have formed in biomechanics research: conceptual, physical, and mathematical. All have proven useful in the study of human
movement. Conceptual models address an issue without mathematical analysis. While these are perhaps the least frequently used in the field of biomechanics they can nonetheless be useful because of their ability to aid understanding without the complications of more complex models. Without using any mathematical foundation, Margaria (1976) developed a conceptual model of human walking by comparing it to an egg which rolls end over end on a level surface. As the egg rolls, its center of mass rises and falls, with accompanying changes in potential and kinetic energy. Margaria related this to the similar changes that occur in potential and kinetic energy during human gait as an individual’s center of mass rises and falls.

**Physical**

Physical models are the second category of modeling used in the study of human movement. Physical models are an actual physical attempt to recreate an existing condition or movement. Physical models have been used for several purposes. They may be used to explain or provide support for proposed or theoretical mechanisms. For instance, Gray (1954) used simple physical models to explain some of the basic principles of animal locomotion. Physical models may also be used to make observations that would be difficult on real animals or people. Smith (1962), for example, used a photoelastic model of the human heel to argue that the epiphysial plate is shaped in such a way to minimize the danger that it will be sheared off by tension in the tendon. A final use of physical models is to validate the results of mathematical modeling. McGeer (1990) for example investigated the stability of bipedal walking by analyzing the motion of a passive physical model walking down a slope.
Mathematical

More complex than conceptual or physical models are mathematical models. For this reason and the fact that they may produce a more accurate model, they are the most frequently used form of modeling in biomechanical research. There use has largely been in two distinct areas: simulation and optimization. Simulation models have been used to provide basic explanations of both simple and complex movements and to predict outcomes. They may for example be designed to calculate the effects of anatomical changes on jumping performance. Other models may be used to determine the optimum conditions or movement variables that result in the desired objective.

Simulation and Prediction

Although not the focus of this section, considerable attention will be paid to simulation models due to the similar methodology used by simulation and optimization models and the fact that there is much overlap between the two lines of research. Simulation involves the use of a validated computer model to evaluate the response of the model to changes in system parameters (Marshall & Elliot, 1995). They can provide a means of performing biomechanical analyses when data collection is difficult or simplification of the topic is necessary. They can also serve as a foundation for optimization modeling.

Examples abound of the use of simulation models to explain various biomechanics related topics from general movement to joint function. Ayoub (2003) developed a model to simulate sagittal lifting activities without the use of video input. This dynamic model simulated the motion of lifting tasks for the elbow, shoulder, hip, knee, and ankle using initial and final joint postures. The model accounted for gender, weight, and height of the performer as well as several parameters for the object and task.
The model was capable of producing angular trajectories for the five joints that were in good agreement with experimentally collected data.

**Optimization**

As previously mentioned, one of the primary uses of biomechanical mathematical models is the optimization of structures, movement patterns or the interaction between a user and their equipment. Optimization modeling involves the iterative use of computer simulation to determine parameter values or control variables that optimize (generally minimizing or maximizing) a specified criterion (Marshall & Elliot, 1995).

The field of optimization research is dependent on a single fundamental philosophical issue being true. That is, whether biological systems can, in fact, be optimized. There are two good reasons to believe that they can: natural selection theory and learning. Natural selection theory suggests that organisms tend to undergo changes, such as the ability to move faster or more efficiently, which would increase their likelihood for survival (Darwin, 1979). Over time, this would account for an optimization effect on basic movements such as walking and running. The more complex motions used by humans however, are far less likely to have been optimized by this process. This is particularly true for sports techniques because in general they are not essential to the survival of the person or the species and as a result are not likely to have evolved into an optimal form. On the other hand, they are much more likely to be influenced by individual learning processes aimed at performing the task in the best possible manner. That is, people may learn rather than inherit the movement patterns that maximize speed or minimize energy costs in “non-essential” movement patterns such as those commonly seen in sporting activities. Inherent in the belief that movement can be optimized through learning processes is the realization that this process is subject to human error. For this
reason, optimal movement patterns are generally unknown. Because of this uncertainty, optimization models can be of great use in understanding “the best way” to perform a movement. An optimization model may provide an idealized or optimal template to accomplish a task objective or objectives.

**Methodological Issues**

**Suitable Tasks for Optimization**

At the current time, not all movements are suitable for optimization research. Tasks that are classified as discrete or continuous are ideal subjects for optimization research. A discrete task is one in which there is a recognizable beginning and end (Schmidt & Lee, 2005). Tasks such as lifting or throwing an object are examples of discrete tasks. In contrast to discrete tasks, continuous tasks have no recognizable beginning and end (Schmidt & Lee, 2005). Examples of continuous tasks include running and walking actions. In some cases continuous tasks are partitioned in such a way that one “cycle” of the task is analyzed for optimization. An example would be examining one gait cycle in walking. In cases such as this, the continuous task is being analyzed in such a way that it is essentially a discrete activity.

**Environmental Concerns**

Another current requirement for optimization modeling is that the activity be taking place in a closed environment. A closed environment is one in which the surroundings are fixed (Schmidt & Lee, 2005). Closed environments are ideal for optimization research because they reduce variability that might otherwise make the optimization process impossible. For instance, in a team sport where a performer must constantly interact with their changing environment (position on field or court, other
athletes, etc.), it is unlikely that a movement could be optimized without taking into account the infinite number of potential interactions that might occur. This would necessitate an enormous computational load that is currently not feasible.

Elements of an Optimization Model

Objective Function

Once a movement that meets the above requirements has been selected for optimization research the process of optimization can begin. There are three fundamental elements in any optimization problem. They are the objective function, variables, and model constraints. Almost all optimization problems have a single objective function. An objective function is the task or movement goal that is being optimized. In most cases models attempt to minimize or maximize the objective function. Some models attempt to minimize a given parameter such as the stress in a hip prosthesis (Huiskes & Boeklagen, 1989). Others may have a goal of maximizing a parameter such as the height of a jump (Hay et al., 1976). There are however two interesting exceptions. The first exception is when the model is developed not for minimizing or maximizing but for the achievement of a task goal. An example would be an optimization model developed to result in the flawless performance of a gymnastics maneuver (Yeadon & Berwin, 2003). The second exception occurs when there are multiple objective functions. This may be used when a researcher wants to optimize a number of different objectives at once (King & Yeadon, 2004). Usually, in cases using multiple objective functions, the different objectives are not compatible; the variables that optimize one objective may be far from optimal for the others. Typically problems with multiple objectives are reformulated as single-objective problems by either forming a weighted combination of the different objectives or by replacing some of the objectives by constraints.
Variables of Interest

The variables of interest are the second element of an optimization model. They are essential because without the variables, the objective function and the model constraints cannot be defined. These unknowns affect the value of the objective function. In other words, for the results of the optimization to truly reflect what it is supposed to, the parameters that are most important to the success of the movement must be included in the analysis. As such, in many cases it is important to review previous research so that all potentially relevant parameters are included.

Model Constraints

Model constraints are the final component of an optimization model. Constraints are often placed on the model to ensure results are within normal or realistic limits. Typically, a set of constraints allows the variables of interest to take on certain values but exclude others. It should be noted however that model constraints are not essential. In fact, it is quite possible for a model to produce reasonable results without putting constraints on the variables.

When all elements of the model are in place, the optimization problem then becomes an attempt to find the values of the variables that result in attainment of the objective function while satisfying the model constraints. Typically this comes in the form of an algorithm that provides an analytical or numerical solution to the variable.

Methods of Optimization

Direct v. Inverse

In addition to the elements comprising the optimization model, there are several other factors that must be discussed in order to understand the various approaches which
can be taken to develop the model. Perhaps the first of these issues is whether the model is to be an inverse or direct model. An inverse model, also known as parameter optimization, examines the captured data of a motion to try to uncover what caused the motion and what made the motion good or bad technique. Another option for optimization modeling is a direct approach. This method, also known as optimal control, involves the use of computer programs to simulate movement to produce an optimal result. A limitation of this method is that when used for muscle modeling, it is difficult to know the force production capabilities because changes in muscle length, contraction history, and the rate of length changes are not well known (J. Dapena, personal communication, July 15, 2004).

**Dynamic v. Static**

In addition to inverse and direct modeling approaches, another concern when formulating an optimization model is whether to use a static or dynamic approach to optimization. Static models perform the optimization procedure without regard to time. Static models typically attempt to optimize one selected position of a movement without regard to prior movement history. While these models have been used in a completely sequential fashion to emulate movements (e.g., Kilpatrick, 1970) to truly optimize an entire movement would result in an extremely large computational load since every instant in time corresponds to a fairly sizable and often non-linear optimization problem. In addition to this drawback, Anderson and Pandy (2001a) noted several other criticisms of static optimization. First, inverse dynamics problems are highly dependent on the precise collection and processing of kinematics (Davy & Audu, 1987; Patriarco et al., 1981). Second, the time-independent performance criterion required by static optimization may not permit the objectives of the motor task to be properly characterized.
(Hardt, 1978; Pandy et al., 1995). Third, the time-independent nature of static optimization makes it relatively difficult to account for muscle physiology appropriately (An et al., 1989; Hardt, 1978; Kaufman et al., 1991; Prilutsky et al., 1997). In addition to these criticisms, another concern is that static models tend to underestimate stresses because they cannot take into account inertial forces (Garg et al., 1982; Leskinen, 1985). Finally, the use of inverse dynamics in static optimization may not be appropriate for examining muscle coordination principles (Kautz et al., 2000; Zajac, 1993).

In contrast to static optimization models, dynamic models optimize the movement patterns with respect to the entire time history. For dynamic movement modeling, many have resorted to and advocated dynamic programming (Ayoub et al., 1974; Yamaguchi, 1990). A dynamic optimization method is potentially more powerful than static optimization for two reasons (Anderson & Pandy, 2001b). First, the goal of the motor task can be included in the formulation of the problem because a time-dependent performance criterion can be used. Second, problems may be formulated independent of experimental data because dynamic optimization is a forward dynamics method. These two strengths combine to allow prediction of a motor task that is not so easily accomplished using a static approach.

Despite its potential strengths, dynamic optimization also has drawbacks. Much like static optimization models however, dynamic models have also been constrained by computational limitations. The number of variables used in a dynamic model has normally been limited for much the same reason that the number of instants in static modeling has usually been limited. That is, computational power has limited the use of highly detailed dynamic models. Because of the enormous computational cost, dynamic
optimization solutions for complex movements have been few and have lagged behind their static counterparts in terms of model complexity (Yamaguchi & Zajac, 1990).

In comparing the two modeling techniques, Davy and Audu (1987) found differences in the results for optimizing the swing phase of gait. Anderson and Pandy (2001a) however found that static and dynamic optimization techniques are capable of producing nearly identical results for gait. The discrepancy between these two findings may be because Davy and Audu only simulated the swing phase of gait in the sagittal plane, only examined nine muscles, and the joint moments used as input to the static optimization were different from those predicted by the dynamic optimization solution.

Many of the computational issues limiting both static and dynamic optimization are beginning to change with advances in computer processing power and new more efficient dynamic algorithms (e.g., Thelen et al., 2003; Zhang et al., 1998). Anderson and Pandy (2001a) suggested that dynamic optimization might be preferred or even necessary under any of four conditions. The first condition under with dynamic optimization may be more appropriate is when accurate experimental data are not available. This is due to the fact that dynamic optimization is not strongly dependent on the accuracy of the input kinematic data. Second, when activation dynamics play an important role in the research, such as during sprint cycling, dynamic optimization may be the best option. Third, dynamic optimization may be necessary when examining activities that are inherently characterized by a time-dependent performance criterion such as jumping for height. Finally, dynamic optimization may be the best option when predicting a novel movement. Combining a forward dynamics approach with a performance criterion it is possible to predict novel movement. Because of this, dynamic optimization offers a powerful framework for investigating the influences of musculoskeletal structure on biomechanical...
performance. In contrast, static optimization is more of a descriptive methodology in which the motion undertaken by the model is prescribed by the measured kinematics.

Overall, static optimization appears to provide a practical means of descriptively estimating in vivo quantities like muscle and joint contact forces with little computational expense. When estimates of these quantities are insufficient for understanding movement, dynamic optimization offers a more powerful, although more costly, alternative.

**Optimization Model Examples**

**Prostheses**

Optimization models have been used for a variety of topics ranging from prosthetic design to sporting movements. Prosthetics make an ideal topic for this type of research because of the complex and varied components used to make them and the need to closely replicate the movement characteristics of the natural appendage. The research in this field typically strives to optimize stress distribution and develop a joint which functions in the same manner as a natural joint. To accomplish this, the use of finite element analysis has proven successful.

In a combination of physical and optimal control mathematical modeling, Huiskes and Boeklagen (1989) optimized the shape of a hip prosthetic to reduce stress concentrations. They used finite element analysis to iteratively determine optimal prosthetic designs to minimize interface stresses. The method was then applied to a simplified one-dimensional model of cemented femoral stem fixation using acrylic cement. The optimized design produced a 30-70% interface stress reduction. The results were then validated using a two-dimensional finite element model. Using similar methodology, Dargahi and colleagues (2003) optimized the geometry of a total knee implant to minimize stresses on the whole tibial component of the implant and create a
normally functioning joint. Lee and colleagues (2004) also used finite element analysis to optimize a monolimb, or transtibial prosthetic that has a socket and shank molded into one piece, to minimize peak stress on the shank of the prosthetic. The results of these studies indicate that optimization of prosthetics can be useful for both prosthetic design to minimize wear and closely replicate a natural limb, appendage, or joint.

**Anatomical**

Closely related to prosthetic optimization is that of anatomical optimization. As such, anatomy has been one of the primary beneficiaries of optimization modeling. Typically this research has used a direct analysis approach to optimize joint parameters for a selected criterion. For example, Mazz`a and Cappozzo (2004) developed an optimized simulation algorithm for estimating ankle, knee and hip joint kinetics and kinematics using external resultant loads and readily available joint parameters. Kinematic functions were iteratively generated using an optimization algorithm and corresponding ground reaction loads. Kinematic coordinates were represented using B-splines and modified by manipulating control points. When the criterion between estimated and measured ground reaction components was satisfied, the iterative procedure produced kinematic and kinetic estimates. The model was elaborated on and the parameters were optimized for accuracy and robustness using a benchmark motion in a simulation exercise. Other anatomical simulation research has involved the estimation joint moments under dynamic conditions (Amarantini & Martin, 2004), optimization of cardiac fiber orientation for homogenizing fiber strain at the beginning (Rijcken et al., 1997) and during ejection (Rijcken et al., 1999), movement of the spinal system (Dietrich et al., 1991), and kinematic modeling of the human shoulder complex (de Groot & Brand, 2001; Turner & Engin, 1989).
Everyday Tasks

Walking

Another subject of optimization research is “everyday” tasks such as walking and lifting objects. In fact, a gait study by Chow and Jacobsen (1971) may have been the first to optimize a human movement using dynamic methods. As mentioned earlier, they proposed that an activity as basic as walking is likely to obey an inherent "principle of optimality." They optimized the moment profiles observed in gait using a dynamic model that actuated the locomotor elements to create the observed patterns of the normal gait. The result produced a multi-arc programming problem with three stages. Each stage involved dynamic constraints that reflect the particular nature of the activity.

Since the early study by Chow and Jacobsen (1971), there have been many other attempts to optimize various aspects of gait, most of which have focused on the muscle dynamics associated with the movement. Typically, those studies which focus on muscles and their mechanical behavior have used a three-element, Hill-type model (Zajac, 1989) and a direct modeling approach. In a review of such models as well as those studying activation patterns, Prilutsky and Zatsiorsky (2002) found that they can provide a reasonably accurate estimation of force output and activation patterns for individual muscles.

An early example of this line of research optimized the muscle forces acting on the hip, knee, and ankle joints during normal walking using a linear programming model to determine the level of muscular activity at each joint with the objective of minimizing the torque at the joints (Seireg & Arvikar, 1975). A single model constraint was placed to ensure that the forces at the joints were in equilibrium. Other studies have solved the muscle force sharing problem (Davy & Audu, 1987). In this study, both static and
dynamic optimization techniques were used for predicting muscle forces in the swing phase of gait. The objective function for the dynamic optimization was a combination of the tracking error and the metabolic energy consumption. The Fletcher-Reeves conjugate gradient algorithm was used to solve the dynamic optimization problem and the static optimization problem was solved using the Gradient-restoration algorithm. The model showed the influence of internal muscle dynamics on muscle control histories in relation to muscle forces. The static optimization results were found to be very sensitive to the differentiation procedure used in the static analysis indicating that results of static and dynamic optimization techniques are not always equivalent.

Noting that a basic and essential movement such as walking should display some inherent optimization, Alexander (2002) tested this notion by developing a direct optimization model that predicts metabolic rates for all conceivable gaits of a simple biped model. The results indicated that humans seem to make slight modifications in their gait to minimize metabolic costs and run only when it is necessary to go faster. At any given speed, stride length, duty factor, and shape factor to minimize energy costs.

In addition to the optimization of muscle forces and energetics in gait, other studies have attempted to optimize muscle excitation patterns in gait (Anderson & Pandy, 2001b; Pedotti et al., 1978). In the study by Anderson and Pandy (2001b) a dynamic model was to optimize muscle excitation histories, muscle forces, and limb motions with the intent of minimizing metabolic energy expenditure per unit of distance traveled. Model constraints ensured symmetry of muscle excitations between the right and left sides. The model reproduced features of normal gait such as patterns of body segment displacements, ground-reaction forces, and muscle activation patterns. The results suggested that human walking movements are optimized to minimize metabolic energy
per unit of distance traveled. Anderson and Pandy (2003) followed up this research with another study using similar methodology to quantify the contributions of individual muscles to support the whole body during normal gait using a muscle-actuated model of the body using a dynamic method. Muscle contribution was defined by its contribution to the time history of the vertical GRFs. The optimization process successfully identified which muscles were responsible for support at various points in the gait cycle.

In an especially ambitious gait study using direct optimization modeling, Collins (1995) used a dynamic optimization technique to examine sagittal-plane movement of the lower limb. The model took into consideration the possibility of antagonistic and synergistic muscle action as well as the load bearing roles of the cruciate ligaments. Optimization models were developed to minimize total muscle force, squared muscle force, muscle stress, intra-articular contact force, instantaneous muscle power, and total ligament force. All possible limiting solutions of the system unknowns were resolved using dynamic equations with constraints that intra-articular contact forces be compressive and muscle and ligament forces tensile. It was shown that of the 498 possible outcomes, the minimum number of simultaneous admissible solutions for any subject ranged from three to 18. This finding supports the notion of redundancy within human movement. Optimizations for minimal total muscle force, squared muscle force, muscle stress, intra-articular contact force and instantaneous muscle power produced very similar muscle activation patterns over the gait cycle. Minimal total ligament force was the least successful tested performance criteria in terms of selecting solutions that closely matched the EMG patterns. The results indicated that the leg musculature does not always act to protect the cruciate ligaments.
Industrial Engineering

In addition to walking, other “every day” activities have been the subject of optimization research. Of particular interest is the research from the field of industrial engineering, especially the specialization of ergonomics, using lifting activities for optimization modeling. This field has optimized various movements using both captured data and computer model simulations. While inverse optimization of tasks such as standing from a chair (Pandy et al., 1995) and reaching movements (Zhang et al., 1998) have come from the field of industrial engineering, the large majority of research has focused on lifting tasks. Lifting models have been developed to estimate the stresses on the musculoskeletal system, especially the lumbar spine. This has proven quite useful because the output of the model can be used for further analyses or as input into other computer simulations.

Both symmetric (e.g., Muth et al., 1976) and asymmetric (e.g., Jager & Luttman, 1989) lifting motions for a variety of optimization criteria ranging from minimization of joint torques (Muth et al., 1976), compressive forces (Jager & Luttman, 1989); moment profiles (Chaffin & Andersson, 1991), mechanical efficiency (Dutta & Taboub, 1989), and prediction of motion patterns (Ayoub, 2003; Smith, 1980). Two notable examples have come from this field of research. In a good example that not all attempts at optimization modeling are successful, Buchanan and Shreeve (1996) critically evaluated the modeling potential of several optimization cost functions for predicting muscle forces in the elbow and wrist during isometric loading. Models accounting for muscle moment arms, physiological cross-sectional area, specific tension, and percent fiber type were used to separately solve for minimization of sums of muscle force, stress, normalized force, and fatigue. The cost functions were examined with the elbow joint under equal
flexion-extension, supination-pronation, and varus-valgus loads. Interestingly, the choice of cost function had little influence on the results. Also notable is the fact that the examined cost functions were not able to reliably estimate muscle activation as a function of load direction and specific synergistic relationships between muscle pairs were not accurately predicted.

In a second notable study, a very flexible and efficient optimization model was developed for the prediction of lifting motions (Chang et al., 2001). The objective function values of the task could be selected depending on the purpose of the model. Lifting patterns were generated using a computer program to generate movement patterns that would reduce the overall objective function values. The authors suggested that the flexibility of this model allows it to have greater applicability to changes in various conditions. With this method, constraints can be added anywhere within the lifting cycle without needing to rewrite the entire program. A similarly flexible model was also developed by Pandy and Anderson (1998). Due in part to the high degrees of freedom used in the development of the model, it was able to simulate a wide range of locomotor tasks such as walking and running as well as jumping.

**Sports**

Not only “everyday” tasks have been optimized. In fact, of all the activities that expert models have been developed for, sporting activities have perhaps received the most attention. Much like the examples mentioned above, the subjects of sports optimization have been either discrete or continuous tasks or movements performed in closed environments. In a related issue, sports optimization research has focused on movements in which performance is highly dependent on technical skill rather than
strategy or gamesmanship. Because of these issues, sports such as track and field, gymnastics, and diving have been the most frequently examined.

**Jumping**

**Vertical Jump**

The vertical jump is a common test used to assess lower body power in sports that require explosiveness (Fleck et al., 1985; Hakinnen, 1993; Hartman & Pandorf, 2000). It involves an athlete performing a maximal effort jump for height from a standing position. This relatively simple movement was perhaps the first athletic movement examined using optimization modeling. In studies by Hay and colleagues (1976, 1981) a theoretical model for the standing vertical jump was developed by describing the performance parameters in the movement and analyzing data from a large number of male athletes to evaluate the model. They calculated the correlation between each of the parameters in the model with the height jumped to determine which parameters might be most important, and then conducted a multiple regression analysis to determine which of the parameters contributed most to explaining the performance of each individual. The results suggested that the torques developed at the shoulder, hip, knee and ankle joints were important in the performance of male subjects.

In contrast to the inverse method used by Hay, direct modeling approaches using simulations of the human body have also been used to determine the optimal muscle activation patterns that would produce a maximal vertical jump (Anderson & Pandy, 1999; Pandy et al., 1990). In the study by Anderson and Pandy (1999) muscle activation dynamics were modeled using a first-order process. A dynamic optimization method was then used to calculate the pattern of muscle excitations that would produce the highest vertical jump. Quantitative comparisons between model and experimental data indicated
that the model was successfully able to reproduce the kinematic, kinetic, and muscle-coordination patterns characteristic of humans jumping to their maximum achievable heights. Similar models have also been used for the optimization of power contribution of individual muscles in the standing vertical jump (Pandy & Zajac, 1991).

**Horizontal Jumping**

In addition to the vertical jump discussed above, the running jumps from the sport of track and field have also been the subject of optimization research. For instance, a study by Hay and colleagues (1986) optimized the track and field event of long jumping. In this study, a model was developed to identify the selected kinematic variables of long jumping technique that are most influential on the distance of the jump. The study examined the best trials of the long jump finalists competing in the U.S. National Championships using 3D motion analysis. An inverse dynamic approach was used. Results indicated that horizontal velocity at takeoff into the fourth-last stride, the change in horizontal velocity during the next support phase, the horizontal and resultant velocities at takeoff and the flight distance accounted for the greatest percentages of variance in the distance of the jump.

A different modeling strategy was used in a more recent study on triple jumping by Yu and Hay (1996). In this study, phase ratios were optimized for four elite triple jumpers using the distance of the jump as the objective function. Preliminary analysis indicated that losses in a jumper’s horizontal velocity during a support phase had a significant positive linear correlation with the gain in the vertical velocity during the same support phase. Based on this relationship, an optimization model for the longest actual distance was developed to determine the optimum phase ratio for each jumper. The optimization model for the longest distance was based on the relationship between
horizontal and vertical velocity during the support phases of each jump. The results indicated that each jumper had a distinct optimum phase ratio. This is notable because it suggests that some models may need to be individualized to a particular performer.

Despite the relatively common use of elite athletes in optimization research, it is not without disadvantages. For example, Lees and colleagues (1994) stated that using elite athletes in experiments makes it difficult to establish the investigated relationships because elite athletes typically have little variability in their performance. Using a more theoretical approach would seemingly allow all input parameters to the equations of movement to be controlled. However under practical circumstances, Ramey (1974) suggested that it is likely that these parameters are dependent on one another and may even be coupled in complex non-linear relationships. If this were indeed the case, it would make it difficult to analytically describe how changes in one input parameter affect the others. These shortcomings could potentially be solved by using muscle function data (e.g., force and contraction velocity) obtained via inverse dynamics analysis. Unfortunately, such analysis has not been reported for any of the takeoffs of track and field jumping events. This may be because the impact encountered at touch down is so great that it makes an inverse dynamics calculation highly sensitive to smoothing procedures. The use of a muscle driven simulation model provides a means of circumventing these problems.

In light of the aforementioned shortcomings, Sørensen and colleagues (1999) developed a muscle driven simulation model of the long jump takeoff. This optimized model was found to move very similar to a real jumper, and as a result was considered valid for studying muscle function during long jump take off. A similar model was later
used by Seyfarth and colleagues (2000) to determine optimum takeoff techniques and muscle design in the long jump.

**High Jump**

The third track and field jumping event, the high jump, has also been modeled using optimization techniques (Alexander, 1990). In this study, Alexander expanded on his earlier model for the standing jumps (Alexander, 1989) by developing a model capable of predicting realistic force patterns and jump performance for the high and long jumps. The model took into account mechanical properties of muscle to predict optimum take-off techniques. The model consisted of a trunk and a 2-rigid-body leg. Dimensionless quantities were used to express forces as multiples of weight of the body \((mg)\); distances as multiples of the leg segment length \((a)\), and times as multiples of \((a/g)^{1/2}\). For purposes of model validation, realistic average values were substituted to test whether the model could reproduce previously observed values. Constraints were placed on the model to ensure that the knee extensors be active throughout the stance phase. Approach speed and leg touchdown angle were also constrained to match values observed in elite level jumpers. The high jump model produced vertical displacements and GRFs consistent with observed values. It was not however able to reproduce ground contact times similar to experimentally observed data. Likewise, the long jump model was able to reasonably produce horizontal displacements but was slightly less successful in its prediction of GRFs. The predicted force curve rose more steeply than observed values. Like the high jump model, ground contact times were also slightly too long. The authors suggested that the deficiencies of the model were likely due to the absence of a foot. Despite these shortcomings, the models were able to reasonably simulate the high and long jump takeoff parameters which result in realistic performances.
Running

As one of the most essential movements to sports in general, it is only natural that running and sprinting has been the subject of much optimization research. Unlike many other human invented sporting activities though, one could expect that running motions would be an optimized product of natural selection. Several studies have attempted to answer this question using force output (Behncke, 1987), force and energy reserves (Behncke, 1993), and physiological parameters based on the first law of thermodynamics (Ward-Smith, 1985) as objective functions. A recent example of running optimization modeling solved for the power generated by a runner’s muscles (Yanai & Hay, 2004). The researchers hypothesized that runners will select the combination of stride rate and stride frequency that minimizes the power generated by the muscles regardless of their running speed. In this study a 2D model of a runner consisting of a trunk and two legs was defined. A force actuator controlled the length of each leg, and a torque actuator controlled the amplitude and frequency of the forward and backward swing of each leg. The sum of these two powers was determined for a variety of stride rates at a range of speeds. The stride rates and length was optimized for the range of speeds by minimizing for power output at each speed. The leg motion was constrained for amplitude of forward and backward movement of the legs and the minimum ground contact time needed to maintain steady-state running. The results of the optimization were similar to human running characteristics indicating that human running is optimized for efficiency.

Throwing

In addition to jumping and running, throwing movements have also been the subject of sports optimization modeling. Optimization techniques have been applied to general overhand throwing motions such as those seen in baseball (Alaways et al., 2001)
and javelin throwing (LeBlanc & Dapena, 2002; Komi & Mero, 1985) but much of the research has focused on the less commonly seen motions of the track and field throwing events.

For example, Alexander (1996) examined 30 male and 31 female subjects in an attempt to determine the relative importance of selected anthropometric, strength, and technique parameters to their performance. They developed optimization models using multivariate analysis of variance with repeated measures for male and female sub-elite level shot putters and found that performance indicators in the event were gender specific. The critical parameters for female throwers included knee extension during the glide, elbow velocity during delivery, and a greater shoulder flexion angle at release. For male throwers, center of gravity velocity during glide, vertical acceleration of center of gravity during delivery, and trunk angle at the start of glide were the most important parameters to produce longer throws. This difference supports the notion that optimization models may need to be gender-specific.

Differences between the optimal technique of men and women were also reported by Hay and Yu (1995). In this study, an inverse optimization was used to determine the kinematic parameters of discus throwing that were most critical to the distance of the throw. This study examined elite male and female throwers. Interestingly, differences in significant performance indicators were observed for each gender. For men, the results indicated that the change in speed of the discus during the second double support phase was more influential on the performance than the change in speed during any other phase of the throw. For females, changes in speed during the flight phase and during the second double support phase accounted for much of the distance of the throw.

The previously mentioned study examining the discus throw (Hay & Yu, 1995)
was later expanded upon using an identical direct optimization method to determine the
effect of selected kinetic and kinematic variables on performance in the men’s discus
throw (Yu et al., 2002). A force plate embedded in the throwing ring was used to collect
kinetic data at specific events. 3D kinematic data were also collected at specific events in
the throw. Multiple regression analysis was performed using measured distance of the
throw as the objective function. Results indicated that the kinetics and kinematics of the
delivery phase of the discus throw are vitally important to performance. Right hip
extension and internal rotation moments and left knee extension moment during the
delivery phase were also significantly correlated with performance. In addition, GRFs on
the left foot during the first single-support phase, on the right foot during the second
single support phase and on both feet during the delivery phase were significant
indicators of performance. Using similar methodology, similar findings were reported in
a previous optimization study on the discus throw (Gregor et al., 1985). This study
indicated that in addition to the release parameters, trunk angle, foot position at release,
linear and angular acceleration, and mechanical energy transfer and net moments of force
about a joint are important for achieving elite throwing.

**Cycling**

Cycling provides another interesting example of sport optimization modeling.
Unlike other sports where performers display greater movement variability the sport of
cycling demands that the movement pattern is constrained by the dimensions of the
bicycle, particularly that of the crank. As such, muscle dynamics more than movement
descriptions are used in the optimization process. For example, using a direct and
dynamic optimization strategy, van Soest and Casius (2000) investigated how the power-
velocity relationship derived from Hill's force-velocity relationship and activation
dynamics affect the optimal pedaling rate. A skeletal model made up of a 2D linkage of rigid segments controlled by eight Hill-type muscles was used to simulate a rider. Activation patterns were analyzed to examine power output over a wide range of pedaling rates. Model simulation results were in good agreement with experimental data on muscle activation, pedal forces, and the power-pedaling relationship. The model predicted an optimal pedaling rate of 120 rpm, however at this rate the muscles were found to contract at velocities below those that maximize their power output. This indicates that the optimal pedaling rate is not completely explained by the power-velocity relationship of muscle and that the pedaling rate that maximizes mechanical power in sprint cycling is a product of the interaction between muscle activation patterns and Hill’s power-velocity relationship.

In more recent research, Thelen and colleagues (2003) introduced a dynamic optimization technique that could be used to compute muscle excitation patterns with a much lower computational cost than previous models. This model combined static optimization with feed-forward and feedback controls to drive the kinematic trajectories of the musculoskeletal model toward a predetermined set of kinematics for bicycle pedaling. The algorithm was tested by computing the muscle excitations that drive a 30 muscle, 3-degree-of-freedom model of pedaling to track measured pedaling kinematics and forces. The models produced almost exact simulations of experimental values for kinematics, pedal forces and muscle excitation patterns.

**Diving**

The sport of diving has also been examined using an expert model approach. For instance, Sprigings and Miller (2004) used a direct model strategy of a diver to gain insight into the primary factors responsible for producing height and rotation in dives.
from the reverse group. The onset times and lengths of activation for the “muscles” were used as variables and total angular displacement of the diver as measured from last contact to the point where the diver’s center of mass passed the level of the springboard or platform served as the objective function. The optimization process indicated that as the number of reverse somersaults increases, both the angle of the lower legs with respect to the springboard and the angle of knee extension at completion of takeoff should decrease.

Another diving model using similar methodology was developed by Cheng and Hubbard (2004) to investigate optimal jumping strategies from compliant surfaces and apply it to springboard diving. The model consisted of a weightless leg actuated by knee torque and a single unit torso mass centered above the leg. Maximum jump height for a male and female was calculated by controlling knee-torque activation level as a function of time. Minimum and maximum knee angle, rate of change of normalized activation level, and contact duration were constrained in the optimization process. The simulation results for springboard depression and diver takeoff velocity were found to be very similar to experimental data. The model did however have difficulty accurately predicting jump height at high springboard fulcrum numbers. The authors speculated this was likely because divers may have difficulty behaving optimally at non-preferred fulcrum settings. The results indicated that increasing leg length is more effective in increasing jump height than increasing mass.

**Gymnastics**

Gymnastics has also provided some interesting additions to sport movement optimization research. In a rare example of a movement being optimized for a task goal rather than minimization or maximization of variables, Yeadon and Berwin (2003)
optimized the performance backward long-swing on the rings apparatus using a direct
dynamic approach. Because points are deducted if gymnasts are in motion when they
complete the backward long-swing, the ability to successfully conclude the movement in
a stationary handstand is vitally important. Previous modeling research (Sprigings et al.,
1998) using a direct optimization strategy found that optimal performance of the task
resulted in a residual swing of more than 3° in the final handstand. Yeadon and Berwin
(2003) expanded on this research to determine whether perfect execution of the maneuver
was realistically possible. As such, attainment of a perfectly vertical and motionless
handstand at the conclusion of a backward long-swing was the objective function. Three-
dimensional data were collected for cable tension and athlete position of an elite gymnast
performing the backward long-swing. Anthropometric data were also calculated. These
data were used to develop a simulation model of a gymnast swinging on rings.
Constraints were placed on the model to ensure apparatus elasticity was within the
mandatory range and performer movement was symmetrical and limited to the sagittal
plane. The movement criterion for perfect execution was cable elevation angle, cable
angular velocity, and the rotation angular velocity having values of zero, and the rotation
angle to be 360°. The simulated performance from the optimization process initiated from
a handstand with 2.1° of swing and using realistic modifications to the gymnast’s
 technique resulted in 0.6° of residual swinging the final handstand. Sensitivity analysis of
the task objective to variations from the optimum indicated that body configuration must
be timed to within 15 ms to attain a handstand with minimal residual swing.

Not all optimization research on gymnastics uses the attainment of a movement
goal as the objective function. Other gymnastics studies for example have attempted to
optimize movement patterns for the backward giant circle (Hiley & Yeadon, 2003),
Yurchenko layout (Koh & Jennings, 2003) and the somersault rotation (King & Yeadon, 2004) to produce the greatest angular momentum. In the study by King and Yeadon (2004) developed a model with the objective of maximizing the angular momentum in a somersault rotation. Approach characteristics and takeoff techniques in somersault rotation were investigated. A five-segment planar simulation model, with variable anthropometry was used to simulate a closely matched recorded performance of an elite gymnast’s double layout somersault. Three optimizations were carried out to maximize the somersault rotation with different sets of initial conditions, each using rotation potential as the criterion measure. The first optimization condition optimized joint torque activation timings while keeping the initial linear and angular momentum the same as the double layout somersault a double straight somersault. Rotation potential under the optimized joint torque activation condition increased 19% over the actual performance. The second condition optimized approach velocity and resulted in a 42% reduction in rotation potential when activation timings were unchanged but increased rotation potential 31% once activation timings were re-optimized. The third condition optimized angular momentum and resulted in a 4% reduction in rotation potential when activation timings were unchanged but a 9% increase in rotation potential when activation timings were re-optimized. These results point to the fact that optimizing one parameter while keeping others unchanged may in fact have a detrimental effect on the performance criterion.

**Speed Skating**

Much like the continuous tasks running and walking, the sport of skating has proven an ideal subject for optimization research. For example, Marino (1983) examined the mechanical factors associated with speed skating acceleration by using Pearson
product moment correlation analysis, followed by multiple regression analysis to predict the time to skate 6 m using a combination of structural and biomechanical performance factors. Allinger and Van den Bogert (1997) expanded and verified the work of Marino by developing a model to optimize stroke time, glide time, push-off velocity, and push-off direction to produce the fastest steady-state speed on a straightaway. This model is notable because it factored in the leg length, instantaneous power, and average power of a skater in the optimization process. The research used a dynamic model, complete with anatomical and physiological constraints. Results from the model indicated that a number of skating techniques can be used to achieve similar steady-state speeds. They also found that increasing a skater’s average power output decreases the range of optimal skating techniques and increases the top skating speed. Increasing instantaneous power output was found to increase the range of techniques a skater may use for a given speed. The authors suggested that this model could easily be applied to individual athletes to determine if changes in technique or if improvements in power production are necessary to improve their steady-state skating speed.

Another study focusing on speed skating on a curve developed an optimization model for power output based on the geometry of the speed skating oval and the sideward push off characteristics exhibited by speed skaters (de Boer et al., 1988). Power delivered by the skater and power lost due to air and ice friction was determined from video and film analysis of the women’s 5,000 m races at the European Championships. The power predictions of the model compared well with measured power used to increase the kinetic energy of the center of gravity thereby validating the model. The results indicated that skaters who want to accelerate in the curves should increase their work per stroke.
**User-Equipment Interaction**

The use of expert models in sport is not confined to movements alone. Optimization models have also been developed for sports equipment as well as the interaction between an athlete and their equipment. The results of this research can be valuable because in many sports, the performance of a given movement is highly dependent on either the equipment itself or the interaction between the performer and their equipment. Because the focus of this review is on optimization of human movement, only studies that optimized the interaction between a performer and their equipment interaction will be reviewed and those studies that solely optimized equipment will be ignored.

Several attempts have been made to optimize the interaction between a sportsperson and their equipment. Optimized interactions have ranged from the bending stiffness of a sprinter’s spike (Stefanyshyn & Fusco, 2004) to golf club head shape (Nakai et al., 2002). In one example of such research, Ekevadand and Lundberg (1995) simulated the pole vaulting action using a 2D finite element model of the pole and the vaulter. The performance of an elite pole vaulter’s performance was recorded and used as a template to match a simulation model whose muscle torques would result in a similar movement of the performer and pole. Optimum pole length was determined constraining the vaulter’s movements to match the pre-recorded performance, stiffness of the pole, and initial kinetic energy of the performer and using performance as the optimization criterion.

As previously mentioned, optimization research for bicyclists is controlled by the fact that the cycle itself constrains the movement patterns of the performer. This very issue makes cycling an ideal subject for optimizing the interaction between the performer
and their equipment. Gonzalez and Hull (1989) used a biomechanical model of the lower limb and its interaction with the bicycle crank to optimize joint moments at various parameters. In this study, the leg-bicycle system was treated as a five-bar linkage.

Average power output was held constant at 200 W. This study used a rider of average anthropometry to determine the optimal values for each bicycle parameter. The effects of pedaling rate, crank arm length, seat tube angle, seat height, and longitudinal foot position on the pedal were examined. A multivariate optimization was performed using the combination of the variables to minimize muscle joint moments. Further tests revealed that rider size had a significant influence on the results. Results indicate that optimal crank arm length, seat height, and longitudinal foot position on the pedal increase as the size of rider increases whereas the optimal cadence and seat tube angle have an inverse relationship. As in the several of the previously mentioned studies, this points to the need for some models to be individualized. Other studies examining a bicycle-rider system have used a dynamic optimization to solve optimal chain ring shape for minimization of energy costs (Kautz & Hull, 1995), predict pedal forces using joint moments and muscle stress (Redfield & Hull, 1986), optimize crank length, pelvic inclination, seat height and rate of crank rotation to maximize power output (Yoshihuku & Herzog, 1990), and solve for rear-wheel suspension parameters to maximize the value of a frame’s rotation (Good & McPhee, 1999, 2000).

Much like cycling, wheelchair athletics makes an ideal subject for optimization. The performance of wheelchair athletes has also been the subject of optimal control research (Cooper, 1990; Guo et al., 2003). Guo and colleagues (2003) developed an expert model for the interaction between a person and a wheelchair by examining the affect of wheel chair design and fit on the relative positions and orientations of the upper
extremity relative to the hand-rim and the wheel axle. Five hand positions from five subjects exerting maximal effort to propel an instrumented wheelchair were examined. A subject-specific quasi-static model of the upper extremity was developed to maximize the wheel progression moment. Model predictions revealed that the optimal progression moment generation is affected by an individual’s anthropometric parameters, joint strengths and also the direction of force applied by the hand on the hand rim.

The previously mentioned studies all attempted to optimize the interaction between a performer and their equipment. One notable study however optimized the interaction between an athlete and their competition environment (Greene & Monheit, 1990). In this study, researchers determined the optimal geometry for an oval sprint track. Track aspect ratio was defined as the ratio of curves to straight portions on an oval running track. Using a simulated runner at various speeds, equations were derived to determine the optimal track ratio for maximizing running performance. Velocity deficits for several varied but common track configurations were used to determine the optimal configuration. Results indicated that a perfect circle is the best shape for running track configuration to maximize performance.

**Projectile Motion**

The final category of sport optimization research that will be reviewed is that of sport projectiles. Sport projectiles cover a wide range of topics from the obvious kicked and thrown balls to the less obvious projected athlete scenarios observed in the track and field jumping events. On the surface, research attempting to optimize the initial projection parameters of objects in flight would appear quite simple. In reality however, this may not always be the case and research in this area has brought new insights into projectile motion theory.
Maximizing Accuracy

Optimization of projectile motion parameters has focused primarily in two areas: maximizing the accuracy of a projected object to a predetermined target and maximizing the range of a projected object. The first category of projection parameter optimization research has attempted to determine the best projection parameters to result in the attainment of a goal task, such as successfully shooting a basketball. Brancazio (1981) examined the release parameters in shooting a basketball and found that the relationship between ball release angle and the chances of the ball going through the hoop is complex because factors such as performer effort and the margin for error that the ball has when it gets to the basket need to be considered. He found that increasing the height of release significantly increases the likelihood of successfully making a basket. Schwark and colleagues (2004) expanded on this research by attempting to maximize the accuracy of a basketball free throw shot from a wheelchair. This study was somewhat unique in that it attempted to optimize both the release conditions and the corresponding arm movement patterns in wheelchair basketball players. Parameters from a 2D, three-segment model were used to optimize the release conditions. The optimization process took two steps. The first step involved an outer computational loop to optimize the magnitude and timing of the muscle torques that generate arms’ motion. The second step used an inner computational loop to determine the optimal angle and speed of the ball at the moment of release. The inner loop validated both Brancazio’s (1981) and Hay’s (1993) approaches to determining the optimal release angle. As would be predicted, the lower release height of a wheelchair basketball player required that the release angle and release speed be greater for successful shots from the same location relative to the baseket. The optimal release angle and speed was determined to be 53.8° and 7.4 m/s, respectively for a
wheelchair athlete shooting the ball at a horizontal distance of 4.09 m from the center of the basket, and 1.30 m below the rim. Because of the greater release angle and speed needed to successfully shoot a basketball from a wheelchair, shoulder torque was also found to be higher. The kinematic optimization model revealed that alterations in initial upper arm position could result in a 43% reduction in flexion torque.

**Maximizing Range**

In addition to the studies mentioned above, optimizing projection parameters for accuracy, several other studies have also attempted to optimize initial projection parameters to maximize the range the projectile travels. Typically, determination of optimal projection angle is the goal of projection parameter optimization. The optimal initial projection angle is the angle that maximizes range. This is because when attempting to maximize range, higher projection velocities and heights will always result in greater displacement. Projection angle on the other hand does not have such a simple relationship with range and as such becomes the obvious choice for optimization.

At first glance, the process of determining optimal projection angles may appear to be a simple matter of calculation using the equation that governs projectile motion:

\[
R = \frac{V^2 \sin 2\theta}{2g} \left[1 + \left(1 + \frac{2gh}{V^2 \sin^2 \theta}\right)^{1/2}\right]
\]

Indeed, early attempts at projectile parameter optimization took this approach (Lichtenburg & Wills, 1978; Soong, 1975). Large discrepancies however have been observed between the mathematically predicted optimal values and measured values from elite (McCoy et al., 1984; Tsirakos et al., 1995) and sub-elite athletes (Cureton, 1939; Dessureault, 1976) for a variety of tasks. Several reviews of the track and field throwing events, (de Mestre, 1990; Hubbard, 2000; Hubbard & Alaways, 1989) have suggested
that other than speed, the optimal projection parameters are dependent on how they are functionally related to maximum achievable release speed. This is likely because humans are limited in such a way that they are not able to produce equivalent velocities at all projection angles. Two mechanisms explaining this phenomenon have been proposed. First, as projection angle increases the performance is opposed by a greater effect of gravity (Linthorne, 2001a; Hay, 1990; Zatsiorsky & Matveev as cited in Zatsiorsky et al., 1981). Second, the structure of the human body may not be able to produce equal force (and as a result velocities) in every position (Linthorne, 2001a). This has profound implications on the optimization of projection parameters for maximizing range because the process must take this dependency into account.

**Throwing**

In light of the aforementioned parameter dependencies, it is crucial to recognize that initial projection speed, height and angle are not independent variables when attempting optimization. Based on the previously cited observations as well as recent research (e.g., Linthorne, 2001a), it appears that both the projection speed and the height are functions of the projection angle. Because of this, when determining the optimum release angle, it is important to understand the relationship between the parameters for a given movement and possibly even for a particular athlete and then substitute the expressions into the projectile motion equation. Several methods may be used to establish these relationships. For example, Red and Zogaib (1977) determined the optimum release angle for throwing a 1.14kg ball by combining the equation which governs the range covered by a projectile in free flight with predetermined relationships between release speed, height and angle for an athlete. The predetermined relationships were established by obtaining measurements of the athlete’s release speed and height over a wide range of
release angles above and below their preferred release angle. The values for release speed and height were then plotted as a function of release angle so that an algebraic expression could be determined for release speed and height as a function of release angle. These expressions were then substituted into the equation governing range of a projectile in free flight and the flight distance was plotted as a function of release angle. The release angle that resulted in the greatest flight distance on the plotted curve was deemed the optimum release angle. Similar methods have been used in other studies to determine the optimal release parameters for the javelin throw (Viitasalo & Korjus, 1988) and the shot put (Maheras, 1995). In these studies, the optimal projection angles were considerably lower than predicted projection angles determined without taking into account the projectile parameter dependencies.

An alternative method to determine the mathematical expressions for the dependent release parameters was used by Linthorne (2001a) to optimize the release conditions for the shot put. In this study, Maheras’ (1995) measurements for release speed, height and angle for five shot putters was presented together with simple models that relate the measurements to the anthropometric and strength characteristics of the athlete. In this study, the expression for height was derived from an anthropometric model of the athlete at the instant of release. The expression for velocity was derived from a model of the forces acting on the shot during the delivery phase of the throw.

Another method for optimization of release conditions relied on a computer simulation model rather than experimental data to develop a simple model of shot-putting that assumed a linear decrease in release speed as release angle increased (Yeadon, 1998). The model predicted the optimum angle of release to be 37°. This was obtained by an appropriate selection of coefficients for the relation between release speed and release
angle. A similar method using a previously developed simulation of javelin flight (Hubbard & Rust, 1984) was also used to determine the release conditions that would maximize the range of the old rules javelin (Hubbard, 1984) as well as the new rules javelin (Hubbard & Always, 1987). A final approach to determine the optimal release parameters for the shot put was used by Hubbard and colleagues (2001; see also de Mestre, 1998). In contrast to the previously mentioned research, Hubbard and colleagues optimized for release speed rather than angle. As in the previous studies the relationship between the projection parameters was determined. 2D data that had been corrected for out-of-plane errors were used in a multivariate regression analysis to determine constraints on each of the projection parameters. As in the previously mentioned studies, the results indicated that achievable release speed has an inverse relationship with release angle and a positive relationship with release height. Release speed was shown to decrease with increasing release angle at about 1.7 (m/s)/rad and decreased with increasing release height at about 0.8 (m/s)/m with small deviation between throwers. Based off of these relationships, the authors suggested that the optimal release parameters for a particular athlete could be determined using similar constraints.

**Jumping**

In addition to throwing motions, jumping actions have also been the subject of projection parameter optimization. Using a similar method to that of Linthorne (2001a), Linthorne and colleagues (2002) collected data on three elite level male long jumpers. The jumpers were instructed to take off at normal, lower and higher than normal takeoff angles. Takeoff speed, angle, and takeoff height for each jump were determined using a 2D filming procedure. As hypothesized, results indicated that all three takeoff parameters
were dependent on each other. In fact, the decrease in projection speed in the long jump was found to be more rapid than for throwing actions. As a result, the optimum projection angle was much lower than even seen in throwing actions (23° vs. 34°). The results were in good agreement with measured data indicating that this method is suitable for establishing optimum takeoff angles for the long jump. Similar results were produced for the optimum takeoff angle in the standing long jump using similar methods (Wakai & Linthorne, 2000).

In an example of projectile motion optimization focused more on aerodynamics and drag forces than initial projection parameters, Seo and colleagues (2002) optimized selected parameters to maximize the flight distance in ski jumping. Wind tunnel test data were used to measure aerodynamic forces acting on a full size model. Body-ski angle and ski-opening angle were used as variables of interest and the flight distance was used as the objective function. Results indicated that the jumper should increase the ski-opening angle in the first half of flight to minimize drag and the body-ski angle should be almost 10˚ throughout the flight to increase lift in the latter half of flight.

**Hitting**

One interesting projectile parameter optimization study developed an optimal control model for the pitch, batting and post-impact flight phases of a baseball to find bat swing parameters which result in maximum range of a hit baseball (Sawicki et al., 2003). The model for batted flight incorporated experimental lift and drag profiles. The model for bat-ball impact included the dependence of the incoming pitched ball angle on speed. The undercut distance and bat swing angle were selected maximize the range of the batted ball. Sensitivity of the maximum range was calculated for all model parameters including bat and ball speed, bat and ball spin, and wind speed. Post impact conditions
were found to be independent of the ball-bat coefficient of friction. Lift was found to be enhanced by backspin produced by undercutting the ball during batting. Results indicated that an optimally hit curve-ball will travel further than an optimally hit fast or knuckle-ball due to increased lift during flight.

**Performance Analysis**

In addition to modeling approaches, other approaches have been taken to provide a framework for the enhancement of performance. While this research has not produced mathematical optimization models per se, this research is nonetheless valuable in a manner very similar manner to optimization models. As such, several notable examples will be given to illustrate the methods and value of this line of research.

Performance analysis with the aim of performance enhancement research has typically used one of three methods: comparison, correlation, and critical review. Research using comparison involves comparison of selected parameters from two or more groups of different performance levels with the aim of determining which parameters are most likely to be responsible for the differences in performance. In an example of research using comparative means, Mann (1986) identified critical parameters for success in sprint races by comparing the results of kinematic data analysis of collegiate level and elite level athletes. Elite level sprinters were found to have lesser hip and knee extension during the support phase and shorter ground contact times.

Correlational studies attempt to determine performance predicting parameters by correlating selecting parameters with a dependent variable. For example, Hay and Nohara (1990) analyzed the long jump technique of elite male and female long jumpers and correlated selected kinematic parameters with the distance of the jump. Similar methods had been used previously on the long jump (Hay & Miller, 1985a) as well to determine
the kinematic parameters that were most influential on the measured distance of a javelin throw (Kunz & Kaufmann, 1983) and triple jump (Hay & Miller, 1985b).

The critical review process involves analytically examining many research sources with the objective of determining which variables are most predictive of performance. An example of the use of critical review for performance enhancement is the review paper on javelin throwing by Barlett and Best (1988). Following a critical review of prior research, the authors provided suggestions for performance enhancement in the javelin.

**Optimizing the Shot Put**

This section of the review has detailed previous successful attempts at optimization and simulation models for a wide range of tasks and optimization functions. Many of these models have even been validated by experimental data (e.g., Anderson & Pandy, 2001b; Ekevad & Lundberg, 1995; Thelen et al., 2003). For the movement of shot putting, several studies have analyzed, and even made suggestions for elite level performance enhancement (Bartonietz, 1996; Dessureault, 1978; Knudson, 1989; Liu et al., 2000; Stepanek, 1990) but there are no known optimization models for the movements associated with elite level shot putting despite it being an ideal subject for optimization (discrete task, closed environment, obvious performance objective).
Chapter 6: Future Considerations for Shot Put Research

Current state of Research

As the previous review indicates much has been written on the action of shot putting. Despite this, much still remains to be known about the movement. Special circumstances unique to the event and the advancement of research methodology make the movement ideal for further research.

Subjects

Doping Influence

Many of the limitations of current and past research on the shot put are related to the participants used in the research. One such limitation is due to the influence of doping on the event. The effects of doping cannot be overlooked when examining past research on the shot put. Doping among elite throwers of the past is well documented (Hilton, 2004). And while it would be naïve to assume that it no longer occurs there two reasons suggest that it is not as prevalent as in the past. First, performance levels in the event at the elite level have slowly declined over the past 20 years (Butler, 2003). Secondly, this performance drop-off has been linked with increased anti-doping efforts over the same time period (Berendonk, 1991; Hilton, 2004; Hoberman, 2005; Ungerleider, 2001). In light of these two points, previous research on athletes competing in an era where doping was more prevalent may not be applicable to current athletes whose physical abilities are not equivalent. While this notion has not been verified, the possibility remains that athletes of previous eras may have achieved greater performance levels despite biomechanical inefficiencies. This is something that would not be reflected in previous research and could make comparison of research findings of different eras difficult.
**Research on Current Elite Athletes is Limited**

In addition to the effect of doping, the techniques used, the skill level of participants, and athlete genders are all issues that leave room for further study. The large majority of current research on the shot put has examined sub-elite athletes ranging from the novice (Jolly & Crowder, 1982) to collegiate level throwers (Hubbard et al., 2001). Only a small number of studies have quantitatively examined elite athletes (e.g., Ariel et al., 2004; McCoy et al., 1984; Young & Li, 2005). Previous research on shot putting (Marhold, 1974; Suskana & Stepanek; 1988) and other activities (Triano et al., 2004) has indicated that the movement kinematics for performers of different skill levels is significantly different even in relatively homogenous subject pools. This may indicate that research findings from one skill level are not applicable to others, especially when the objective is performance enhancement.

**Emergence of Spin**

Another confounding subject-related issue in previous shot putting research is the use of the two shot put techniques. Unlike most activities the shot put is unique in that two very distinct movement patterns have been used to achieve equivalent performances. Previous literature has largely focused on athletes using the glide technique. This is likely because it is more permissible to use less time-consuming 2D motion analysis techniques with the largely linear movement and also because it has been the dominant technique up until recently. Literature is divided on the comparability of the two techniques of throwing the shot. Several authors have noted the differences between the two techniques (Bosen, 1985; Oesterreich et al., 1997; Stepanek 1987) while others considered them similar enough to make comparisons (e.g., McCoy et al., 1984; Young & Li, 2005). Only one known study compared the two techniques (Lindsay, 1994). This study examined the
kinematics of athletes using both techniques and found that while there are similarities the differences were great enough to conclude that the two techniques are distinct movement patterns requiring different skills. This indicates that best results of kinematic research would likely come from examining the two techniques independently.

**Gender Inequity**

As previously indicated current and past research on the shot put has largely focused on men. Previous research has indicated that the temporal and anthropometric parameters related to performance in females are different from those related to male performances (Alexander et al., 1996; Ballreich, 1983; McCoy, 1990; McCoy et al., 1984; Schulter, 1983; Stepanek, 1990). Furthermore, research by Alexander and colleagues (1996) indicated that there are important kinematic parameters that differentiate male and female shot put athletes. This suggests that the findings of research conducted on men may not be applicable to women; and in light of the fact that women have rarely been examined, reinforces the need for further research on women athletes.

**Methods**

In addition to the subject-related issues mentioned above regarding the shot put several methodological issues also leave room for further research. First of all, the large majority of research on the shot put has been descriptive kinematics. Very few attempts have been made to analyze the movement at a deeper level.

**Kinetic Research Limited**

Kinetic research on the shot put is especially limited. Those studies that have examined the kinetics of the movement tend to have one of three drawbacks. First, much of the kinetic research is outdated. Indeed, most of the available kinetic research originates from decades old unpublished Eastern Bloc research. In light of the
aforementioned potential effects of doping on shot put research, and considering the
effect that doping might particularly have on a performer’s capacity to produce force it
would appear that further research is necessary. This research would compliment the
kinematic research and provide insight into the forces that result in the observed
movements.

Much of the kinetic research has also used potentially less accurate indirect means
of determining the forces involved in the movement (Samotsvetov, 1961). This research
examines force dynamics as well as work and energy relationships in the shot put by
using known relationships with mass and acceleration. In fact only one known study
(Machabelli as cited in Lanka, 2000) examined the forces directly applied to the
implement. Others have attempted to determine ground reaction forces by examining the
acceleration of the implement. This method can produce errors and does not provide as
much information as data from a force platform.

A final drawback of shot put kinetic research is that as with all shot put research,
the subjects have largely been males using the glide technique. Due to the size and
strength differences of both genders, as well as differences in their throwing kinematics
and implement weight, it may be safe to presume that GRFs would be significantly
different between genders.

Electromyography Research Limited

In addition to the lack of research on the external forces associated with the
movement of shot putting, EMG studies are similarly few. In fact, no known study has
examined the EMG of both the upper and lower extremities. The only known EMG
studies have examined either the upper (Hermann, 1962; Peng et al., 2005) or lower
extremities (Ohyama et al., 1995) but not both. This is despite the fact that the action of
Putting the shot is a full body movement demanding the powerful contraction of practically every muscle in the athlete’s body. Additionally, all of these studies examined males using the glide technique. No known research has examined the activation patterns during the spin technique. Further research is needed to quantitatively evaluate the timing and magnitude of each muscle’s activation patterns over the course of the throw. Results of this research would provide useful information to athletes and coaches. Understanding the activation patterns of each muscle group could potentially help direct exercise selection and training means.

**Current Research is Largely Descriptive**

As stated above, much of the current research on shot putting has been descriptive in nature. While attempts have been made to model the movement of shot putting these attempts have typically attempted to determine the optimal release parameters (e.g., Hubbard et al., 2001; Linthorne, 2001; Maheras, 1995). Despite the fact that these parameters directly determine the projected distance of the throw, they do not give any indication of the events leading up to the instant of release and they offer limited information to those seeking improve the aspects of technique that will result in the best release parameters. Other studies have been descriptive in nature. They have ranged from quantitative (e.g., Ariel, 1979; Bartonietz, 1996; Liu et al., 2000) to completely qualitative (e.g., Grigalka & Papanov, 1984; Ward, 1974; Wilt, 1982). While these studies do provide information regarding the kinematics associated with the performance; they too offer limited evidence as to which parameters are most influential to performance.

Attempts to optimize the release parameters of the shot put have conclusively indicated that release velocity and release angle are interdependent and that the optimum
release angle is the one which permits the highest release velocity while still being great enough to achieve elite level throws (e.g., Hubbard et al., 2001; Linthorne, 2001a). Despite this, attempts to optimize the movement of shot putting have been few. Two studies (Alexander et al., 1996; Young & Li, 2005) have examined the shot put with the objective of finding the kinematic parameters most critical to success but the results of these studies were not inconclusive. This is likely due to the fact that Alexander and colleagues examined sub-elite athletes and Young & Li (2005) used a small subject pool of national class female throwers.

**Recommendations for Future Research**

As indicated above, greater research on the shot put is necessary using a wider range of populations (especially women, spinners, and elite athletes). Also, new research should look to take advantage of technological advancements in methodology that ease the data collection and analysis process. Throwing circles embedded with force platforms, implements imbedded with accelerometers, and automated motion capture methods would provide considerable depth to the current research and likely provide new insight about the movement.

In addition to examining the aforementioned populations and using new data capture technologies, new approaches to research would also be advantageous. The action of shot putting is an ideal task for optimization modeling because it has a clearly defined objective (measured distance of the throw) and it is a discrete task performed in a closed environment. Optimization modeling of the shot put may provide important information to coaches and shot putters and provide direction for future biomechanical studies on this event.
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VITA

Michael Anthony Young was born on January, 1977, in Buffalo, New York. He was raised in Buffalo, where his mother placed a strong emphasis on academics and analytical thought. From an early age Michael had a love of sports, specifically swimming and track and field. It was this love of human movement that led him on his path to Louisiana State University. Michael graduated from Canisius High School. Following graduation, Michael attended Canisius College in Buffalo, New York, on an academic scholarship where he majored in biological sciences. While at Canisius he competed for the track and field team as a decathlete. Following three years at Canisius College, Michael transferred to Ohio University in Athens, Ohio, where he graduated with a Bachelor of Science in Exercise Physiology and competed for the track and field team. Michael stayed at Ohio University to earn a Master of Sport Science in Athletic Administration. Michael also served as an assistant track coach during this time and coached his future wife, Calah Gilders. Following his studies at Ohio University, Michael moved to Baton Rouge, Louisiana, to study and research under Dr. Li Li on topics ranging from peripheral neuropathy to gait transition at Louisiana State University on a Board of Regents HEF Grant. Michael was also on the staff of the LSU track and field that won 6 Team National Championships during this time. He also founded his athletic development and consulting company, Human Performance Consulting, LLC. Following 4 years at Louisiana State University, Michael took a job as a track and field coach at the United States Military Academy at West Point, New York. After three years at West Point, he resigned to finish his dissertation and pursue the growth of his business, Human Performance Consulting, full time. Michael currently resides in Cary, North Carolina, with his wife and daughter Eva.