A BIOMECHANICAL ANALYSIS OF THE FOOTBALL QUARTERBACK PASS AND COMPARISON BETWEEN UNIVERSITY AND HIGH SCHOOL ATHLETES

By:

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A Thesis submitted to the Faculty of Graduate Studies of

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in partial fulfilment of the requirements of the degree of

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Of

MASTER OF SCIENCE

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ABSTRACT

The purpose of the study was to determine the most effective joint movements, velocities and body positions to perform the fastest and most accurate pass in high school and university football quarterbacks. Secondary purposes included developing a quarterback throwing test to assess skill level, determining which kinematic variables were different between high school and university athletes as well as determining which variables were significant predictors of quarterback throwing test performance. Ten high school and 10 university athletes were filmed for the study, performing nine passes at a target and two passes for maximum distance. Thirty variables were measured using Dartfish Team Pro 4.5.2 with Microsoft Excel and StatView being used for statistical analysis. University athletes scored slightly higher than the high school athletes on the throwing test, however this result was not statistically significant. Correlation analysis and forward stepwise multiple regression analysis was performed on both the high school group and the university group in order to determine which variables were significant predictors of throwing test score. Ball velocity was determined to have the strongest predictive effect on throwing test score ($r = 0.900$) for the high school athletes, however, position of the back foot at release was also suggested as important ($r = 0.661$) for the university group. Several significant differences in throwing technique between groups were noted during the pass, however, body position at release showed the greatest differences between the two groups. High school players could benefit from more complete weight transfer and decreased throw time to increase throwing test score. University athletes could benefit from increased throw time and greater range of motion in external shoulder rotation and trunk rotation to increase their throwing test score.

CHAPTER 1

INTRODUCTION

The game of football in North America was developed in 1876. Its roots come from the game of rugby which originated in England in 1823 (*American Football History, 2002*). Around the same time that rugby was originated, football started at the college level as freshmen and sophomores from Princeton and Harvard would play a game called 'Ballown' in which the teams would try to move the ball past the opposing team. Despite the lack of a formal set of rules, this was the earliest recorded attempt at the game we know as football (*American Football History, 2002*). This meeting between Princeton and Harvard would occur on the first Monday of the school year, and was commonly referred to as 'Bloody Monday' because of the game's vicious nature.

Walter Camp is credited as the founder of the game played today in North America. He attended Yale from 1876-1882 studying medicine and business. Despite being a good runner, swimmer and tennis player, he chose football as the subject of his attention (*Walter Camp 1859-1925, n.d.*). In 1876, at the Massasoit Convention, the first official rules of American football were recorded. Camp was heavily involved from the very beginning, editing every rulebook until his death in 1925. Camp is responsible for the backbone of the current game. His major contributions include the numerical assessment of goals and tries, having 11 players per side instead of 15, set plays, and strategy. Camp wanted to make the game more tactical than rugby. Rugby was in constant flux with teams instantly changing from offense to defense since the ball was always dropped and scrambled after. Camp tried to solve this issue by instituting a rule stating that one side retained possession of the ball until that side gives up the ball as a result of its own violation. The line of scrimmage was introduced, allowing more structure (Bellis, 2007). The scrimmage was not an instant success, as teams realized they could simply waste time, and run very safe short plays, not allowing the opposition time with the ball. This set the basis for the downs system in which a team needs to advance the ball a specified distance within a certain number of tries. Initially this was set at five yards in three tries. To assist in measurement, the field was marked in five yard increments. This rule was implemented in 1882, and was the beginning of modern football rules as we know them.

Football took a big step in 1906 with the introduction of the forward pass. The game was often criticized for its brutality based on its forceful play, making physical force primary with little emphasis on skill and science (*Walter Camp 1859-1925, n.d.*). Walter Camp introduced the forward pass in 1906 to open up the game. This reduced the brute force aspect of the game and forced teams to play tactically now that there was a threat of the opposition throwing the ball. Football continued at the amateur and college levels until 1920, when the American Professional Football Association was created with 11 teams, ten of them from the mid-western states. Official standings were recorded and released beginning in 1921. The league changed its name to the National Football League the following year. The league was fairly unsuccessful for the first 30 years. Teams would enter and leave the league frequently as many teams were from small towns. By 1934, all the small town teams had folded and replaced with big city teams, with the Green Bay Packers being the exception. Popularity was on the rise with the recent addition of a National Championship game the previous year.

Football finally made its mark as a legitimate professional sport in the 1950's, as it utilized television, providing all Americans a chance to follow the sport and the athletes participating. The NFL Championship Game was televised nationwide for the first time in 1951, with the DuMont Network purchasing the rights to air the game for $75,000 (*NFL History 1951-1960, 2007*). Around that time, professional football was established in Canada, as the Grey Cup began to be awarded only to professional teams (amateur teams were allowed) starting in 1954 (*Timeline: 1950's, n.d.*). The Canadian Football League, however, was not officially founded and named until 1958. In the opening game of the new CFL, the Winnipeg Blue Bombers defeated the Edmonton Eskimos in front of 18,206 spectators.

The Canadian and American professional leagues differ slightly in rules, which is always a topic of debate for enthusiasts of each league. The CFL has three downs while the NFL uses four downs per possession. The CFL uses a slightly more spherical ball, but this difference does not affect throwing technique, and the skill is taught the same regardless of the ball.

The ball used has evolved along with the style of the game (Oldham, 2001). In the 1820s the ball used was round, similar to a soccer ball, making it very awkward to throw. In 1874 a rugby-type ball was used and was not much easier to throw, but lateral and short flips became more common. In 1935 the NFL shortened the ball's short axis to between $21^{1}/_{4}$ and $21^{1}/_{2}$ inches and the length was shortened to between 11 and $11^{1}/_{4}$ inches. The long axis remained the same at this time ranging from 28 to $28^{1}/_{2}$ inches. This made the football much easier to throw and skill in the quarterback position began to increase. The ball's dimensions and shape remain the same today, which has been called a prolate spheroid (Oldham, 2001).

Since that time the sport has enjoyed great success. The NFL is a great example of football's popularity, having sold out every regular season and playoff game in the 2006/2007 season for all teams. Both leagues continue to operate, and show signs of expansion. With the increasing payrolls of professional athletes, football does encounter similar problems to other major sports, namely the difficulty of a small market being able to support a professional team.

PURPOSE OF THE STUDY

1) To develop a quarterback throwing test to assess the quarterback pass with regards to velocity, accuracy and throwing distance.
2) To compare the kinematic differences in variables related to throwing technique between university aged quarterbacks and high school aged quarterbacks. Variables include release velocity, throwing accuracy, step length, maximal lateral shoulder rotation, lateral trunk flexion, forward trunk flexion, shoulder abduction, lead knee flexion, and elbow flexion.
3) To determine the predictors of pass performance with regards to the kinematic variables measured.

RATIONALE FOR THE STUDY

Since the implementation of the forward pass in 1906, the role of the quarterback has become increasingly important. The quarterback is considered the captain and leader of the offense. The quarterback has possession of the ball on every offensive play whether he in turn hands it off on a running play or decides to throw. The quarterback position is the most important position on the football team. If the quarterback is not the most important person on the team, then that team has an inadequate quarterback (DeLuca, 1978). While some teams prefer one method of attack over another, a team with a balanced attack has an ever-present threat of both pass and run, although this does not necessarily mean the number of passing plays and running plays are equal. It is the quarterback's job to deliver an accurate pass to the receiver and away from the defenders (DeLuca, 1978). As the level of play increases the game becomes faster, and the margin of error is small. Passes are required to be very accurate as the quarterback is expected to hit a running target moving at top speed downfield, often allowing only a few inches between a complete and incomplete pass.

There are variations of throwing technique used at all levels. The most commonly coached is the overhead throw (Fig. 1.1). This throw has a higher point of release as the ball is released at a position above and 6-8 inches ahead of the throwing shoulder (Yessis, 1984). This higher release is beneficial because it allows the quarterback to release the ball above the defensive linemen reducing the chance of deflections and allowing more ball control (DeLuca, 1978). This technique is thought by some to increase risk of shoulder injuries often seen in overhead throwing skills, particularly if the athlete increases release height by increasing shoulder abduction rather than lateral trunk lean. This increased shoulder abduction past 90-degrees puts the superior aspect of the shoulder under compression. Compressive stresses are placed on the supraspinatus and sub-acromial bursa, as well as the tendon of the biceps brachii. Impingement of these structures may result if shoulder abduction is greater than 90-degrees (Alexander, 2007). Although overuse injuries are a possibility, there is less risk in the football pass compared to the baseball pitch due to lower rotational velocities, decreased extremes of range of motion, and decreased rotator cuff activity seen in football due partially to the increased mass of the football (Kelly, Barnes, Powell and Warren, 2004).

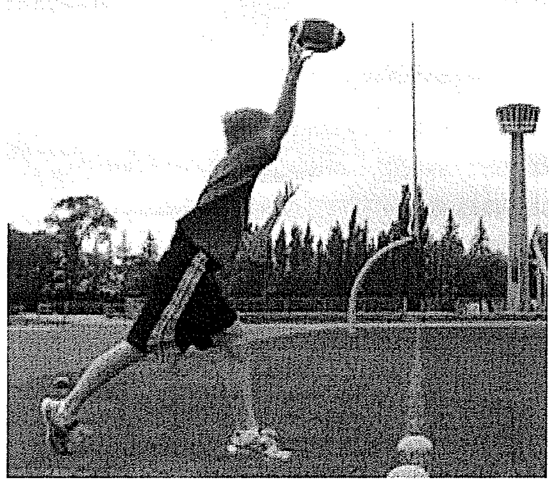

Figure 1.1: A quarterback demonstrating an overhead release, increasing the release height of the pass.

The other technique adopted by some quarterbacks is more of a side arm motion, in which the arm has less shoulder abduction, resulting in a lower release height. Some believe that the side arm technique puts the shoulder at lower risk of injury due to less shoulder abduction during external shoulder rotation and it is argued that this will reduce impingement of the rotator cuff muscles due to decreased shoulder abduction. This reduces risk of impingement of the supraspinatus muscle as well as the sub-acromial bursa. However, an overhead throwing technique may not be achieved solely by increased shoulder abduction. Some quarterbacks choose to increase release height by increasing lateral trunk flexion, while others adopt a combination of trunk lean and shoulder abduction. Quarterbacks have far fewer impingement injuries than other high speed overhead throwers such as baseball players. Only 14% of NFL quarterback injuries are overuse injuries, with 6.1% of those being rotator cuff injuries (Kelly at al., 2004).

According to football coach, T. Shea of the St. James Rods (personal communication, March 5, 2007) the side arm technique may also prove to be more accurate. An overhead throw has a shorter time in which the ball can be released and thrown accurately. If released too early, the ball will be released with a high trajectory, and if not done intentionally, could lead to overthrown passes. The ball can also be released after peak height which will cause the pass to be thrown downward upon release and result in underthrown passes. T. Shea (personal communication, March 5, 2007) suggested that the sidearm pass allows the ball to move horizontally for a longer period of time, allowing a larger range in which the ball can be released accurately.

By further examining the quarterback pass, it can be determined which technique is most beneficial for improved performance. Also, the key variables of the pass can be identified. After identifying the key contributors to pass accuracy, technique can be taught to athletes with a focus on the most important variables affecting accuracy.

HYPOTHESIS

1) University quarterbacks will have a higher release velocity than high school age quarterbacks.
2) University quarterbacks will have higher quarterback throwing test scores.

DESCRIPTION OF THE QUARTERBACK PASS

Drop Back

The quarterback starts facing forward, scanning the defense prior to the snap. The athlete is flexed at the knees with the feet approximately shoulder width apart. Some quarterbacks start with a parallel stance with the weight distributed on the inside edge of the left foot for a right handed quarterback (Axman, 1997a). The athlete should have the weight evenly distributed to avoid tipping the defense as to the direction of the play. Some athletes prefer a staggered stance in which a right handed quarterback will stand facing forward with the left foot six inches back from the right foot. The advantage of the staggered stance is that it allows the athlete to take a direct step without any stutter steps, allowing the quarterback to gain separation from the line of scrimmage faster (Axman, 1997a).

The number of steps used during the drop back will depend largely on the length of the pass. When attempting shorter passes the quarterback will use a three step drop, while using a five or seven step drop for deep passes. Although the number of steps may vary, the technique remains similar. The last two steps of the drop back are short, quick steps to allow the quarterback to gather and plant to get into the set position. Regardless of the length of the drop, the previous steps are used to gain depth. A three step drop will contain one depth step followed by the gather and plant, while a five step drop will use three depth steps followed by two quick steps to gather in preparation for the pass (McElroy, 2003). The initial step should be close to 180-degrees from the front foot. A step that is over 180-degrees will rotate the quarterback away from the line of scrimmage and limit his/her vision (Fig. 1.2). During the first step of the three step drop the athlete should be leaning 30-degrees from vertical, away from the line of scrimmage (Axman, 1997a). This allows a larger step and creates more distance from the line of scrimmage. The last two steps are short, quick steps bringing the quarterback back to an upright position and into a set position for the throw. The second step is a cross-over step which brings the athlete back to vertical. If the second step is too long, the athlete will gain too much distance, and roll the knee outside the base of support created by the feet. The final step is a plant step which stops the backward motion of the quarterback, and puts him in the set position ready to throw the ball (Axman, 1997a). In the case of a quick pass route or pressure from the defense, the quarterback may have to throw with no extra steps. The quarterback must be able to roll forward on the back foot without resetting, stepping in the direction of the target to throw the ball on time (Ash, 2006). Being able to step onto the front foot increases force production by allowing greater hip rotation and utilizes the muscles of the lower body. Pushing off the back leg will drive the right hip forward and help segment the rotation of the trunk and shoulder girdle.

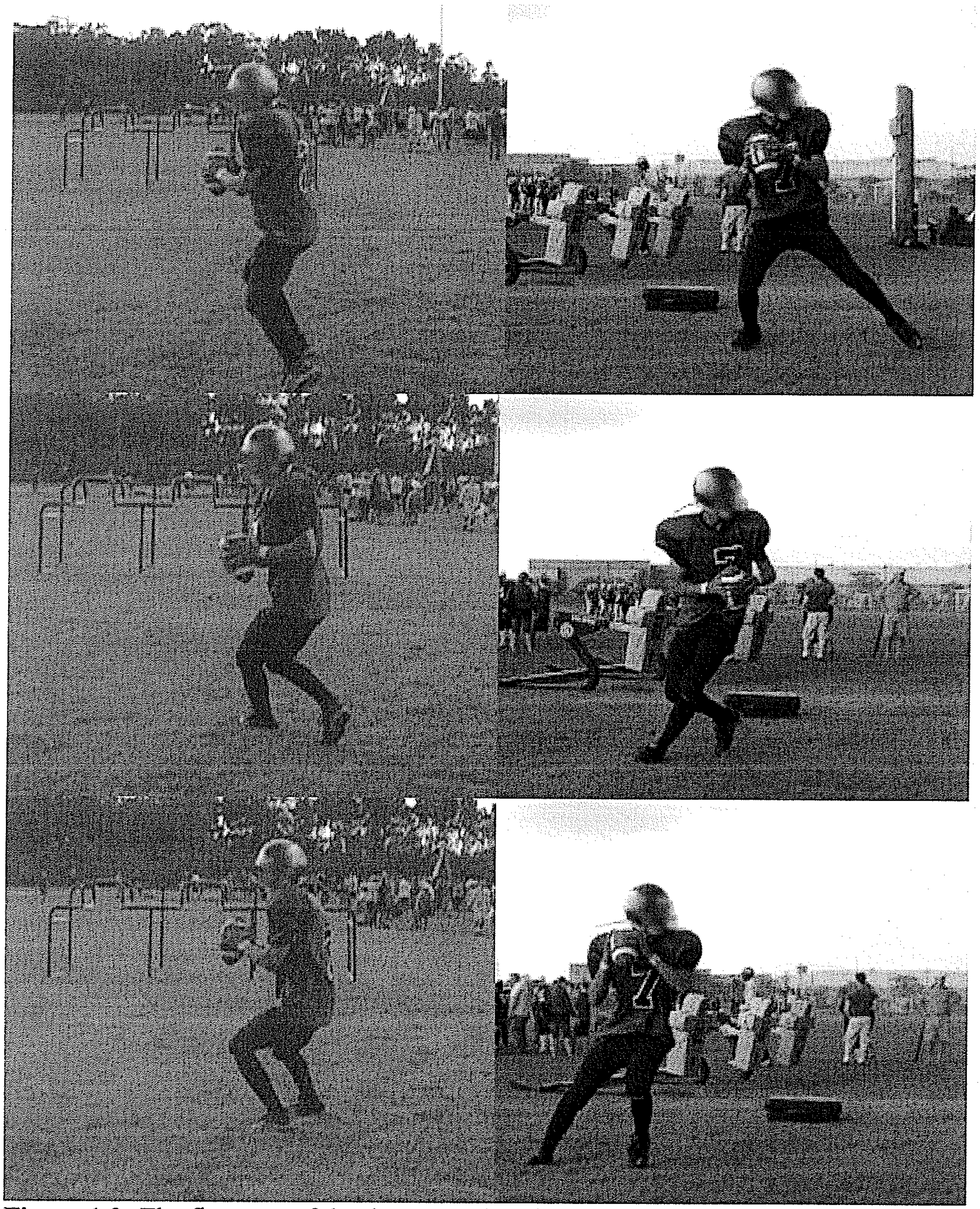

Figure 1.2: The first step of the three step drop is a long step to gain depth from the line of scrimmage. The second step is a quick cross-over step to bring the athlete back to an upright position. The final step is another quick step to plant and put the quarterback in the set position.

Grip

Athletes will differ slightly in how they grip the football for throwing. Each quarterback will find a grip that is most comfortable for them, and this is often related to hand size. Athletes with smaller hands will grip closer to the back of the ball. This will cause less finger contact with the laces of the football. Larger hands allow the athlete to grip closer to the center of the ball, putting the fingertips on the laces. Fingers are spread to ensure a large area of contact with maximum friction (Fig. 1.3). This helps prevent slippage, and allows the quarterback to apply more torque to the ball, creating a desired spiral (Fracas and Marino, 1989). The thumb and index finger should form a 'V', with both fingertips being equal distance from the end of the ball. The ball should not touch the palm of the hand, being held only by the fingertips (McElroy, 2003). The grip between CFL and NFL footballs may vary slightly, but in a similar fashion to those differences between athletes in the same league. The CFL ball has a slightly greater diameter so some athletes may choose to hold further back on the ball with only the index and middle finger on the laces. This also happens in the NFL for athletes with smaller hands so the variety in grip will be consistent within leagues as well.

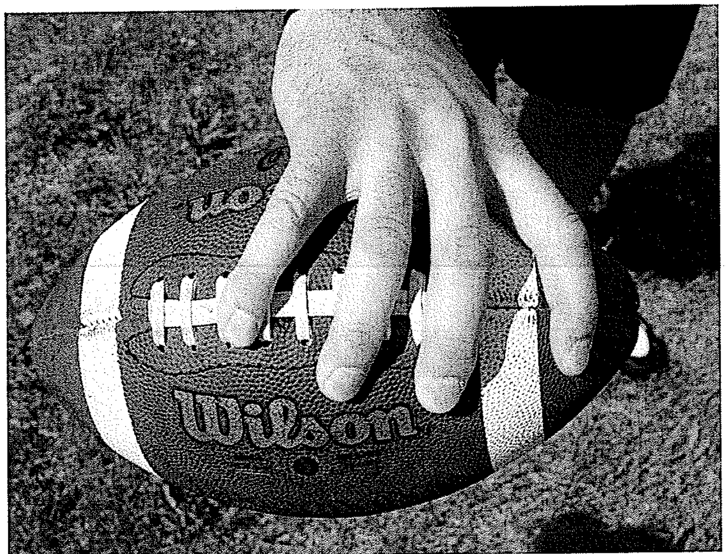

Figure 1.3: When gripping the football fingers are spread to increase area of contact with the ball to create greater friction, which allows more torque to be applied to the ball.

Preliminary Movements

The athlete's ready position should consist of bent knees to allow an aggressive drive step during the throw. Feet should be shoulder width apart with most of the weight on the back foot to allow for a large step (Fracas and Marino, 1989). The feet should be perpendicular to the target and parallel to each other (Yessis, 1985). A wide stance will distribute the weight more evenly between the feet and will allow the quarterback to take an extra shuffle step to get the weight onto the back foot (Fracas and Marino, 1989). The ball should be held level with the shoulders and close to the body (Alexander, 1992). This places the quarterback into a cocked position early, allowing for a quick release (McElroy, 2003). The front elbow should also point downward, but the front shoulder may be abducted slightly (Fig. 1.4). The ball should be held close to or just past the midline of the body, level with the back ear (McElroy, 2003). This will help initiate trunk rotation away from the target, stretching the muscles of the trunk.

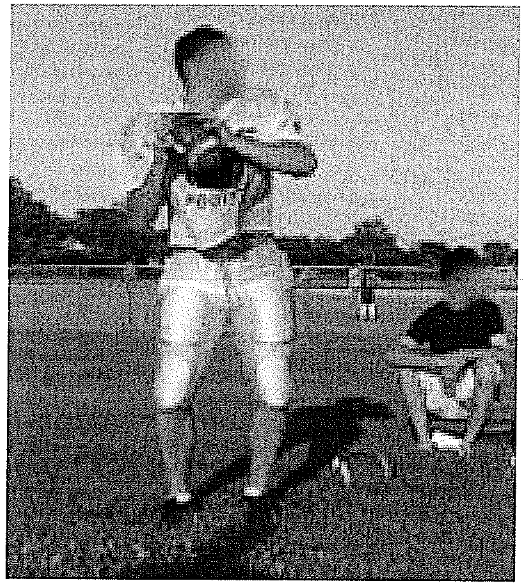

Figure 1.4: Ready position of an elite quarterback. The ball is held level with the upper chest, and close to or just past the midline of the trunk.

Backswing

During the backswing, the shoulder is abducted and laterally rotated with the free arm staying at shoulder height to allow maximal shoulder rotation (Fig. 1.5). As the athlete begins external shoulder rotation, the athlete takes a long step forward and weight transfer onto the front foot begins (Alexander, 1992). The toe of the front foot should be pointing towards the target, with the shoulders and hips perpendicular to the target to allow full range of motion during force production. The front foot contacts the ground as the athlete reaches the end of the backswing associated with maximal shoulder abduction. The athlete is forcefully rotating the pelvis forward to face the target.

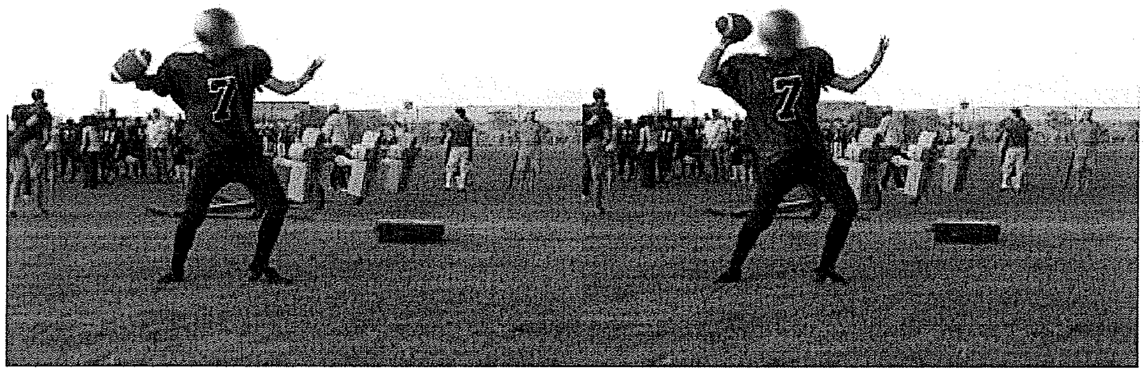

Figure 1.5: Early backswing of the quarterback throw. The throwing shoulder is abducted and moves into lateral rotation. The pelvis begins to rotate forward towards the target.

Force Production

Further external rotation of the throwing shoulder will occur as the mass of the hand and ball segment causes an inertial lag during force production. This position is more exaggerated in other overhead throws, such as baseball due to the greater rotational speeds of the arm and trunk. A heavier ball will reduce the arm speed during the throw (Fleisig et al., 1996). The quarterback leads with the shoulder girdle as the hips rotate towards the target. The ball should be kept near the axis of rotation of the spine to reduce the moment of inertia relative to the spinal axis. The moment of inertia is reduced by flexing the elbow, bringing the ball closer to the body, and results in greater velocity of the throwing arm (Fracas and Marino, 1989). This maximal external shoulder rotation initiates a stretch-shortening cycle to increase force production during medial rotation up to release of the football.

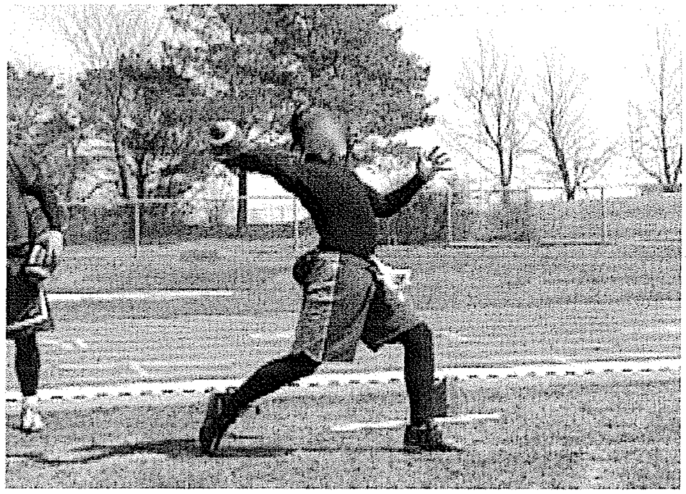

Figure 1.6: The quarterback steps onto the front foot, with the pelvic rotation leading the rotation followed by the trunk and shoulders.

The athlete has transferred most of his weight onto the front foot, as the athlete drives forward from the back foot (Fig. 1.6). Rotation is initiated at the hips resulting in the hips and trunk rotating to face squarely to the target (Alexander, 1992). The free arm stays high and close to the body, reducing the moment of inertia of the body and allowing faster trunk rotation.

Release

As the ball passes the ear, the elbow is extended, maximizing the radius for shoulder abduction from the shoulder joint to the ball and creating more velocity and increasing ball height at release (Fracas and Marino, 1989). Elbow extension is accompanied by medial shoulder rotation, radio-ulnar pronation, and wrist flexion which will apply an off-centre force to the football. Torque is generated as a result of the off-centre force, resulting in a spiral upon release (Alexander, 1992). The shoulder of the free arm is horizontally extended throughout the force production phase with the elbow driving downward during release (Fig. 1.7). This will raise the opposite shoulder, causing lateral trunk lean that will increase the height of release (McElroy, 2003). The shoulder is still in external rotation at the point of release. The amount of external rotation is dependent on the trajectory of the throw with higher, deeper throws being released with greater external shoulder rotation (Rash and Shapiro, 1995).

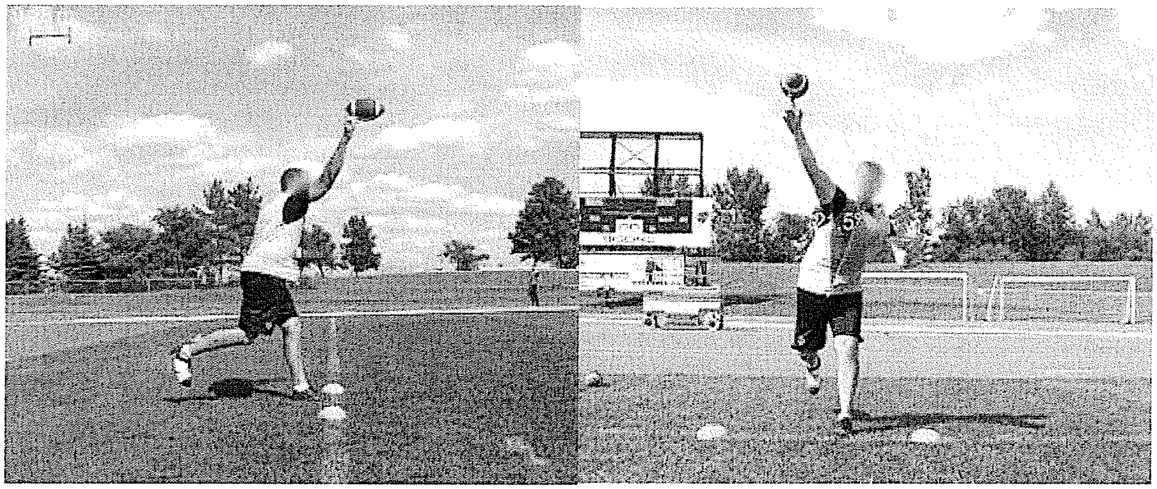

Figure 1.7: The quarterback has dropped the opposite shoulder, resulting in lateral trunk lean. The athlete has slight external shoulder rotation at the moment of release.

Follow-through

During the follow-through, the shoulder continues to horizontally adduct and flex. Radio-ulnar pronation and medial shoulder rotation cause the thumb to be pointed downward as it crosses the body and stops close to the opposite hip. A large follow-through across the body helps reduce the stress on the shoulders, allowing more time for the throwing arm to decelerate (Alexander, 1992). In a right handed quarterback, the right foot becomes completely unweighted before release and swings forward to land parallel to the left foot, re-establishing a wide base of support to put the athlete back into a stable position (Yessis, 1985).

There is some variability in throwing technique, and debate associated with various styles. Some quarterbacks will have a more overhead throwing motion, while others will have more of a side-arm technique (Fig. 1.8). The overhead technique is generally recommended as it has a higher point of release making it more difficult for the defensive linemen to deflect the pass (Fracas and Marino, 1989.).

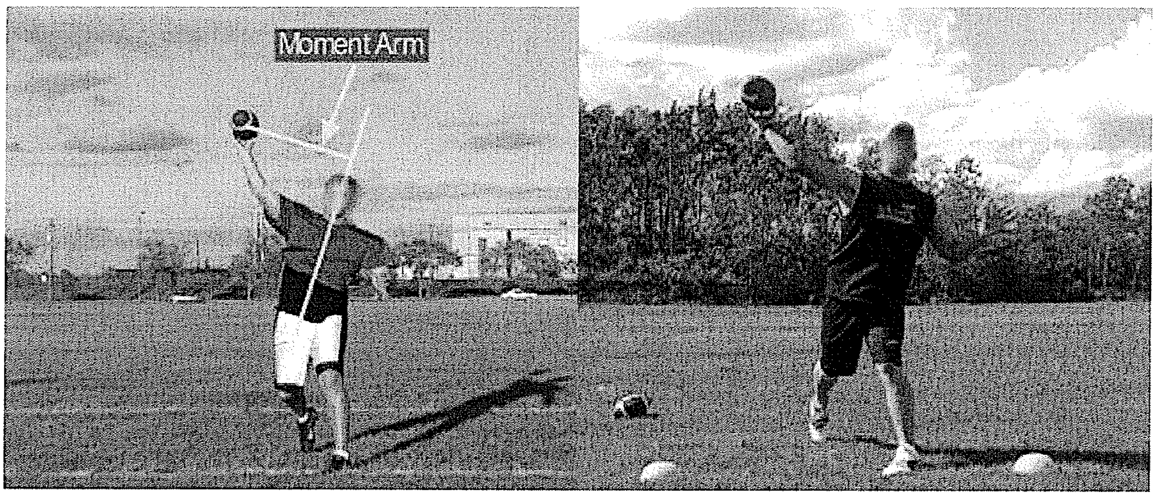

Figure 1.8: Overhead versus sidearm throwing technique. The overhead technique relies on lateral trunk flexion to increase release height to prevent pass deflections.

The amount of trunk lean will vary between individuals throwing overhead. As trunk lean increases, the amount of shoulder abduction necessary to maximize release height decreases.

LIMITATIONS

1) Due to the age of the athletes used in this study, it is difficult to generalize the results to athletes of younger age levels.
2) There is limited research on the topic of football pass accuracy, making comparisons of the results of this study difficult.

3) The athletes' throwing data were collected in a controlled setting, as opposed to a competition setting. This could affect the mechanics of the athletes and decrease the reliability of the results.

4) The sample size of each group makes it difficult to determine if the differences in accuracy found in the study are a result of the throwing mechanics of the subjects or inter-subject differences.

5) Potential strength and flexibility differences between athletes may affect performance and contribute to some differences found between athletes. Athletes with limited flexibility may alter throwing mechanics to compensate. Less shoulder rotation may be evident in athletes with limited flexibility. Stronger athletes may also display less range of motion if they are able to produce similar amounts of force with less range of motion.

DELIMITATIONS

1) No professional athletes were used for analysis as there were not enough professional quarterbacks accessible to participate in this study. Therefore generalizations about professional athletes could not be made.

DEFINITION OF TERMS

Acceleration: The rate at which velocity changes with respect to time (Hay, 1993). $a = (v_f - v_i)/t$: where a = the average acceleration; v_f = the final velocity; v_i = the initial velocity; and t = time.

Angular acceleration (α): The rate of change in angular velocity (Hay, 1993). $\alpha = (\omega_f - \omega_i)/t$: where α = angular acceleration; ω_f = final angular velocity; ω_i = initial angular velocity; and t = time.

Angular displacement (Ø): Change in angular position or orientation of a line segment (Hall, 2007).

Angular velocity: Rate of change in angular position or orientation of a line segment (Hall, 2007). $\omega = Ø/t$: where ω = angular velocity; Ø = angular displacement; and t = time.

Axis of rotation: Imaginary line perpendicular to the plane of rotation and passing through the centre of rotation (Hall, 2007).

Balanced Attack: A team is said to have a balanced attack if it can move the ball effectively by passing and running (DeLuca, 1978).

Bullet Pass: A pass thrown hard and straight. There is usually less chance of an interception when the pass is thrown hard, but on short passes the ball can be thrown too hard making it difficult to catch (DeLuca, 1978).

Centre of Mass (centre of gravity): Point around which the mass and weight of a body are balanced, no matter how the body is positioned (Hall, 2007).

Early Cocking Phase: The initial movements of the backswing of the arms going from start position to a position of maximal shoulder abduction and internal shoulder rotation (Kelly et al., 2002).

Hand Off: An exchange of the football from one offensive player to another (DeLuca, 1978).

Impulse: Product of force and the time interval over which the force acts (Hall, 2007). I = Ft: where I = impulse; F = force; and t = time.

Impulse-momentum Relationship: When an impulse acts on a system, the result is a change in the system's total momentum (Hall, 2007).

Inertia: Tendency of a body to resist a change in its state of motion (Hall, 2007).

Interception: When a defensive player catches a pass intended for an offensive player. The intercepting team keeps possession of the football (DeLuca, 1978).

Late Cocking: The portion of the backswing of the upper body from maximal shoulder abduction and internal shoulder rotation until maximal external shoulder rotation (Kelly et al., 2002).

Loft: A long, high pass that the receiver has a chance to run under, as opposed to a bullet pass (DeLuca, 1978).

Moment Arm: shortest (perpendicular) distance between a force's line of action and an axis of rotation (Hall, 2007).

Moment of Inertia: Inertial property for rotating bodies representing resistance to angular acceleration; based on both mass and the distance the mass is distributed from the axis of rotation (Hall, 2007).

Quick Release: The ability of the quarterback to get rid of the ball quickly once he spots an open receiver (DeLuca, 1978).

Sack: When the quarterback is tackled for a loss of yards while attempting to pass (DeLuca, 1978).

Sidearm: The arm is moved forward in a horizontal plane because of the spinal action and pelvis rotation. The spine also laterally flexes towards the throwing arm (Hamilton and Luttgens, 2002).

Snap: The initiation of the play by the center when he passes the ball between his legs into the hands of the quarterback (DeLuca, 1978).

Spiral: The rotation of the ball on its long axis after it has been passed or punted. This rotation will stabilize the flight of the ball (*The Football Dictionary, n.d.*).

Stretch-Shortening Cycle: Eccentric contraction followed immediately by concentric contraction (Hall, 2007).

Three Quarter Throwing Motion: The ball is released closer to head height with the upper arm approaching parallel to the ground (Van Brocklin, 1960).

Touchdown: When a player carries the ball into the opposition's end zone. Six points are awarded (DeLuca, 1978).

CHAPTER II

REVIEW OF LITERATURE

A review of literature of the quarterback pass has been done to review the elements. Quarterback throwing tests used in the development of the test in the current study have also been reviewed. Biomechanics principles were reviewed and applied to the skill of the quarterback pass.

The quarterback position is the centerpiece of the offensive unit in football. A balanced team will pass approximately half the time. As the level of competition improves the room for error decreases. The quarterback must deliver an accurate pass to his receiver and away from the defenders. This could require a fast bullet pass or a high floating pass (DeLuca, 1978). Therefore the athlete needs to be able to deliver an accurate and fast pass to be successful. The time allotted to deliver a pass varies with the pressure created by the defense but a quick release is an asset, allowing the quarterback to wait as long as possible for his receiver to become open. The athlete starts the throw holding the ball high and toward the back shoulder while facing perpendicular to the target. The athlete steps toward the target and begins to rotate to face the target prior to release. The ball is released above and slightly in front of the head, and after release the throwing shoulder continues to adduct and extend as the arm decelerates.

A review of literature has been conducted on the quarterback pass which is broken down into the following phases: start position, backswing, force production, critical instant, and follow-through.

Some of the key features of a skilled quarterback include a quick release which allows the quarterback to avoid having to hurry throws as well as not allowing the defense time to react to the throwing motion (DeLuca, 1978). The total throw from start position to the end of the follow-through should take approximately one second (Kelly et al., 2002). A throwing motion that takes longer than one second will allow the defense the necessary time to react and result in a lower pass velocity due to decreased acceleration of the arm during force production (Kelly et al., 2002). On pass routes across the middle of the field the quarterback is often required to place the ball between defenders, making accuracy a key attribute of his passing. A quarterback must also be able to get the ball to the receiver quickly. A ball that takes longer to reach its target is more likely to be deflected or intercepted as it allows the defenders more time to react to the pass. Therefore accuracy and a reasonable amount of throwing velocity are two of the most important factors when determining the success of a pass.

Phases of the Quarterback Pass

Start Position (Note: the following description applies to right handed quarterbacks)

After the quarterback drops back, he stops with his shoulders perpendicular to the line of scrimmage (Figure 2.1). If an athlete fails to turn his shoulders away from the line of scrimmage he will be forced to cock the shoulders back before throwing, resulting in a slow release (Axman, 1997a). The feet should be parallel to each other and should be 90 degrees from the direction of the throw, with most of the athlete's weight distributed on the right leg (McElroy, 2003; Yessis, 1985). The athlete should be up on the balls of the feet while in the ready position in case he is forced to move quickly to avoid oncoming defenders (Berezowitz, 2000). The quarterback will often be forced to throw to someone other than his primary receiver. The receiver the quarterback throws to may be on the other side of the field from his first option. In these cases the quarterback must shift his feet accordingly, making sure to have the feet, hips and shoulders at a 90 degree angle to the direction of the throw (Axman, 1997a).

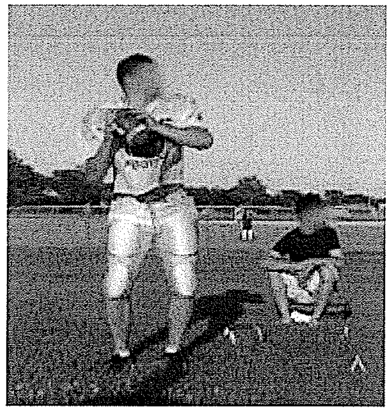

Figure: 2.1: In the ready position the athlete has his feet shoulder width apart with the feet perpendicular to the direction of the throw. The majority of the weight is distributed over the right leg.

The feet should be shoulder width apart with both knees flexed slightly, ready to thrust forward with the right leg (Alexander, 1992; Ash, 2006; Fracas and Marino, 1989; Yessis, 1985). A wider stance will cause a false step during the delivery which wastes valuable time. A false step occurs when the athlete takes a small shuffle step with the right foot in order to place it closer to the line of gravity in preparation for the throw. A shoulder width stance allows the quarterback to step on to the left foot during the throw without having to shuffle the right foot forward before stepping on to the left foot (Axman, 1997a; Berezowitz, 2000). The quarterback should be looking straight ahead with the chin pointing downfield, using only his eyes to scan the field rather than rotating the entire head (McElroy, 2003). The right knee should be lined up on the inside of the right foot, keeping the line of gravity of the athlete medial to the right foot to allow the athlete to step forward and generate force through the hips during the pass (McElroy, 2003).

The ball is held at shoulder height and close to the body to keep the ball away from nearby defenders and protect against fumbles (Alexander, 1992; Yessis 1985). Keeping the ball at shoulder height shortens the length of the backswing and allows for a quick release (Axman, 1997a; Yessis, 1984). The ball should be held just past the midline of the trunk toward the right shoulder. This will vary slightly with some quarterbacks holding the ball in front of the right side of the chest (Axman, 1997a). The right elbow should be pointed downward but the shoulder may abduct slightly (Figure 2.1). Some shoulder abduction is acceptable but the quarterback should avoid approaching 90 degrees of abduction as this may decrease ball protection (McElroy, 2003). The left hand should remain in contact with the ball at all times. The quarterback should not pat the ball with the left hand, nor should he pull the ball away from the left hand prior to the backswing (McElroy, 2003). Both hands on the ball will provide optimum protection of the ball and assist ball movement into the backswing. Both hands should remain in contact with the ball until the last possible instant before throwing (Frala, 2007).

Backswing

The backswing phase is the phase that puts the athlete in position to generate force for the throw by bringing the ball behind the head and cocking the throwing arm (the term used to describe the wind up for the throw). Early cocking of the throwing arm starts at foot plant until the shoulder reaches maximal abduction and internal rotation. Late cocking occurs from the position of maximal shoulder abduction and internal rotation until maximal external shoulder rotation. During the backswing the left hand should guide the ball during the initial take away and cocking of the right shoulder (Berezowitz, 2000; McElroy, 2003). The left hand helps protect the ball and reduces the chance of the defender knocking the ball away or the quarterback losing grip of the ball. Keeping both hands in contact with the ball also assists trunk rotation during the backswing, allowing a large range of motion during force production.

During the backswing the quarterback takes a short step forward with the left foot (Axman, 1997a). As the weight is on the right foot, the left foot becomes the directional foot. The quarterback steps towards the target with the toe pointing towards the target (Frala, 2007). The step should be 4-6 inches since the feet are already separated prior to the step. This will allow the athlete to fully transfer his weight over the left foot during force production. A longer step could result in the quarterback locking out the left knee and cause the pass to fall too short or too long (Berezowitz, 2000; Danischewsky, 2007). The total stride length from ankle to ankle is approximately 61% of the quarterback's standing height (Fleisig et al., 1996). The step should be short and the knees should remain bent throughout the step (Alexander, 1992; Berezowitz, 2000). However, an excessively short step will reduce the time and range of motion for hip and trunk rotation causing a loss in ball velocity due to reduced force production. When the front foot is planted the shoulders should be rotated backwards to their maximal position (Alexander, 1992). The left toe points in the direction of the throw during the step and weight is transferred on to the left foot (Fracas and Marino, 1989; McElroy, 2003). The quarterback should step slightly left of the line to the receiver, allowing him to open his hips and increase the range of motion of trunk rotation. If the step is too far left, the hips will open too much, and the athlete will be rotating away from the target throughout the pass, resulting in an inaccurate pass. A step that fails to open the hips limits hip rotation and will reduce force produced, increasing the possibility of an underthrow (Axman, 1997a). As the left hip is flexed it also abducts and laterally rotates and allows the pelvic and shoulder girdles to rotate through a maximal range of motion and increase the time force can be generated (Tarbell, 1970). Stepping at or to the right of the target with the lead foot can result in passes being thrown behind the intended receiver when he is running a crossing route parallel to the line of scrimmage (Danischewsky, 2007).

The trunk should remain relatively vertical during the stride to maximize the rotation of the shoulders and hips (Figure 2.2). An excessive forward lean will limit the range of motion through which rotation can occur (Tarbell, 1970). The step forward is accompanied by raising the ball above the right shoulder and behind the head using shoulder girdle elevation and shoulder abduction (Hay, 1993). The shoulder girdle elevates along with shoulder abduction to allow more rotation of the upper portion of the trunk. This will allow a larger range of motion during force production as the trunk rotates to face the target (Alexander, 1992; Yessis, 1984). The cocking which involves lifting the ball into position for force production through shoulder abduction does not occur until the forward step is taken, with the final cocking occurring when the shoulders rotate forward during trunk rotation (Yessis, 1984). External shoulder rotation increases due to inertial lag as the quarterback transfers weight onto the left foot and the hips rotate to face the target.

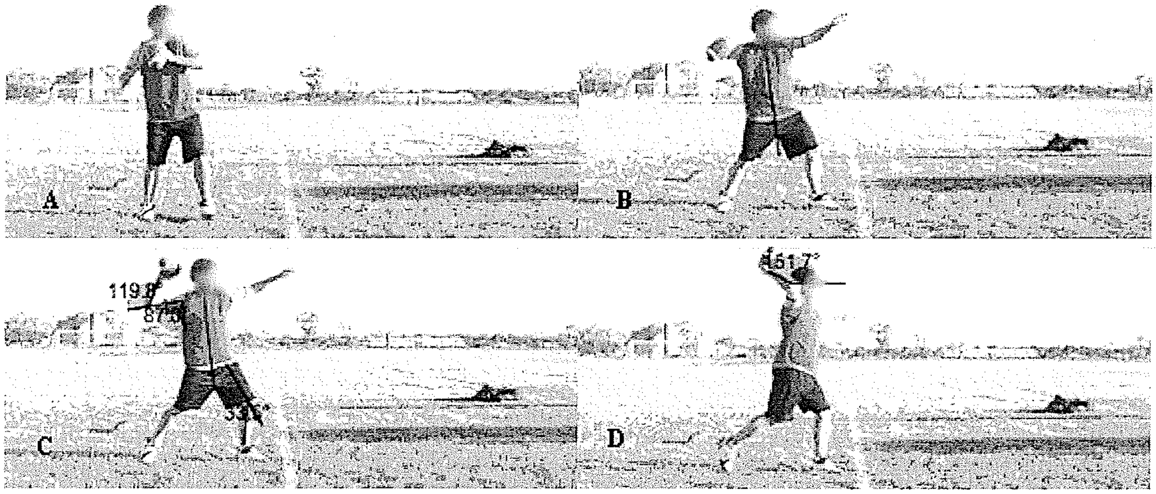

Figure 2.2: During the backswing the athlete remains fairly vertical. The elbow is flexed over 100 degrees to reduce the moment of inertia of the arm as the shoulder abducts to 90 degrees to cock the throwing arm. As the trunk rotates forward, the shoulder lags behind and assumes a position of maximal external rotation.

The left hand loses contact with the ball as the quarterback reaches a cocked position with the elbow flexed and shoulder abducted close to 90 degrees. The left hand must come off the ball in order to contribute to force production by driving across the body to assist in trunk rotation (Ash, 2006; Axman, 1997a). The quarterback should rotate the ball slightly as he takes the ball back so the back point of the ball is pointing towards the helmet of the quarterback (Figure 2.2B)(Ash, 2006). The back point is defined as the end of the football furthest from the target at release. Rotation of the ball to move the back point of the ball towards the helmet is achieved during horizontal shoulder extension with the ball remaining above the elbow. If the ball is not rotated close to 180 degrees during the take-away, the quarterback uses a dart throwing motion using only the elbow joint reducing the velocity of the throw by limiting the length of the backswing and the muscles used (Ash, 2006). Kelly et al. (2004) divided the backswing into two phases during their study of the overhead football throw. The backswing consists of an early and late cocking phase (Figure 2.3). The early cocking phase starts with touchdown of the right foot and continues until maximal shoulder abduction with push off occurring from the back foot. Late cocking follows from maximal shoulder abduction and internal rotation and occurred until maximal external shoulder rotation and the back foot is raised with all the weight is over the front foot. The force production or acceleration phase begins once the shoulder begins to internally rotate even though the hips may be considered to be in force production prior to this because it is the rotation of the shoulder girdle that produces the lag in the upper arm, resulting in external rotation of the shoulder. The 'peak windup' is represented by maximal external rotation of the arm (Gainor, Piotrowski, Puhl, Allen and Hagen, 1980). Maximal external rotation of the shoulder is 164 degrees from the front horizontal for the average college quarterback (Fleisig et al., 1996). The upper right arm is parallel to the ground during backswing with the ball being brought back further for longer passes (Fracas and Marino, 1989). During the backswing the right shoulder is abducted between 83 degrees at foot contact and 96 degrees at maximal external rotation of the shoulder. Horizontal shoulder adduction was found to be between 1 and 7 degrees, placing the elbow close to the frontal plane acting through the shoulders (Rash and Shapiro, 1995).

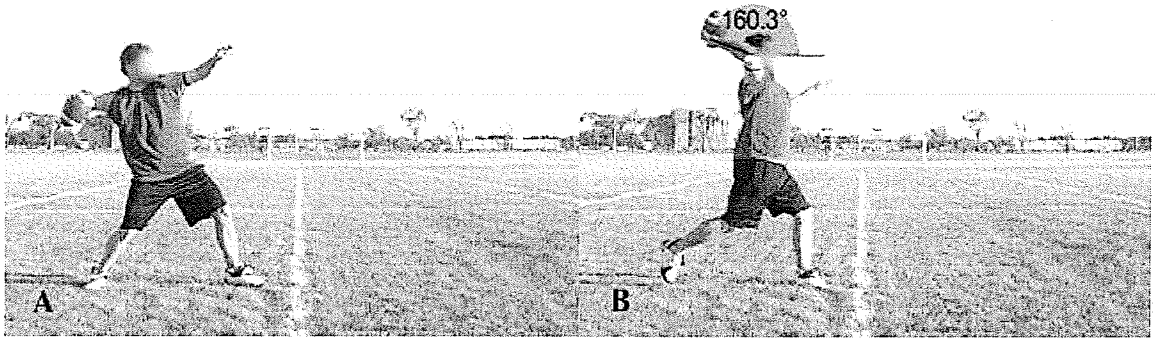

Figure 2.3: Early cocking occurs until maximal shoulder abduction and internal rotation (2.3A). Late cocking follows from the end of early cocking until maximal external shoulder rotation (2.3B).

More trunk rotation and horizontal shoulder extension stretches the pectoralis muscles to initiate the stretch reflex. The primary movements of the pectoralis muscles are shoulder flexion, medial rotation, adduction and horizontal adduction. During force production the shoulder adducts and flexes to generate velocity. Increased velocity of the ball during force production will result, allowing for greater release velocity and throw distance. The ball is kept close to the head at the end of the back swing by flexing the elbow to reduce the moment of inertia of the arm-forearm-hand-ball segment and allows for a short, quick backswing (Fracas and Marino, 1989). The right elbow should reach approximately 105 degrees of flexion to assist in reducing the moment of inertia of the arm to allow the quarterback to increase arm speed (Rash and Shapiro, 1995).

Force Production

The primary goal of the throwing motion is to produce optimal velocity of the ball which is achieved through a smooth transfer of momentum and summation of forces. The force generated by the smaller and more distal limb segments is added to the force generated by the larger proximal limbs. The smaller limbs begin to move once the larger proximal limbs reach maximal velocity. This transfer should be very smooth and rapid as each body part transfers its forces to the next body part (Yessis, 1985). This force production begins in the lower body with a step forward transferring all of the athlete's weight from the back foot to the front foot as the ball is brought back (Alexander, 1992, Fracas and Marino, 1989) (Figure 2.4).

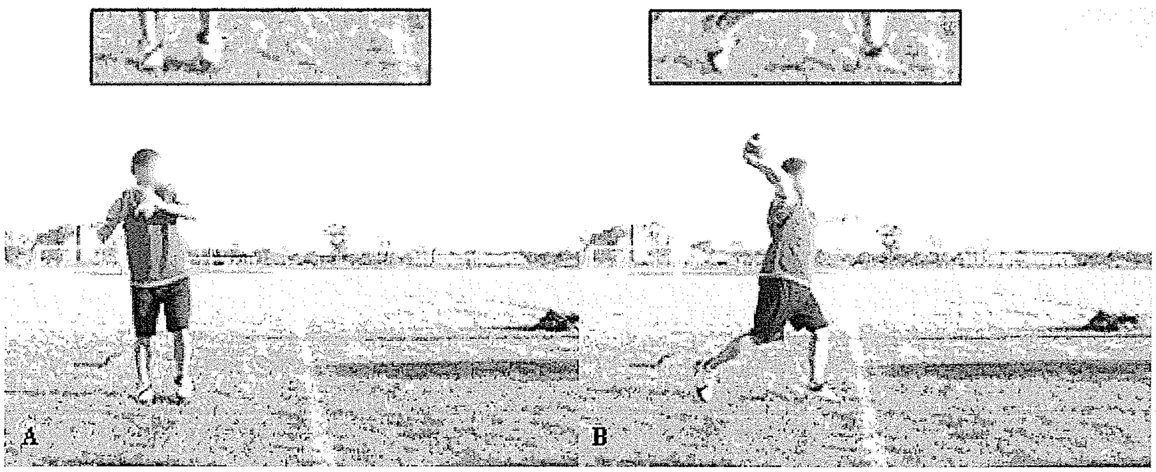

Figure 2.4: The athlete takes a moderate step and the right knee extends to transfer the athlete's weight onto the front foot during force production.

The right hip extends and drives the athlete's body weight forward (Hay, 1993). The quarterback should transfer all of his weight over the front foot and roll over the left foot during the throw (Axman, 1997a). The back hip and back shoulder should start to move forward before the arm begins the throwing motion (Ash, 2006). The rotation is initiated with the hips starting sideways to the throw and rotating to face the direction of the throw (Figure 2.5). Hip rotation is produced by the medial rotators of the front hip to rotate the pelvis about the left hip joint (Alexander, 1992; Yessis, 1984). The quarterback leads with the trunk, avoiding a forward flexion at the hips that increases trunk flexion during the throw (Axman, 1997b). Snapping forward of the hips causes the quarterback to pull down on the ball during release and results in a low pass into the ground (Axman, 1997a). The football quarterback remains more upright than other overhead throwers such as baseball pitchers who have a great forward trunk lean at release. Baseball pitchers can afford this trunk flexion since there are no defenders trying to block the pass and the throw can have a more direct path to its target (Fleisig et al., 1996).

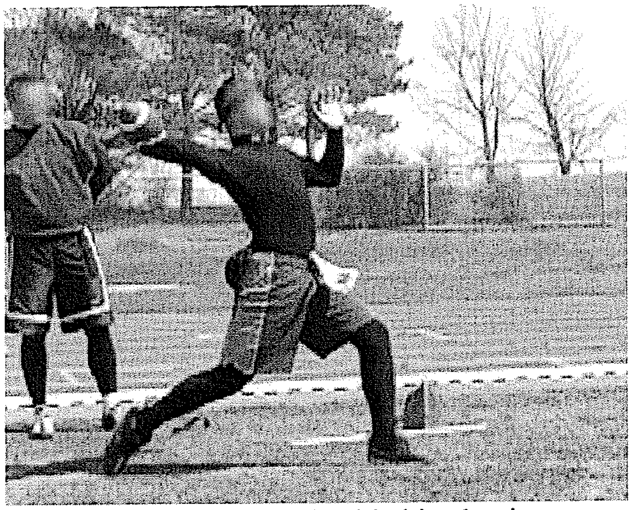

Figure 2.5: The quarterback's hips begin rotation as the trunk and shoulders lag behind, causing a stretch in the trunk, pectoral muscles.

Hip and trunk rotation creates a lag in the shoulder girdle as the shoulders become square to the target after the hips (Figure 2.5). As the shoulders lag behind the hips the right external oblique and left internal oblique muscles are in a stretch, initiating a stretch reflex (Yessis, 1984). The elbow and shoulder joints are both close to 90 degrees of flexion and abduction respectively. Fleisig et al. (1996) found an average of 108 degrees of shoulder abduction during force production compared to 96 degrees in the study by Rash and Shapiro (1995). Following the hips and trunk, the shoulder girdle rotates around from the side facing position as the right shoulder externally rotates, reaching a fully cocked position (Yessis, 1985). During shoulder rotation the pelvic girdle is held stable to stabilize the lower attachments of the oblique muscles and allow for a more effective pull of the trunk muscles. When shoulder girdle rotation occurs over 90 degrees or more it can account for over 50% of the total force generated. This makes effective shoulder rotation the most important in the throwing action when maximal force is required (Yessis, 1984). During shoulder girdle rotation the left arm drives down with aggressive shoulder extension (Figure 2.6). Release height is increased approximately 5cm due to the drop in the left shoulder during the rotation of the left arm (Berezowitz, 2000; McElroy, 2003).

Figure 2.6: During shoulder rotation the left shoulder aggressively extends causing the left shoulder to drop. The tilt of the shoulder girdle increases release height by raising the right shoulder as the left shoulder lowers. The elbow also extends during force production.

As the shoulder girdle decelerates and comes to a stop facing the direction of the throw, the throwing arm is automatically moved into external rotation at the shoulder joint with the elbow remaining at 90 degrees of flexion (Yessis, 1984). The primary muscles in internal shoulder rotation include latissimus dorsi, teres major, subscapularis, and pectoralis major. The internal rotators of the shoulder are put onto a stretch as the forearm reaches a position close to parallel to the ground to apply maximum tension to the internal rotators (Figure 2.5). From maximal external rotation, the internal rotators undergo a stretch to produce a stretch reflex and increase force during internal shoulder rotation.

When a muscle is stretched suddenly the muscle spindles in the muscle send a sensory impulse to the spinal cord. The spinal cord activates the alpha motoneurons to contract the muscle (McArdle, Katch, and Katch, 2000). The main functions of this stretch reflex are to generate power (Enoka, 2002). This will help improve the force produced by taking advantage of the elasticity of the pectoralis major, subscapularis, latissimus dorsi and teres major muscles. Many components of the muscle have elastic qualities that also contribute to force production. The myofibrils that make up a muscle fibre are invested by a plasma membrane called the sarcolemma. Endomysium, a connective tissue, surrounds the muscle fibre. Bundles of muscle fibres, called fascicles, are encased by another layer of connective tissue called the perimysium. From there, several fascicles are further grouped together by another layer surrounding the whole muscle called the epimysium. The perimysium, endomysium, epimysium and sarcolemma act together as a parallel elastic component that stores strain energy when stretched (Nordin and Frankel, 2001). The sarcomeres, which are repeated subunits along the length of the myofibril that make up the muscle fibre, also contain elastic components. The myosin within the sarcomere contains elastic filaments that help give the muscle fibre elastic qualities. The actin and myosin myofibrils can also store strain energy when stretched that can increase contractile force.

Fleisig et al. (1996) found an average of 164 degrees of maximal external shoulder rotation from the front horizontal. From the moment of maximal external rotation to release, abduction/adduction velocities are close to zero showing little change in shoulder position in the frontal plane (Rash and Shapiro, 1995).

The elbow joint undergoes extension during internal shoulder rotation to straighten the arm and increase the release height of the pass (Figure 2.6). Internal shoulder rotation is a primary contributor to force production, but elbow extension also creates additional force extending at 1760 degrees/sec compared to 4950 degrees/sec of internal shoulder rotation (Fleisig et al., 1996). The shoulder horizontally adducts during the force production phase to 26 degrees from the frontal plane leading up to release of the football (Fleisig et al., 1996). Horizontal shoulder adduction occurs first, followed by shoulder medial rotation to bring the ball to its release point (Hay, 1993). Rash and Shapiro (1995) found elbow extension velocity increased more rapidly, starting midway through force production until release.

In similar throwing motions such as baseball pitching, the angular velocity of the throwing arm is twice that of a kicking leg. The momentum of the arm is four times greater than the kicking leg; as a result it overloads the extremity and could predispose it to injury. Momentum is the product of the mass of the object and its velocity (Gainor et al., 1980). Momentum acts as an overload due to the increased speed of the arm. A large strain is placed on the external rotators as they contract eccentrically to decelerate the arm during follow-through. However, football quarterbacks do not achieve the same arm speed as baseball pitchers since the football is heavier and requires more force to accelerate. Newton's second law of linear motion states that force is a product of an object's mass and its acceleration ($F = ma$). This means that for a given force an athlete can apply to an object, as the object's mass increases its acceleration will decrease proportionally. Fewer deceleration injuries related to football throwing are experienced as a result (Fleisig et al., 1996).

A previous study found a strong relationship between the movements of wrist and elbow extension and throwing velocity (Bartlett, Storey and Simons, 1989). As the shoulder internally rotates the wrist is hyper extended and the lower arm is supinated, preparing the wrist for flexion and the lower arm for pronation during release (Yessis, 1984). Furthermore, the previous study by Bartlett et al. (1989) suggests the greatest correlation between throwing velocity and joint movements were found between velocity and shoulder adduction and shoulder extension. Shoulder adduction was the only movement found to be significant at the 0.05 level, although a trend was apparent in shoulder extension. During the acceleration phase of the pass the pectoralis major and subscapularis muscles appear to work closest to their maximal voluntary contraction strength at 81 and 86% respectively. These muscles were classified in the maximal activation category and were the only two muscles reaching greater than 70% during the phase (Kelly et al., 2004).

Release

At release there will be variability among quarterbacks, but a high point of release is ideal to reduce the risk of the throw being deflected by defenders. An overhead throwing technique is generally recommended over the sidearm technique because of a higher release and improvement in control (Figure 2.7A) (DeLuca, 1978). The typical side arm technique used in other throwing events has the athlete laterally flexing the trunk toward the throwing arm (Hamilton and Luttgens, 2002; Kreighbaum and Barthels, 1996). The arm is moved forward in the horizontal plane due to pelvic and spinal rotation, but is also combined with horizontal shoulder adduction at the shoulder (Hamilton and Luttgens, 2002). In football it is unreasonable for the quarterback to lean toward the throwing arm and lower the release height of the ball, making deflections by the defenders more likely. Football's version of a sidearm throw is sometimes referred to as a 'three-quarter arm motion'. The three-quarter throwing style is closer to sidearm in the sense that the release height is lower than the overhead style. Many passers find this style more natural because of the common handicap of a lack of flexibility in the shoulder joint. The ball is released closer to head height with the upper arm approaching parallel to the ground (Van Brocklin, 1960) (Figure 2.7A).

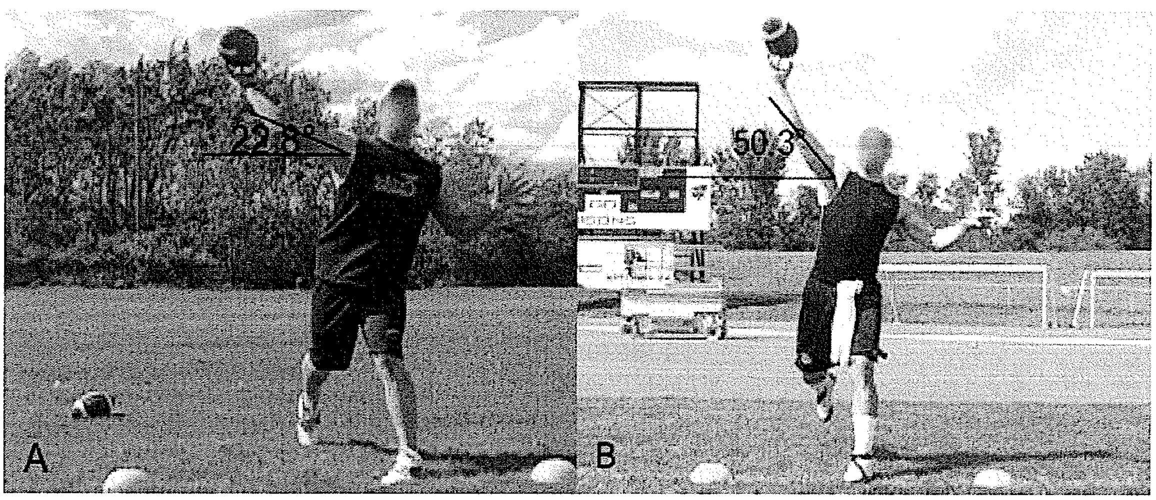

Figure 2.7: In the sidearm throw (2.7A) the upper arm is closer to parallel to the ground at release. The overhead throw (2.7B) has a more vertical position of the upper arm at the moment of release.

As the ball is released, and into the follow-through, the back right foot is unweighted and brought forward, parallel to the left foot (Alexander, 1992; Fracas and Marino, 1989). The front knee remains slightly flexed approximately 28 degrees at release (Fleisig et al., 1996) (Figure 2.8). Locking the front knee into extension can result in an over or underthrown pass by limiting weight transfer and affecting the trajectory of the pass (Danischewsky, 2007).

Figure 2.8: At release the back foot is completely unweighted and the left knee remains flexed close to 30 degrees.

The elbow should be close to fully extended with the athlete leaning away from the ball to increase the length of the lever arm from the spinal axis (Alexander, 1992). However, Rash and Shapiro (1995) found 59 degrees of flexion in the elbow at the moment of release in university quarterbacks compared to 36 degrees found by Fleisig et al. (1996). Torque is the product of force and the perpendicular distance from the axis to which the force is applied. The perpendicular distance from the axis is referred to as the moment arm and as the moment arm is increased, torque will increase proportionally. In the quarterback pass the athlete rotates about two major axes. The athlete's shoulder girdle and trunk rotates about the spine and the pelvis rotates about the front hip as the front foot is planted. Lateral trunk lean also allows a higher point of release to produce a more direct throw (Alexander, 1992; Yessis, 1984). Fleisig et al. (1996) reported lateral trunk lean of 26 degrees from the vertical at release. A pass with increased release height can have a lower trajectory and more direct flight path, allowing the defense less time to react to the pass.

At release the trunk should be rotated to face the target, allowing a full range of motion of the shoulders and hips for force production (Alexander, 1992). The trunk is flexed forward approximately 25 degrees from the vertical at release which is slightly more vertical than seen in baseball pitching (Fleisig et al., 1996) (Figure 2.9). The quarterback stands more upright than other overhead athletes because of the defenders in front of them. A high release is needed to avoid the defenders and allow a direct path for the pass. If the quarterback does not have enough forward trunk flexion at release the pass will have an increased angle of release because the shoulders will be tilted back and will cause the ball to be thrown too high (McElroy, 2003; Danischewsky, 2007). The shoulders should remain level unless the quarterback is attempting a very deep pass.

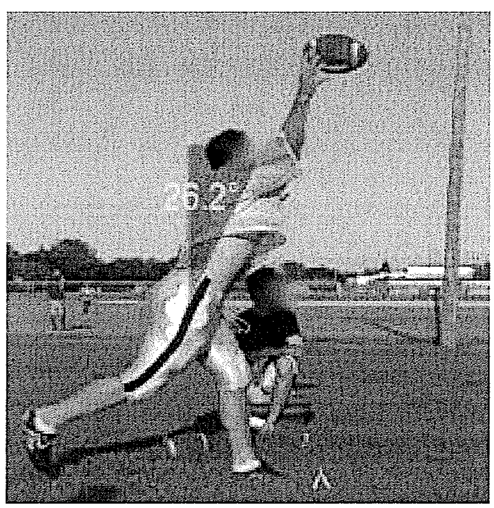

Figure 2.9: The quarterback is flexed at the trunk causing his body weight to be transferred onto the front foot at release.

Shoulder horizontal adduction is occurring and increases in velocity into the follow-through (Fleisig et al., 1996; Rash and Shapiro, 1995). The right shoulder should be horizontally adducted 26 degrees from the frontal plane at the point of release (Fleisig et al., 1996). Rash and Shapiro (1995) found horizontal shoulder adduction of 12 degrees at release. Horizontal shoulder adduction from the frontal plane causes the ball to be released approximately 6 inches ahead of the frontal plane through the shoulders of the quarterback, close to the ear (Reade, 1994; Yessis, 1984). The shoulder may be externally rotated at release with the amount of rotation dependent on the trajectory of the throw. Higher throws requiring greater external shoulder rotation to aim the front tip of the ball in the direction of the trajectory (Figure 2.10) (Rash and Shapiro, 1995). The shoulder is also close to 90 degrees of abduction at the instant of release, showing very little change through the force production phase into release (Rash and Shapiro, 1995). Some quarterbacks will vary in their overhead release with some releasing directly over the ear, while others may release the ball further away from the head. Position of the ball relative to the ear depends on the combination of shoulder abduction, elbow flexion, and lateral trunk flexion (Axman, 1997a). Increasing release height through lateral trunk flexion to the left has the lowest risk of injury since excessive shoulder abduction has increased risk of shoulder impingement. In excessive shoulder abduction the sub-acromial bursa and supraspinatus tendon can become impinged between the humerus and the acromion process of the scapula.

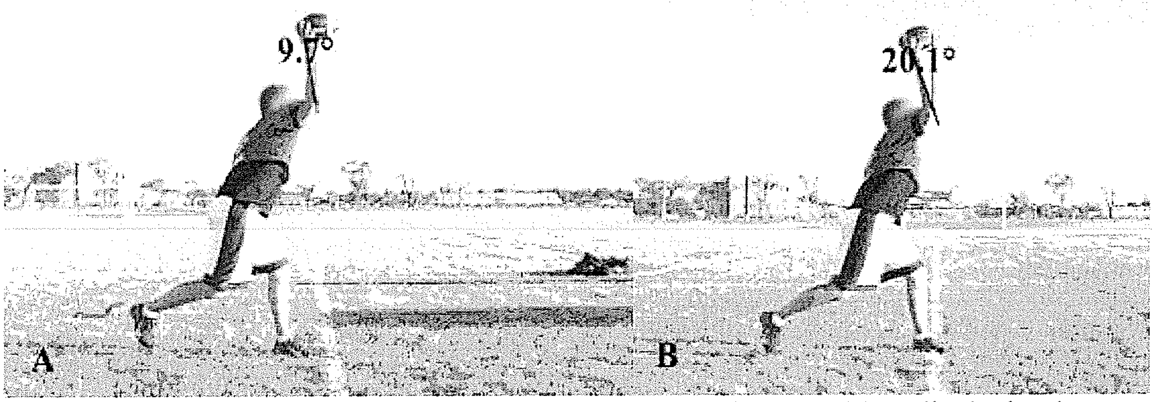

Figure 2.10: Shorter passes may have lower trajectory with the athlete displaying less shoulder external rotation at release (2.10A) than a longer pass requiring a greater trajectory (2.10B).

The ball rolls off the fingers, with the index finger being the last finger to leave the football and pointing towards the target briefly as it leaves the ball (Figure 2.11). The little finger initiates spiral rotation and each finger follows in succession by pulling down on the ball (Ash, 2006; McElroy, 2003). The wrist flexes and the forearm pronates to rotate the fingers and wrist outward to produce a tight spiral (Fracas and Marino, 1989). A good spiral provides stability to the ball in the air allowing for a longer pass, and makes the ball easier to catch for the receiver. The wrist also flexes and may be combined with finger flexion as torque is applied to the ball (Yessis, 1984). Fleisig et al. (1996) reported a ball velocity of 21m/s at release in university quarterbacks compared to 21 and 18m/s found by Rash and Shapiro (1995). The time from foot contact of the front foot to release of the ball is 0.21 ± 0.03s in a group of high school and university athletes (Fleisig et al., 1996). The entire throw from the ready position to release occurs in approximately 0.5 seconds (Mountjoy, 2007). The speed of release is important to allow the quarterback to wait until the last possible instant for his receiver to get open. Long, looping throwing motions will increase throw times and provide the quarterback less time to let the play develop. Longer throw times also make the pass vulnerable to deflections because the defenders have more time to react to the throwing motion and can attempt to block the pass.

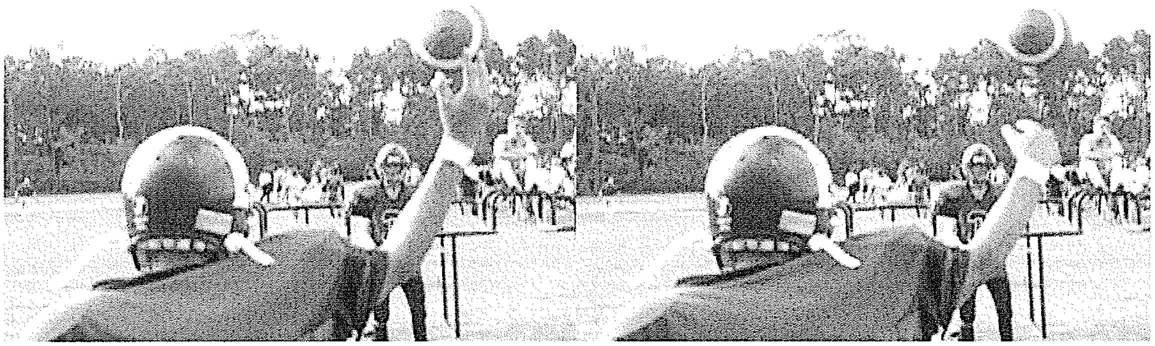

Figure 2.11: At the release the index finger is the last to lose contact with the ball. After release the index finger briefly points to the target.

Follow-through

The follow-through of the quarterback pass will not affect the flight of the ball, but serves a notable purpose. A longer follow-through will reduce the risk of injury by allowing the arm to decelerate over a large range of motion and ensure that the proper actions were executed during the release (Alexander, 1992; Yessis, 1985). Velocity and accuracy are maintained while reducing strain on the throwing arm (Ash, 2006). The follow-through action should allow the index finger of the throwing hand to point to the target spot momentarily (Figure 2.11). The hand should continue through with the forearm pronating to point the thumb downward (Axman, 1997a; McElroy, 2003).

A common trend of horizontal shoulder adduction and shoulder adduction is noted through the follow-through (Figure 2.12). Shoulder abduction changes to adduction between 110-120% of the throwing motion. The throwing motion was determined to range from front foot contact (0%) until release (100%) (Rash and Shapiro, 1995). The combination of medial shoulder rotation and shoulder adduction requires activation of the rotator cuff muscles and shoulder adductors. The supraspinatus and infraspinatus reach values of 87% and 86% of their voluntary eccentric contraction during the follow-through acting to decelerate medial rotation of the shoulder while pectoralis major and latissimus dorsi reach 79% and 72% of maximum respectively (Kelly et al., 2002). The pectoralis major and latissimus dorsi muscles are the primary movers for shoulder adduction as the quarterback follows through to bring the arm back to the midline. Infraspinatus and subscapularis are also synergists for horizontal shoulder adduction, explaining their increased activation. The rotator cuff muscles act to resist forces of the anterior shoulder muscles. As the pectoral muscles contract to accelerate the arm, the head of the humerus is pulled anteriorly in the socket. The rotator cuff muscles contract eccentrically to decelerate the arm, keep the head of the humerus in the centre of the socket and maintain the integrity of the joint during follow-through (Moore and Dalley, 2006). Therefore the primary accelerators during force production have a dual responsibility by providing co-contraction during follow-through to stabilize the joint (Kelly et al., 2002). Bringing the right arm across the body during the follow-through also provides some protection in the event that the quarterback is hit by a defender shortly after release (Figure 2.12). The arm is close to the body and reduces the risk of injury from impact such as seen in shoulder dislocation (Hay, 1993).

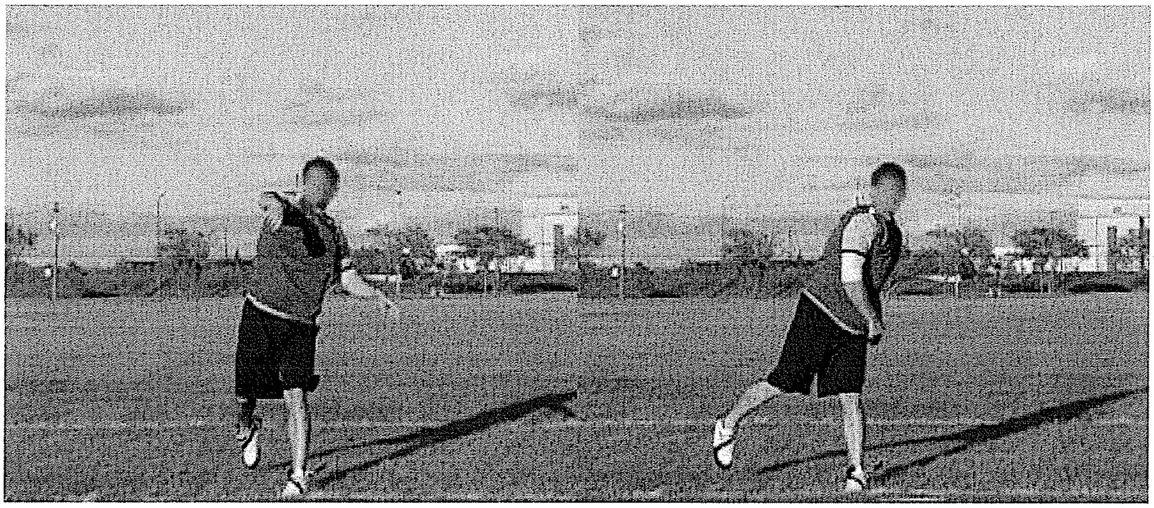

Figure 2.12: During follow-through the forearm pronates to point the right thumb towards the left hip. The arm goes through a large range of motion and finishes close to the body for protection in case of a hit.

When stepping straight ahead into the throw the quarterback should bring the right thumb across and down to point to the left hip (Ash, 2006, McElroy, 2003). The right shoulder continues to medially rotate at a maximum velocity of 4950 degrees/second during the deceleration of the throwing arm immediately after release (Fleisig et al., 1996). The elbow remains slightly flexed at least 24 degrees during the follow-through (Fleisig et al., 1996).

Before release the back foot may come up on to the toes or come off the ground completely, depending on the force and trajectory of the pass. The right hip and pelvis should rotate to face the target with the quarterback in a square and balanced ready position (Ash, 2006; Yessis, 1985). During the throw the athlete drives with the right leg and initiates hip rotation. After release the right foot is completely unweighted and continues to rotate with the hips. If the right leg fails to come forward the quarterback is forced to throw primarily with the arm and limits the summation of forces. Strain on the shoulder and reduced throwing velocity can occur as a result of not unweighting the back foot (Fracas and Marino, 1989). The trunk continues to rotate through follow-through while horizontal shoulder adduction decreases and reduces the total horizontal shoulder adduction angle. The horizontal flexion angle of the shoulder is actually decreased as a result (Gainor et al., 1980). The trunk also continues to flex forward while the athlete decelerates the forward velocity of the throwing arm (Alexander, 1992).

Quarterback Skill Tests

There are very few standardized quarterback throwing tests used by teams, schools or leagues. The lack of a standardized skill test makes it very difficult to test and compare various groups of quarterbacks throwing the football. Without a consistent test, athletes of various skill levels and age groups cannot be objectively compared.

Professional Skills Tests

The National Football League has an annual skills challenge during their All-Star weekend. Each year the event has a quarterback skills test, however the protocol varies from year to year. The quarterback challenge is called 'On the Mark', and has not been the same in the past three years.

In 2005 the NFL adopted a point scoring system for their quarterback challenge (NFL Films 2005). Athletes had 25 seconds to complete three pass attempts at each of three targets. If an athlete took more than 25 seconds at one station, his time would be reduced in the final station. Each target had a separate throwing zone five yards apart. Right-handed quarterbacks would run to the right, while left-handed quarterbacks would run to the left to the next station. Targets were placed 10, 20, and 30 yards from their respective throwing zones. The targets differed from the subsequent years in the sense that they were not ringed targets. The targets had a hollow centre meaning the points were awarded on a hit or miss scale and did not account for how close to the centre of the target the ball was. Any balls passing through the target received maximum points. Each successful target at the 10 yard distance was worth 10 points, the 20 yard throws worth 20 points, and the 30 yard throws worth 30 points. Ties were settled with re-runs of the test. Although this test had a point system, the scoring for accuracy was not as precise as subsequent years. The test was, however, effective in distinguishing competitors. Out of a potential 180 points, the top three contestants scored 130, 70, and 50 points respectively.

Two years ago, in 2006, at the Pro Bowl weekend the 'On the Mark' quarterback event again emphasized time, but awarded bonuses for accuracy at each target. The test consisted of four targets, each with a separate throwing zone (NFL Films, 2006). The athlete was allowed two throws per target for the first three targets, and only one for the final target, which was a throw on the run. After throwing both balls at each of the first three targets the right-handed athlete would run to his right five yards. If the quarterback was left handed the test was flipped to allow the athlete to pick up the ball while facing the proper direction for a quick delivery. Each target was 42 inches in diameter and consisted of three rings. The accuracy of the pass determined the time deducted from the total time at the end of the test. The innermost circle was worth a four second deduction, the middle ring worth two seconds, and the outer ring worth one second. The first three targets were 10, 15, and 20 yards away from their designated throwing zone. After completion of the third station the athlete ran five yards to the fourth station to grab the ball and continued to run with the ball for ten yards, throwing on the run at the final target. The fourth target was the same size as the previous three, however the final target had no rings, and hitting any part of the target resulted in a four second time reduction. At the end of the test, time deductions were distributed and the athlete with the lowest total time was declared the winner. Similar to other years, ties were settled with a re-run of the test. Although a point scoring system was not used, accuracy was scored more precisely than the previous year since the time awarded for accuracy depended on the precision of the pass.

Damon Allen, of the Toronto Argonauts also sponsors his own quarterback skills competition, called the Damon Allen Quarterback Challenge. Similar targets to the one to be used in the current study were used for the 2006 Damon Allen Quarterback Challenge (*Damon Allen's Quarterback Challenge*, 2006). The targets were large three-ringed targets, except the bull's eye was cut out to allow the ball to pass through. The athletes competed in several competitions similar to that of the NFL challenge in the Cayman Islands. The athletes attempted throws at varying distances; however the details regarding target distance and point scoring were not available from the web site or the program coordinator. The challenge did not take place in 2007 due to complications with the Grey Cup preparations, however it returned in May, 2008.

In the 2007 'On the Mark' event the quarterbacks were required to hit four different targets. Targets were arranged right to left with the exception of the bonus target which was 40 yards directly downfield (NFL Films 2007). The first target was 10 yards away with the centre of the target approximately six feet high. After successfully hitting the target, the athlete remained in the same throwing zone and attempted a 20 yard target. The third target was also a 20 yard target on the opposite hash mark. The fourth target was a 15 yard pass to the left. After completion of throwing at each of the four targets, each athlete received one throw at a net 40 yards down the middle of the field. The frame of the net was 45 degrees from horizontal, and successfully hitting the net gave the quarterback a five second credit to their score. During the specific test, wind was a factor and none of the contestants successfully completed the bonus ball task to receive the time bonus. The quarterback who completed all four targets and the bonus ball the fastest won. In case of a tie, the athletes did the event over from start to finish.

In May, 2007 the NFL also produced the DIRECTV NFL Quarterback Challenge, held in the Cayman Islands (*Cayman to host NFL Quarterback Challenge*, 2007). The quarterback challenge was broken up into four categories: Accuracy, Speed and Mobility, Long Distance Throw, and No Huddle. The most relevant category to the current study is the accuracy section. The targets were a two-ringed circle. The targets were large, inflatable, moving targets. Each athlete took throws at the targets from 10, 20, and 40 yard distances. Points were awarded based on the area of the target that was hit. The precise scoring system for the accuracy test was not available. Points were awarded for the players' standings in each competition. The quarterback with the highest overall score after all four events was declared the winner.

Pass velocity has not been taken into account in previous quarterback challenges in the NFL, however the 2006 and 2007 versions of the challenge were time dependent which may have been intended to force the athletes to throw harder. This was not overly effective in eliciting hard throws as most athletes chose to sacrifice time in their delivery to help improve accuracy. If throwing velocity itself had been measured using a radar gun, similar to that in baseball, the athletes may have reacted differently and attempted to increase throwing velocity.

These professional tests have not been used in research and they are difficult to compare because the tests differ each year. In order to establish some validity to determine if the tests were accurate in finding the best quarterback, results of the previous NFL Skills Challenges were compared to the quarterback ratings for the respective season. The quarterback rating is used in the NFL as a statistic giving the overall measure of a quarterback's performance. The rating is determined using a formula that considers pass attempts, pass completions, passing yards, touchdowns, and interceptions. A perfect quarterback rating according to the formula is 158.3. Tables 2.1 to 2.3 illustrate the comparisons between Skills Challenge results and quarterback ratings for the 2007, 2006 and 2005 seasons. The tables list the Skills Challenge participants in order of their placing. The regular season quarterback rating is also given for each athlete.

Table 2.1: 2007 Skills Challenge results and quarterback ratings for the previous regular season.

2007 NFL Skills Challenge		
Standings	**Time**	**Regular Season Rating**
Tony Romo	16.1	95.1
Carson Palmer	16.8	93.9
Drew Brees	17.4	96.2
Marc Bulger	35.6	92.9

Table 2.2: 2006 Skills Challenge results and quarterback ratings for the previous regular season.

2006 NFL Skills Challenge		
Standings	**Time**	**Regular Season Rating**
Matt Hasselbeck	5.8	98.2
Peyton Manning	7.9	104.1
Trent Green	8.2	90.1

Table 2.3: 2005 Skills Challenge results and quarterback ratings for the previous regular season.

2005 NFL Skills Challenge		
Standings	Points	Regular Season Rating
Drew Brees	130	104.8
Peyton Manning	70	121.1
Michael Vick	50	78.1
Daunte Culpepper	20	110.9

In 2007 and 2006 the results of the competition followed the same general trend as the quarterback ratings with the exception of one athlete each year. However, 2006 only had three participants compared to four in 2007. The 2005 challenge had less success matching results with the quarterback ratings for the regular season. That test used a hollow centered target which reduced the variety of scoring. This makes it more difficult to distinguish athletes since each athlete scores one of only two possible outcomes. The tests used in the past have generally been able to adequately assess athletes compared to their quarterback ratings. The NFL has modified its test each year, which makes it difficult to compare results. The similarities between test results and quarterback ratings show that the tests are valid and measure the aspects of the position they are meant to. The tests challenge the athlete's pass accuracy as well as velocity by varying in target distance.

Other Skills Tests

A test designed by the American Alliance for Health, Physical Education, Recreation and Dance (AAHPERD) for use with school football athletes from elementary to high school uses slightly larger targets than this study (Hastad and Lacey, 1998). A target, 72 inches (183cm) in diameter, with three concentric circles is placed 15 yards (13.8m) away from the quarterback. The lower edge of the outer circle is 36 inches

(91cm) above the ground. The athlete takes ten throws at the 15 yard distance and points are awarded for accuracy. Athletes are instructed to stay behind the 15 yard line while throwing. Three points are awarded for passes that hit the inner circle, two points for the middle circle, and one point for the outer circle. Throws that hit the line between circles are awarded the higher point value. The points for all ten throws are added and recorded as the students score.

Baumgartner, Jackson, Mahar and Rowe (2007) suggest that accuracy tests have a basic disadvantage of not being able to discriminate among skill levels. Many tests lack variability by having a limited scoring system. For example a target with a range from 0-1 has less variability than a target that ranges from 0-3 or 0-5. Another way to improve reliability of the accuracy test is to increase the number of trials. Given 10 throws at a target ranging from 0-3 would provide a more precise measure ranging from 0-30 points (Baumgartner et al., 2007). More trials are ideal to increase precision, however this can make a test difficult to administer in mass testing situations.

Borleske created the Borleske Touch Football Test in 1936. Normally football is considered to be tackle football, however football taught in physical education is usually touch or flag football (Collins and Hodges, 1978). The initial test battery had 18 items but was later reduced to five, and then to three. Using expert judgment, validity coefficients of 0.93 and 0.88 were found for the five-item and three-item batteries respectively. Similar to the revised version of the test, the most relevant item of the test battery for the current study is the forward pass for distance. The forward pass for distance is administered on a regulation football field. If a regulation field is not available, yard markers are placed at 5 yard intervals. The quarterback receives the ball while standing on the end line and executes three passes for distance. The athlete should throw as straight as possible at right angles to the end line, and parallel to the side line. The subject is instructed to remain behind the end line throughout the throw. The quarterback is allowed as many steps as they prefer prior to the throw as long as they remain behind the end line. Each subject attempts three throws and the final score is the distance of the longest throw measured to the nearest yard (Collins and Hodges, 1978). Scores are converted to T-scores to enable the instructor to classify athletes according to ability levels. T-scores range from 20-80 and relates to population percentiles. A T-score of 50 corresponds to the mean of the sample which is equal to the 50th percentile (*MedFriendly*, 2008).

The test was administered to 87 college physical education students, but these students were not necessarily football players. A throw of 30 yards received a T-score of 42 which is equivalent to the 21st percentile (*MedFriendly, 2008)*. This shows that 79% of college physical education students are capable of throwing a football 30 yards. Not all participants in this study played organized football and results may be lower than a sample of competitive football quarterbacks.

The Jacobson-Borleske test is a revised version of the test battery by Borleske designed for collegiate athletes (Tritschler, 2000). The Jacobson-Borleske Touch Football Test consists of three sections to assess the essential skills of football (Tritschler, 2000). The first section assessed the forward pass for distance. The athletes take three throws and the score is the longest of the three attempts. The athletes take their throws from behind a restraining line and throw along the field sideline. Any throws that deviate from the sideline are measured at right angles to the sideline. The throws are measured to the nearest yard. Accuracy was directly assessed in this test; however throws that deviated from the sideline were measured at right angles from the sideline. As a result the total distance traveled was not measured and results in a lower score. For example, a 50 yard throw that deviates from the centre line by ten yards will be measured at a right angle from the sideline, resulting in a measured throw of 49 yards when measured to the nearest yard (Figure 2.13). The three item battery had a validity coefficient of 0.88 when compared to expert judges' ratings of overall playing ability. Reliability of each individual item or the battery as a whole was not reported.

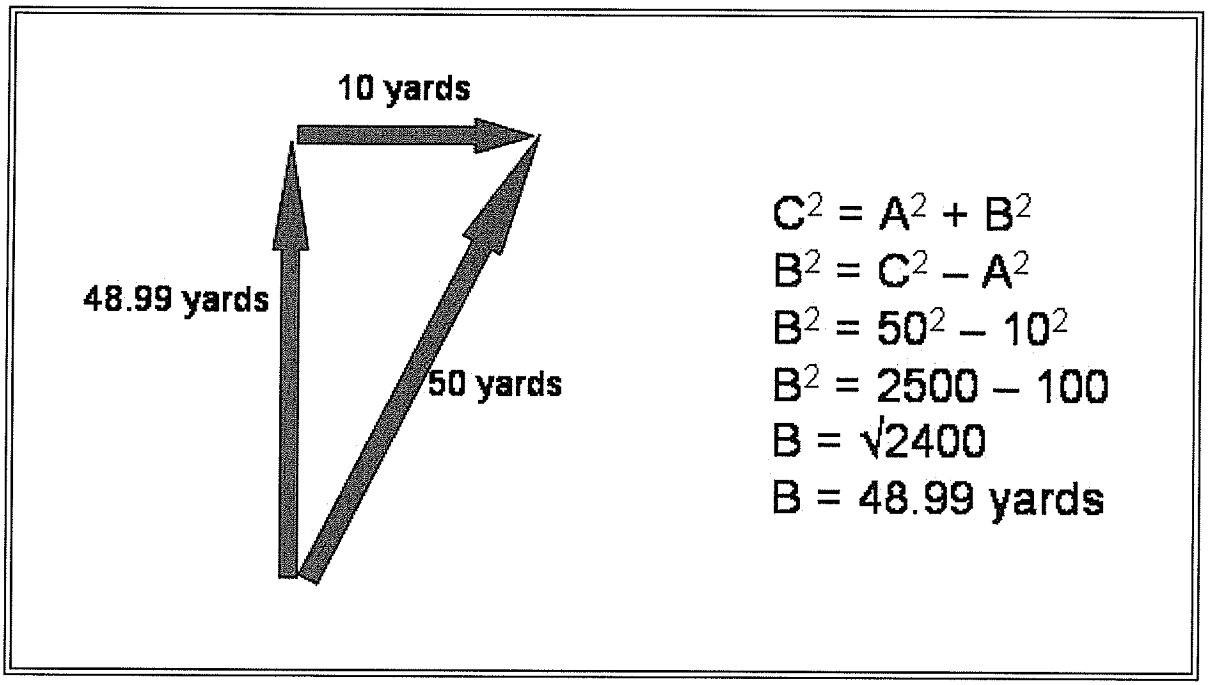

Figure 2.13: In the Jacobson-Borleske test for pass distance, the more a pass deviates from the sideline the more the total score will decrease since the throw is measured relative to the sideline.

The Borleske test and the Jacobson-Borleske test have both been used in studies to distinguish skill levels in collegiate and high school aged quarterbacks. These studies determined that the majority of collegiate students can complete a 30 yard throw despite not being competitive football quarterbacks. The Jacobson-Borleske test was administered to children of all high school grades, and the ability to throw for distance increased with age.

A quarterback's ability to throw greater distances allows him to force the defense to prepare for the possibility of a long pass. If a quarterback has limited ability in throwing distance the defense is able to emphasize the short passing game. At the Senior Bowl, a camp for university seniors across the United States in Mobile, Alabama the winner of the longest throw competition had a throw of 74 yards (Pauline, 2008). In 2006 a similar high school camp was held in Naperville, Illinois called the Blue Chips Summer Football Leadership Camp which had a longest throw competition with a the winner throwing 56 yards. Third place finished with a throw of 54 yards, showing a number of athletes able to throw similar distances (Rudny, 2006). Longest throw results were not available for Canadian university athletes; however in 1994 Bobby Campbell of Sturgeon Creek Secondary School in Winnipeg, Manitoba set a new high school record with a throw of 54 yards (*What is the High School Record for Longest Pass in Football,* 2007). Despite the size of ball, high school athletes are able to throw similar distances.

A quarterback's technique is crucial for accuracy, throwing speed and overall efficiency. An inaccurate passer will not be successful at a higher level, while a passer without sufficient throwing speed will also be limited in his repertoire of passes. Efficient mechanics allow the athlete more time to scan the field for an open receiver by having a quick release. He can also increase release height to reduce the risk of having the defense deflect the pass.

There are a variety of quarterback throwing tests with many of them having similarities in protocol and scoring. Tests that award points for accuracy tend to award more points for increasingly difficult throws regardless of the scoring system. Though some tests vary in target structure, more scoring options are recommended. A target that only has two point options will limit the ability of the test to distinguish skill levels. Varying pass difficulties are also recommended to assure that the test accurately assesses all the requirements of the position. A quarterback must be able to successfully complete a variety of throws, and therefore the test must include various throw distances to accurately assess the athletes. Despite several different tests, a standardized test for various skill levels has yet to be developed. With the exception of the Borleske Touch Football Test and the Jacobson-Borleske Touch Football Tests, there have been no previous research studies using these protocols. The Borleske and Jacobson-Borleske tests were used to distinguish skill levels but the tests were not combined with biomechanical analysis to determine the key variables affecting pass performance.

Application of Biomechanics to Football Passing

Law of Acceleration (F = ma)

Newton's' Second Law of Motion states that for a body with a constant mass, a force applied to a body causes an acceleration with that body of a magnitude proportional to the force, in the direction of the force, and inversely proportional to the body's mass (Hall, 2007). Linear acceleration is defined as a change in velocity over time (Hall, 2007) and is common in most sport skills. In the quarterback throw the ball is accelerated from rest to its release velocity. The football weighing 0.425kg is accelerated from rest (0m/s) to its release velocity by a force applied to it by the quarterback. The following is an example of the law of acceleration in the quarterback pass taken from the pilot study video analysis.

Example 1:

An athlete releases the football with a linear velocity of 19.81m/s in 0.116s from rest. With the final and initial velocities of the ball and the time in which the change of velocity occurs we can determine the acceleration of the ball using the acceleration equation (Equation 2.1) (Hall, 2007).

Equation 2.1

$$a = (v_f - v_i)/t$$

a = acceleration, v_f = final velocity, v_i = initial velocity, t = time

Once acceleration is calculated it can be used to determine the force required to accelerate the ball using Newton's Second Law of Motion ($F = m \cdot a$).

$a = (v_f - v_i)/t$

$a = (19.81\text{m/s} - 0)/.116\text{s}$

$a = 170.78\text{m/s}^2$

$F = ma$

$F = 0.425\text{kg}\ (170.78\text{m/s}^2)$

$F = 72.58\text{N}$

This formula indicates that in order to accelerate the football at $170.78 m/s^2$ a force of 72.58N must be applied to the ball. The magnitude of this acting force applied by the quarterback during release will determine the acceleration of the ball.

Impulse-Momentum

From the time of foot contact the quarterback has approximately 0.21 seconds to apply the necessary force to the ball before it is released (Fleisig et al., 1996). From the ready position the entire throw takes less than one second including backswing. A large impulse (force x time) (Hall, 2007) must be applied to the ball to increase velocity of the pass. The athlete achieves this impulse by taking a long step and transferring his weight on to the front foot and initiating rotation of the hips to face the target. This leads to segmented rotation and a summation of forces through the trunk and shoulder girdle. As the shoulder girdle rotates to face forward the shoulder joint of the throwing arm is forced into shoulder lateral rotation as the arm experiences a lag relative to the shoulder girdle (Hay, 1993). A stretch reflex occurs, causing an aggressive internal rotation of the shoulder as the ball accelerates until release above the throwing shoulder. The throwing motion involves a progressive contribution of body segments beginning in the base of support and progressing through the hand (Enoka, 2002). The athlete's ability to increase the ball's velocity from rest to the velocity at release utilizes the impulse-momentum relationship (Equation 2.2) (Hall, 2007).

Equation 2.2

$$Ft = mv_f - mv_i$$

F = force, t = time, m = mass, v_f = final velocity, v_i = initial velocity, mv = momentum

Impulse is equal to the change in momentum over time (Hall, 2007). With the implement having a constant mass, a change in momentum corresponds with a change in velocity (Enoka, 2002). The change in momentum is dependent on the duration of the forces acting on the system. Changes in momentum can occur due to a large force over a short period of time or a small force over a large period of time (Hall, 2007; Kreighbaum and Barthels, 1996). The force producing phase of the quarterback throw occurs over a very short period of time, requiring a large force to increase the ball's velocity prior to release. The impulse-momentum relationship can be observed in an example of a quarterback throw. The time of the throw from the cocked position is measured and the force required for the impulse is determined.

Example 2:

A male football player starts from a stationary position. The throw takes 0.1s from the fully cocked position until it is released. At the fully cocked position there is a brief moment where the ball has 0m/s of forward velocity. The linear velocity of the ball at release is 19.11m/s and the ball has a mass of 0.425kg.

$Ft = mv_f - mv_i$

$F (0.1s) = (0.425kg (19.11m/s)) – (0.425kg (0m/s))$

$F (0.1s) = 8.12kg\ m/s$

$F = 8.12kg\ m/s / 0.1s$

$F = 81.2N$

From a cocked position with the shoulder abducted and externally rotated the athlete needs to apply 81.2N of force to increase the ball's linear velocity to 19.11m/s at the moment of release. This value is positive because the direction of the pass is forward therefore the direction of the force applied is also forward.

Torque

Torque is a rotary effect created by an applied force and is the angular equivalent of force (Hall, 2007). Torque is the product of the force applied and the moment arm where moment arm is the perpendicular distance from the applied force to the axis of rotation (Equation 2.3).

Equation 2.3

$$T = F (d\perp)$$

T = Torque F = Force $d\perp$ = perpendicular distance from the line of force to the axis of rotation.

The quarterback applies torque to the ball to produce a spiral which gives the ball stability during flight. The force applied comes from the fingers rolling off the ball, with the perpendicular distance being the distance from the force of the fingers to the long axis of the football (Figure 2.14).

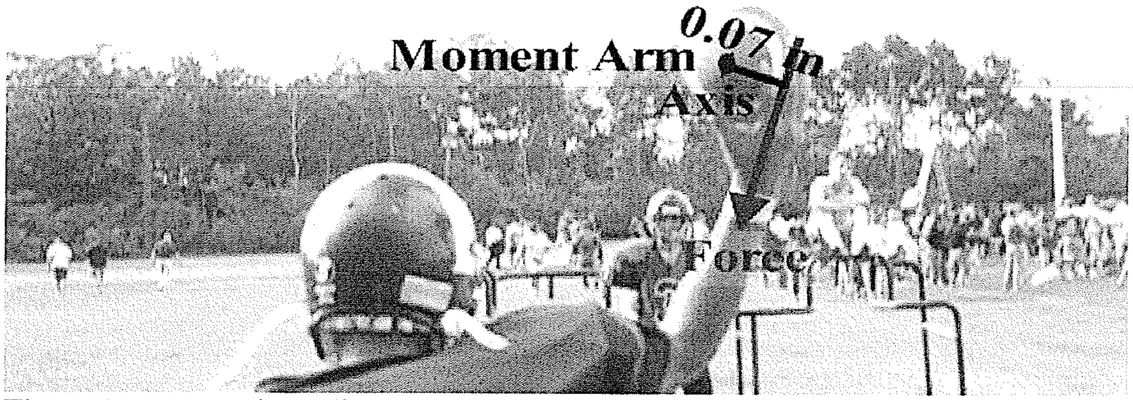

Figure 2.14: Force is applied to the ball by the fingers at a perpendicular distance to the long axis of the ball, producing a torque.

The athlete pulls down on the side of the ball 0.07m from the axis of the ball and a torque results which creates a spiral as the ball is released. The amount of force applied to the ball will determine the rate of spin of the ball. This will be further examined later on in the section.

During the throwing motion the elbow extends and the shoulder horizontally adducts as the trunk rotates about the spine. A torque is applied to the ball at a distance from the spine which acts as the axis of rotation. Simultaneously, the athlete rotates about the front hip which is firmly planted on the ground as the hips rotate to face the target (Figure 2.15). Recalling the formula for torque (Equation 2.3), a larger moment arm allows more torque to be produced. As the moment arm increases the quarterback will generate more torque and increase pass velocity. Since the ball is further from the axis its arc is much longer than a point closer to the axis. This greater angular distance traveled will produce greater linear velocity at the end of the system of levers, since linear velocity is the product of angular velocity and the radius from the implement to the axis of rotation (Equation 2.4).

Equation 2.4

$$V = r\omega$$

V = linear velocity, r = radius, ω = angular velocity

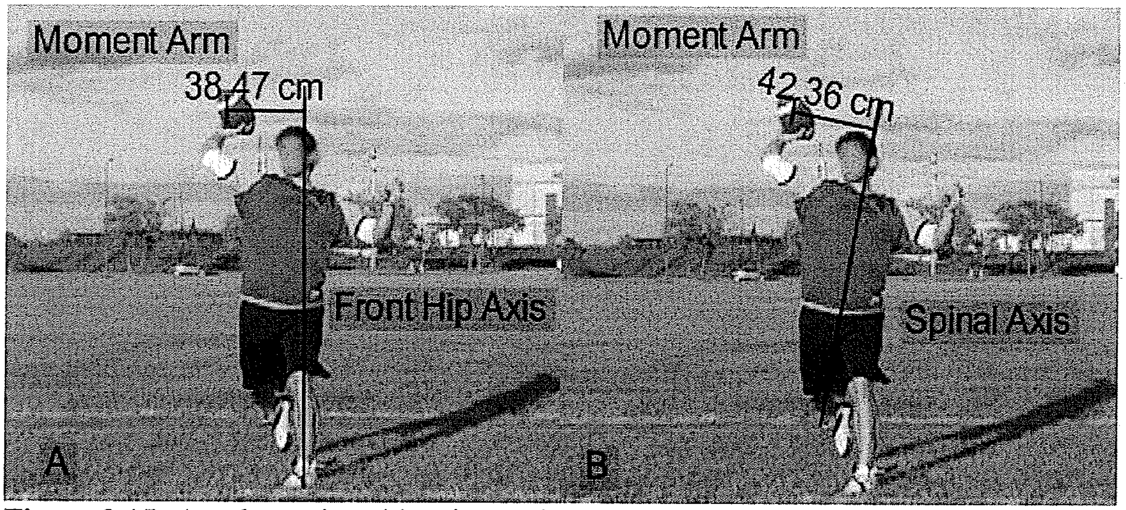

Figure 2.15: At release the athlete is rotating about the front hip (2.14A) and the spine (2.14B)

Moment of Inertia

The moment of inertia of an object is the object's resistance to angular motion (Hay, 1993). It is calculated as the product of the mass of the object and its radius of gyration squared (Equation 2.5). The radius of gyration of an object is the distance the mass of an object is distributed relative to the axis of rotation (Hay, 1993). A body with its mass packed in close to the axis has a small radius of gyration. An object with a small radius of gyration has a smaller rotational inertia which is a body's resistance to change its state of angular motion (Kreighbaum and Barthels, 1996). Moment of inertia is affected by both mass and the distance that mass is distributed from the centre of rotation (Oatis, 2004). The moment of inertia is expressed in kilogram meters squared (kg m^2).

Equation 2.5

$$I = mk^2$$

I = moment of inertia, m = mass, k = radius of gyration

As the athlete rotates during force production of the throw his radius of gyration increases as the elbow extends and the shoulder remains abducted. The mass of the lower arm, upper arm and ball all move away from the axis of rotation. As a result the limb's moment of inertia will increase and will require more torque to move since it's resistance to motion has increased. This forces the athlete to increase the torque applied to the ball, but requires more strength to accomplish. If the athlete is strong enough to overcome this resistance the moment arm can be increased and velocity of the ball can increase, as previously mentioned in Equation 2.4.

The positioning of the free arm also plays a role in force production. As the athlete rotates to the left, the left shoulder (for a right handed quarterback) remains slightly abducted as it extends to contribute to the torque produced to generate rotation (Frala, 2007). Keeping the free arm too close to the body would minimize its moment of inertia and minimize the torque produced to assist in rotation about the spinal axis and front hip axis.

Angular Impulse Momentum

Just as impulse is applied to change an object's linear velocity, a similar impulse can be applied to increase the angular velocity of an object. Torque is the angular equivalent to force in linear motion. Angular impulse is the product of torque and the time the torque is applied and is equal to the change in angular momentum (Equation 2.6). Similar to linear momentum, angular momentum is the product of the moment of inertia and angular velocity. Angular momentum is the amount of angular motion an object or body possesses and is a measure of how force is required to start or stop angular motion (Hamilton and Luttgens, 2002). Objects undergoing angular motion have angular momentum in a similar fashion as objects undergoing linear motion. Angular momentum can be increased or decreased by the application of an angular impulse.

Equation 2.6

$$Tt = \Delta H$$

$$Tt = I\omega_f - I\omega_i$$

T = torque, t = time, H = angular momentum, I = moment of inertia, ω_f = final angular velocity, ω_i = initial angular velocity

During the throw the quarterback applies an angular impulse to the football to change its angular momentum. Angular momentum is illustrated in the spinning of the football. The quarterback applies a torque to the side of the ball prior to release causing it to spin. Angular impulse is the product of torque and time, and since torque is dependent on the force and the perpendicular distance of that force from the axis, both factors also affect angular impulse (Hall, 2007). The application of angular impulse is illustrated in the following example.

Example 3:

A quarterback applies a force to the side of the football for 0.02s, and the length of the moment arm is 7cm (Figure 2.14). Assuming the moment of inertia (I) of the football is 0.0038kg m^2 and the ball has an angular velocity of 20rads/sec at release. It is possible to calculate how much torque is applied to the ball and how much force is required to create the torque.

$$Tt = I\omega_f - I\omega_i$$

$$T(0.02s) = (0.0038 \text{ kg m}^2)(20\text{rads/sec}) - (0.0038\text{kg m}^2)(0\text{rads/sec})$$

$$T(0.02s) = 0.076\text{kg m}^2 - 0\text{kg m}^2$$

$$T = 0.076\text{kg m}^2 / 0.02s$$

$$T = 3.8\text{Nm}$$

$$T = F\, d\perp$$

$$3.8\text{Nm} = F(0.07\text{m})$$

$$F = 3.8\text{Nm} / 0.07\text{m}$$

$$F = 54.29\text{N}$$

The angular momentum of the ball at the beginning of the throw is zero since there is no tangential force applied to the side of the ball causing it to rotate. A torque is applied to the ball for 0.02s changing the angular momentum of the ball by increasing its angular velocity. The torque used to create this change in angular momentum was 3.8Nm. Torque is the result of force and the perpendicular distance that force is applied from the axis. The radius of the ball is 0.07m and produces the force necessary to generate 3.8Nm of torque. The athlete applies 54.29N of force to the side of the ball to create a torque. The quarterback contracts the pronator teres causing forearm pronation. Pronation allows the index finger to leave the ball last as the fingers pull down on the side of the ball. A downward force is applied to the side of the ball as the latissimus dorsi and pectoralis muscles contract, bringing the throwing shoulder into extension. These forces are applied to the side of the ball, away from the long axis of the ball, creating a torque that results in the spinning of the ball about the long axis.

In throwing events, the object is to maximize the angular impulse exerted on the ball before release to maximize its angular momentum and the ultimate final velocity of the ball (Hall, 2007). During force production of the throw the athlete's trunk is rotating towards the target, and therefore has angular momentum. The linear velocity of the throw is directly related to the angular velocity with the radius from the axis of rotation determining the objects linear velocity after release. Angular velocity can be related to linear velocity by multiplying the angular velocity by the radius from the implement to the axis of rotation (Equation 2.4). It is unlikely that the radius remains constant in the quarterback pass since the athlete is extending at the elbow during force production which increases the radius during the throw by moving the ball (Figure 2.16).

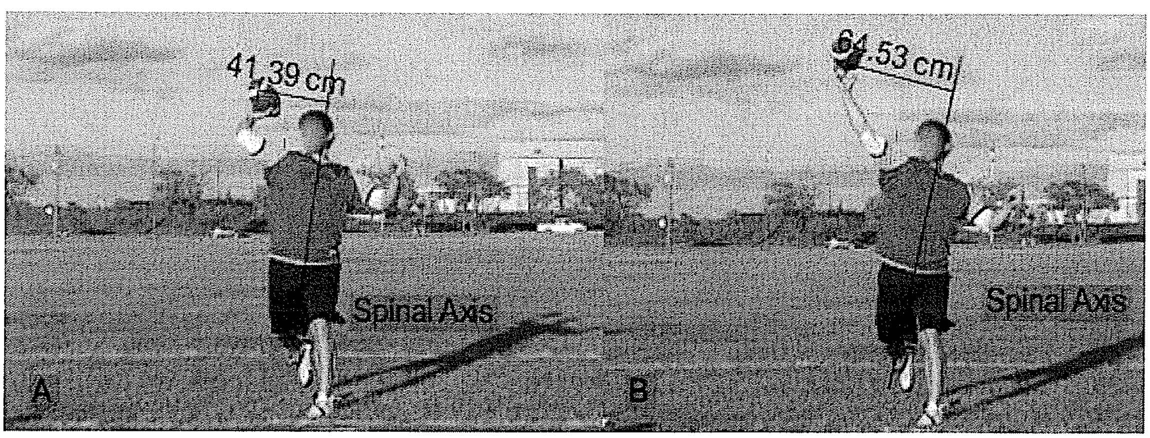

Figure 2.16: As the athlete accelerates the ball the elbow extends to increase the moment of inertia of the limb.

Once the ball is released it spins with constant angular momentum. The athlete applies torque to the ball while he is in contact with it, and when the ball is released all the momentum that has been created is conserved while the ball is in the air as long as no external torques are applied to the system (Kreighbaum and Barthels, 1996). This is referred to as conservation of momentum and is best observed in the football spiral. Since the ball remains the same shape, the moment of inertia also remains the same during flight. Once in the air the ball will also continue to rotate at the same angular velocity until it hits the target, maintaining the same momentum until another force is applied to it to slow it down. The receiver applies an angular impulse to the ball to change its angular momentum from its rate of spin at release to zero as he gains possession of the ball.

CHAPTER III

METHODS

Introduction

To assess the quarterback pass each athlete attempted three throws at a target set at three different distances. The results of each throw were recorded and awarded points based on pass accuracy and velocity measured from the film. The score given was a combination of points awarded for both aspects of the throw to provide a complete assessment of the athlete's skill level. Following the target throws, each athlete attempted two throws for maximum distance and could score a maximum of 100 points. The longest throw of the two was recorded for scoring. The highest scoring throw from each distance was further analyzed using Dartfish Analysis Software in order to determine the key variables affecting quarterback performance. Athletes from the university level were compared to athletes from the high school level in order to determine the primary differences between skill levels.

Subjects

Twenty Canadian football quarterbacks ranging in age from high school to university levels participated in this study. Ten football quarterbacks were recruited from local high school and community based teams for athletes of high school age (15-18). Ten more quarterbacks were recruited from local university and junior league teams and were 18 years old and older. If ten subjects at each level could not be found community teams of the same age group were used to satisfy the desired sample size.

The age groups chosen were determined through conversation with the provincial governing body regarding potential differences. Ethics approval was attained prior to data collection (Appendix A)All of the participants completed an informed consent form prior to filming (Appendix B). All athletes under the age of 18 required parental consent. The same consent form was used but had a line for the guardian to sign.

Data were collected from a total of 20 subjects on eight separate filming sessions: including the University of Manitoba Bison's football spring camp in Winnipeg Manitoba, St. James Rods football practice in Winnipeg Manitoba, Churchill Bulldogs football practice in Winnipeg Manitoba, Kelvin Clippers football practice in Winnipeg Manitoba and four separate organized filming sessions. Ten high school quarterbacks and ten university quarterbacks participated in the study, with all athletes considered skilled for their age being either prospective or current members of elite sports programs.

Quarterback Throwing Test

Development of Quarterback Throwing Test

The quarterback throwing test used in the current study used targets similar in size to those used in previous NFL "On the Mark" competitions (NFL Films, 2006). The target stand placed the centre of the target 1.37 meters above the ground. This height approximates the centre of the torso for a 6 foot tall receiver. The targets in this study were 18 inches lower than the NFL version of the test. The previous NFL test placed the centre of the ring around head height compared to mid-torso in the current study. This change was made because the centre of the target placed at head height would place the outer edge of the third ring just out of reach of a 6 foot tall receiver making the pass impossible to catch without jumping. Lowering the target to mid torso lowers the upper edge of the third ring to just above head height while the lower edge is approximately waist height. This pass range is more manageable for a receiver when making a catch.

The current study used the same throwing distances as the 2005 "On the Mark" competition and also shared similarities in point distribution (NFL Films, 2006). As the distances of the throws increase, it is more difficult for the athlete to be successful. More highly skilled athletes are expected to continue to score more consistently as the throws become more difficult, allowing the test to distinguish different skill levels. Points were awarded for accuracy in the NFL test, similar to the current study, however the targets were cut out, which allowed only two options for each pass. The passer either received full points or none at all. The test adopted for this study allowed a greater range of scoring to provide more detailed results and further distinguish between performances similar to that of the AAHPERD test for football pass accuracy (Hastad and Lacey, 1998). Both tests used three ringed targets, with points in the AAHPERD test ranging from 1 to 3 points. The test used in the current study also awarded points based on the velocity of the pass in order to assess strength and discourage the quarterback from sacrificing throwing velocity to improve accuracy. Velocity was measured using video analysis.

To further assess strength the athlete took two throws for maximum distance without the use of a target. Each athlete took two throws from the designated throwing line. The longest throw of the two was measured in a similar way to that of the Borleske Touch Football Test. The longest throw was measured at a right angle from the sideline to measure the distance traveled down the sideline. Points were awarded based on throw distance in five yard intervals.

In the current study, it was anticipated that most of the high school aged quarterbacks would be in their last 2-3 years of high school since older high school athletes are likely more developed and will make the team over younger athletes. In order to help improve validity of the quarterback throwing test the target scores ranged from 0-50 depending on where the ball contacted the target and each athlete had a total of nine attempts. This should have improved validity by creating a more precise measure of quarterback skill level. Pass velocity was measured for all nine throws creating a more complete measure of pass velocity as well. The average ball velocity of all nine throws was used for comparison. Measuring only one throw velocity would not distinguish skill levels accurately. Validity and precision in assessing pass velocity was increased by allowing more throws to be analyzed and by reducing the risk of measuring a non-typical throw or having minimal emphasis on pass velocity.

Targets

The targets used were donated by the Manitoba Rifle Association (Figure 3.1). The targets had a diameter of 42 inches (106.68cm) and were divided into three concentric circles. The outer ring had a 21 inch (53.34cm) radius. The middle ring had a radius of 14.5 inches (36.83cm) while the inner ring had a radius of 7.5 inches (19.05cm). The target was laminated and fastened to a plywood backing using duct tape. The plywood backing was 36 inches (91.44cm) wide and 48 inches (121.92cm) tall. Cardboard attachments were used on the sides of the plywood to allow the overhanging portion of the target to be supported since the target surface was slightly wider than the plywood backing. The stand was built using two two-by-four boards, each 78 inches (198.12cm) long, attached to the outer edges of the plywood. The two inch (5.08cm) width of the board was screwed into the plywood four times along the 48 inch (121.92cm) plywood sheet. A second pair of two-by-fours 72 inches (182.88cm) long was bolted 18 inches (45.72cm) from the top of the other boards. These boards were able to swing back and act as adjustable supporting legs. The adjustable boards had the ability to rotate back as much as necessary to allow the target to be perfectly vertical. Prior to each participant's throws a leveling device was used to ensure the target remained vertical.

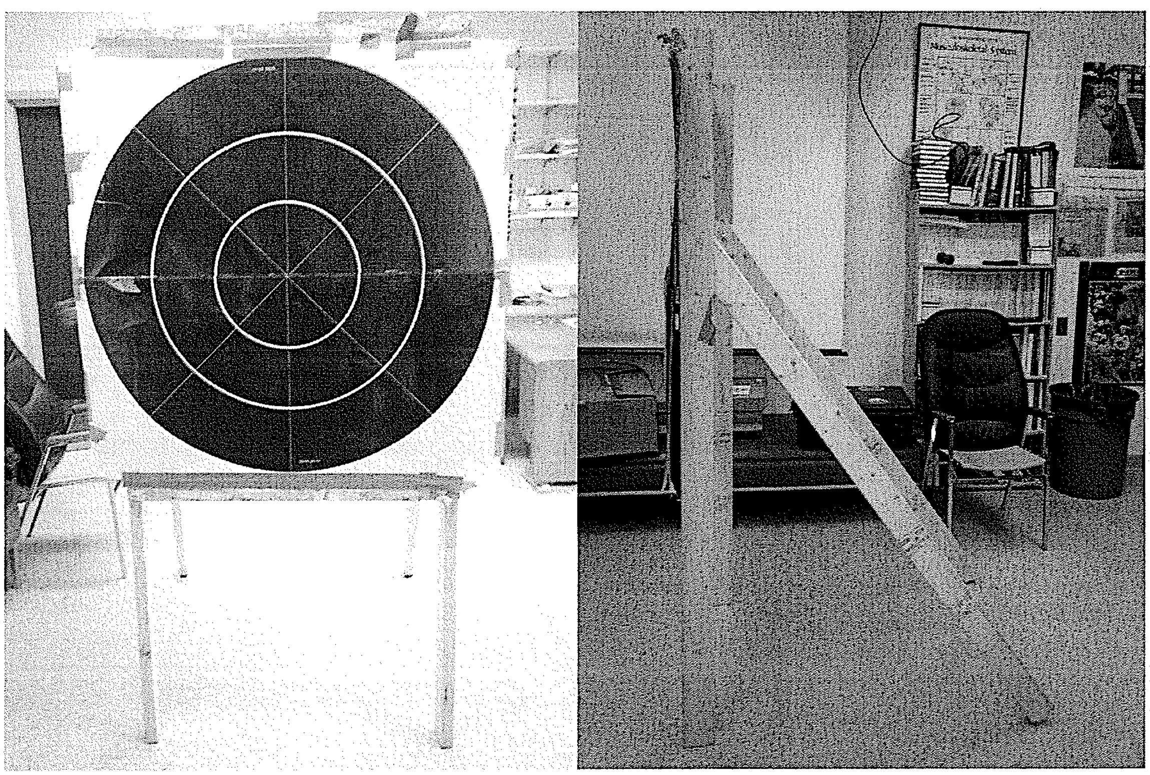

Figure 3.1: Target and stand used in the quarterback throwing test

Test Protocol

The quarterback throwing test took place outdoors at the high school or community club practice fields or the University of Manitoba Pan Am Stadium practice field. An outdoor test was chosen because most games at the amateur level are played outdoors so the surroundings during the throwing test were made similar to game situations. The weather conditions on the day of testing were documented for future reference but were not measured as a variable. The number of athletes filmed at each session was dependent on the athletes available. The maximum number filmed at a single session was five since most teams did not carry more than five quarterbacks on the roster at any given time. If a team only had one or two participants, their filming session may was combined with another team. The filming sessions lasted approximately one hour including warm up and test time.

Information regarding each athlete's age, height, weight, and team were also recorded (Appendix D).

The athletes were given instruction prior to participation. No instruction regarding throwing technique was given to avoid influencing the performance of the athlete. The latter half of the warm up was standardized beginning with an individualized warm up consisting of passing to other participants before being given standardized practice throws for the study. Each athlete took two consecutive practice throws at 9, 18 and 27 meters for a total of six warm up throws. In the sport of football distances are expressed in yards. For the sake of this study distances were converted and expressed in meters. The same throwing order was used for all three targets in order to keep rest periods consistent. The researcher provided balls for the throwing test. However, athletes were permitted to use their own balls if they preferred, provided they were standard Canadian Football League size footballs. Accuracy results for each of the throws during the warm up were given to the athletes for feedback.

After warm up was completed each athlete attempted three consecutive passes at each of the three distances. The athletes took their turns in a pre-determined order to allow consistent rest between sets of throws. The amount of rest was determined by the number of athletes participating during the filming session, but a minimum of two minutes was given between sets of throws while the targets were moved to the next distance. The throwing area was marked for the participants and they were advised to complete their throws behind the marker.

After each athlete had completed all nine throws at the targets, the athlete attempted two throws for maximum distance along the sideline of the field. The landing of the ball was marked by one of the testers with the longest of the throws being measured.

Test Scoring

Scoring for accuracy was determined according to the ring that was hit by each pass with the innermost circle being worth more points, and the furthest circle from the centre being worth the fewest points. Throws that hit the line between circles were awarded the higher score. The throws were filmed and scored from the film results for each throw at each target and were recorded and entered into an Excel spreadsheet for scoring (Table 3.1). The bull's eye of each target was worth 50 points while the other zones from inside to outside were worth 30 and 10 points. For example, a bull's eye thrown at the 30 yard target would have been given 50 points. Each athlete took three consecutive throws at each of the targets with a minimum of 2 minutes rest between sets of throws.

Table 3.1: Points given per throw at 9, 18, and 27 meter distance.

Ring	Points
Inside	10
Middle	30
Outside	50

Pass velocity was determined from film measurements of displacement and time. Points were allotted for pass velocity with passes under 61km/hr awarded 10 points, 20 points for passes between 61 and 65km/hour, 30 points between 66 and 70km/hr, and 40 points for a velocity between 71 and 75km/hr. The maximum of 50 points was awarded for a throw with a velocity greater than 76km/hr (Table 3.2). The scale used to score velocity was based on velocities measured in previous studies.

Table 3.2: Point distribution based on pass velocity.

Average Velocity (km/hr)	Average Velocity (m/s)	Points
≤60.99	≤16.94	10
61-65.99	16.95 - 18.33	20
66-70.99	18.34 - 19.72	30
71-75.99	19.73 - 21.11	40
76+	21.12	50

For the two throws for maximum distance, the longest throw was measured at a right angle from the sideline if the ball deviated from the line. Points were awarded for throw distance to a maximum of 100 points. Maximum points were given for a pass of 65 yards or greater and were reduced by ten points for each five yards below this distance (Table 3.3).

Table 3.3: Point distribution based on throw distance.

Throw Distance	Points
>65	100
60	90
55	80
50	70
45	60
40	50
35	40
30	30
25	20
20	10
<20	0

A perfect score of 1000 points was achievable in this test (accuracy: 450, velocity: 450, distance: 100) Results were also calculated as a percentage of the perfect score (i.e. 500 points = 50%).

Biomechanical Analysis

Filming Protocol

Filming took place at each team's practice facility during an outdoor practice session or at the University of Manitoba Pan Am Stadium. Each filming session followed the same filming protocol. Two Canon GL2 Digital camcorders were used to film the throw. One camera was placed five meters to the right of the designated throwing area (left of the throwing area from a frontal view) to capture the throwing motion and release from the sagittal plane. If the athlete was left handed the camera was moved left of the throwing area to face the athlete. This view was used primarily to measure release velocity and various joint angles. The second GL2 camera was placed five meters in front of the throwing area to capture the throw and release from an anterior view to measure various joint angles throughout the throwing motion (Figure 3.2). Both cameras were secured to tripods to prevent any unwanted movement. Following camera set up the throwing area was filmed by each camera with a meter stick in the field to be used as a conversion factor. This measurement was used as a reference for distance measurements during video analysis.

Each target was recorded with two additional cameras capturing an oblique view from the left and right sides. The left camera was placed two meters to the left and one meter anterior to the target while the right camera was placed two meters to the right and one meter anterior to the target (Figure 3.2). The target cameras were used to capture ball contact with the target to determine where the ball contacts the target and how many points should be awarded for each throw.

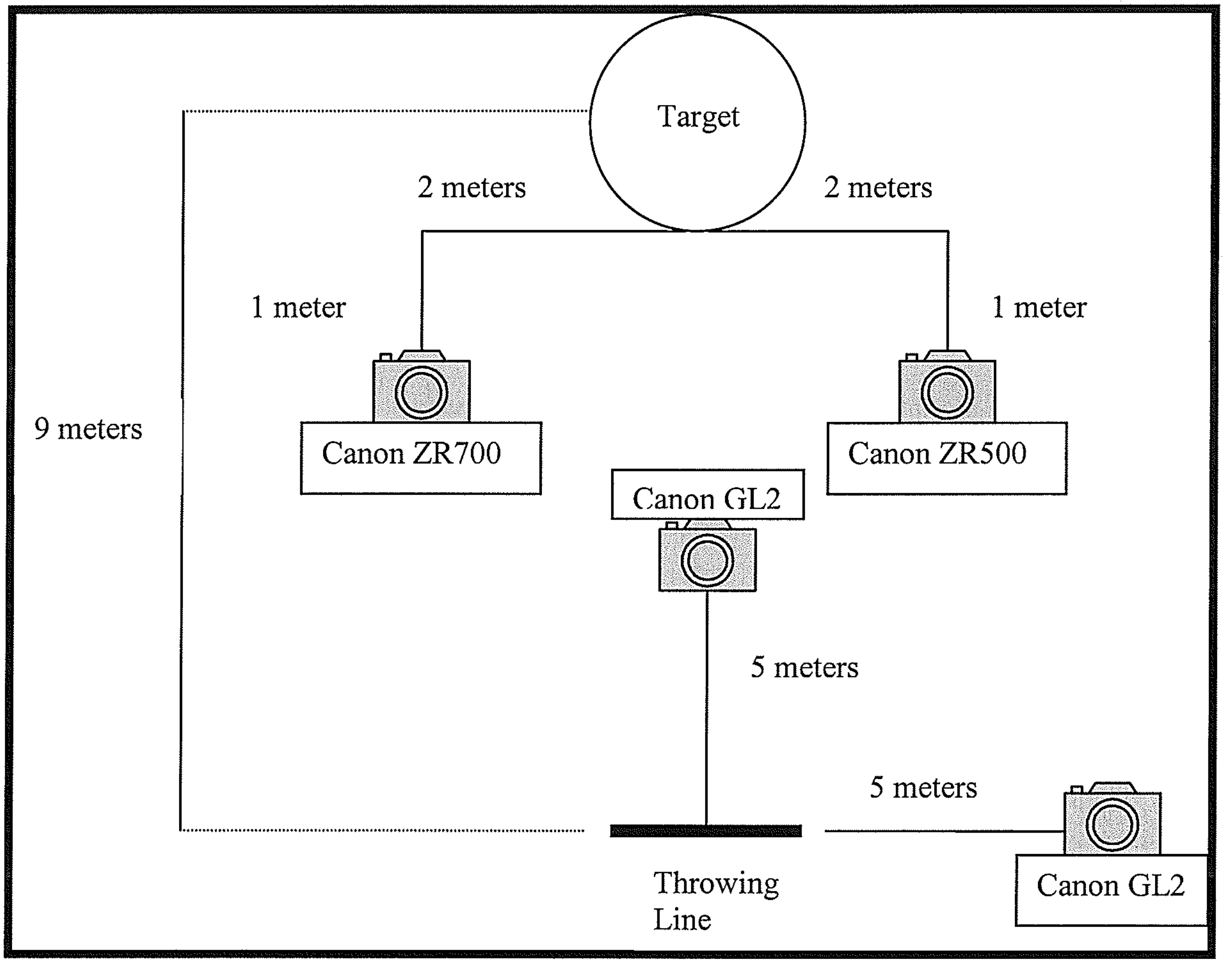

Figure 3.2: Camera and target placement during the Quarterback Throwing test.

Following the 9 throws at the targets, each athlete was filmed in the same manner for the maximum distance throws. One Canon GL2 camera was five meters to the right of the athlete to film the athlete from a sagittal view. A second GL2 camera was placed 5m in front of the athlete to film from the front. The landing of the ball was not be filmed since throw distances will vary greatly between athletes.

Biomechanical Variables Measured

The biomechanical variables were chosen based on previous studies that have analyzed throwing technique. The key variables were selected from the start of the backswing which is also referred to as the early cocking phase (Appendix F, Appendix

G). Video analysis was conducted to measure the resultant throw velocity for each throw, angular velocity of the throwing shoulder's internal rotation, angular velocities of the elbow extension (left or right depending on whether the athlete is right or left handed), elbow extension and shoulder abduction of the throwing arm, shoulder abduction of the free arm, along with knee flexion of both legs. All the variables that were calculated are included in Table 3.4.

Table 3.4: List of variables calculated during the throw.

Phase of Skill	Variables Measured (Units)
Backswing	Right Shoulder Abduction (deg) Right Knee Flexion (deg) Right Elbow Flexion (deg) Left Knee Flexion (deg) Maximum Lateral Shoulder Rotation (deg)
Force Production	Internal Shoulder Rotation Velocity (deg/sec) Right Shoulder Abduction @ MER (deg) Step Length (cm) Percent Standing Height Right Knee Flexion (deg) Left Knee Flexion (deg) Elbow Extension Velocity (deg/sec) Left Shoulder Abduction (deg)
Critical Instant	Right Elbow Flexion (deg) Right Knee Flexion (deg) Left Knee Flexion (deg) Forward Trunk Lean (deg) Ball Velocity (m/s) Ball Velocity (km/hr) Lateral Trunk Lean (deg) Right Shoulder Abduction (deg) Throw Time (sec) Back Foot Unweighted (Yes=1; No=0) Release Height (cm) Relative Release Height
Follow-through	Minimum Elbow Flexion (deg) Shoulder Adduction (deg) Shoulder Internal Rotation (deg) Forearm Pronation (deg) Forearm Pronation Velocity (deg/sec)

The Dartfish Team Pro 4.5.2 Analyzer angle tool was used to measure all joint angles, using the 180-degree system. In anatomical position, according to the 180-degree system, all joints are in a position of zero degrees and any deviation from anatomical position is measured (Figure 3.3). Knee flexion, hip flexion, shoulder flexion, shoulder abduction, elbow flexion, trunk forward flexion, and lateral trunk flexion were measured throughout backswing, force production and release. Shoulder rotation and elbow extension velocities were also recorded and calculated. To measure elbow flexion from a front view a line was drawn from the centre of the shoulder joint to centre of the elbow joint. A second line from the centre of the elbow joint to the centre of the wrist joint was drawn and the angle between the lines was measured. The angle was re-measured two frames later and the angular velocity was calculated by dividing the change in elbow flexion by the time in which the change occurred (Figure 3.3). The time was calculated using the time function in the Dartfish software which accurately measures real time elapsed. The same lines were drawn on the sagittal view to calculate the angle of external shoulder rotation. The rate of shoulder rotation was re-measured after two frames to calculate the internal shoulder rotation angular velocity.

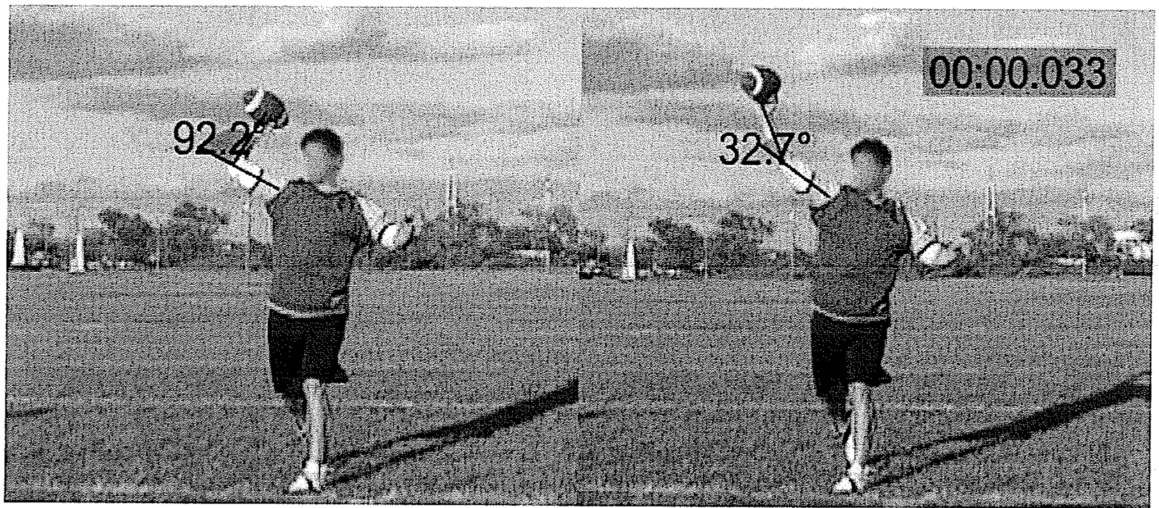

Figure 3.3: Example of joint angles measured using the 180-degree system. The differences between angles are extension in degrees/second.

Digital Video Analysis of the Throws

All video was imported into a Toshiba Satellite A100 laptop using the 'In the Action' feature of the Dartfish 4.5 Software. The highest scoring throw at each distance for each participant was used for analysis of the throwing technique. These three throws were then averaged for all variables to give one composite set of variables for each subject. The examination of these throws was used to determine if technique varied between athletes of different age groups. During analysis all views of each throw were synchronized using timeline and split screen mode. Clips were put into a storyboard in Analyzer mode.

Dartfish analysis included the angle measuring tool, distance tool, and line drawing tool. The angle measuring tool was used to measure lateral shoulder rotation of the throwing arm, front knee flexion, shoulder abduction of the throwing arm, lateral and forward trunk lean, and elbow flexion. Joint angles were measured by starting at the joint centre and extending lines to the joint centers of adjacent joints. For example, knee flexion was measured by starting at the joint centre of the knee and extending lines along the long axis of the femur and lower leg to the joint centers of the hip and ankle respectively (Figure 3.4).

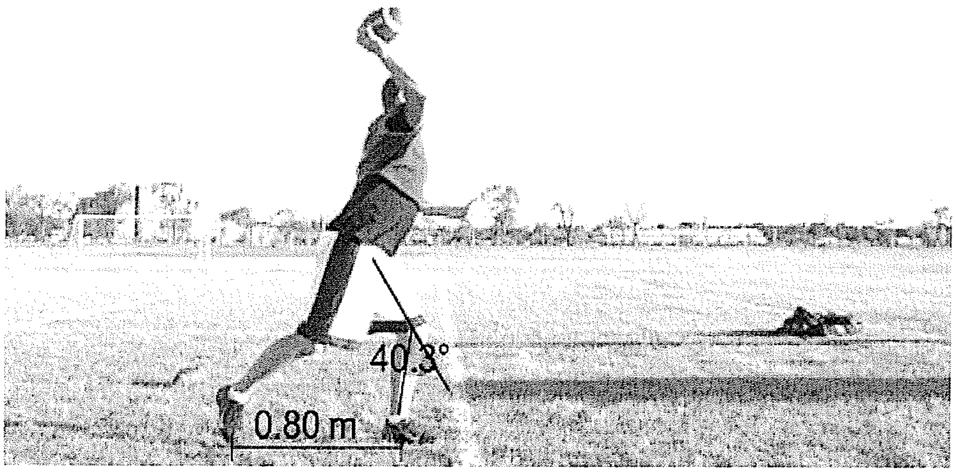

Figure 3.4: Measurement of front knee flexion and stride length from the sagittal view.

Stride length and pass velocity were measured using the distance and tracking tools (Figure 3.4). Once a conversion factor was created, stride length could be determined using the distance tool. The joint centers of the ankles were used as the markers since this was the method used in a previous study by Fleisig et al. (1996) regarding quarterback throwing mechanics.

Lateral trunk lean, shoulder abduction and elbow flexion were measured from the front view (Figure 3.5). Trunk lean was measured from the vertical, with any deviation forward or laterally measured. A vertical line was drawn from the midline of the trunk and another was drawn from the centre of the trunk to the centre of the shoulder girdle. The resulting angle was measured and recorded as lateral trunk lean. Forward trunk flexion was also measured relative to the vertical from the sagittal view. A vertical line was drawn starting from the hips and a second line was added connecting the hips and the shoulder joint (Figure 3.5). The angle of these lines represented the amount of forward trunk flexion of the athlete.

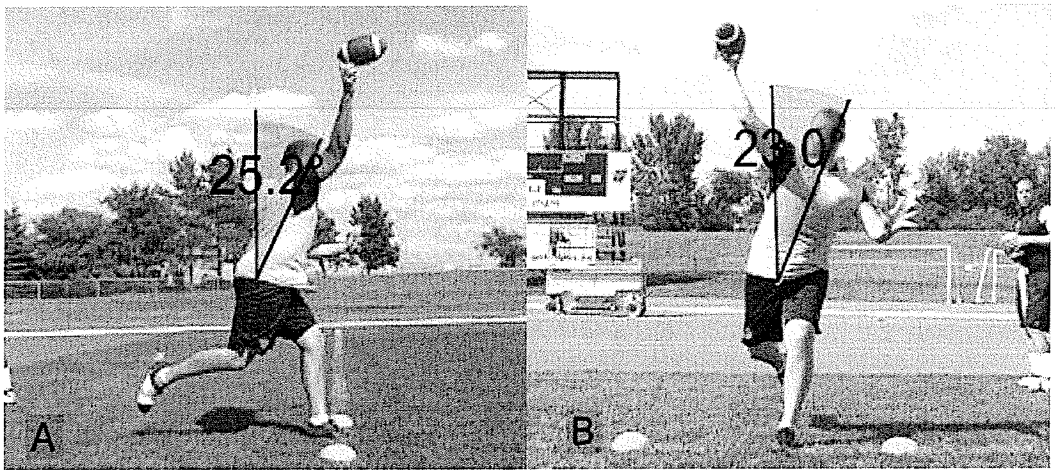

Figure 3.5: Trunk flexion was measured relative to the vertical with forward trunk flexion measured from the sagittal view (3.4A) and lateral trunk flexion measured from the frontal view (3.4B).

Statistical Analysis

The dependent variable for this study was the subjects' score from the quarterback throwing test. The independent variables were based on those from previous studies that have analyzed the quarterback throwing technique. Means and standard deviations for the variables were calculated for quarterbacks of each age group using the Microsoft Excel software program. Multiple *t*-tests were conducted to determine the significant differences between age groups. A p-value of 0.05 was used to indicate statistical significance of differences between the two groups. A p-value of 0.05 leaves a 5% chance of committing type I error in which the null hypothesis is rejected when there is in fact no significant difference. Because multiple *t*-tests were conducted, a false discovery rate adjustment (FDR) was done to determine a new p-value (Narum, 2006). Due to the high number of comparisons, the new critical p-value was determined to be 0.0126.

A Pearson's product-moment correlation analysis was conducted to examine the relationship between each independent variable and the test score except for the variable measuring the position of the back foot at release - a Spearman's rank correlation was used because the measure of back foot position is not a continuous variable. Back foot position was also compared between groups using a Chi square test rather than a *t*-test to determine if the occurrence of back foot position was significantly different between groups. In order to determine if sample size affected results both groups were also combined and each independent variable was correlated with the quarterback throwing test score. If the two groups were different, the differences between them may be cancelled out when treated as one group. Any significant correlations were reported.

A forward stepwise multiple-regression analysis was also used to eliminate parameters from the regression equation that were found to be insignificant predictors of throw velocity and accuracy. The stepwise multiple-regression analysis listed the most important variables for predicting throw accuracy and velocity ranked in order beginning with the most important. A separate stepwise multiple-regression analysis was done for each age group. If the ranked list of variables differed between groups, it could suggest differences in throwing technique between age groups. No previous studies of the quarterback pass have attempted to find a relationship between independent variables and throwing accuracy or velocity. A previous study by Bartlett et al. (1989) used similar methods to determine the primary muscles used for throwing velocity

Of the 30 variables measured, 29 were entered into the regression equation. Ball velocity was measured in meters/second and converted to kilometers/hour. Since both values are relatively the same, it was only entered into the equation once. The strongest predictor of quarterback performance was entered into the regression equation first. After the first variable was determined the remaining variables were tested for a relationship between the dependent variable and the first variable entered. The variable that explained the most of the remaining variation and was found to be most significant was added to the equation as the second step. The process was repeated until as much variation as possible was accounted for by the regression equation. The stepwise regression equation indicated which variables were the strongest predictors in overall quarterback performance for each group.

Reliability

To confirm reliability of the quarterback throwing test scoring, results for each of the athletes were recalculated to ensure accuracy of the scoring. Recalculations were done at least two weeks after initial scoring with the tester blinded to the results to reduce bias. A paired *t*-test was completed to determine if the calculations of test scores were significantly different.

Reliability of biomechanical variable measurement was also tested. Ten variables were chosen and measured from the film on five separate days and recorded on an Excel spreadsheet (Appendix E). The ten variables chosen were: right elbow flexion in backswing, right shoulder abduction in backswing, left knee flexion in backswing, maximum external shoulder rotation, left knee flexion in force producing, right knee flexion in force producing, step length, forward trunk lean at release, left knee flexion at release and right knee flexion at release. A correlation matrix relating the variable measurements between days was done to determine if the measurements were similar. A correlation of greater than 0.7 is considered significant in reliability tests using this method (Hopkins, 2000).

CHAPTER IV

RESULTS

Chapter four will present the subject characteristics, throwing test score comparison, kinematic variable comparisons between groups, correlation analyses for each group and regression analysis results for each group. The results of the statistical analysis outline several key factors which were found to be important in the quarterback pass.

The age, height and weight of the participants in the study are described in Table 4.1 below.

Table 4.1: Descriptive characteristics of subjects. $*p \leq 0.05$

	High School Athletes N = 10		University Athletes N = 10		
	Mean ± SD	Range	Mean ± SD	Range	t-value
Age (years)	16.90 ± 0.99	15-18	22.5 ± 3.72	19-30	4.600*
Height (cm)	186.1 ± 6.79	177-202	184.6 ± 5.8	176-192	0.531
Weight (kg)	79.71 ± 15.12	65.8-110.5	96.38 ± 10.83	83.8-114.5	2.834*

Reliability Tests

Kinematic Variables

Reliability tests were conducted to assess the accuracy of the measurement of the kinematic variables from video film. Ten variables were chosen and measured on five separate days and recorded on an Excel spreadsheet. The ten variables chosen were: right elbow flexion in backswing, right shoulder abduction in backswing, left knee flexion in backswing, maximum external shoulder rotation, left knee flexion in force producing, right knee flexion in force producing, step length, forward trunk lean at release, left knee flexion at release and right knee flexion at release. Various methods have been used in reliability tests in the past including measuring the coefficient of variation of each variable measured or correlation between days (Hopkins, 2000). A correlation between days was done to determine if the measurements were similar. The measurements of each day were compared to each other day to determine if the scores were correlated. A correlation of greater than 0.7 is considered significant in reliability tests using this method. A correlation of 0.99 between each day was determined which suggests that the values between days are very closely related (Table 4.2). This correlation is very high and shows significant consistency in variable measurement. The range of values for the variables measured over the five days is shown in Table 4.3.

Table: 4.2: Results of the reliability test.

Correlation Matrix

	Sept 11	Oct. 4	Oct. 14	Oct. 28	Oct. 31
Sept 11	1.000	.999	1.000	.999	.999
Oct. 4	.999	1.000	.999	.999	.999
Oct. 14	1.000	.999	1.000	.999	1.000
Oct. 28	.999	.999	.999	1.000	.999
Oct. 31	.999	.999	1.000	.999	1.000

10 observations were used in this computation.

Table 4.3: Variable measures over 5 different days.

Variable	Minimum	Maximum	Range
Backswing			
Right Elbow Flexion (deg)	111.10	113.30	2.20
Right Shoulder Abduction (deg)	80.10	84.50	4.40
Left Knee Flexion (deg)	28.60	32.50	3.90
Force Production			
Maximum External Shoulder Rotation (deg)	151.20	154.50	3.30
Left Knee Flexion (deg)	32.70	35.50	2.80
Right Knee Flexion (deg)	35.20	38.50	3.30
Step Length (cm)	71.00	71.00	0.00
Critical Instant			
Forward Trunk Lean (deg)	15.80	17.70	1.90
Left Knee Flexion (deg)	28.60	31.20	2.60
Right Knee Flexion (deg)	45.80	48.40	2.60

Quarterback Throwing Test Scores

The quarterback throwing test score for each athlete was re-calculated to test reliability of scoring. After all scores were re-calculated they were compared to the original test scores to determine if there were any significant differences in scoring. A paired *t*-test was chosen to compare the two measurements. A p-value of $\leq .05$ would indicate a significant difference between group scores, and suggest inconsistent measurement of throwing test scores. The results of the comparison are shown in Table 4.4.

Table 4.4: The *t*-test comparison of means for the original test scores and re-score values.

	Original N = 20		Re-Score N = 20			
Variable	Mean	SD	Mean	SD	t-value	p-value
Test Score (%)	48.2	11.76	47.8	11.67	0.1079	0.9146

The results of the *t*-test show that both mean scores of the throwing tests were not significantly different. A p-value of .9146 suggests very little difference between the original scores and the values obtained from the second calculation.

Throwing Test Score

The total quarterback throwing test scores were calculated by adding the points from pass accuracy, velocity and distance. Table 4.5 presents the means for the three factors for both groups along with the percentage of each factor relative to the total score. The *t*-tests for each factor were not significant.

Table 4.5: *t*-test comparison of means of throwing test point distributions between high school and university athletes.

	High School Athletes		University Athletes		p-value
	Mean	Percent	Mean	Percent	
Accuracy	113	0.24	131	0.26	0.518
Velocity	296	0.64	303	0.61	0.843
Distance	55	0.12	62	0.13	0.196
Total	464	1.00	496	1.00	n/a

A *t*-test was conducted to determine if there was a significant difference in the quarterback throwing test scores between high school and university quarterbacks. Although the university athletes scored somewhat better in the throwing test (496 compared to 464), this difference was not found to be significant. The results of this test are shown in Table 4.6 and will be examined in detail in the discussion section.

Table 4.6: *t*-test comparisons of means of quarterback throwing test scores between high school and university athletes. Significance at *p ≤ 0.0126.

	High School Athletes n = 10			University Athletes n = 10				
Variable	Mean	SD	Range	Mean	SD	Range	t-value	p-value
Test Score (/1000)	464.00	134.68	320-690	496.00	110.07	340-700	0.58	0.57

Comparison of Kinematic Variables Between High School and University Quarterbacks

One of the purposes of the study was to determine kinematic differences between high school and university quarterbacks. The following section describes the means and standard deviations for the two groups in the study as well as the results of the independent *t*-tests which were performed. The section is broken down into the key phases of the skill which were highlighted in the methods section, beginning with the backswing.

Backswing

In the backswing, five variables were measured. The variables as well as the means and standard deviations for both the high school and university quarterback trials are presented in Table 4.7. Based on an adjusted p-value of 0.0126, only one of the five measured variables was shown to be significantly different - maximal external shoulder rotation. This indicates that during the backswing, the main difference between the two skills is the amount of external rotation in the throwing shoulder. The calculated mean for the athletes' forward trunk lean for the high school group was 172.63° from the horizontal. For the university group the mean was 155.6° from the horizontal. This comparison is displayed graphically in Figure 4.1. The position of maximum external shoulder rotation is shown in Figure 4.2.

Table 4.7: *t*-test comparisons of means of the measured variables during the backswing. Significance at *$p \leq 0.0126$.

Variable	High school Athletes n = 10 Mean	SD	University Athletes n = 10 Mean	SD	t-value	p-value
Right Shoulder Abduction (deg)	98.86	11.77	94.41	13.94	1.33	0.190
Right Knee Flexion (deg)	30.37	11.21	28.24	6.89	0.89	0.380
Right Elbow Flexion (deg)	110.51	15.31	114.48	16.33	0.97	0.340
Left Knee Flexion (deg)	33.10	11.29	34.58	6.02	0.63	0.530
Max External Shoulder Rotation (deg)	172.63	14.10	155.60	8.92	5.59	**0.0001***

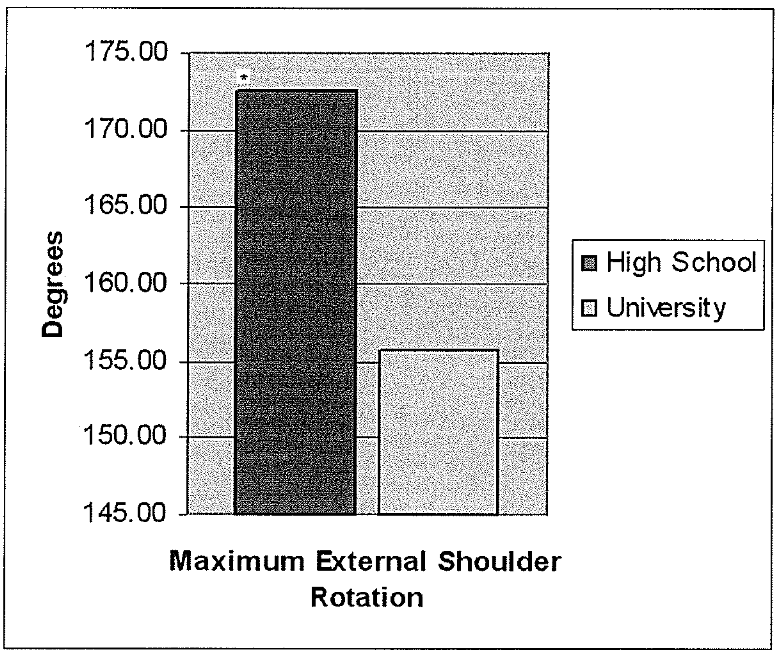

Figure 4.1: Comparison of the mean angles of maximum external shoulder rotation indicating the significant difference between the two groups (*$p \leq 0.0126$).

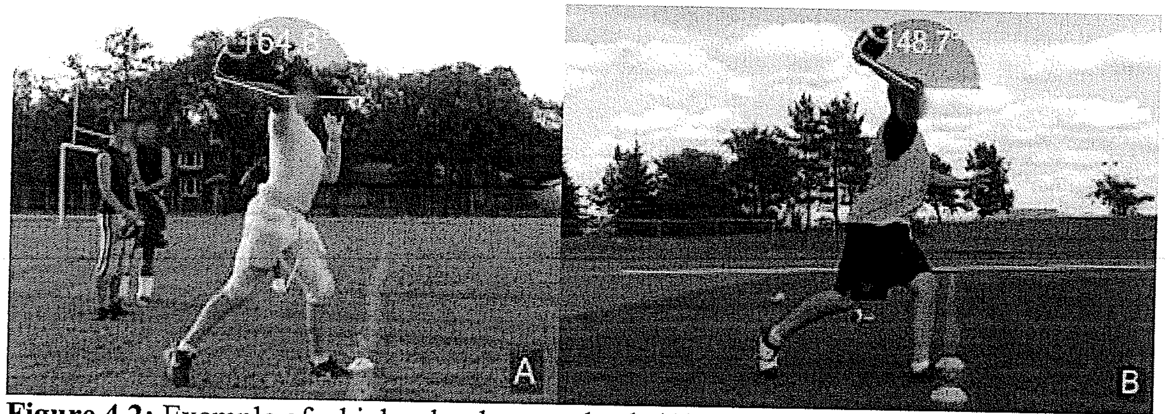

Figure 4.2: Example of a high school quarterback (A) and a university quarterback (B) during maximum external shoulder rotation. High school quarterbacks get into a position of greater external shoulder rotation at maximum backswing of the upper body.

Force Production

During force production, eight variables were measured for each of the athletes. These variables were: internal shoulder rotation velocity, right shoulder abduction at maximum external shoulder rotation, step length, percent standing height, right knee flexion, left knee flexion, elbow extension velocity and left shoulder abduction. Comparisons of the means for the measured variables are presented in Table 4.8. The variable which was calculated to be significantly different between the two groups was right knee flexion. The mean angle of right knee flexion for high school quarterbacks was 25.5° while the mean angle of right knee flexion for university quarterbacks was 31.81° (Figure 4.3). The p-value for this relationship was 0.0033. Left shoulder abduction approached significance but was not found to be significant with the adjusted p-value. The mean angle of left shoulder abduction for the high school quarterbacks was 63.13° compared to 51.46° in the university quarterbacks. This suggests that more mature athletes are more effective manipulating their moment of inertia to increase their rate of trunk rotation. However, left shoulder abduction is beneficial in generation of torque and it would be expected that more mature athletes would be strong enough to fully capitalize on this position. This was found to approach significance with a p-value of 0.0356 (Figure 4.3). A comparison of left shoulder abduction can be seen in Figure 4.4.

Table 4.8: *t*-test comparisons of means and standard deviations of the measured variables during force production. Significance at p *≤ 0.0126.

Variable	High school Athletes n = 10 Mean	SD	University Athletes n = 10 Mean	SD	t-value	p-value
Int. Shoulder Rotation Vel. (deg/sec)	1170.11	293.75	1064.96	308.36	1.35	0.180
Right Shoulder Abduction at MER (deg)	100.20	8.18	100.97	10.55	0.31	0.750
Step Length (cm)	81.57	11.32	80.53	9.27	0.39	0.710
Percent Standing Height	0.44	0.06	0.44	0.05	0.25	0.800
Right Knee Flexion (deg)	25.50	7.52	31.81	8.42	3.06	**0.0033***
Left Knee Flexion (deg)	31.08	9.10	33.65	8.75	1.11	0.270
Elbow Extension Velocity (deg/sec)	1651.01	615.94	1606.67	489.39	0.31	0.760
Left Shoulder Abduction (deg)	63.13	26.22	51.46	14.00	2.15	0.036

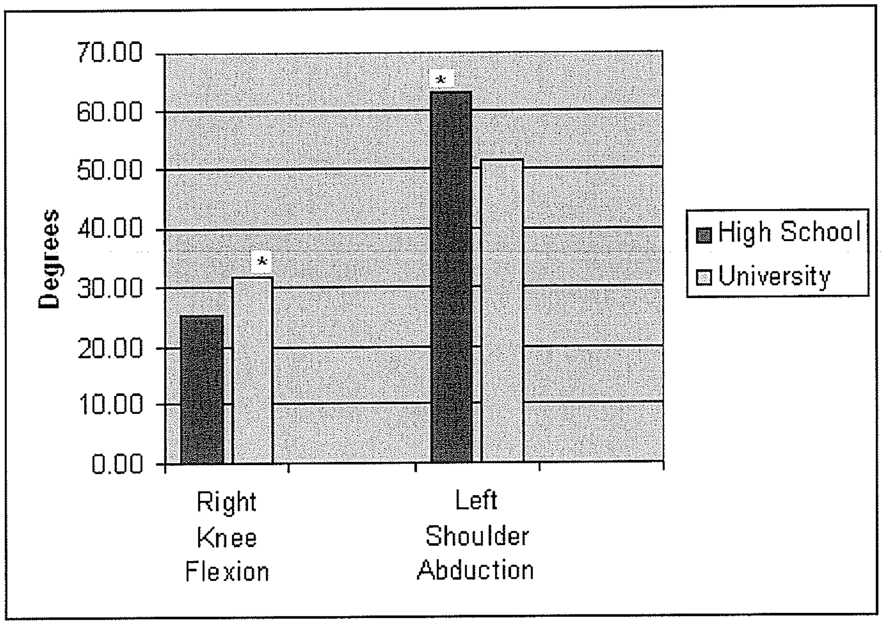

Figure 4.3: Comparison of the mean angles of right knee flexion and left shoulder abduction during force production indicating the difference between high school and university athletes approaching significance (*p ≤ 0.0126).

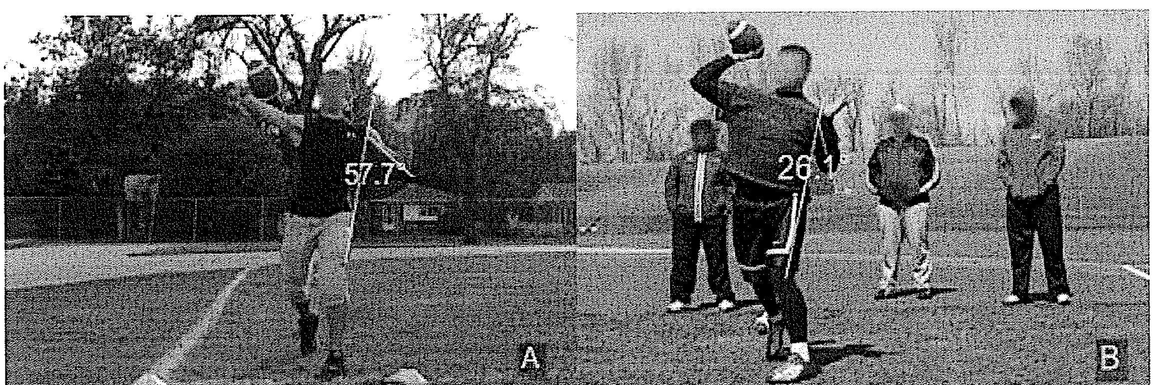

Figure 4.4: High school quarterbacks (A) have greater abduction of their non-throwing shoulder than university quarterbacks (B).

Release

Eleven variables were measured during release of the quarterback pass. Variables measured included right elbow flexion, right knee flexion, left knee flexion, forward trunk lean, ball velocity, lateral trunk lean, right shoulder abduction, throw time, back foot unweighted, release height, and relative release height. Out of these 11 variables, five were determined to be significantly different between high school and university quarterbacks. The significant variables shown in Table 4.9 included right elbow flexion, right knee flexion, forward trunk lean and throw time. Back foot unweighted will be discussed later. The high school group had a mean right elbow flexion of 22.3°. The university group had a mean right elbow flexion of 31.21°, suggesting that greater elbow flexion was related to more mature athletes (Figure 4.5). This difference was significant with a p-value of 0.0106. Right knee flexion was significant with a p-value of 0.0056. The high school athletes had a mean right knee flexion angle of 30.82° and university athletes had a mean right knee flexion angle of 40.24° (Figure 4.5). This was expected because it suggests full weight transfer and is likely accompanied by a completely unweighted back foot. University athletes flex the right knee as the foot loses contact with the ground.

Forward trunk lean was found to be significantly different with a p-value of 0.0044. The high school athletes showed a mean forward trunk lean of 22.29° from the vertical compared to 17.97° of mean forward trunk flexion in the university athletes (Figure 4.6). Throw time was also significantly different between groups with the university quarterbacks having a faster release. This faster time allows the athlete to throw the ball quickly before the defense reaches him. The high school quarterbacks had an average throw time of 0.21s. University quarterbacks had an average throw time from left foot touchdown to release of 0.17s (Figure 4.7). Throw time was shown to be significant with a p-value of 0.0003. The last variable that was significantly different between groups was back foot position at release.

The fifth variable found to be significantly different was back foot unweighted. A *t*-test could not be done because the variable was not continuous. Therefore a Chi square test was done to compare the frequency at which university quarterbacks had their back foot completely unweighted relative to high school quarterbacks and is not included in Table 4.9. The university group had the back foot unweighted on 22 of 30 throws. The high school group only had the back foot unweighted 6 times in 30 throws. This suggests the more mature group has more complete weight transfer during the throw, which is necessary to maximize force production. This was significant with a p-value of 0.001 (Figure 4.8). An example of the back foot position of university and high school quarterbacks is shown in Figure 4.9.

Table 4.9: *t*-test comparisons of means and standard deviations of the measured variables at release. Significance at $*p \leq 0.0126$.

Variable	High school Athletes n = 10 Mean	SD	University Athletes n = 10 Mean	SD	t-value	p-value
Right Elbow Flexion (deg)	22.30	14.63	31.21	11.26	2.64	**0.0106***
Right Knee Flexion (deg)	30.82	11.21	40.24	13.98	2.88	**0.0056***
Left Knee Flexion (deg)	22.32	10.37	26.28	8.52	1.57	0.120
Forward Trunk Lean (deg)	22.29	6.29	17.97	4.93	2.96	**0.0044***
Ball Velocity (km/hr)	70.84	6.99	71.19	4.28	0.23	0.820
Lateral Trunk Lean (deg)	17.74	5.56	17.00	5.24	0.53	0.600
Right Shoulder Abduction	109.12	8.46	109.76	9.01	0.28	0.780
Throw Time (sec)	0.21	0.05	0.17	0.03	3.80	**0.003***
Release Height (cm)	204.53	12.23	202.37	11.04	0.72	0.470
Relative Release Height	1.10	0.05	1.10	0.05	0.22	0.830

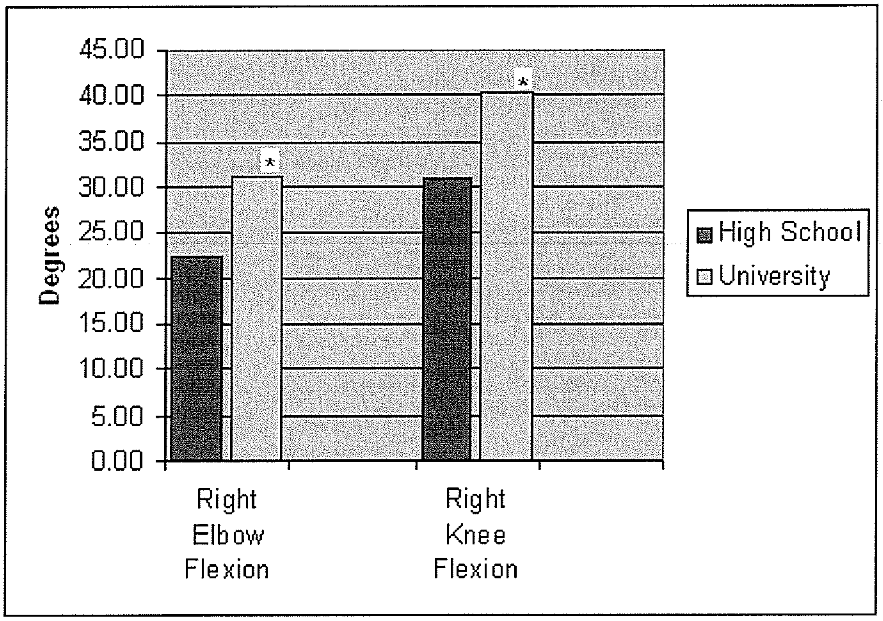

Figure 4.5: Comparison of the mean angles of right elbow flexion and right knee flexion during release indicating the significant difference between high school and university athletes (*p ≤ 0.0126).

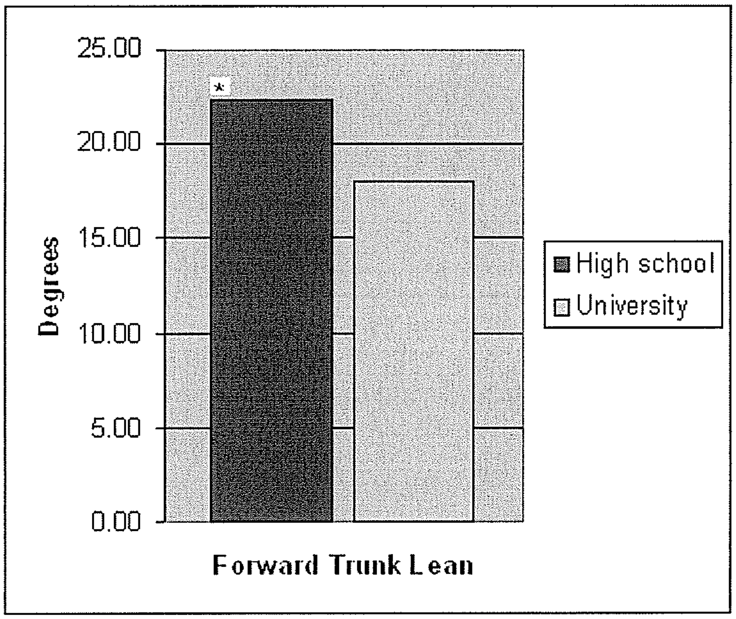

Figure 4.6: Comparison of the mean forward trunk lean angles indicating the significant difference between high school and university athletes (*p ≤ 0.0126).

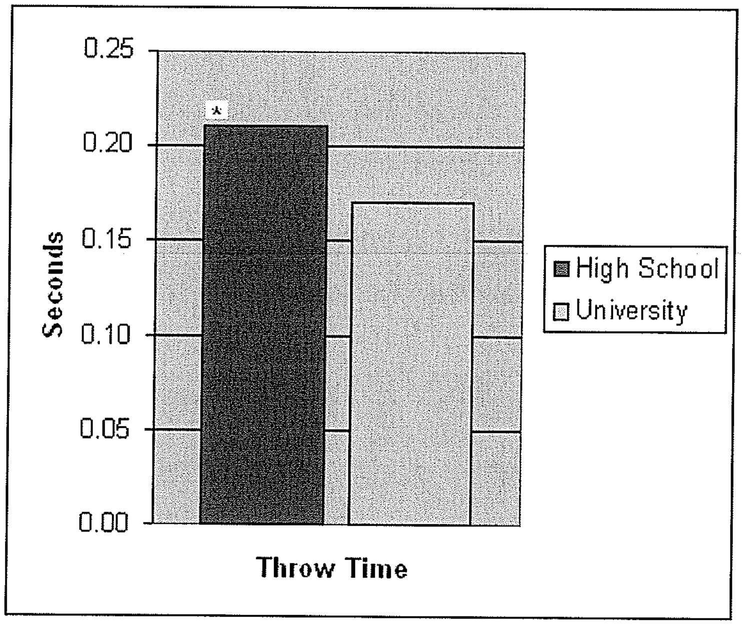

Figure 4.7: Comparison of the mean values of throw time from left foot touchdown to release indicating the significant difference between high school and university athletes (*$p \leq 0.0126$).

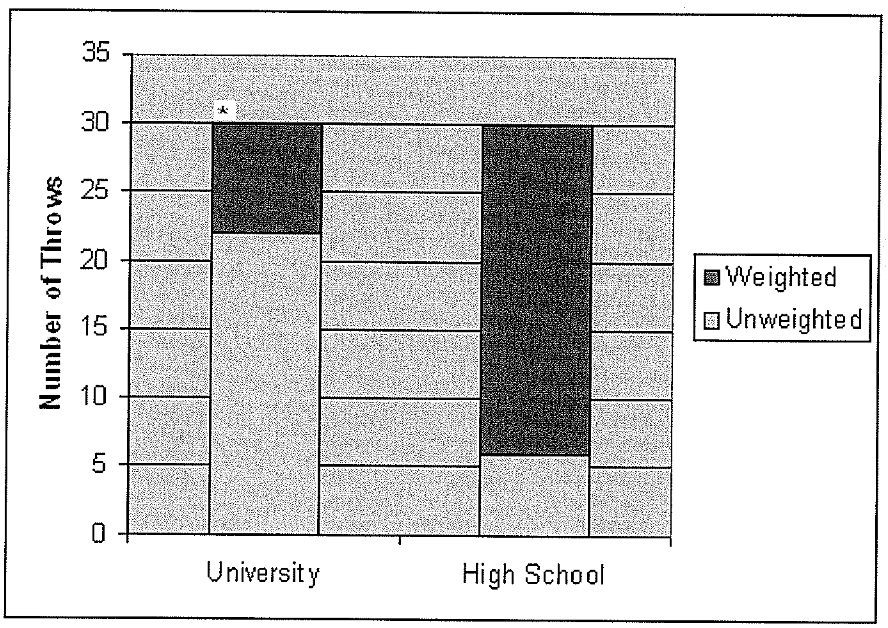

Figure 4.8: Comparison of the back foot position at release indicating the significant difference between high school and university athletes (*$p \leq 0.0126$).

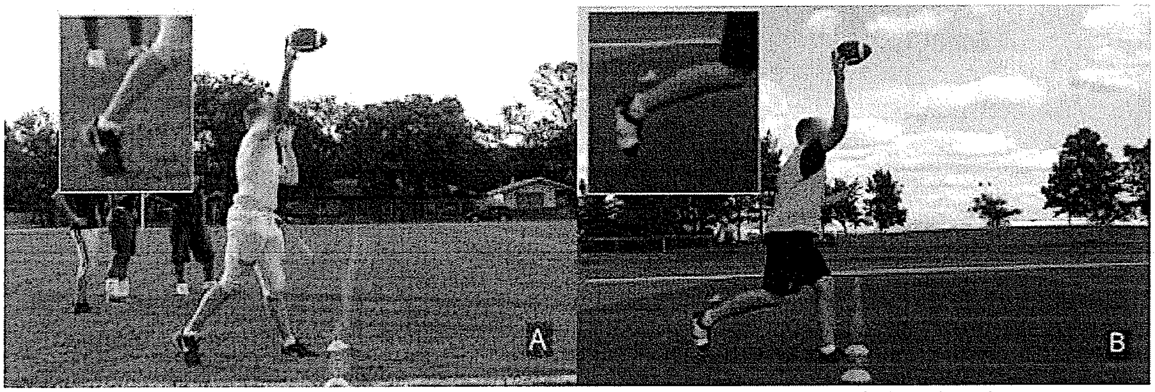

Figure 4.9: Example of the back foot position during release of a high school quarterback (A) and a university quarterback (B). The university athlete has completely unweighted his back foot, while the high school athlete still has his back foot in contact with the ground.

Follow-through

During the follow-through of the pass, five variables were measured: minimum elbow flexion, shoulder adduction, shoulder medial rotation, forearm pronation and pronation velocity (Table 4.10). None of the variables were significantly different between the high school and university groups.

Table 4.10: *t*-test comparisons of means and standard deviations of the measured variables during follow-through. Significance at $^*p \leq 0.0126$.

Variable	High school Athletes n = 10		University Athletes n = 10		t-value	p-value
	Mean	SD	Mean	SD		
Minimum Elbow Flexion (deg)	31.62	24.86	33.05	11.37	0.29	0.780
Shoulder Adduction (deg)	44.09	15.02	44.32	9.59	0.07	0.940
Shoulder Medial Rotation (deg)	23.55	13.84	21.01	11.05	0.78	0.440
Forearm Pronation (deg)	77.81	16.18	76.78	13.28	0.27	0.790
Pronation Velocity (deg/sec)	1841.49	416.02	2026.03	384.25	1.78	0.080

Of the follow-through variables measured, only pronation velocity was close to significance with the high school athletes pronating with an average angular velocity of 1841.49°/sec. The university athletes showed a faster average velocity of 2026.03°/sec. The p-value for this comparison was .08 which suggests there is a trend for university athletes to pronate with greater velocity than high school athletes during the follow-through.

Relationships of Kinematic Variables with Test Score

A second purpose of the study was to determine which variables were most strongly correlated to the athletes' throwing test scores. A Pearson's product moment correlation analysis was performed for both the high school and university groups separately in order to determine which variables were significantly related to the group's quarterback throwing test score. Upon completion of the correlation analysis, all of the variables were entered into a forward stepwise multiple regression equation for the high school and university groups separately, in order to determine which variables had the strongest predictive effect on the athletes' throwing test score.

High School Quarterback Correlation Analysis

Table 4.11 shows ten variables which have a strong correlation to the high school athletes' quarterback throwing test scores, with six of the variables being significant at $p \leq 0.05$: step length, percent standing height, right knee flexion during force production (FP), lateral trunk lean during critical instant (CI), ball velocity and throw time.

Table 4.11: Variables demonstrating the strongest correlation to test score for the high school athletes.

Variable	Correlation (High School Athletes) N = 10	
	r-value	p-value
Backswing		
Right Shoulder Abduction (BS)	-0.589	0.1
Force Production		
Step Length	0.709	**0.020***
Percent Standing Height	0.684	**0.050***
Right Knee Flexion (FP)	-0.703	**0.020***
Release		
Left Knee Flexion (CI)	0.577	0.1
Forward Trunk Lean (CI)	0.571	0.1
Lateral Trunk Lean (CI)	0.749	**0.010***
Ball Velocity (km/hr)	0.9	**0.001***
Throw Time	-0.699	**0.020***
Follow-through		
Pronation Velocity (FT)	0.56	0.1

Where: BS = backswing, FP = force production, CI = critical instant and FT = follow-through.

The variable which showed the highest correlation to throwing test score in high school athletes was ball velocity (a positive correlation of 0.900), meaning that the faster the athlete throws the ball, the higher his score was on the test. This relationship was significant to a value of $p \leq 0.001$. Since the test score takes throw velocity into account, a strong correlation between ball velocity and test score was expected. This emphasizes how important throwing speed is to the quarterback throwing test score as it is highly correlated to the final score. Figure 4.10 represents the relationship of ball velocity graphically.

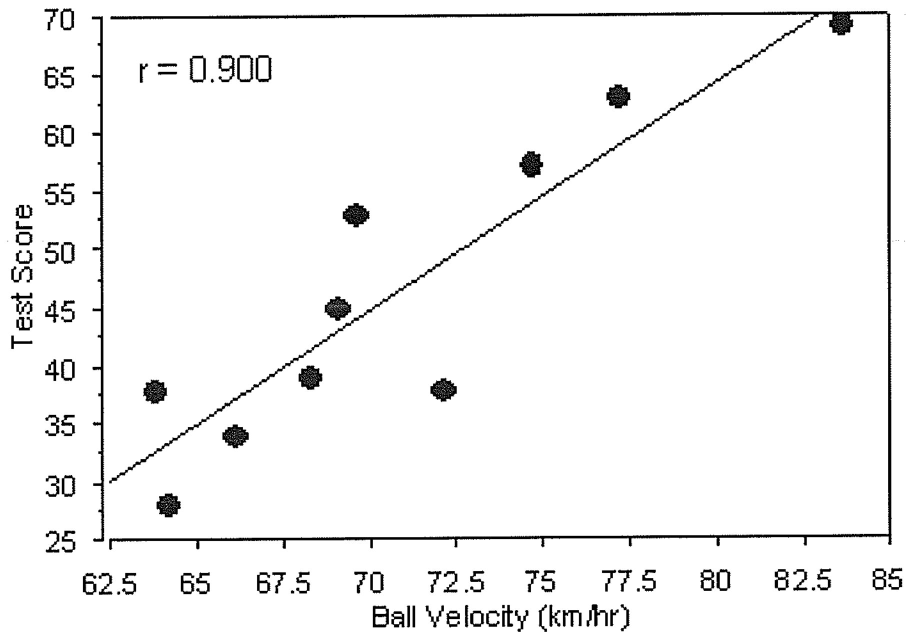

Figure 4.10: Relationship between ball velocity and test score for high school quarterbacks. $r = 0.900$; $p \leq 0.001$

Lateral trunk lean at release was also shown to have a strong, positive correlation to throwing test score (0.749). This indicates that greater lateral trunk lean away from the vertical when the ball is released was associated with increased quarterback throwing test score. This relationship was significant at $p \leq 0.01$ and is displayed graphically in Figure 4.11.

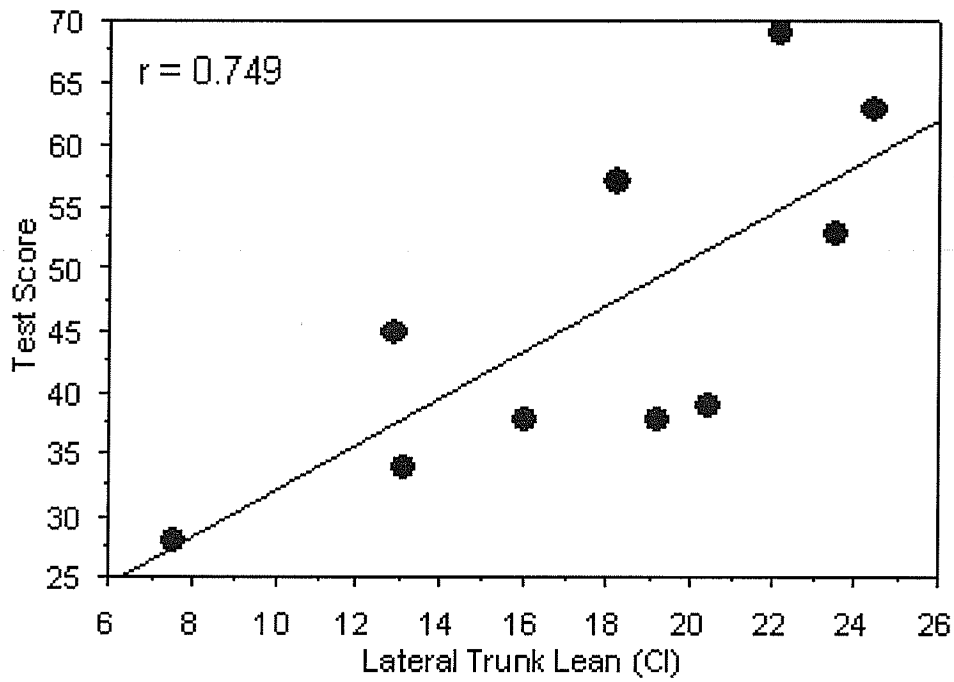

Figure 4.11: Relationship between lateral trunk lean and test score for high school quarterbacks. $r = 0.749$; $p \leq 0.01$

The length of the step of the quarterback during force production was found to be significantly correlated to test score ($r = 0.709$) at a level of $p \leq .02$. This means that those athletes that had a longer step with the left foot generally performed better in the throwing test than those who had a shorter step. A longer step improves force production with an aggressive drive off the back leg which should improve throw velocity. This relationship is presented graphically in Figure 4.12. Furthermore, the athlete's step relative to standing height was also found to be positively correlated with test score ($r = 0.684$) at a significance level of $p \leq .05$.

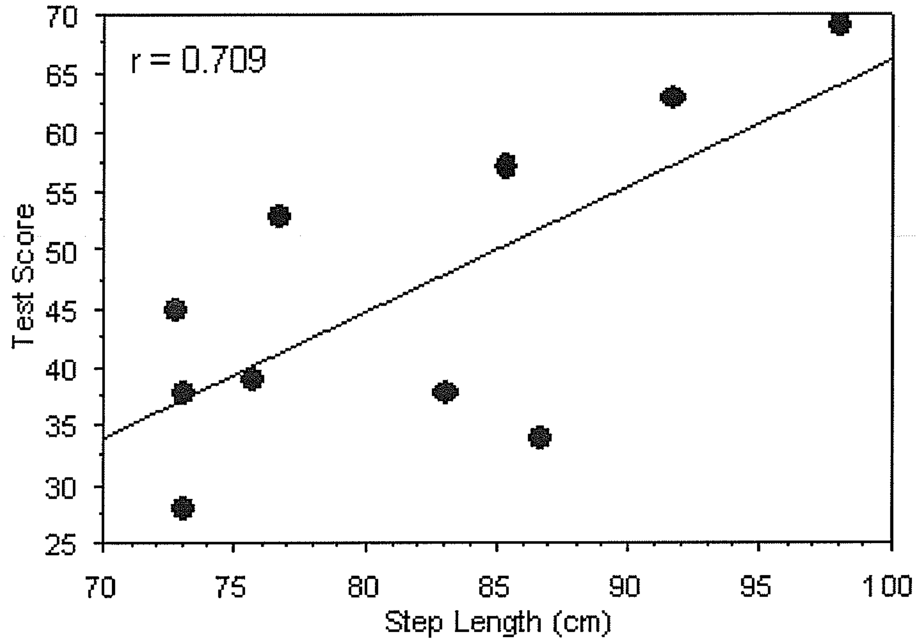

Figure 4.12: Relationship between step length and test score for high school quarterbacks. r = 0.709.

During force production the athlete starts to transfer weight onto the left foot. Interestingly, right knee flexion during force production was shown to have a strong negative relationship with test score. This indicates that those athletes who maintained a large amount of knee flexion during force production were associated with lower test scores. This relationship was significant at $p \leq 0.02$ and is displayed graphically in Figure 4.13.

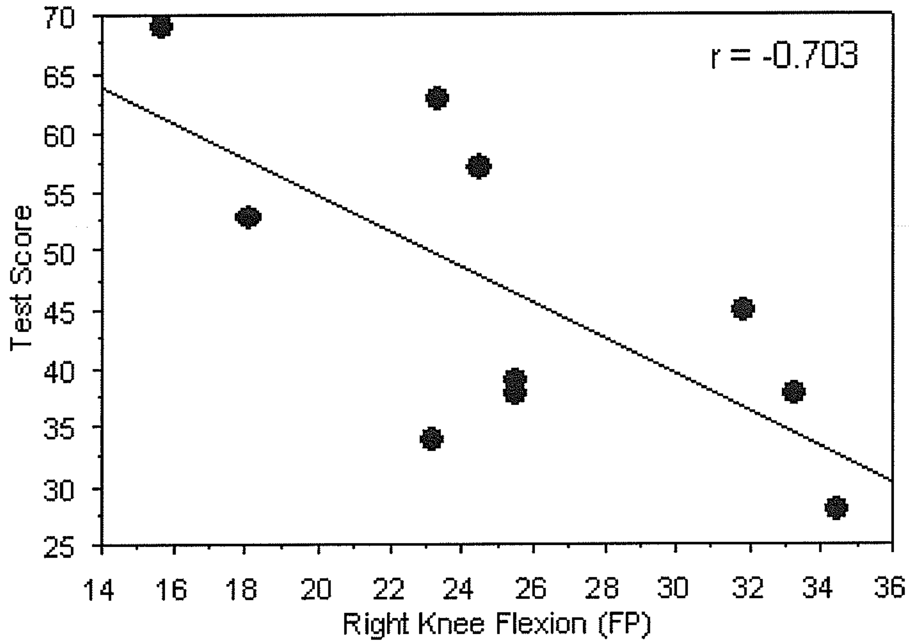

Figure 4.13: Relationship between knee flexion during force production and test score for the high school quarterbacks. r = -0.703.

Throw time from touchdown of the left foot to release also had a strong negative relationship with test score. The faster an athlete was able to release the ball relative to touchdown of his front foot the better his throwing test score should be. A quick release also allows the athlete to quickly deliver a pass before the defense reaches the quarterback. This relationship was significant at $p \leq .02$ and is represented graphically in Figure 4.14.

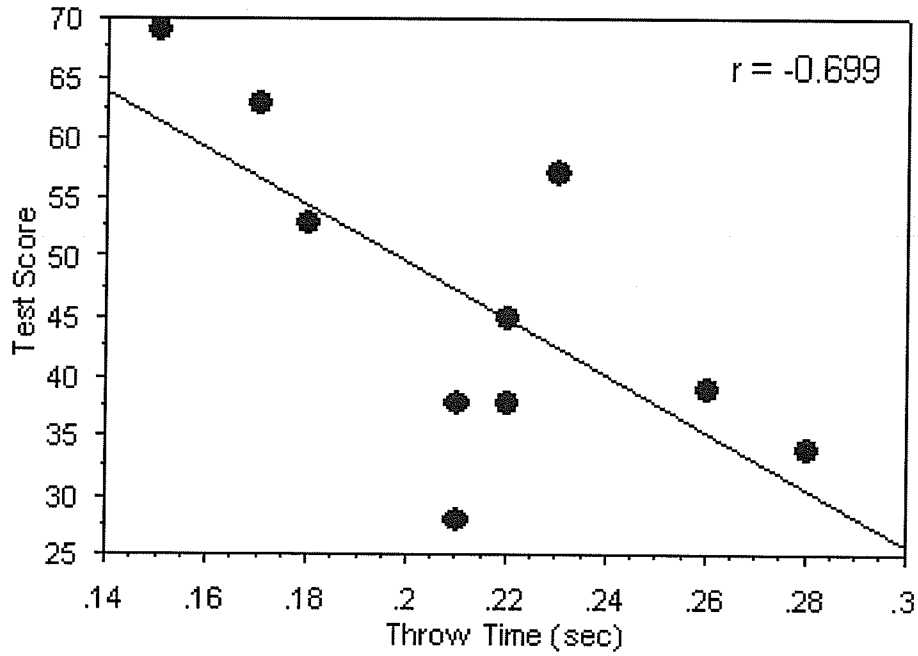

Figure 4.14: Relationship between throw time and test score for the high school quarterbacks. r = -0.699.

University Quarterback Correlation Analysis

A correlation analysis was performed on the variables from the university quarterback group in order to determine which variables were strongly correlated with the athletes' throwing test score (Table 4.12). Five variables were shown to be significantly correlated to the athlete's throwing test score with a p-value $\leq .1$ and only two significant at $p \leq .05$. The variable which was most significantly correlated to throwing test score for the university group was the position of the back foot at release ($r = 0.661$). This was significant at a level of $p \leq 0.05$. Because this independent variable was not continuous, a Spearman's rank correlation was used instead of Pearson's product-moment correlation. Scores of one for unweighted and zero for weighted were given for each throw and averaged over the three throws analyzed. This correlation suggests that athletes who fully transfer their weight onto the front foot and completely unweight their back foot will score higher on the throwing test. This theory will be discussed further in the discussion section. This relationship is presented graphically in Figure 4.15. The other variable with a significant correlation to test score was throw time. Right shoulder abduction during backswing, right knee flexion during backswing, right elbow flexion during backswing also showed a trend but were not found to be significant.

Table 4.12: Variables demonstrating the strongest correlation to test score for the university athletes.

Variable	Correlation (University Athletes) N = 10 r-value	p-value
Right Shoulder Abduction (BS)	0.545	0.1
Right Knee Flexion (BS)	-0.564	0.1
Right Elbow Flexion (BS)	-0.576	0.1
Throw Time	0.607	**0.05***
Back Foot Unweighted (a)	0.661	**0.05***

(a) analyzed using a Spearman's Rank Sum Correlation.

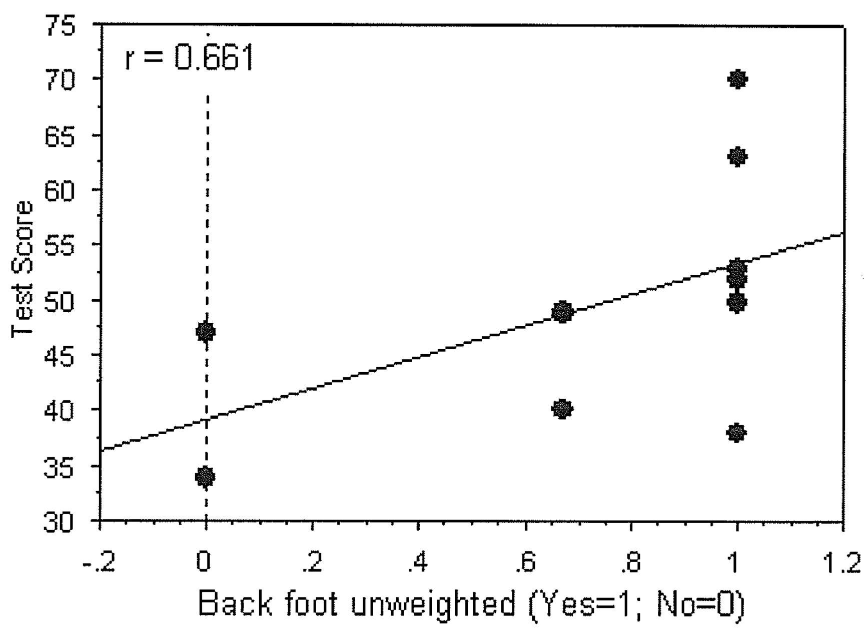

Figure 4.15: Relationship between back foot position at release and test score for the university quarterbacks. r = 0.661.

The variable with the second most significant relationship to throwing test score was throw time from left foot contact to release. This variable had a strong, positive correlation ($r = 0.607$) and was significant at $p \leq 0.05$, indicating that, contrary to high school athletes, quarterbacks who released the ball later relative to left foot touchdown were also shown to perform well in the test (Figure 4.16).

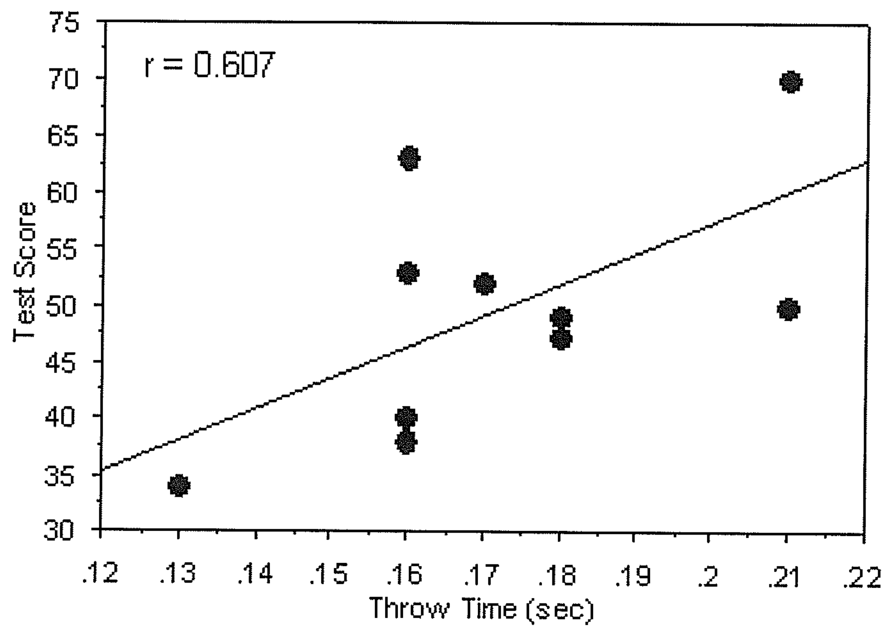

Figure 4.16: Relationship between throw time and test score for the university quarterbacks. $r = 0.607$.

Another highly correlated variable for the university quarterbacks was their right elbow flexion during backswing. This had a negative correlation with test score ($r = -0.576$) which was significant with a $p \leq 0.1$. This means the university quarterbacks that had greater elbow flexion in their throwing arm during the backswing did not score as high in the throwing test. This relationship is displayed graphically in Figure 4.17.

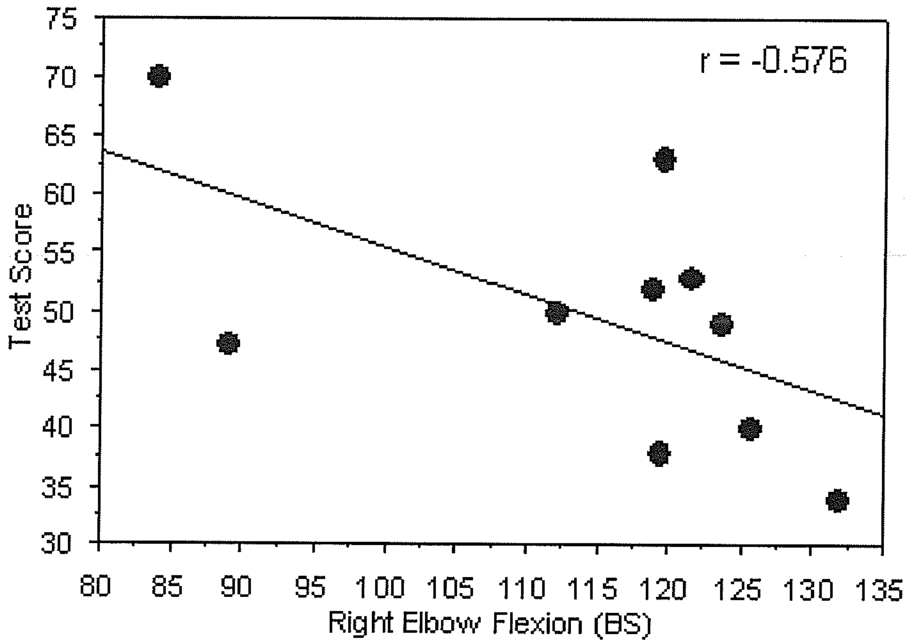

Figure 4.17: Relationship between elbow flexion during backswing and test score for the university quarterbacks. r = -0.576.

Right knee flexion during backswing was also negatively correlated with test score (r = -.564). This suggests that if the quarterback has increased knee flexion in his back leg during the backswing of his throws he will not score as high in the throwing test, which is opposite than expected. A flexed knee position during backswing was expected to improve throwing test score because it allows the athlete to create more force during the throw with a larger range of knee extension. This relationship is significant to a level of $p \leq 0.1$ and is presented in a scatter plot in Figure 4.18.

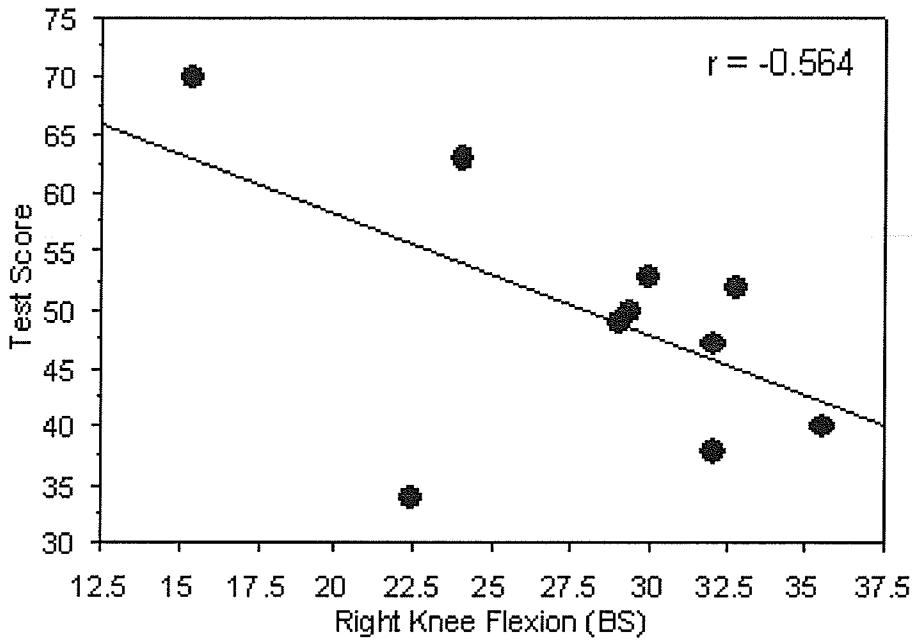

Figure 4.18: Relationship between right knee flexion during backswing and test score for the university quarterbacks. r = -0.564.

Another variable highly correlated to test score was right shoulder abduction during backswing ($r = 0.545$). Shoulder abduction is positively correlated with a significance level of $p \leq 0.1$ suggesting that increased shoulder abduction of the throwing shoulder will increase the athlete's test score. This relationship is presented visually in Figure 4.19.

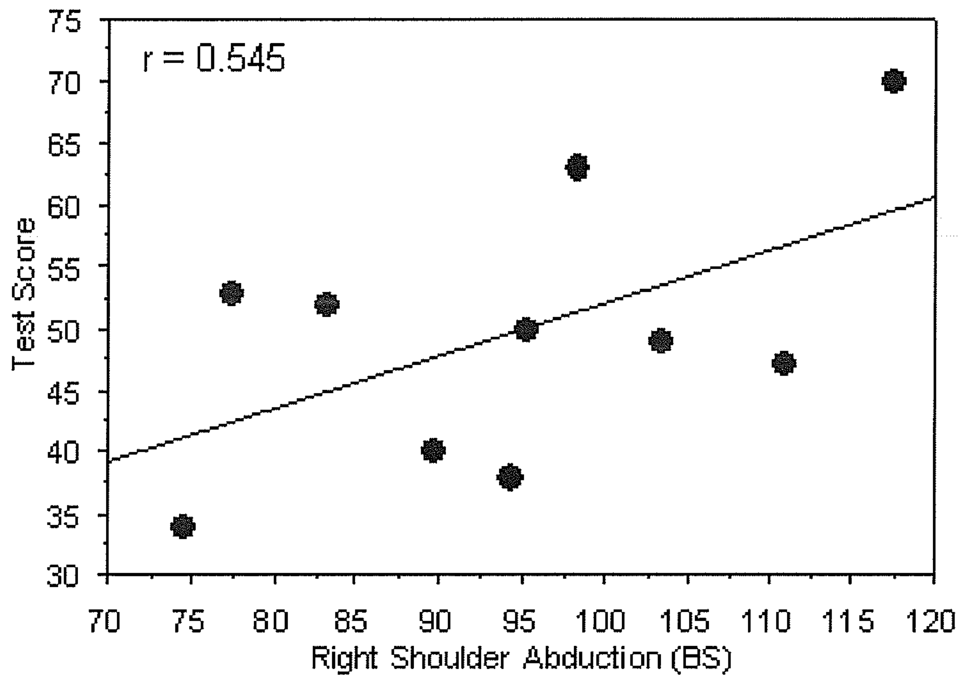

Figure 4.19: Relationship between right shoulder abduction during backswing and test score for the university quarterbacks. r = 0.545.

Both groups were combined and each independent variable was tested for correlation to quarterback throwing test score. Results were found to be less significant with combined groups, with only ball velocity showing significant correlation (r = 0.739).

Stepwise Multiple Regression Analysis

The final step in the statistical analysis was performing two separate stepwise multiple regression analyses separately for high school and university athletes in order to develop a regression equation that best explained variation in the quarterback throwing test scores and could predict test scores based on significant variables. All 29 variables were entered into the stepwise multiple regression analysis and the most significant variables were chosen for the multiple regression equation to predict throwing test scores for each group.

High School Athletes

The stepwise multiple regression analysis of the high school quarterbacks only included two variables. The rest of the variables were not found to be significant predictors and were eliminated. The variables selected by the stepwise multiple regression analysis are reported in Table 4.13.

Table 4.13: Summary of variables selected by the stepwise multiple regression analysis for high school athletes.

Variables	Coefficient t	Std. Error	Std. Coefficient	F
Left Knee Flexion (FP) (deg)	0.55	0.195	0.318	7.968
Ball Velocity (km/hr)	1.977	0.245	0.911	65.246

The variables identified in Table 4.13 explained throwing test scores with an $r^2 = 0.911$. The regression equation to predict test scores is reported in Figure 4.20.

Regression equation for high school athletes:

$$y = -110.771 + 1.977x_1 + 0.550x_2$$

Where:

Intercept = -110.771

y = Test score

X_1 = Ball velocity (km/hr)

X_2 = Left knee flexion (FP) (degrees)

Figure 4.20: Regression equation for high school group's test score.

In order to verify the multiple regression equations for the high school group, the researcher entered the values for three of the subjects into the regression equations. The results of test score prediction are reported in Table 4.14.

Table 4.14: Predicted quarterback throwing test scores for high school athletes.

Variables	Coefficients	Subject 2	Subject 6	Subject 10
Ball Velocity (km/hr)	1.977	69.60	83.56	66.08
Left Knee Flexion (FP)	0.550	30.63	29.63	34.50
Intercept	-110.771	-110.771	-110.771	-110.771
Predicted Test Score (%)	n/a	43.68	70.72	38.84
Actual Test Score (%)	n/a	53	69	34

The high school regression equation was reasonably successful in two out of three subjects. The predicted score for Subject 2 was more than 10 percent different from actual while the other two remained within 5 percent different from actual. Because the regression equation accounts for 91% of variation it should be accurate for predicting most throwing test scores. On average the high school regression equation predicted that test scores were only 5.29% away from the actual throwing test scores.

University Athletes

The stepwise multiple regression analysis for the university athletes only identified one variable as a significant predictor of quarterback throwing test score. The variable selected by the regression analysis is shown in Table 4.15

Table 4.15: Summary of variables selected by the stepwise multiple regression analysis for university athletes.

Variables	Coefficient	Std. Error	Std. Coefficient	F
Throw Time (sec)	273.881	126.7	0.607	4.673

The variable identified in Table 4.15 explained variation in test score to an r^2 = 0.368. The regression equation for the prediction of test score in university athletes is expressed in Figure 4.21.

Regression equation for university athletes:

$y = 2.493 + 273.881x_1$

Where:

Intercept = 2.493

y = test score

x_1 = Throw time (sec)

Figure 4.21: Regression equation for university groups test score.

Three university quarterbacks test scores were selected randomly to test the multiple regression equation in order to verify the multiple regression equations for the university group. The athletes' actual and predicted throwing test scores are reported in Table 4.15.

Table 4.16: Predicted quarterback throwing test scores for university athletes.

Variables	Coefficients	Subject 2	Subject 6	Subject 10
Throw Time	273.881	0.170	0.210	0.160
Intercept	2.493	2.493	2.493	2.493
Predicted Test Score (%)	n/a	49.05	60.01	46.31
Actual Test Score (%)	n/a	52	70	38

The regression equation for university athletes explains less of the variation in athletes, and as a result, is less accurate at predicting throwing test score than the regression equation for high school quarterbacks. The range between the worst prediction and its corresponding actual score was approximately 10 percent. On average the university regression equation predicted test scores were 7.08% away from the actual throwing test scores on average.

CHAPTER V

DISCUSSION

The quarterback pass is a complex skill that requires both accuracy and velocity to be effective. One of the primary purposes of this study was to compare the throwing technique of high school and university quarterbacks to determine if there were any significant differences between them. Another purpose of this study was to develop a quarterback throwing test that could accurately assess quarterback passing skill and distinguish between athletes of different skill levels. The study also attempted to determine which kinematic aspects of the pass were most closely related to pass performance in the quarterback throwing test. Identifying the most significant predictors of the quarterback pass is important in order to help coaches focus their attention on the key variables associated with a successful pass.

This study analyzed the four phases of the throw: backswing, force production, release and follow-through of the pass. Variables identified by previous studies on the quarterback pass were measured at key points of the throw using Dartfish 4.5.2 software. Following the measurement of variables, statistical analyses were performed in order to determine which variables differed between the two groups, which variables were strongly correlated to the athletes' quarterback throwing test scores for the two groups separately, and which variables were the best predictors of throwing test scores for the two groups separately.

Phases of the Pass

Backswing

The backswing for the quarterback pass is broken into two phases: early cocking and late cocking (Kelly et al., 2004). The early cocking phase of the backswing begins with touchdown of the left foot (right handed thrower) and ends with maximum right shoulder abduction and internal rotation which is accompanied by the beginning of push off with the right foot. Late cocking continues until maximum external shoulder rotation of the throwing arm as the athlete's weight is transferred over the front foot. The study by Kelly et al. (2004) suggested the athlete should have complete weight transfer by the end of late cocking, which was not evident in either of the groups in this study. During the backswing the athlete should remain flexed in both knees to allow for an aggressive step and weight transfer during force production. As the upper body is still moving into maximum external shoulder rotation the athlete takes a step forward with the left foot (Axman, 1997a). The toe of the front foot should point to the target (Fracas and Marino, 1989).

Maximum External Shoulder Rotation

When the variables measured during the backswing were compared between groups, only maximum external shoulder rotation was found to be significantly different in favor of the high school athletes. Fleisig et al. 1(996) state that during peak backswing the right shoulder reaches an average maximum external shoulder rotation of 164 degrees from the horizontal in university athletes. However, some authors suggest it is ideal and not uncommon to reach closer to 180 degrees, with the lower arm parallel to the ground

(Fracas and Marino, 1989). These larger values were measured in some of the university age subjects in the current study. When comparing the angle of maximum external shoulder rotation between groups, the high school quarterbacks were able to achieve a significantly better position of maximum external shoulder rotation with a mean angle of 172.63 degrees from the horizontal (Figure 5.1). The university group had an average angle of 155.60 degrees from the horizontal. This benefits the high school group by giving them a larger range of shoulder rotation to produce force during the throw. It is also important to increase the stretch on the medial rotators of the shoulder to initiate a stretch reflex.

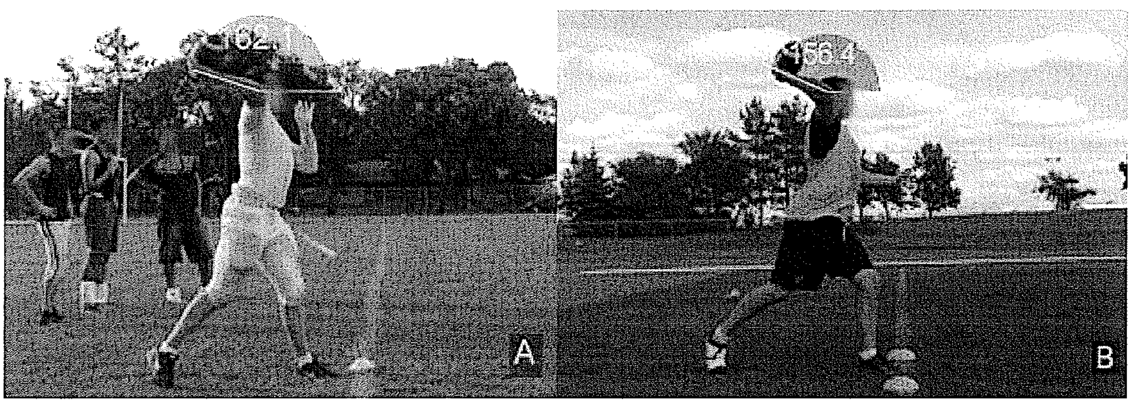

Figure 5.1: Comparison of maximum external shoulder rotation in high school (A) and university athletes (B).

The difference between high school and university athletes regarding their external shoulder rotation could be explained by differences in strength. It is expected that university athletes are more developed physically than high school athletes, which was evident in the current study. University athletes had an average body mass of 96.38kg while the high school group had an average mass of 79.71kg with similar standing heights (Table 4.1). The subject characteristics of the university group supports

Secora, Latin, Berg and Noble's (2004) study that reported an average body weight of 94.6kg in NCAA division I quarterbacks. The high school group characteristics were also consistent with past studies. Tuberville, Cowan, Owen, Asal and Anderson (2003) recorded measurements of high school football players in the Oklahoma City district and found an average body weight of 74.77kg. The sample taken in the study by Tuberville et al. (2003) showed slightly lower average body weight in high school quarterbacks than the sample in the current study. This could have been a result of the range of athletes used in the study. The current study used mainly athletes in grades 11 and 12 compared to an even distribution of athletes from grade nine to twelve in the study by Tuberville et al (2003). As a result of greater physical development, it is possible that university athletes do not require the same range of motion to produce equal force. The *t*-test comparisons of measured variables between groups showed no significant differences in throw velocity and could be a result of limited range of motion (Table 4.4). Throw time, or a "quick release", is thought to be great asset to a quarterback at any level as it allows the athlete more time to scan the field for receivers and still deliver the ball before the defense can get to the quarterback. It also allows the defense less time to react to the throw if the quarterback is not "telegraphing" his throw (DeLuca, 1978). At various levels of competition the speed of the game increases. From high school to university to professional football, a common progression is in the speed of the game. Because of this change of pace, university athletes may put more emphasis on throw time and sacrifice range of motion to decrease their throw time.

It seems unlikely that the shorter range of motion of lateral rotation in university athletes is not because they are not as flexible as high school quarterbacks. Bassey (1998) showed a slight reduction in shoulder flexibility in individuals 65 years old and up over an eight year period, but this value was not found to be significant. Shoulder flexibility was measured as the arm was swung upwards and outwards on a path halfway between the sagittal and frontal planes. This test only showed a 4.8 degree decrease over an eight year period. In studies looking at football players, specifically, there is also little difference between high school and university athletes in terms of general flexibility. Pratt (1989) recorded an average sit and reach score of 34.1cm in 17 year old high school football players. In comparison, Davis, Barnette, Kiger, Mirasola and Young (2004) found an average score of 36.6cm in Division I college football players. As quarterbacks continue to age and mature, they manage to maintain equal or even slightly improved flexibility. Although flexibility of the subjects in the current study was not assessed, it seems likely that university athletes maintain similar levels of flexibility as they progress from high school to university.

Since there was a significant difference in throw time between athletes and no significant difference in throw velocity, the likely cause of the difference is a trading off of ball velocity for a quick release. University athletes will be more developed and will need less range of motion to throw a football as fast as high school athletes. As a result of the reduced range of motion, the university athletes are able to deliver a pass significantly faster than the high school athletes. This difference will be discussed further later in the chapter.

Correlation Analysis

The variables measured during the backswing for each group were entered into a correlation analysis independently to determine which variables were most strongly related to quarterback throwing test scores. In the high school and university groups no variables were found to be significantly correlated to throwing test score. Right shoulder abduction was a common variable that was found to approach a relationship to throwing test score with an r = .589 for the high school group and r = .545 for the university group. The right shoulder abduction should not change drastically from backswing to release, and should remain close to 90 degrees throughout the throw (Figure 5.2). Greater shoulder abduction of the throwing arm in backswing would put the shoulder in good position earlier in the throw and limit any deviations during the rest of the throw. This would keep the force production smooth to reduce the chance of an inconsistent arm swing, and a resulting inaccurate pass.

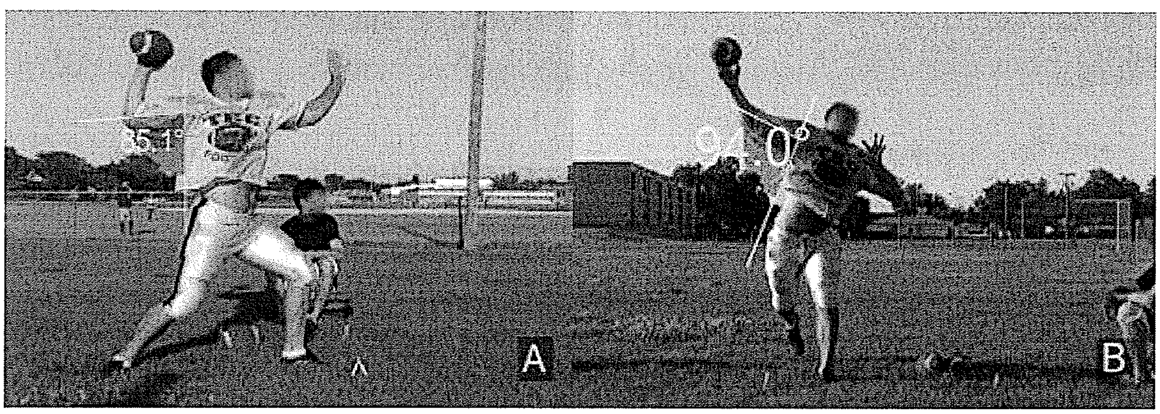

Figure 5.2: Right shoulder abduction during backswing (A) and release (B).

Force Production

Force production of the lower body begins when the athlete pushes off the right foot by extending the right hip. The thrower utilizes segmented trunk and limb rotation to maximize force production, so the upper body will still be in backswing at this time (Fracas and Marino, 1989). Segmented rotation allows a progressive contribution of body segments beginning in the base of support and progressing through the hand (Enoka, 2002). The bigger and stronger muscles initiate rotation and there is a summation of forces as the next distal segment begins to rotate once the segment proximal to it achieves maximum angular velocity. The upper body commences force production from maximum external shoulder rotation until the quarterback releases the ball. During this time the trunk and shoulder girdle rotate to face the target and the right shoulder is left in a position of external rotation due to inertial lag. Once hip and trunk rotation stops and the athlete is facing the target, the throwing shoulder starts to internally rotate as the elbow extends and the forearm pronates. During shoulder rotation the pelvic girdle is held stable to stabilize the lower attachments of the oblique muscles and allow for a more effective pull of the trunk muscles.

Right Knee Flexion

Early in force production the right knee should remain flexed close to 30 degrees to keep the athlete's head at a constant level during the throw (Fracas and Marino, 1989). When right knee flexion during force production was compared between groups, the university quarterbacks showed significantly more flexion. The university group had a mean knee flexion of 31.81 degrees, while the high school group had a mean right knee flexion of 25.50 degrees. Right knee flexion benefits the university quarterbacks by allowing a flatter path of the head during the step and improves pass accuracy by improving the athlete's ability to track the target during the throwing motion. It also assists in weight transfer because it allows the athlete to push off using hip extension rather than knee extension. Maintaining knee flexion will allow the back foot to become unweighted prior to release and allow complete weight transfer.

At release, the left knee should remain flexed. If the left knee fully extends and reaches full extension, weight transfer will be limited. The pass may also be overthrown because the extended left knee will keep the quarterback leaning back and increase the angle of release of the ball (Danischewsky, 2007). Staying in a slightly flexed position allows the athlete to stay lower during the step and keep the left knee flexed at touchdown. However, an excessively long step could still cause the left knee to be extended at touchdown and result in an errant pass.

Hay (1993) suggests the quarterback should extend the right hip rather than the knee to drive the athlete forward during the step. If the athlete drives forward with an emphasis on hip extension, having greater knee flexion will help fully unweight the right foot since it would lose contact with the ground sooner with an aggressive step onto the left foot. Hip extension was not measured in this study, but if the subjects were effective at driving forward with hip extension, the greater right knee flexion in the university quarterbacks compared to the high school athletes would support the higher incidence of fully unweighting the back foot at release.

Left Shoulder Abduction

In many throwing sports the action of the free arm is used to increase force production and the quarterback pass should illustrate the same action. Similar to baseball pitchers, driving the free arm down and back during trunk rotation can help to increase force produced and trunk rotation velocity (Yessis, 1984). The amount of shoulder abduction plays a role in the contribution of the arm to trunk rotation with greater abduction producing more trunk rotation. When comparing high school and university quarterbacks, the mean angle of left shoulder abduction was approaching a significant difference between groups. The high school athletes had greater shoulder abduction with a mean angle of 63.13 degrees, while university athletes had a mean left shoulder abduction angle of 51.46 degrees (Figure 5.3). This result was not expected, as it takes greater strength to be able to take advantage of the increased moment of inertia to generate more torque about the spinal axis. A lower abduction angle will benefit the university group by decreasing the moment of inertia of the trunk around the spinal axis. As a result, the rate of trunk rotation could increase if the torque remains constant and the greater angular velocity could be transferred to the ball.

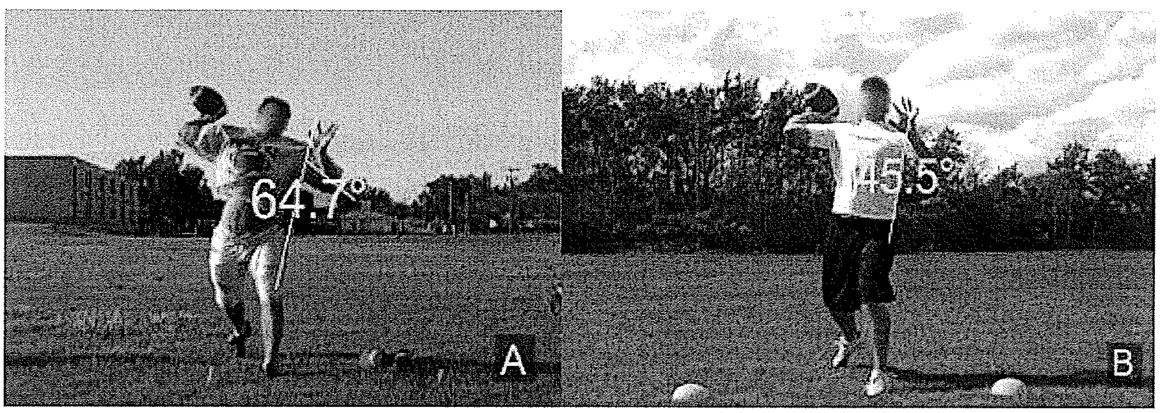

Figure 5.3: Comparison of left shoulder abduction in high school (A) and university (B) quarterbacks.

The results of the shoulder abduction were not expected as the researcher expected to see greater left shoulder abduction in the university group. This could be a result of the university group putting a greater focus on the free arm drive. High school athletes may keep the left arm more abducted because they do not actively drive the elbow back during force production to increase trunk rotation velocity. Quarterbacks are often taught to hold the ball level with the back ear (McElroy, 2003). This position causes the left shoulder to abduct during the ready position. If high school quarterbacks do not actively use their free arm during force production it could remain abducted during this phase of the throw.

Correlation Analysis

When the correlation analysis was completed for each group separately, no variables in the force production phase were found to be significantly correlated to the quarterback throwing test score in the university group. The high school group showed three variables with significant relationships with throwing test score: step length, right knee flexion and percent standing height. The variable with the strongest correlation with quarterback throwing test score for the high school group was step length ($r = .709$). This means that as the length of the step increases, the throwing test score tends to be higher. The step length should be approximately 61% of the athlete's standing height (Fleisig et al., 1996). The step should be planted directly towards or just left of the target. A step that lands right of the target limits the time and range of motion for hip and trunk rotation by blocking hip rotation, which results in passes thrown behind the intended target (Axman, 1997a). Also, high school quarterbacks who have a longer step will allow themselves greater time for force production in hip and trunk rotation (Alexander, 1992).

Right knee flexion also had a significant relationship with quarterback throwing test score in high school athletes ($r = -.703$). High school athletes who showed less right knee flexion during force production tended to score higher in the throwing test. As mentioned earlier, a flexed right knee means that the athlete is staying in a level position to allow tracking of the target to improve pass accuracy (Figure 5.4). It was unexpected that lower knee flexion angles would relate to increased throwing test score. Keeping the right knee flexed would mean that the push off during the quarterback's step is occurring primarily with hip extension. Using hip extension as the primary source of power during the step would benefit the quarterback for several reasons. However, since high school athletes achieve full weight transfer with the back foot becoming unweighted at release less frequently, knee extension is their primary mechanism of weight transfer.

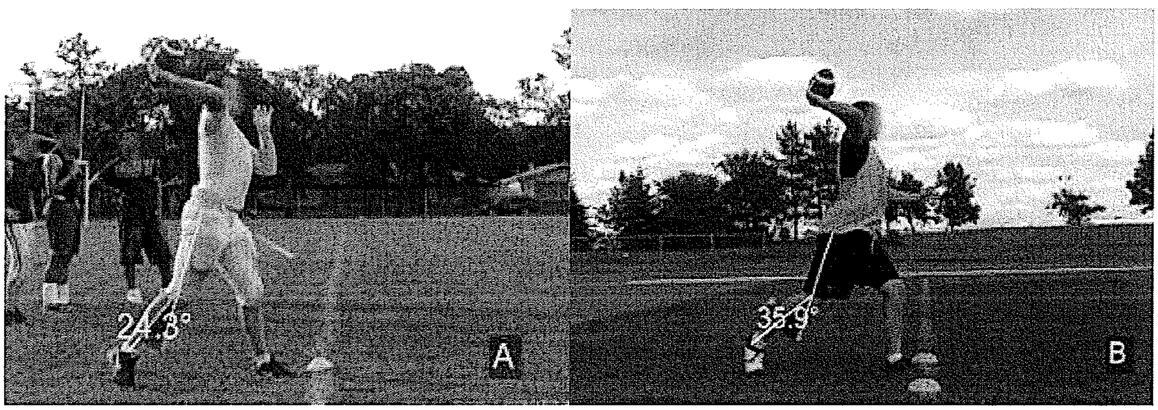

Figure 5.4: Example of a quarterback extending the right knee during push off (A) and maintaining knee flexion during push off (B).

Keeping the right knee flexed during the push off would allow the back foot to lose contact with the ground earlier in the throw. This would ensure a full weight transfer with all of the athlete's weight being successfully shifted onto the front foot prior to release. Full weight transfer will assist force production by increasing the forward linear velocity of the athlete and the ball and will result in faster ball velocity in the quarterback throwing test.

Another benefit that greater right knee flexion could have on throwing test performance is its effect on left knee position and the vertical deviation of the athlete during the throw. Keeping the right knee flexed and using hip extension to drive the athlete forward could cause a lower and flatter step by the quarterback. By maintaining right knee flexion during force production, the centre of gravity of the athlete remains lower and moves forward in a flatter path. The athlete will be in a lower position that is more likely to have a flexed left knee at touchdown which, although not shown in the current study, has been said to improve accuracy of the quarterback pass. When the quarterback has minimal left knee flexion he is unable to rotate onto the front foot and does not allow the athlete to level his shoulders. This can result in high passes due to the increased trajectory of the throw. Left knee flexion allows the quarterback to fully transfer his weight over the front foot. Failing to successfully drive onto the front foot would reduce the force generated during the step and could result in an underthrown pass. Keeping a flattened path during the step may also improve the athlete's accuracy by allowing the athlete to maintain a level head position. This would assist the quarterback when tracking his target by keeping the head level during the throw.

As expected, percent standing height was also strongly correlated to throwing test score ($r = .684$). Percent standing height is the step length percentage relative to standing height, and was expected to have a similar relationship to absolute step length. Both the high school and the university groups had a mean relative step length of 44%. However, when conducting the correlation analysis for both groups, only the high school group showed a significant relationship between percent standing height and quarterback throwing test score. High school quarterbacks showed an increased throwing test score with an increase in step length relative to their standing height. The relationship between relative step length and absolute step length is likely the same. A longer step is a sign of a more dynamic step which will increase the velocity of the throw by increasing the linear horizontal velocity of the athlete during the throw. A longer step also allows a longer time for complete hip and trunk rotation to allow greater force to be generated during the throw (Alexander, 1992). This increases ball velocity by increasing the time that the athlete can generate force and increases the rate of hip and trunk rotation. This increased rate of rotation increases the angular velocity of the ball around the spine and front hip which will transfer into greater linear velocity upon release.

Both groups of athletes were well below the suggested step length of 61% of standing height reported by Fleisig et al. (1996). However, the relationship between throwing test score and the university group was not found to be significant. It is possible to maintain a flexed left knee and a level path of the head with a short step so accuracy should not be affected by a shortened relative step length. There could be a decrease in ball velocity with a shortened step; however the university group may be more effective at producing good ball velocity without maximizing step length. This could be yet another attempt to decrease throw time by the more mature athletes. There was no significant difference between age groups in ball velocity and step length. However, within the high school group, it is possible that they need to maximize step length in order to achieve good ball velocity. University athletes may be strong enough to produce similar ball velocities without maximizing step length and increasing range of motion in hip and trunk rotation.

Regression Analysis

A stepwise multiple regression analysis was completed for each group separately. Only the high school analysis produced a variable from the force producing phase to enter the regression equation to predict quarterback throwing test score. Left knee flexion during force production was selected as the second and final variable by the multiple regression analysis as a significant predictor of throwing test score. As mentioned previously in this chapter, left knee flexion at release has been determined to be a critical aspect in pass accuracy. It was not expected that left knee flexion would be a predictor during force production rather than release, but left knee flexion during the step could help determine flexion during release (Figure 5.5).

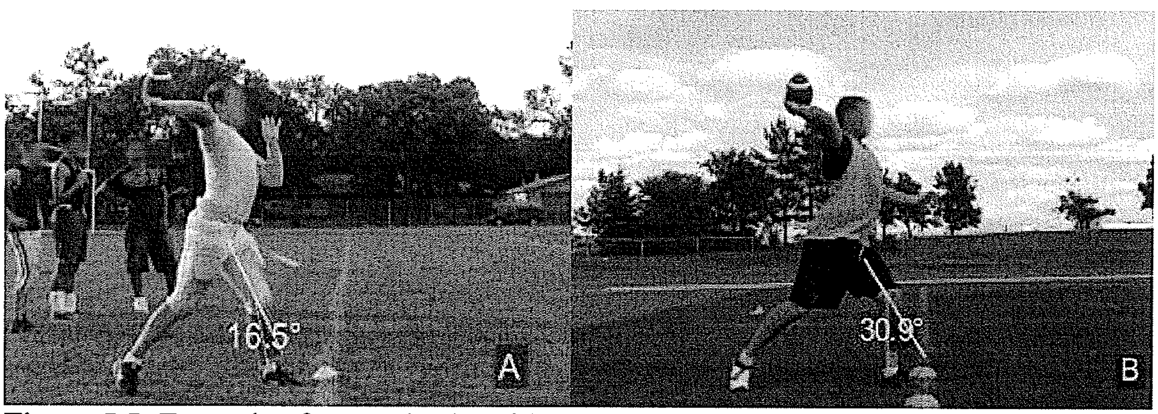

Figure 5.5: Example of quarterbacks with an extended left knee (A) and flexed left knee (B) during force production.

Release

The release is also referred to as critical instant as there is no action the quarterback can take to affect the outcome of the pass after the ball has left the athlete's hand. At release the athlete's trunk is flexed forward and laterally away from the throwing arm. The right shoulder is also abducted to further raise the ball over the throwing shoulder. The amount of lateral trunk flexion and shoulder abduction varies among athletes and also depends on the throwing technique and whether the athlete adopts an overhead or three-quarter throwing motion. The three-quarter throwing motion is also sometimes referred to as a side arm technique and has less shoulder abduction and lateral trunk lean which results in an upper arm position closer to parallel than the overhand throwing motion. The athlete should be square to the target when the ball is released, and the back foot should be completely unweighted.

Back Foot Unweighted

At release the back foot should be completely unweighted as the athlete brings all of his body weight forward over the left foot (Alexander, 1992). The university group was found to reach a position of full weight transfer significantly more frequently than the high school group (Figure 5.6).

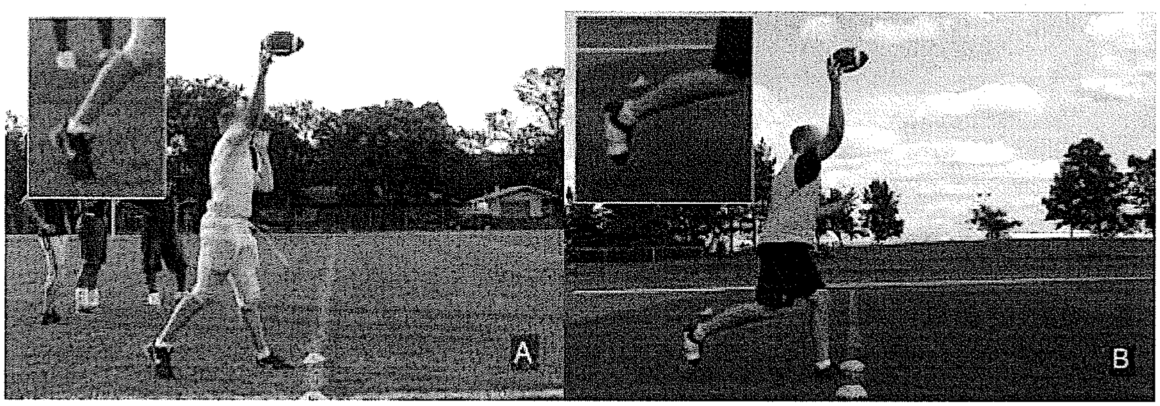

Figure 5.6: Comparison of back foot position at release in high school quarterbacks (A) and university quarterbacks (B).

The university group benefits from this difference by being able to generate more linear horizontal velocity. As the athlete drives forward, he is moving forward and that velocity is transferred to the ball. This should help improve their throwing velocity and could make up for some of the shortcomings in the university group such as reduced range of motion in shoulder external rotation and less forward trunk flexion at release, which will be discussed more later in this chapter. Accuracy may also be affected by the position of the back foot. Left knee flexion allows the shoulders to become more level at release and prevent increased trajectory of the pass (Danischewsky, 2007). Not shifting all of the athlete's weight onto the front foot could also cause the athlete to be more vertical and prevent the quarterback from rotating over the front foot to a level shoulder position.

University athletes showed a greater tendency to shift their body weight completely over the front foot when compared to high school quarterbacks. At the university level, athletes are much bigger and possibly taller, although not seen in this study, since size is one factor taken into consideration by university recruits. The university athletes may use this weight transfer to help increase the height of release. High school athletes seem to attempt to achieve their weight transfer through forward trunk flexion, which will be discussed later. However, neither relative nor absolute release height was found to be significantly different between groups.

Throw Time

Throw time is measured from touchdown of the left foot until the ball is released. The independent *t*-test revealed a significant difference between the high school and university quarterbacks. University quarterbacks had a mean throw time of 0.17s compared to 0.21s in the high school group. The university group had a significantly quicker release than the high school quarterbacks (Figure 5.7). This is thought to be beneficial for efficiency, but not necessarily a benefit for throw velocity or accuracy. A faster throw time allows the quarterback time to scan the field and still deliver a pass before the defender reaches the quarterback. In identical situations an athlete with a longer throw time will need to decide and commit to a throw sooner than an athlete with a quick release in order to get the pass off in time. Professional quarterbacks analyzed for comparison to the subjects in the current study had an average throw time of .172s which is almost identical to the university athletes in this study. Efficiency seems to be of more importance as level of play increases.

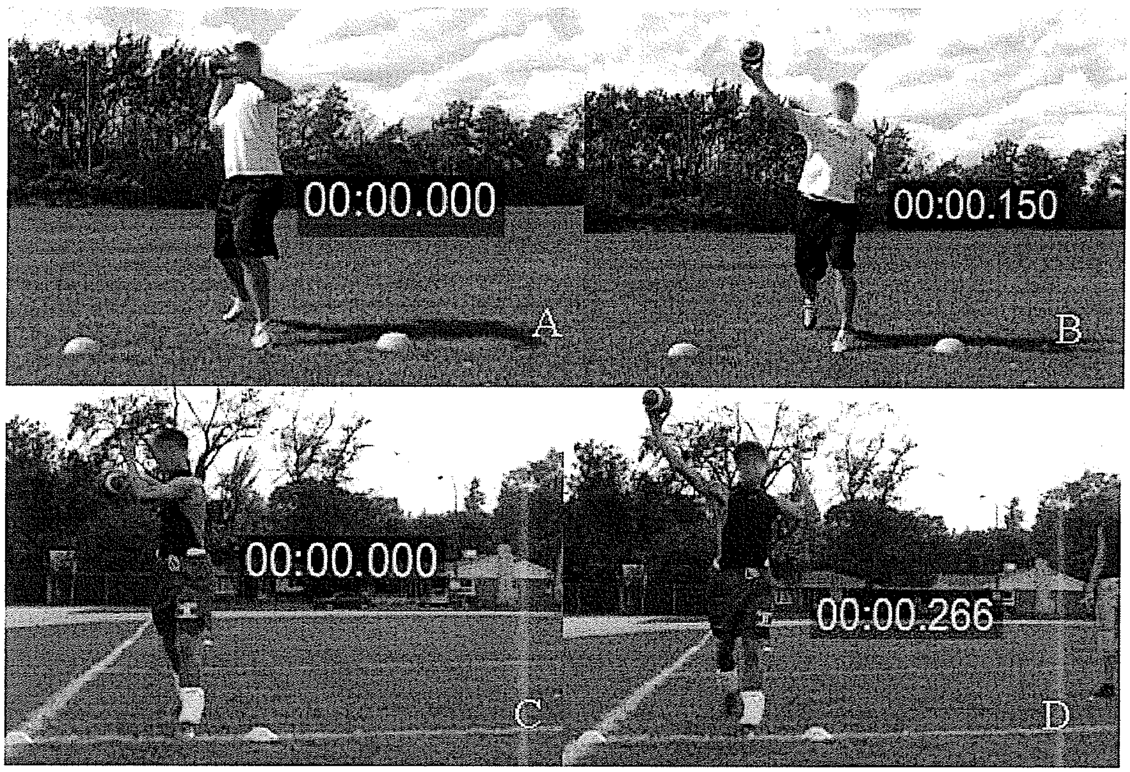

Figure 5.7: University quarterback throw time from start (A) to finish (B) compared to high school quarterback throw time from start (C) to finish (D).

Forward Trunk Lean

Forward trunk lean was another variable found to be significantly different between groups. As the athlete steps and transfers his weight into the throw he flexes forward at the trunk. Approximately 25 degrees of forward trunk flexion is recommended

(Fleisig al., 1996). A lean greater than 25 degrees would have a negative effect on release height and make passes more susceptible to deflections.

The high school group had significantly greater forward trunk flexion at release which was not expected (Figure 5.8). Good forward trunk flexion is an indicator of weight transfer, but the high school group has complete weight transfer significantly less frequently than university athletes. High school athletes may use forward trunk flexion as an attempt to transfer weight towards the front foot. University quarterbacks remain more upright during the throw, but fully unweight the back foot prior to release more frequently. Forward trunk flexion helps move the centre of gravity towards the front foot, but as long as the back foot is in contact with the ground, weight transfer is not complete. The high school group reaches a position of greater trunk flexion, but this position does not make up for the inability to fully transfer their weight onto the front foot during the step. Excessive forward trunk flexion will also result in decreased release height. This will reduce the release angle and time in the air. Low release height will also make the pass more susceptible to deflections by the oncoming defenders.

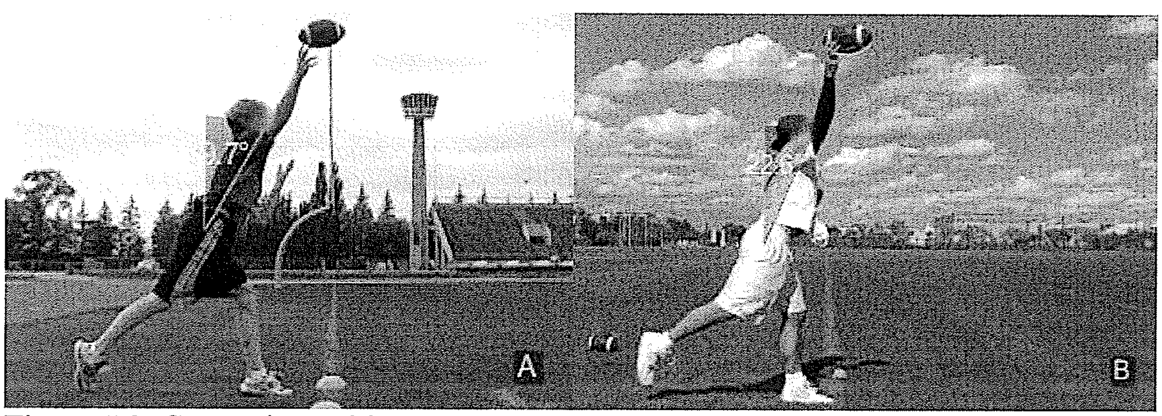

Figure 5.8: Comparison of forward trunk flexion in high school (A) and university (B) quarterbacks at release.

Right Knee Flexion

The right knee is flexed at release and the right foot may or may not be in contact with the ground. Greater knee flexion would accompany an unweighted back foot as the knee flexes to pick the right foot off the ground (Figure 5.9). When high school and university athletes were compared using independent *t*-tests, the university group had significantly greater right knee flexion at release.

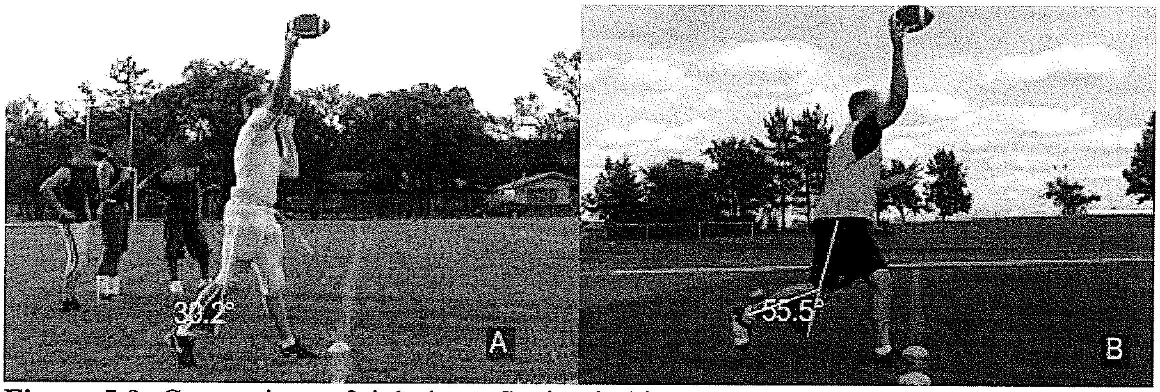

Figure 5.9: Comparison of right knee flexion in high school (A) and university (B) quarterbacks at release. Note pelvic rotation in the high school athlete (A) is incomplete due to the back foot being on the ground at release.

The university quarterbacks had a mean right knee flexion angle of 40.24 degrees compared to 30.82 degrees in the high school quarterbacks. This supports the significantly greater tendency for the university athletes to have their back foot unweighted at release. If the back foot was in contact with the ground and had higher right knee flexion, the athlete's rear shoulder would drop as a result or the left knee would also have to increase flexion and sacrifice release height. University quarterbacks benefit from this position by ensuring they have maximized the force they can produce during the step and will increase the ball velocity as a result. University athletes will also have increased range of motion in pelvic rotation. Having the right foot unweighted allows the pelvis to rotate to squarely face the target (Figure 5.9).

Right Elbow Flexion

During force production the elbow extends as the athlete rotates his trunk to face the target. At release the elbow is flexed approximately 36 degrees (Fleisig et al., 1996). A more extended elbow up to 36 degrees of flexion is beneficial for torque production by increasing the distance of the ball from the axis of rotation (Alexander, 1992). An increased radius from the ball to the axis of rotation at the spine and front hip will increase the linear velocity of the ball at release (Figure 5.10).

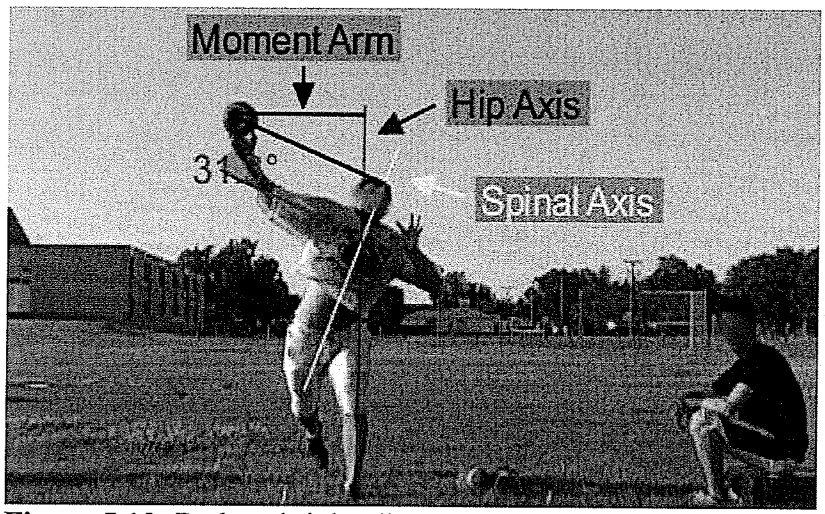

Figure 5.10: Reduced right elbow flexion increases the radius from the ball to the axis of rotation at the spine and front hip.

High school quarterbacks had a mean right elbow flexion angle of 22.30 degrees. This was significantly lower than the university athletes who had a mean elbow flexion of 31.21 degrees. The researcher expected to find the university group to have less elbow flexion than the high school group to increase the moment of inertia and increase the radius to the axis of rotation through the shoulder, spine, and front hip. A lower elbow flexion angle in high school athletes allow them to generate more torque by creating a larger distance between the ball and the spinal and front hip axes. Less elbow flexion also benefits the high school quarterbacks by increasing their release height if they adopt an overhead throwing technique.

The university athletes have more muscular development and as a result have the potential to be significantly stronger than younger athletes (Table 4.1). It was for this reason the investigator expected the university group to take advantage of the greater moment of inertia about the spinal axis by having less right elbow flexion at release than the high school group. An increased radius from the axis of rotation would increase the angular velocity of the hand by increasing the distance traveled during the throwing motion. The increased angular velocity of the ball would translate into greater linear velocity of the ball at release, since $V = r \cdot \omega$. The rate of elbow extension is very similar between groups and this, combined with reduced throw time, could result in a position of greater elbow flexion at release. At no other point in the throw was elbow flexion significantly different. It could be that university quarterbacks are placing so much emphasis on a quick release that they are not able to achieve better elbow extension at release. In the current study elbow extension velocity was measured during the final two frames prior to release, therefore the university athletes did not attempt to make up for their lack of time with greater elbow extension velocity through the end of force production.

Elbow flexion angles seem to be the result of reduced throw time in university athletes. The high school quarterbacks with a slower release would need slower elbow extension velocities to reach the same position in time for release.

Correlation Analysis

The correlation analysis produced more significant relationships between quarterback throwing test scores and the kinematics of the release than any other phase of the throw. The high school group had three significant relationships with throwing test score during the release: ball velocity, lateral trunk lean and throw time. The correlation analysis for the university group showed a significant relationship between quarterback throwing test score and two variables: back foot unweighted and throw time.

Ball velocity was found to have the strongest correlation with quarterback throwing test score in high school athletes ($r = .900$). This relationship was expected since ball velocity is scored in the throwing test. Interestingly, this relationship was not seen in the university group. The fact that ball velocity was correlated to throwing test score in high school athletes is not surprising considering the distribution of test scores. When looking at the point distribution in each group we can see why ball velocity is more strongly correlated in high school athletes. University athletes averaged 303 points based on velocity and 131 points for accuracy in the quarterback throwing test. In contrast, the high school group averaged 296 points for velocity and just 113 points for accuracy. The difference in velocity seemed to be minimal between groups however the university group scored 18 more accuracy points on average. The greatest difference in throwing test score between groups came in the points for accuracy. Due to reduced accuracy points, ball velocity played a larger role in point distribution for high school athletes. This might prove to be significant in future studies with larger sample sizes.

On their missed passes high school athletes were low relative to the target 43.6% of the time. The rest of the misses were evenly distributed between high, left and right

(19.1%, 19.1% and 18.1%). University athletes also missed low most frequently, but with only 35.2% of their missed passes. The university athletes were right of the target 29.5% of the time and were high or left of the target 18.1% and 17% respectively. Throws that missed in a combination of directions were counted as half of a miss in either direction. For example, a pass that was high and to the right of the target counted as half of a miss towards the high and right categories. The higher number of low passes in the high school group was not determined to be caused by lack of strength since the occurrence of low passes was evident throughout the throwing test. Also, the scoring in the throw for maximum distance was similar between groups. The university group scored an average of 62 points on the distance throw compared to 59 points by the high school group. Therefore, the frequency of low passes was not likely related to a strength deficiency in the high school group.

The second strongest correlation to throwing test score in high school quarterbacks was found in lateral trunk lean ($r = .749$). As high school athletes increased their lateral trunk flexion away from the vertical, they tended to score higher on the quarterback throwing test (Figure 5.11). Lateral trunk lean is used in many other overhead throws such as baseball pitching and javelin throwing to increase the moment arm about the spinal and hip axes, and increase torque production. Since ball velocity is so important to the performance of high school athletes on the quarterback throwing test, it makes sense that a key contributor to ball velocity would also have a significant relationship with throwing test score. Lateral trunk lean also helps increase release height which will help throw over the defenders attempting to block the pass as well as throw distance by giving the ball more flight time.

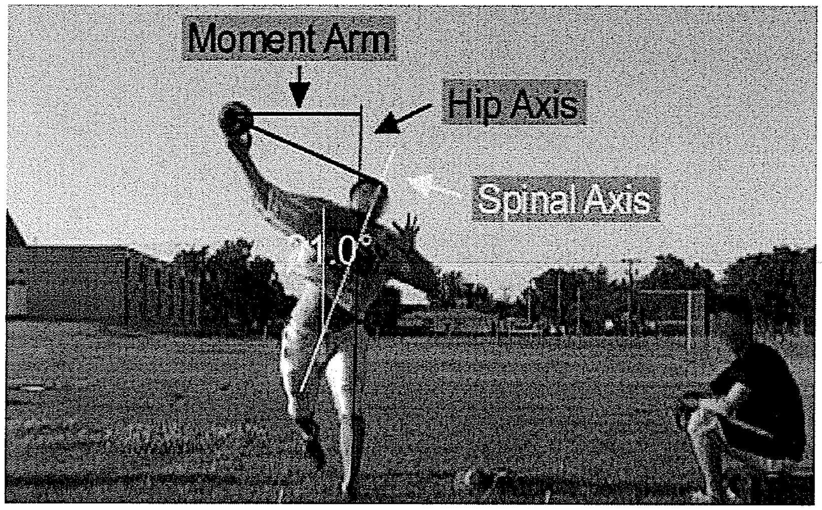

Figure 5.11: Lateral trunk lean from the vertical increases the release height of the ball.

The final variable that had a significant correlation to quarterback throwing test score in high school athletes was throw time (r = -.699). High school quarterbacks showed a significantly slower release than the university group. A quick release is more efficient and this relationship implies that a quicker release would also result in a better throwing test score. In this study university athletes began the backswing of the upper body sooner than high school athletes and reached maximum external shoulder rotation earlier in the throw. This could mean that high school quarterbacks have a less aggressive or poorly timed trunk rotation. This would limit the contribution of the trunk muscles in force production and reduce ball velocity. High school athletes also seemed to hold the ball longer while they move into greater forward trunk flexion which was mentioned earlier in the chapter. The lower arm of the high school athlete is closer to the horizontal at release and this causes the ball to have a lower trajectory with the tip of the ball pointing more downward at release (Figure 5.12). Pulling down on the ball at release could result in underthrown passes and have a negative effect on pass accuracy.

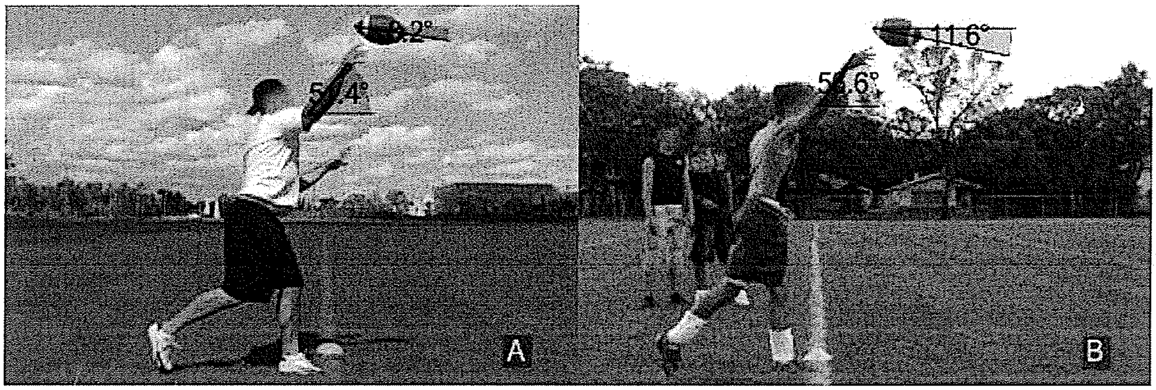

Figure 5.12: University quarterbacks (A) let go of the ball sooner than high school quarterbacks (B) to avoid pulling down on the ball.

The variable most correlated to quarterback throwing test score in university athletes was whether or not the back foot was unweighted at release (r = .661). University quarterbacks who had their back foot completely unweighted at release performed significantly better in the quarterback throwing test. This is a sign of full weight transfer onto the front foot, which is beneficial for force production. University athletes that have the back foot off the ground at release have likely increased their horizontal linear velocity during the step and this velocity can be transferred to the ball. This increases the horizontal velocity of the quarterback at release which is also imparted to the ball to increase throw velocity. Having a complete weight transfer can also help accuracy by allowing the athlete's shoulder girdle to reach a more level position and prevent an unwanted increase in trajectory similar to what the literature suggests occurs with a fully extended left knee at release (Danischewsky, 2007). An unwanted increase in angle of release will result in inaccurate passes thrown high of their target.

Throw time was also correlated to quarterback throwing test score in university athletes (r = .607). Interestingly the correlation between throw time and throwing test score was a positive relationship, contrary to the high school group. This suggests that university quarterbacks with a slower release time scored better on the throwing test. A faster release is desired in terms of efficiency, allowing the quarterback more time to find a receiver before having to throw the ball. However if the throwing time is fast, the segmented motions of the throw can become more simultaneous. During segmented rotation the distal segments should begin to rotate once the proximal segment has reached its maximum velocity. This summation of forces should be smooth in order to transfer momentum (Yessis, 1985). The shoulder girdle should come to a stop facing forward as the elbow extends and the shoulder internally rotates until release (Yessis, 1984). University athletes had a significantly faster throw time which did not allow time for shoulder rotation to come to a stop in time for release (Figure 5.13). This causes the university athletes to continue to rotate through release of the football, which is undesirable for pass accuracy. This will have a negative effect on the accuracy of the pass as the upper body is not stationary and makes tracking of the target more difficult.

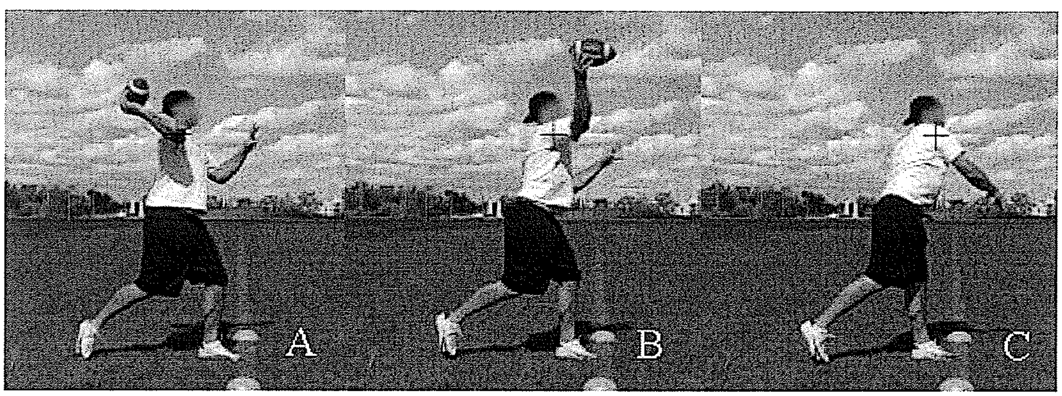

Figure 5.13: Trunk rotation continues at a continuous rate after the ball is released.

Shortened throw time may also have a negative effect on pass velocity. As previously mentioned, the distal segment should begin rotation once the proximal segment has reached maximum angular velocity. If the throw is rushed, and the athlete does not have sufficient angular acceleration of the trunk, the athlete will not have enough time to generate maximum velocity in each of the segments beginning with the pelvic girdle, then to the trunk, shoulder girdle, shoulder medial rotators, elbow extensors and forearm pronators. This finding would also explain differences between groups in maximum external shoulder rotation values since the university group had not maximized angular velocity in previous segments and had less momentum to transfer to distal segments. The investigator in this study believes the inverse relationships between throw time and throwing test score in both groups suggest an ideal throw time between the mean values of the two groups. Rash and Shapiro (1995) measured throw time using the same technique as the current study, which was from touchdown of the front foot until release and found a mean throw time of .21s in university quarterbacks. The current study had a mean of .17s in the university group, indicating a much faster throw time. The high school group had a mean throw time of .21s.

Regression Analysis

In the stepwise multiple regression analysis for each group one variable was selected from the release phase for the regression equation to predict quarterback throwing test score in high school and university athletes. The analysis for the high school group selected ball velocity as the first variable to be used in the regression equation. This finding suggests that ball velocity is the strongest predictor for throwing test score. As discussed earlier in the chapter, ball velocity as a strong predictor of test score was expected since it is responsible for almost half of the potential points in the quarterback throwing test. However, the regression analysis did not find ball velocity to be a predictor of test score in the university group. As mentioned previously, this is largely due to the fact that a larger portion of the high school subjects' score were from points awarded for ball velocity. The university group relied less on velocity for the quarterback throwing test score since they were able to get a larger portion of their points from the accuracy and throwing distance section.

The regression analysis for the university group selected just one variable for the regression equation to predict throwing test score: throw time. Similar to the correlation analysis, a slower throw time should result in a higher score in the quarterback throwing test. University quarterbacks tended to focus on reducing throw time in order to have more time to process the field situation and select a receiver. As a result, the throwing motion was rushed and they did not allow enough time to maximize force production by utilizing a full range of motion. The university group shows less range of motion and also releases the ball while the shoulder girdle is still rotating which makes tracking of the target difficult and makes the pass inconsistent. Therefore, slowing the throwing motion to allow a full range of motion would help improve throwing test score.

Follow-through

Once the ball is released the athlete continues into follow-through. The purpose of follow-through is to decelerate the arm to a stop and put the quarterback in a position to react to the play. Along with forearm pronation, the right shoulder continues to medially rotate, extend and horizontally adduct. This should bring the arm across the athlete's body with the thumb of the throwing hand pointing towards the left hip (for a right handed quarterback). A long follow-through serves a dual purpose. It allows the arm to be close to the body and reduce risk of injury if the athlete is hit (Hay, 1993). It also allows a long range of motion for the infraspinatus, supraspinatus and teres minor muscles to eccentrically contract to decelerate the medial rotation of the arm. More time to decelerate will require more force and produce less strain on the muscle to reduce risk of injury (Kelly et al., 2002).

There were no significant kinematic differences found between groups in the follow-through phase. There was a trend suggesting that university athletes had greater forearm pronation velocity during follow-through with a p-value $\leq .08$. Forearm pronation is used to apply a torque to the ball and increase its angular momentum in the air. This makes the ball more stable in flight and less susceptible to having its path altered by external forces such as wind.

Quarterback Throwing Test Scores

The quarterback throwing test score was out of a maximum of 1000 points. Accuracy and ball velocity each accounted for a potential 450 points with an additional 100 points for a maximum distance throw. When throwing test scores were compared between groups there was no significant difference between high school and university athletes. High school athletes had a mean score of 464 (46.4%) compared to 496 (49.6%) points in the university group. This comparison had a p-value $\leq .57$. Although there was a very slight trend in favor of the university athletes there was no evidence to suggest a difference between groups.

The sample sizes may have been too small to detect a difference between groups, which increases the possibility of saying there is no difference when there is in fact a genuine difference, and committing Type II error. Larger groups increase the sensitivity of the study by decreasing the standard error, and increasing the ability to detect true differences (Hassard, 1991). With only ten subjects per group it becomes more difficult to find significant differences. Another potential reason for the similar outcomes could be in the subjects available. The subjects used for the university group came from two teams. One team had six quarterbacks while the other had four at the time of filming. The high school quarterbacks used in the study came from six teams with three of the teams only having one quarterback available for filming. For many of the high school teams filmed only the top quarterback was filmed, which is the most likely athlete to make the transition to the university level. Therefore, the high school sample may not illustrate the full range of skill levels and may have had more athletes closer to the university level. Elite high school quarterbacks and less skilled university athletes may have been too close in skill level to show a difference in quarterback throwing test score and kinematic variables of technique.

Evaluation of Quarterback Throwing Test

The throwing test involved throws of varying distances and allowed the participants to take numerous throws to improve validity of the test. The athletes' accuracy, velocity and distance were assessed in order to test all the critical aspects of the pass. Despite examining the major aspects of the pass the results for the quarterback throwing test were not significantly different between groups.

Although throwing test point allocation was evenly distributed between pass accuracy and velocity, more points for velocity were achieved by the subjects. In order to score points for accuracy the pass had to hit one of the rings of the target. As a result, many athletes received accuracy points on less than half of their attempts. Velocity points were awarded regardless of the result of the pass, therefore it was easier to score points based on velocity than it was for pass accuracy. In order to make the test more valid the allotment of velocity points needs to be adjusted.

Points for velocity and accuracy both ranged from 10 to 50. However velocity had five separate scoring possibilities compared to three for pass accuracy. Reducing velocity scoring to three potential scoring options and adjusting the velocity range would make scoring points through pass velocity more difficult and reduce the contribution of velocity points to total throwing test score.

Throw distances were assessed, however there was little difference between groups. This was largely due to the similar release height and pass velocity between groups since throw distance is affected by release height, angle of release and ball velocity. The throwing test successfully examines the three most important attributes of a successful pass, but the point distribution needs to be modified to improve test validity by making points for accuracy and velocity equally attainable.

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

The quarterback is a pivotal position on any football team, and the quality of the quarterback can often be one of the primary determining factors of a team's success. The quarterback must be able to deliver a fast and accurate pass to his receivers in order to maintain possession of the ball and lead his team down the field. The purpose of the study was to determine the kinematic differences between the quarterback pass executed by high school athletes and the pass executed by university athletes. This was done by investigating the key variables which were associated with maximizing the athletes' pass performance as determined by the quarterback passing test. Video analysis was performed on both high school and university quarterbacks by measuring key kinematic variables. Statistical analyses were performed in order to determine if any differences existed between the two groups. It was hypothesized that the quarterback throwing test score and kinematic variables of the quarterback pass in high school athletes would differ from the university athletes. A secondary purpose was to determine which body movements and body positions best predicted performance in the quarterback pass. The final purpose of the study was to develop a quarterback throwing test that was effective in assessing quarterback skill level.

Twenty subjects were used in this study and divided into two groups. Ten high school aged quarterbacks and ten university aged quarterbacks were compared based on their throwing test scores and kinematic variables.

Twenty-nine variables were measured at various points during the quarterback pass. Five variables were measured during backswing, eight during force production, eleven at release of the ball, and five during the follow-through phase. The variables were measured through the use of Dartfish Team Pro 4.5.2. These variables included: angles of the trunk, hip, knee, ankle and shoulders, as well as angular velocities for elbow extension and internal shoulder rotation, step length, throw time, release height and linear velocity of the ball at release. The data collected allowed the researcher to analyze several aspects of the throwing technique and determine what similarities and differences occurred between the two groups. Statistical analyses were performed on the measured variables through the use of *t*-tests, Pearson's Product-Moment Correlations, Spearman's Rank Correlation and Forward Stepwise Multiple Regression analyses.

T-Tests

The statistical analysis of the two groups revealed several differences in technique with the majority of the differences occurring during release of the football. *T*-Tests were performed in order to determine the kinematic differences in passing technique between the high school and university athletes.

Backswing

Only one of the variables measured during the backswing was shown to be significantly different between the two groups. This variable was maximum external shoulder rotation of the throwing shoulder in maximum backswing of the upper limb. The high school group was shown to move into a position of greater maximum external shoulder rotation during the backswing and measured from the horizontal. This difference seems to be a result in decreased throw time in the university group. Previous studies showed maintenance or slight improvement of flexibility from high school to university football players (Davis et al., 2004, Pratt, 1989). Although flexibility was not measured in the current study it is unlikely that decreased flexibility was the cause of reduced external shoulder rotation in university athletes.

Force Production

The force production phase showed slightly more significant differences between high school and university groups. During force production, one of the eight variables measured was found to be significantly different – right knee flexion. Left shoulder abduction approached significance but was found to be insignificant with the adjusted p-value. Right knee flexion was the only variable that was also found to be significantly different at release, however left shoulder abduction was not measured at the point of release.

In force production the university athletes displayed greater knee flexion than the high school athletes. This knee flexion is in the back leg in right handed quarterbacks and suggests that high school athletes flex the right knee less during the step forward while university quarterbacks have greater right knee flexion as they transfer their weight onto the front foot. The university group went from a position of slightly less right knee flexion in the backswing (Table 4.2) to significantly greater right knee flexion during force production (Table 4.3). This finding suggests that university athletes were more effective at pushing off the back leg using right hip extension rather than right knee extension, however hip extension was not measured in this study. Hip extension is the recommended method for weight transfer (Hay, 1993). Maintaining right knee flexion will help flatten the path of the head which will improve the athlete's ability to track the target and improve accuracy. Right knee flexion will also assist in producing a more complete weight transfer, allowing the back foot to become unweighted by release.

High school athletes showed greater shoulder abduction of the left arm during force production than the university athletes (Table 4.3). In many sports that require trunk rotation, such as tennis and baseball pitching, the free arm is actively driven down and back in order to assist in force production and increase trunk rotation velocity. The increased left shoulder abduction angles observed in high school athletes require greater strength in order to maintain similar trunk rotation velocities due to the increased moment of inertia. Because university athletes are muscularly more developed, it was expected that they would display greater shoulder abduction. The lower shoulder abduction position in the university group reduced moment of inertia and should allow greater trunk rotation velocities. This difference could suggest that more mature athletes put more emphasis on free arm drive as a source of force production than younger athletes.

Release

The majority of differences between high school and university quarterbacks were seen during release. Five of 11 variables were found to be significantly different between the two groups. The variables that were significantly different included: back foot unweighted, throw time, forward trunk lean, right knee flexion and right elbow flexion.

Since the frequency of having the back foot unweighted was not a continuous variable, a *t*-test could not be performed. A Chi-square test was conducted instead and it determined that the frequency of having the back foot unweighted at release in university athletes was significantly greater than in the high school athletes (Figure 4.8). This position suggests full weight transfer by the university quarterbacks which allowed them to maximize forward linear velocity with an aggressive drive of the back leg. This helped increase pass velocity, but pass accuracy can also benefit from this position. Failing to transfer all of the athlete's weight over the left foot can prevent the athlete from rotating over the left foot and bringing the shoulder girdle to a level position. A tilted shoulder girdle can result in an unwanted increase in release angle and cause passes to be thrown high relative to their target.

Throw time was measured from touchdown of the left foot until release of the football. The *t*-test revealed a significantly shorten throw time in the university group (Figure 4.4). A reduced throw time is not always beneficial in terms of force production, but does increase the efficiency of the pass. Reduced throw time in university athletes may be related to the reduced range of motion in external shoulder rotation during backswing and could detract the athlete from completing pelvic and trunk rotation at the time of release. This rushed throwing motion will reduce time and range of motion for force production and limit the velocity of the pass. Joint movements measured in this study, such as elbow extension and internal shoulder rotation velocities were not found to be significantly different. Therefore, university athletes did not achieve reduced throw times by increasing the speed of their movements. University athletes appear to sacrifice time in the force production phase for a quick release which allows the athlete to hold on to the ball longer while finding his receiver as well it allows the defender less time to react to the throw. Since university athletes are more physically mature, they are able to sacrifice time in force production and still throw the ball with similar velocity as the high school quarterbacks.

At release the quarterback remains more upright than in other throwing sports due to the defenders in front of him trying to deflect the pass. The high school group had significantly greater forward trunk flexion at release than the university group (Figure 4.4). High school quarterbacks appeared to increase their forward trunk flexion in an effort to transfer their weight over the front foot. This is unsuccessful as the back foot is often still weight bearing at release in high school athletes. Some forward trunk lean is acceptable in order to assist in weight transfer but the high school group will have the release height of their passes reduced as a result. This increases the possibility of having passes deflected by defenders, resulting in incomplete and possibly intercepted passes.

Right knee flexion was also significantly different between high school and university groups and this could be related to the back foot being unweighted at release and the mechanism used during push off of the back leg. The university athletes had significantly greater right knee flexion during force production and release. Maintaining knee flexion at release will allow the back foot to lose contact with the ground prior to release as the right hip extends and the left internal and right external obliques contract to rotate the hips to face the target. Less knee flexion suggests less hip extension as the mechanism of force production for the push off. Maintaining knee flexion also helps to keep the path of the athlete's head level during the step to improve tracking of the target. This will also contribute to pass accuracy.

Once the trunk rotates to face the target, internal rotation of the right shoulder commences and is accompanied by right elbow extension. At release the university group remained in a position of significantly greater elbow flexion. This is beneficial to the high school group because a more extended elbow combined with lateral trunk lean away from the throwing arm allows the players to increase the release height of the ball. Increased release height will prevent the ball from being deflected by defenders as well it allows the ball more time in the air which will increase throw distance. Pass velocity is also increased with reduction in elbow flexion at release. Less elbow flexion increases the distance of the ball from the shoulder and creates a larger arc for the ball to travel through. This increased arc of the ball is transferred into increased linear velocity at release. Elbow flexion angles during the backswing and elbow extension velocities were not significantly different between groups. This suggests that the difference in elbow flexion angle at release is a result of the reduced throw time in university athletes. The university quarterbacks rush their throwing motion and allow less time to go through the range of motion necessary to reduce elbow flexion sufficiently by release. As a result, release height is decreased and pass velocity is reduced due to the smaller arc traveled by the ball during force production. However, slight elbow flexion is required to reduce the risk of injury to the biceps brachii tendon. The elbow should remain flexed close to 36 degrees to protect from injury (Fleisig et al., 1996).

Quarterback Throwing Test Score

Overall, the two groups were shown to have several significant differences in the kinematic variables which were measured during the quarterback pass. The two groups were not shown to be significantly different in their quarterback throwing test score, however, the university group had an average test score of 496 points compared to the high school group with a score of 464 points. One interesting finding from the study was that the high school athletes tended to miss the target low more often than the university group. This was consistent throughout the testing and not localized to the longer throws. Since this difference occurred over throws of all distances it should not be attributed to lack of strength. The difference may be explained by increased throw time in high school quarterbacks. Holding onto the ball too long can result in a lower trajectory and underthrown passes. Also, the high school group lacked the ability to successfully transfer weight onto the front foot. This can lead to an increased angle of release if the shoulders are unable to get level by release, but this could also reduce the linear velocity of the athlete at release which is transferred onto the ball.

The quarterback throwing test examined athletes' throwing velocity, accuracy and distance but was unable to find a significant difference between groups. This could be a result of small sample size and selection because there was a wide range of skill level in the high school group compared to the university group. The lack of significant difference could also be a result of throwing test scoring. Points for velocity and accuracy were evenly distributed but points for velocity were easier to achieve. This allowed for high school athletes to score higher since they scored a higher portion of their points from pass velocity scoring. Scoring for the quarterback throwing test needs to be adjusted to make points for accuracy and velocity equally difficult to attain.

Relationships with Quarterback Throwing Test Score

Correlation analyses were conducted on all the measured kinematic variables to determine which variables were significantly correlated to the quarterback throwing test score. This statistical test allowed the researcher to answer the secondary purpose of the study by determining which variables were key contributors to throw performance for the two groups separately.

High School Correlation Analysis

The results of the correlation analyses determined six of the variables to be significantly related to the athletes' throwing test score with a $p \leq 0.05$ or lower. Step length, percent standing height, lateral trunk lean during critical instant (CI), ball velocity were all positively correlated to the athletes' throwing test scores. Right knee flexion during force production (FP) and throw time were both negatively correlated to the athletes' throwing test scores.

Percent standing height is the relative measure of step length and both are expected to have similar relationships with throwing test scores. As mentioned previously, ball velocity was expected to have a strong relationship with throwing test performance since it accounted for 450 out of a potential 1000 points in the throwing test. Interestingly, this relationship was not evident in the university group suggesting that the university quarterbacks did not depend on the throwing test points based on pass velocity as much since they have a larger portion of their points awarded for pass accuracy.

Increased throw time could cause the athletes to pull down on the ball and cause a reduced angle of release. This could result in low passes and have a negative effect on throwing test score. Lateral trunk flexion was found to be positively correlated to throwing test score, and this could be due to its effect on release height. Increasing release height by leaning laterally away from the throwing arm could help reduce the negative effects of increased throw time.

University Correlation Analyses

The results from the university correlation analyses identified only two variables which were significantly correlated to the athletes' throwing test score. Throw time and back foot unweighted were the only two variables significantly correlated with throwing test score and both had positive relationships.

While high school athletes showed a negative relationship between throw time and throwing test score, university athletes produced a positive correlation between throw time and throwing test score. University athletes appear to put greater emphasis on decreasing throw time in order to improve efficiency. This faster throw results in reduced range of motion and limited force production. A rushed passing motion also does not give the athlete the opportunity to stop pelvic and trunk rotation during release which can result in reduced pass accuracy.

Stepwise Multiple Regression Analysis

A forward multiple stepwise regression analysis was conducted in order to determine which variables were the best significant predictors of throwing test score. Forward multiple stepwise regression equations allowed the researcher to answer the secondary purpose of the study which was to determine the most important body movements and body positions to improve pass performance and maximize quarterback throwing test score. Separate regression equations were determined for both the high school group and the university group.

High School Regression Analysis

The regression equation to predict the high school athletes' throwing test score included two variables that explained 91.1% of the throwing test score variance. These variables included left knee flexion during force production and ball velocity (km/hr). Due to the large portion of points scored from ball velocity the regression equation is relatively successful at predicting throwing test performance in high school quarterbacks.

University Regression Analysis

The regression equation to predict the university athletes' throwing test score included just one variable and explained 36.8% of the variance in throwing test score. The variable found to be the main predictor was throw time. Since there was only a single variable selected for the regression equation in university athletes, the ability to successfully predict throwing test score is limited.

Conclusions

Based on the findings of this study, the following conclusions appear to be justified:

1. University athletes had more muscular development than high school players but this did not translate into increased pass velocity or better quarterback throwing

test scores. Ball velocity and throwing test scores were not significantly different between the high school and university quarterbacks.

2. High school quarterbacks utilized a significantly greater range of motion in external shoulder rotation at peak backswing.
3. University athletes achieved full weight transfer to the front foot with the back foot losing contact with the ground prior to release significantly more frequently.
4. University athletes had a significantly shorter throw time than high school quarterbacks which limited their time and range of motion to generate force. Reduced throw time also limited the athletes' ability to stop pelvic and shoulder rotation and stabilize the upper body prior to release.
5. High school quarterbacks reached greater elbow extension at the point of release which increased ball velocity by increasing the angular velocity of the lower arm during force production. The university group had a faster throw time and similar elbow extension velocity which prevented them from reaching a similar position.
6. High school athletes had greater forward trunk flexion at release to assist in weight transfer but this had a negative effect on release height.
7. Although not significantly different between groups, the regression analysis suggested that high school quarterbacks need to focus on maintaining left knee flexion. This would allow the shoulder girdle to become level to reduce an unwanted increase in release angle and allow better weight transfer.

Recommendations

The following recommendations are suggested for future studies conducted on the quarterback pass in high school and university athletes:

1. Future studies should have an overhead camera in order to measure pelvic and shoulder rotation timing and values. This view would also assist in measurement of forearm pronation and shoulder rotation.
2. An improved protocol for scoring of the quarterback throwing test should be developed. Although point distribution for accuracy and velocity was even, ball velocity contributed more to test scores. It was much more difficult to score points for accuracy since the pass had to hit the target while every pass scored velocity points regardless of the outcome of the pass.
3. A wider range of skill levels of athletes at the high school level is needed. Some of the teams filmed only supplied their best quarterback, therefore the sample of high school athletes may not have been a fair representation of the population.
4. Future studies need to include more subjects to ensure significant results and better generalization to a wider range of subjects.
5. There is a need for more studies examining potential differences between professional athletes in order to determine if there are differences between university and professional athletes.

Coaching Recommendations

The quarterback pass, in both high school and university football, plays an important role in the success of a football team. During athlete development it is important that coaches and athletes understand the effects of specific technique flaws and how to improve these technique errors before they become habit and more difficult to correct. As a result, some coaching recommendations have been made based on the significant findings of this study:

1. University athletes need to allow themselves slightly more time to execute the pass to increase range of motion in force production and allow all proximal segments to come to rest prior to release.
2. When the quarterback is forced to rush the throwing motion he needs to accelerate elbow extension and trunk rotation to allow both to go through sufficient range of motion. Trunk rotation must be fast enough to come to a stop facing the target before the ball is released to improve target tracking.
3. High school athletes need to emphasize hip extension during push off of the back leg and full transfer of weight onto the front leg prior to release. The back foot should be off the ground when the ball is released.
4. High school quarterbacks need to reduce throw time to improve pass trajectory and release height by releasing the ball before they begin to pull down on the ball.
5. High school quarterbacks should work on maximizing release height by increasing lateral lean during release and trying to reduce forward trunk flexion. Forward trunk flexion is used in high school athletes to assist in weight transfer and creates a lower release height which makes passes more susceptible to deflection.
6. High school athletes should focus on maintaining knee flexion in both right and left knees in order to flatten the path of the head. This allows the target to remain

stationary and improves pass accuracy. Left knee flexion also allows the shoulder girdle to reach a level position and prevents an unwanted increase in release angle.

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Appendix A

Ethics Approval

UNIVERSITY OF MANITOBA | OFFICE OF RESEARCH SERVICES
Office of the Vice-President (Research)

CTC Building
208 - 194 Dafoe Road
Winnipeg, MB R3T 2N2
Fax (204) 269-7173
www.umanitoba.ca/research

APPROVAL FOR SERVICES

23 January 2008

TO: **Marion Alexander**
Faculty of Physical Education

FROM: **Stan Straw, Chair**
Education/Nursing Research Ethics Board (ENREB)

Re: **Approval for Services to Elite Canadian and Manitoba Athletes**

Film Analysis of the Skills of Elite Canadian and Manitoba Athletes has been approved for 2008.

Appendix B

Informed Consent Forms

Informed Consent Form

Research Project Title: A Biomechanical Analysis of the Football Quarterback Pass and Comparison between University and High School Athletes.
Approach: How quarterback throwing technique differs between groups.
Researcher(s): Adam Toffan B.E.S.S. and Advisor: Marion J.L. Alexander, professor, Faculty of Physical Education and Recreation Studies

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

Outline of the Study:

The purpose of this study is to examine the quarterback throwing techniques of members of Fort Garry Lions Football, in order to determine the key movements of throwing technique and assist coaches in improving the technique of throwing a football. You are either currently a member of this team, or are considered to be a prospect for membership in this elite program.

Methodology:

You will be filmed, on one occasion, while practicing at Pan Am Stadium using filming equipment from the Biomechanics Laboratory in the Faculty of Physical Education. All practices are administered by the coach and the investigator, who will instruct you regarding the skills to perform. Prior to filming you, the filming procedures will be explained. You will be asked to perform the skills as you normally would in a competitive situation, and your techniques will be filmed. You must provide informed consent for the study prior to filming. All filming procedures will be organized and administered by the graduate student, Adam Toffan, who will be assisted by the principal investigator, Dr. Marion Alexander and other qualified graduate students.

Video cameras will be used to film the athletes. The investigator will instruct you regarding which skills are to be performed while the cameras are filming. The cameras will continue to film you until all of the skills of interest have been performed

When filming is completed, the videos will be analyzed by the principal investigator and the graduate students working on the project. The types and ranges of motion in each of the skills, as well as selected linear and angular velocities in each of the skills will be described. An overall evaluation of the technique of each skill for each athlete will be provided to the coaches. Photos can be made from the collected video and do play a useful role in illustrating key features of throwing technique for instructional materials and papers. The technique descriptions developed from this analysis and pictures developed from the video may eventually be published in a thesis titled "A biomechanical analysis of the football quarterback pass and comparison between university and high school athletes".

Risk:

There is no additional risk involved in this study, as you will perform the skills as you would normally perform them in a practice situation. The cameras will be out of the way, and will not interfere in any way with your performance of the skills.

Confidentiality:

The film will be viewed only by the researchers involved in the study, the coaches, and by the athletes in the study. The amount of data available to the athletes will be determined by the coaches. The data derived from the film will be available to the coaches and athletes in order to help to improve performance. The video films and all of the research data will be kept in the Biomechanics laboratory. It is possible that the technique analysis data will be published in a technical journal, however the identity of all subjects in the study will be kept confidential. The photos made from the video film may be used to illustrate the thesis or technical papers prepared from the data.

Signature:

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and/or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

<u>Principal Researcher</u>: Marion J.L. Alexander, Professor, Faculty of Physical Education and Recreation Studies, Ph 474 8642

This research has been approved by the Education/Nursing Research Ethics Board. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Secretariat at 474-7122.

______________________	______________________	________
Participant's name (print)	Signature	Date
______________________	______________________	________
Parent/Guardian (if under 18 years of age)	Signature	Date
______________________	______________________	________
Researcher and/or Delegate	Signature	Date

Dear Athlete:

It is our practice when preparing work for external publications or on the internet to seek your permission before including your photo. Photos can be made from the original videos and these photos are useful to illustrate key features of starting technique for instructional materials and papers. If you would prefer to have you identity concealed in the photo please note that here. Identity would be concealed by blacking out the face on the photo to ensure confidentiality is maintained. Your name will not be published on the internet or in the written document itself. In order to include your photo, we must have your signed permission.

Sincerely,

Adam Toffan
Graduate Student
University of Manitoba

For additional information, please contact:

Adam Toffan
University of Manitoba
Phone: (204) 474-6875
atoffan@gmail.com

SIGN AND RETURN TO PHOTOGRAPHER

Adam Toffan and the University of Manitoba have my permission to publish my photo for an external publication or on the internet in a document describing the start.

Full Name ________________________________

Signature ________________________________ Date ________________________

Daytime Phone ______________________ Evening Phone _______________________

Appendix C

Pilot Study

APPENDIX C

PILOT STUDY

INTRODUCTION

The primary purpose of this pilot study was to establish a quarterback throwing test that can be used to compare football quarterbacks. A secondary purpose of the study was to identify any key difference in kinematic variables affecting pass velocity and accuracy between two players of different ages and skill levels. The pilot study will also serve to establish appropriate filming techniques for future studies.

METHODS

Subjects:

Two male subjects ranging from 18 to 24 years old participated in this study. Both of the subjects had formal football training and played organized football at the university level. Filming took place during the competitive season and the athletes were in peak condition for the study. All subjects completed informed consent forms (see Appendix B) and all video was captured and analyzed using Dartfish 4.5 Software.

Quarterback Test:

Both athletes participating in this study completed informed consent forms. Information regarding each participant's age and height was also retrieved from the team's testing measurements and recorded. Each participant was instructed about the protocol prior to the test; however no instruction regarding throwing technique was given to avoid influencing the performance of the athletes.

Each athlete did an individualized warm up including passing the football to each other before being given practice throws for the study. Each athlete took 2 consecutive practice throws for 9, 18, and 27 meters for a total of 6 official warm up throws in order to familiarize themselves with the requirements of the test. In football all distances are expressed in yards. For the purpose of this study all distances have been converted to metric. The same throwing order was used for all three targets in order to keep rest periods consistent. Results were given for each of the throws during the warm up.

For the quarterback throwing test each athlete attempted three passes at each of three different target distances. The athletes took all three of their throws consecutively and went in the same order as the warm up throws for each of the distances to allow consistent rest between throws. The throwing area was marked on the ground and the athletes were instructed to have their step behind the marker. A minimum of 2 minutes rest was given between sets of throws as the targets were moved to the next distance.

The target was fastened to plywood backing on an adjustable stand. The adjustable legs allowed the target to be set perfectly vertical despite changing location. The target was checked prior to each set of throws to ensure it was vertical before the athlete attempted his throws. The centre of the target was 1.37m above the ground and approximates the centre of the torso of a 1.83m tall receiver. The target was 1.07m in diameter with the upper edge approximately head height and the lower edge estimating hip height. The targets size and height was designed to imitate an acceptable range of a pass. A pass that is outside of this range was determined to be poorly thrown and has an increased possibility of being unsuccessful.

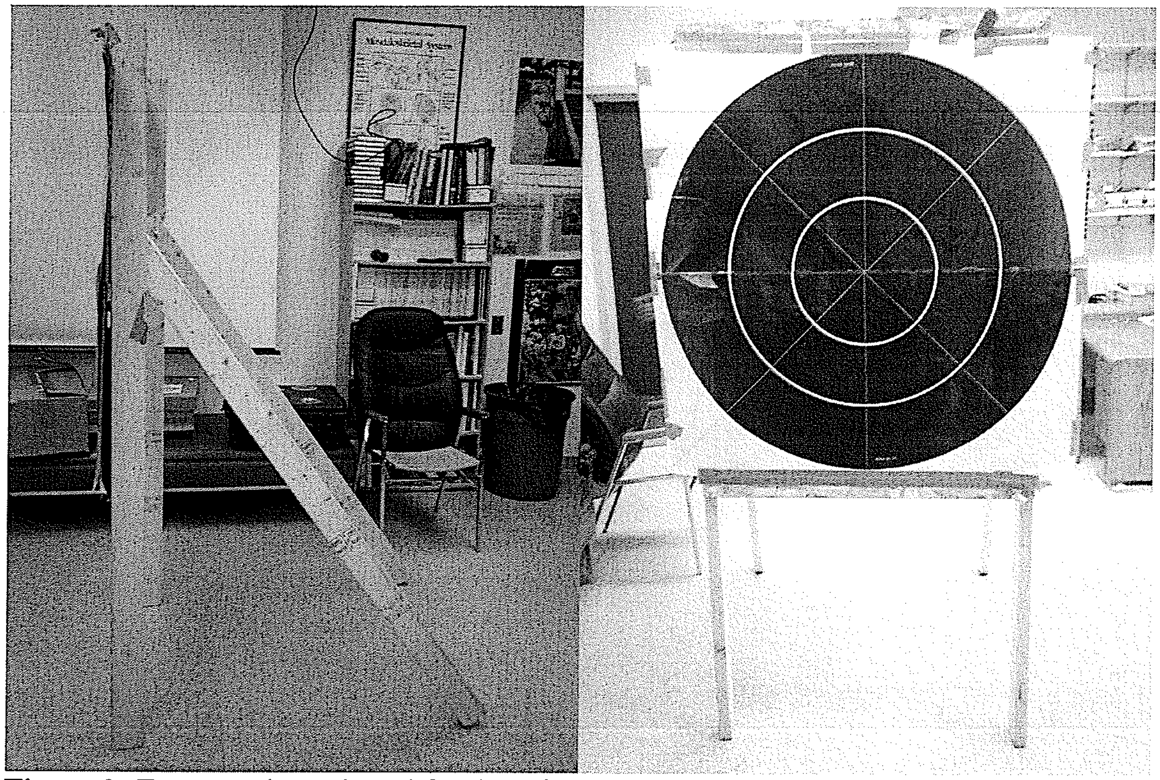

Figure 2: Target and stand used for throwing test.

Each target had three concentric circles for scoring with the innermost circle being worth more points, and the furthest circle being worth the fewest points. The bulls eye of each target was worth 50 points while the other zones from inside to outside were worth 30 and 10 points. For example, a bull's eye throw at the thirty yard target would be given 50 points. Each athlete took three consecutive throws at each of the targets with a minimum of 2 minutes rest between sets of throws. Results for each throw at each target were recorded and entered into an Excel spreadsheet for scoring.

Points were allotted for pass velocity with passes under 61km/hr awarded 10 points, 20 points for passes between 61 and 65km/hour, 30 points between 66 and 70km/hr, and 40 points for a velocity between 71 and 75km/hr. The maximum of 50 points was awarded for a pass velocity greater than 76km/hr. Feedback on pass velocity was not given immediately following each throw since the video software is required to calculate pass velocity. Pass velocity was scored for all throws to avoid the quarterback having one hard throw and focusing on accuracy for the remainder of the test. A perfect score of 900 points is achievable in this test and results were also given as a percentage of the perfect score (i.e. 450 points = 50%).

Filming Technique:

Filming took place on September 25, 2007 at the University of Manitoba Pan Am Stadium. Two Cannon GL2 Digital Camcorders were used to film the throw. One camera was 5 meters to the right of the designated throwing line (left of the throwing line from a frontal view) to capture the throwing motion and release from the sagittal plane. This view was used primarily to measure release velocity and various joint angles. The second GL2 camera was placed 5 meters in front of the throwing area and captured the throw and release from an anterior view to measure various joint angles throughout the throwing motion. Both cameras were secured to tripods to prevent any unwanted camera movement. Following camera set up, the throwing area without any participants in view was filmed by each camera with a meter stick filmed to be used as a conversion factor for velocity measurement. This will allow a reference measurement to be used with the software to measure distances during video analysis.

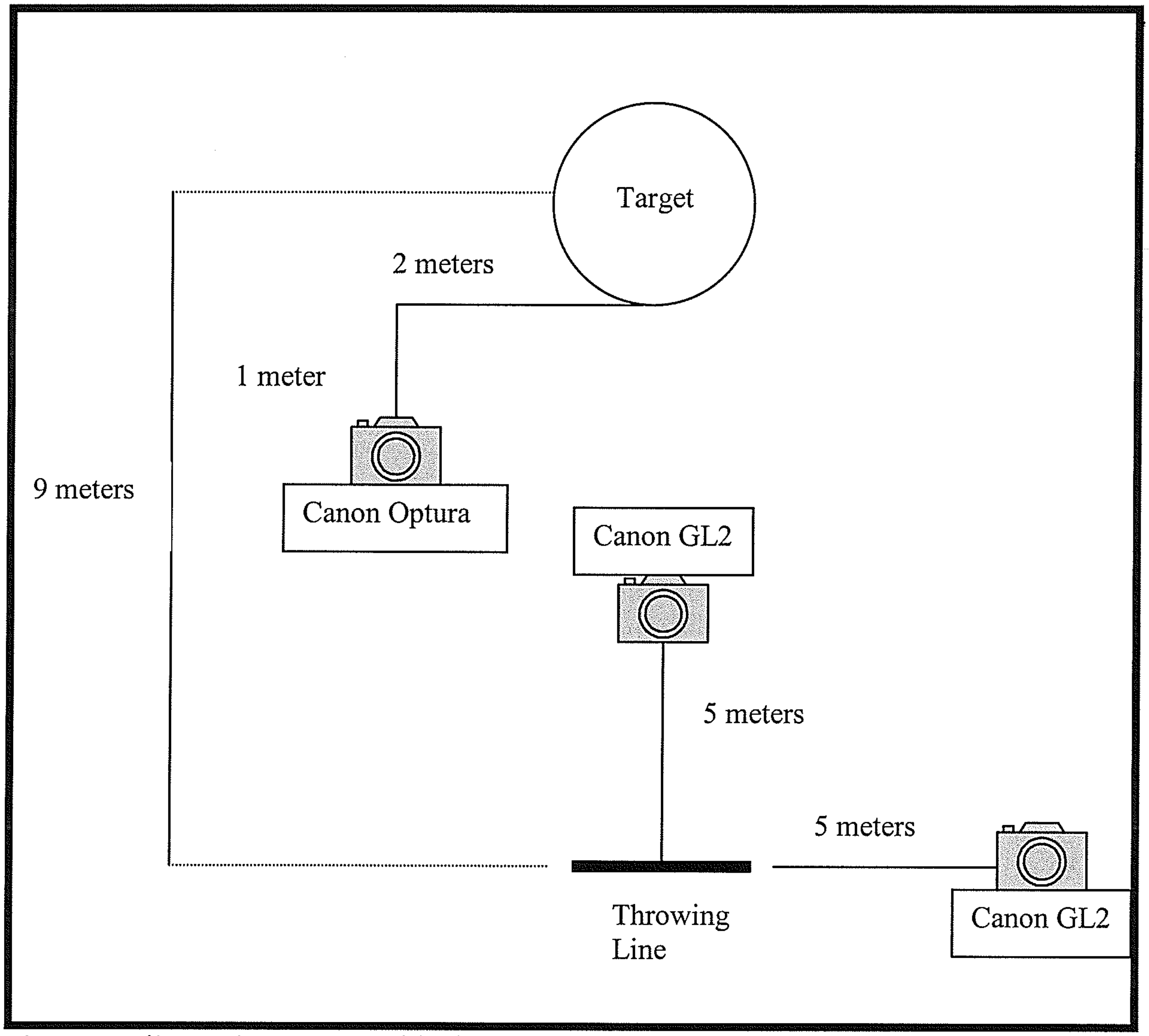

Figure 1: Pilot study camera positioning

At each distance the target was recorded with a Cannon Optura Camcorder camera capturing an oblique view from the left side. The camera was placed 2 meters to the left and 1 meter anterior to the target. The target camera was used to capture ball contact with the target to determine where the ball contacted and how many points would be awarded for each throw.

Digital Video Analysis:

All video was imported into a Toshiba Satellite A100 laptop using the 'In the Action' feature of the Dartfish 4.5 Software. The best throw at each distance was determined as the throw with the highest total score, calculated by adding the velocity and accuracy points for each pass. It is expected that scores will decrease as the throw difficulty increases. The highest scoring throws at each distance for each athlete were used for analysis of the throwing technique. These throws were used to determine if technique varied between athletes of different skill levels. During analysis all views of each throw were synchronized using timeline and split screen mode. Clips were put into a storyboard in Analyzer mode.

Dartfish tools used in the analysis include angle measuring tool, distance tool, and line drawing tool. The angle measuring tool was used to measure lateral shoulder rotation of the throwing arm, front knee flexion, shoulder abduction of the throwing arm, lateral trunk lean, and elbow flexion. Joint angles were measured by drawing a line from the centre of the joint to the centre of adjacent joints. The deviation from anatomical position was measured using the 180-degree system. Stride length and pass velocity was measured using the distance and tracking tools. A conversion factor was used to allow Dartfish to convert the distance traveled by the football. The front end of the football was tracked, and velocity was calculated. Quantitative data was collected by measuring the following variables:

Phase of Skill	Variable
Backswing	Right Shoulder Abduction (deg) Right Knee Flexion (deg) Right Elbow Flexion (deg) Left Knee Flexion (deg) Maximum Lateral Shoulder Rotation (deg/sec)
Force Production	Internal Shoulder Rotation Velocity (deg/sec) Right Shoulder Abduction @ MER (deg) Step Length (cm) Percent Standing Height (%) Right Knee Flexion (deg) Left Knee Flexion (deg) Elbow Extension Velocity (deg) Left Shoulder Abduction (deg)
Critical Instant	Right Elbow Flexion (deg) Right Knee Flexion (deg) Left Knee Flexion (deg) Forward Trunk Lean (deg) Ball Velocity (m/s) Ball Velocity (km/hr) Lateral Trunk Lean (deg) Right Shoulder Abduction (deg) Throw Time (sec) Relative Release Height (percent)
Follow-through	Minimum Elbow Flexion (deg) Shoulder Adduction (deg) Shoulder Internal Rotation (deg) Forearm Pronation (deg) Shoulder Internal Rotation Velocity (deg/sec)

RESULTS

Quarterback Test Results:

The subjects in the study (n=2) had competitive football history, and both were familiar with the skill. Subject 2 would be grouped in the high school age group well subject 2 would be in the university age group. Each athlete followed the same testing protocol. Throws hitting the outer ring of the target were awarded 10 points, 30 points for the middle ring and increasing to 50 points for the inner ring. At the 9 meter target, both athletes successfully hit the target on all 3 throws with points ranging from 20 to 100 points on an individual throw. Subject 2 failed to hit the target at the 18 meter distance while subject 1 successfully completed all three of his attempts. Accuracy declined for both athletes at the 27meter target. Subject 1 remained successful on all three throws but was less accurate than the attempts at the closer target. Subject 2 managed only one successful throw at the 27 meter target which was awarded 10 points for hitting the outer ring of the target (Table 1.1).

Table 1.1: Scoring summary for the quarterback throwing test.

Distance-Attempt	Accuracy		Velocity		Total	
	Subject 1	Subject 2	Subject 1	Subject 2	Subject 1	Subject 2
9m - 1	30	30	50	10	80	40
9m - 2	30	10	50	10	80	20
9m - 3	50	10	50	20	100	30
18m - 1	30	0	40	30	70	30
18m - 2	10	0	50	20	60	20
18m - 3	30	0	50	10	80	10
27m - 1	30	0	50	10	80	10
27m - 2	10	10	50	20	60	30
27m - 3	10	0	50	20	60	20
Total	230	60	440	150	670	210
Percent					74.44	23.33

Throwing velocities from all nine attempts were measured for velocity. The velocity of each throw was analyzed to prevent the athletes from throwing harder on one particular throw while focusing on accuracy for the remaining throws. The average throwing velocity for the athletes was 70.2km/hr (19.5m/s) with both athletes throwing above 61km/hr (16.94m/s) and qualifying for increased velocity points. Table 1.1 summarizes the scoring among athletes. Each throws total score was determined by adding the velocity and accuracy points awarded for that throw. The total scoring was out of a possible 900 points (450 for velocity; 450 for accuracy). Scores were also given as a percentage of the maximum possible points.

Phase Comparison:

The kinematic variables of interest were measure for both athletes on the highest scoring throw at each distance. The variables for each throw were averaged to give a mean throughout the test. The variables with substantial differences are summarized below.

Backswing:

The backswing is the phase in which the athlete transfers his weight onto his right foot and raises the ball by abducting and laterally rotating at the shoulder. The backswing puts the athlete in a position to apply maximal force to the ball before release. Body positioning was analyzed using video analysis beginning with the backswing of the throws to allow for comparison between athletes. During the backswing, both athletes approached 90 degrees of right shoulder abduction with subjects 1 and 2 averaging 93.93 and 79.6 degrees respectively (Table 1.2). Right shoulder abduction during the backswing elevates the shoulder girdle and increases trunk rotation to assist in segmented trunk rotation to stretch the abdominal muscles. Both athletes maintained moderate knee flexion in both knees during the backswing to allow the athlete to push with the right leg to transfer his weight onto his front foot during force production. The right knee averaged 31.2 degrees of flexion between athletes. At peak backswing the shoulder reaches maximal external shoulder rotation. Despite throwing significantly faster, subject 1 had less range of motion in external shoulder rotation. Subject 1 averaged 148.07 degrees compared to 177.73 degrees in subject 2.

Table 1.2: Means of kinematic values for both subjects.

Phase	Variable	Subject 1	Subject 2	Mean
Backswing	Right Shoulder Abduction (deg)	93.93	79.60	86.77
	Right Knee Flexion (deg)	32.77	29.63	31.20
	Right Elbow Flexion (deg)	93.83	113.07	103.45
	Left Knee Flexion (deg)	46.30	43.13	44.72
	Maximum External Shoulder Rotation (deg)	148.07	177.73	162.90
Force Production	Right Shoulder Abduction @ MER (deg)	108.20	94.73	101.47
	Left Shoulder Abduction (deg)	44.63	33.70	39.17
	Internal Shoulder Rotation Velocity (deg/sec)	1822.22	1667.78	1745.00
	Elbow Extension Velocity (deg/sec)	1713.13	393.01	1053.07
	Left Knee Flexion (deg)	42.07	40.17	41.12
	Right Knee Flexion (deg)	28.07	28.50	28.29
	Percent Standing Height	45.14	41.22	43.18
	Step Length (cm)	86.67	76.67	81.67
Release	Right Shoulder Abduction (deg)	105.30	78.47	91.89
	Lateral Trunk Lean (deg)	16.57	11.13	13.85
	Relative Release Height (percent)	107.64	103.58	105.61
	Forward Trunk Flexion (deg)	27.17	19.93	23.55
	Right Elbow Flexion (deg)	31.83	52.30	42.065
	Ball Velocity (m/s)	22.08	16.92	19.50
	Ball Velocity (km/hr)	79.50	60.90	70.20
	Left Knee Flexion (deg)	29.60	33.77	31.685
	Right Knee Flexion (deg)	48.13	42.57	45.35
	Throw Time (sec)	0.22	0.26	0.24
Follow-through	Minimum Elbow Flexion (deg)	38.60	35.80	37.20
	Shoulder Adduction (deg)	38.47	36.27	37.37
	Shoulder Internal Rotation Velocity (deg/sec)	2444.45	1721.21	2082.83
	Shoulder Internal Rotation (deg)	80.67	65.87	73.27
	Forearm Pronation (deg)	35.23	15.17	25.20

Force Production:

Force production begins from peak backswing and ends at release of the ball. During this time the quarterback is applying as much force as possible to the ball in order to increase the velocity of the throw. Shoulder abduction increased by approximately 15 degrees from backswing to maximal external rotation of the shoulder. Subject 1 maintained greater shoulder abduction through the throw averaging 108.2 degrees during force production compared to 94.73 degrees in subject 2. The left shoulder also remains abducted during force production as the athlete extends the left shoulder to contribute to force production and increase the rate of trunk rotation. Subject 1 averaged 10.93 degrees more abduction in the left shoulder during force production (Table 1.2).

During force production the elbow extends as the right shoulder begins to rapidly internally rotate. Subject 1 averaged 1822.22 degrees/second of internal shoulder rotation velocity while subject 2 averaged 1667.78 degrees/second and showed greater variability (Appendix). The greatest internal shoulder rotation velocity achieved by subject 2 corresponded with his fastest of his measured throws at the time of release, but the same was not the case with subject 1 whose fastest throw was 209.09 degrees/second slower than the next fastest throw (Appendix). The rate of elbow extension between subjects showed great variation, but remained consistent within each athlete's throws. Subject 1 extended the right elbow at an average velocity of 1713.13 degrees/second while subject 2 had just 393.01 degrees/second (Table 1.2).

During weight transfer both athletes remained flexed at both knees and the position was very similar for both athletes. The left knee remained flexed with an average of 41.12 degrees. The right knee flexion in both athletes was significantly lower.

Release:

At critical instant the abduction of the throwing shoulder decreases from force production as the athlete increases lateral trunk flexion at release. The combination of trunk lateral flexion and shoulder abduction determine the release height of the ball. Both athletes remained consistent in right shoulder abduction but showed slight increases as throw distance increased (Appendix). Subject 1 achieved much greater shoulder abduction at release (105.3) degrees while subject 2 only maintained 78.47 degrees of shoulder abduction. Subject 1 also increased lateral trunk flexion slightly as the target distance increased while subject 2 showed very little variation as the throw distance increased (Appendix). Subject 1 averaged 16.57 degrees of lateral trunk flexion from the vertical compared to 11.13 degrees by subject 2 (Table 1.2). Having less lateral trunk flexion and right shoulder abduction will result in a lower release height relative to the athlete's standing height. Release height relative to standing height was measured using an estimated standing height for subject 2 since his standing height was not available. Standing height for subject 2 was measured using the Dartfish measuring tool based on the conversion factor. Subject 1 was 192 cm tall while subject 2 stood 186cm tall. Subject 1 had greater relative release height through all of his measured throws. Subject 1 had relative release height range from 103.65 percent to 114.58 percent while subject 2 had between 101.61 percent and 105.91 percent of standing height. The trunk also flexes forward from the vertical to assist in weight transfer. Both athletes had reasonable forward trunk flexion with subject 1 averaging 27.17 degrees and subject 2 averaging 19.93 degrees (Table 1.2). Previous studies have found approximately 25 degrees of forward trunk flexion in collegiate quarterbacks (Fleisig et al., 1996).

The elbow is extending up to release but is not fully extended at release. Close to full extension is recommended for greater pass velocity by increasing the radius of the ball from the axis of rotation at the hip and spine. Subject 2 kept excessive right elbow flexion through release, averaging 52.3 degrees. Subject 1 had 31.83 degrees of elbow flexion at release, increasing the radius from the spine and front hip axes.

At release both athletes showed significant left knee flexion with an average of 31.685 degrees between both athletes. The right knee also remains flexed averaging 45.35 degrees of flexion with subject 1 showing slightly greater flexion than subject 2 (Table 1.2). Throw times were measured from the instant of left foot plant until release with subject 1 averaging a throw time of 0.22s compared to 0.26s in subject 2. Both athletes showed a decrease in throw times for the longer throws, despite showing no significant increase in pass velocity (Appendix).

Follow-through:

The follow-through does not affect the outcome of the pass, but can be a result of the athlete's mechanics during force production and critical instant, and also protects the quarterback from injury. The right shoulder adducts to bring the arm close to the body and protects it from injury. Both athletes had good shoulder adduction during follow-through with an average of 37.37 degrees.

Internal shoulder rotation velocity was measured immediately after release which will be a result of rotation velocity during force production. Both athletes remained consistent and did not increase velocities with throw distance. Subject 1 showed greater shoulder rotation velocity than subject 2 during the follow-through. Subject 1 averaged

2444.45 degrees/second while subject 2 achieved a maximum internal rotation velocity average of 1721.21 degrees/second (Table 1.2). The rate of internal rotation will also affect the range of internal shoulder rotation during follow-through. With his increased internal shoulder rotation velocity, subject 1 also went through a larger range of motion for internal shoulder rotation. Subject one averaged an extra 14.8 degrees of medial rotation during follow-through with 80.67 degrees compared to 65.87 degrees by subject 2.

Pronation and medial shoulder rotation occur simultaneously during follow-through and pronation is thought to contribute to the spiral of the ball by applying a downward force to the side of the ball. Both athletes showed some variation between their throws, with subject 1 varying from 27.6 degrees to 45 degrees of pronation and subject 2 ranging from 10.5 degrees to 20 degrees (Appendix). Despite the range within the individual athlete, subject one had consistently greater pronation throughout the follow-through.

DISCUSSION

The highest scoring throw at each distance was analyzed for each athlete. One of the subjects had his most accurate and highest velocity throw on the same attempt while subject 2 had the most accurate throw separate from the fastest throw. In total each athlete had their three best throws analyzed to ensure that a better overall analysis of each athlete was achieved. Analyzing just one throw increases the possibility of choosing an uncharacteristic throw that does not accurately illustrate his normal throwing technique. Both athletes had their best throw at the 9 meter distance. Subject 1 outscored subject 2 at the 9 meter distance and continued to score more consistently as throw difficulty increased despite having a drop in pass scores.

Backswing:

During the backswing subject 1 was able to achieve greater average right shoulder abduction to elevate the shoulder girdle. Elevating the shoulder girdle makes it easier for the athlete to increase shoulder rotation and segmentation between the trunk and shoulders (Alexander, 1992; Yessis, 1984). The abdominals are put on a stretch, allowing a stretch-reflex to occur to contribute to force production. The shoulder girdle is able to rotate with greater angular velocity which will increase the linear velocity at release. Subject 1 had greater average shoulder abduction during the backswing allowing him to elevate his shoulder girdle and rotate with greater segmentation between the shoulder girdle and trunk (Table 1.2). Greater shoulder abduction also puts the athlete in a better position early in the skill to increase release height. When the quarterback has greater release height he is able to flatten the trajectory of the pass and reduce the ball's time in the air. This leaves the defender less time to react to the pass and attempt to deflect it. Release height also protects the pass from being deflected by the defensive linemen at the line of scrimmage.

The right elbow should flex close to 100 degrees to shorten the moment arm of the ball to the axis through the shoulder (Fleisig et al., 1996; Rash and Shapiro, 1995). This allows for faster rotation of the shoulder girdle during the beginning of force production. Subject 2 had more right elbow flexion to reduce the ball's moment arm from the spine. Subject 1 had decent elbow flexion, but reduced elbow flexion will require more force to accelerate the ball (Table 1.2. Both knees also remain flexed well in both athletes. Slight knee flexion allows the quarterback to keep the weight on the balls of the feet in case he is forced to move. Flexion in both knees during backswing also allows the athlete to transfer his weight onto the front foot during force production as the athlete steps onto the left foot.

Peak backswing of the upper body occurs as the shoulder goes into maximal external rotation. At this point the athlete has already taken a long step and started to transfer weight onto the front foot as the hips and trunk begin to rotate. Maximal external shoulder rotation allows the athlete to stretch the medial rotators of the shoulder and initiate a stretch reflex, and gives the athlete a large range of motion to apply force to the ball (Yessis, 1984). Subject 2 had much greater external shoulder rotation giving him a longer time to apply force to the ball prior to release. Both athletes continued to increase right shoulder abduction through maximal external shoulder rotation, but subject 1 maintains greater abduction, further elevating the shoulder girdle (Table 1.2). The most efficient throws for each athlete typically had lower external shoulder rotation values, potentially allowing more control and accuracy for the pass but a shorter range of motion for medial rotation.

Force Production:

The lower body begins force production before the upper body creating a lag that results in segmented rotation where the distal segments lag behind the proximal segments. A torque is applied to the base segment, such as the hips, and is followed by the forward rotation of the next distal segment. The next distal segment comes forward as its proximal segment reaches its greatest angular velocity (Kreighbaum and Barthels, 1996). The athlete takes a long step onto the front foot, and step length should be slightly greater than have the athlete's standing height (Fleisig et al., 1996). Standing height information was unavailable for subject 2, but subject one stepped 45.14% of his standing height (Table 1.2). A slightly longer step is recommended to allow the athlete to push off with the right foot and transfer his weight to the left foot. The stride should be long, but the athlete should avoid stepping too far. Overstepping will limit the athlete's ability to transfer his weight and also causes the athlete's shoulders to tilt up while facing perpendicular to the target rather than staying level. In this position the front shoulder is higher than the throwing shoulder as the athlete is leaning towards the back foot. If the shoulders tilt up the pass will be overthrown due to an increased trajectory (Berezowitz, 2000; Danischewsky, 2007). The pass can also be overthrown if the quarterback fully extends the left knee to prevent full weight transfer and tilting the front shoulder upwards. The left knee should stay slightly flexed to allow full weight transfer and keep the shoulders level through release (Berezowitz, 2000). Both athletes maintained close to 40 degrees of flexion in the left knee during force production, allowing full weight transfer onto the front foot.

The free arm is also active in force production as the left shoulder extends while partially abducted to apply additional torque as the athlete rotates about the spine and front hip (Ash, 2006; Axman, 1997a). Subject 1 had increased left shoulder abduction through force production allowing a greater torque to be applied due to the increased perpendicular distance the force of the arm is applied from the axis of rotation (Table 1.2). As a result subject 1 is able to increase his angular velocity as his trunk and shoulders rotate to face the target. Greater angular velocity during force production will also result in greater linear velocity of the ball after release.

As the shoulder rotates to face the target, the right elbow extends and the shoulder internally rotates. Internal shoulder rotation continues through the follow-through and was measured just prior to release for the current study. Both subjects showed some variation in regards to internal shoulder rotation velocity, but this was not related to throw velocity or accuracy (Appendix). The highest scoring throw for each athlete did not have exceptionally high or low velocity. Subject 1 showed greater average rotation velocities of 1822.22 degrees/second versus 1667.68 degrees/second in subject 2, which increases the force applied to the ball and increase pass velocity even though the current study did not illustrate that trend (Appendix). Previous studies calculated values of 4950 degrees/second (Fleisig et al., 1996), which were significantly higher than the current study. The discrepancy in results could be due to measurement techniques used. The current study filmed from the sagittal and frontal views but the athlete is continuing to rotate through the throw and may not be square to the camera at release.

The elbow also extends during force production approaching extension at the moment of release. The elbow can have extension velocities around 1760 degrees/second (Fleisig et al., 1996), therefore contributes a significant force to the ball to increase pass velocity. Subject 1 showed variation in elbow extension velocity (Appendix) but still maintained much greater average velocity than subject 2. This allows subject 1 to apply additional force to the ball while increasing the radius from the ball to the spine and front hip axes (Figure 3). A greater radius will increase the linear velocity of the pass after release. Elbow extension also showed a negative trend with pass accuracy. Both subjects had lower accuracy as elbow extension velocity increased. This is likely caused by the increased lateral force applied to the ball as the elbow is pointed to the side during extension (Yessis, 1984). As a result, lower elbow extension velocities corresponded with increased throw performance.

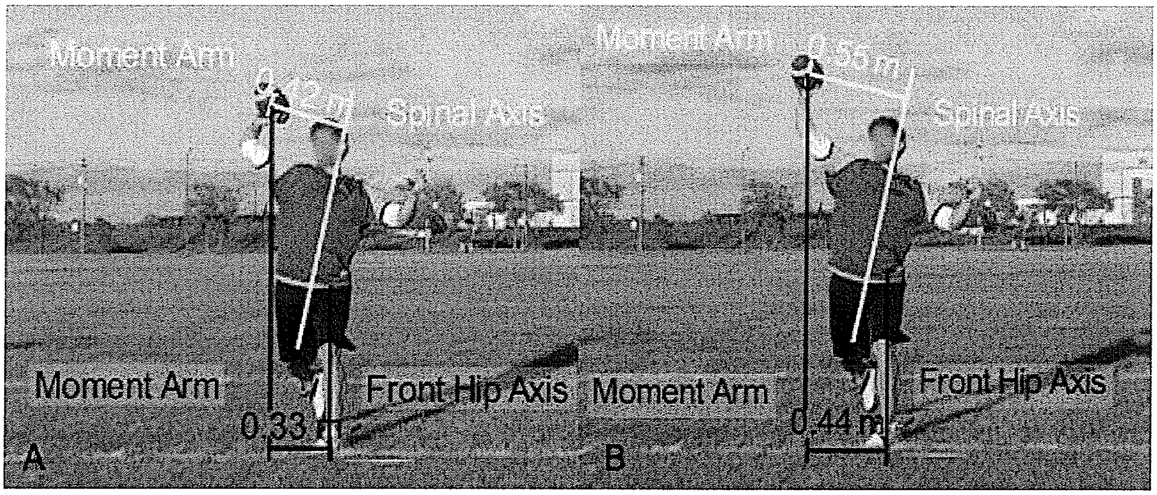

Figure 3: As the elbow extends the ball's distance from the spinal and front hip axis increases.

Release:

A quick release is desired to allow the quarterback more time to scan the field and wait for the play to develop. In the current study throw time was measured from foot contact of the front foot until release of the ball. In both athletes throw times decreased as throw distance increased, but this did not correspond with increased pass velocity. Subject 2 showed greater changes in throw time as throw distance increased ranging from 0.3 seconds to 0.216 seconds while subject 1 ranged from 0.266 seconds to 0.2 seconds. In this test a faster throw time did not necessarily imply a faster throw. This could be due to the timing of the step with the back swing. In longer throws the quarterback may start the cocking of the ball sooner and start rotating the hips and trunk closer to foot contact.

Throw time showed a negative relationship to pass accuracy. Both athletes accuracy decreased as throw time decreased. It is possible that control is lost as the speed of the limbs increases and timing is negatively affected as a result.

Both athletes averaged close to 30 degrees of left knee flexion at release. Some flexion is desired to allow full weight transfer onto the front foot (Fleisig et al., 1996). A flexed front knee also allows the quarterback to keep his shoulders level and avoids tilting the front shoulder up which can lead to high throws (Danischewsky, 2007). Both athletes also showed a slight decrease in knee flexion as throw distance increased. A possible explanation could be to intentional tilting the shoulders and increase the pass trajectory for the longer throw. Both athletes also showed a trend of increased right knee flexion at release (Appendix). More right knee flexion can be a result of full weight transfer. The athlete further flexes the right knee as the back foot becomes completely unweighted and loses contact with the ground.

Weight transfer is also affected by forward trunk flexion. As the athlete releases the ball, he flexes forward at the trunk to further move his line of gravity over the front foot. The highest scoring throws for both athletes had increased forward trunk flexion (Appendix). Trunk flexion allows the athlete to achieve full weight transfer to increase force production as well as prevent overthrown passes by flattening the trajectory of the pass by tilting the shoulders up (McElroy, 2003; Danischewsky, 2007). Excessive trunk flexion should also be avoided because it will limit the hip rotation about the front hip and creates a downward force on the ball that can lead to low passes (Axman, 1997a).

Release height, as previously mentioned is partially determined by lateral trunk flexion and right shoulder abduction. Fleisig et al. (1996) found lateral trunk flexion close to 26 degrees can increase release height and increase the perpendicular distance from the ball to the spine to increase the torque produced. Subject 2 never achieved 26 degrees of lateral flexion, averaging 11.13 degrees. Subject 1 had an average of 16.57 degrees with the highest scoring throw calculated at 13.9 degrees of lateral trunk flexion (Table 1.2). Subject 1 increases his relative release height and moment arm of the ball to increase the torque created. Right shoulder abduction also increases release height and the moment arm created from the ball to the spine. Both athletes were very consistent between throws with subject 1 having consistently greater shoulder abduction to increase the perpendicular distance and release height (Appendix). At least 90 degrees of shoulder abduction should be maintained with very little change from force production to release (Rash and Shapiro, 1985). Subject 1 remained consistent in shoulder abduction through the throw, staying above 90 degrees through release while subject 2 decreased shoulder abduction at release. This lowers release height as well as applies a downward force on the ball that can result in low passes. Subject 2 had lower relative release height due to decreased lateral trunk flexion and shoulder abduction at release. Release height allows a flatter trajectory and will increase accuracy since the path of the ball to the target is more direct (Alexander, 1992; Yessis, 1984). Relative release height did not illustrate a relationship with pass score, but both athletes demonstrated increased relative release height with longer passes (Appendix).

Follow-through:

The right shoulder continues to internally rotate as the forearm pronates after the ball is released. Internal shoulder rotation velocity was measured as an average over the two frames prior to and after release to determine velocity for force production and follow-through. Subject 1 had increased internal shoulder rotation velocity with his most efficient throw (Appendix). This could imply that internal rotation at the moment of release was actually highest in his best throw, even though the average velocity measured just prior to release was not his fastest. Subject 2 did not follow this trend as his most efficient throw had his lowest internal shoulder rotation velocity (Appendix). Subject 2 may have decreased arm speed in order to maintain control since his fastest throw had the greatest rotation velocity but failed to score any accuracy points.

Subject 1 also increased the range of internal shoulder rotation as rotation velocity increased, allowing a larger range of motion for the arm to decelerate. The highest scoring throw for subject 1 possessed greater internal rotation and was likely a result of the increased rotational velocity, although subject 2 did not show this trend for his throws (Appendix). Internal rotation increased with throw distance, but did not correspond with throw score or internal rotation velocity.

Previous studies have found a relationship between shoulder adductor activation and pass velocity (Bartlett et al., 1989). In the current study subject 1 had increased shoulder adduction with higher efficiency throws but the same was not true for subject 2. However the fastest throw by subject 2 did have the greatest shoulder adduction during follow-through (Table 1.2). The range of shoulder adduction during follow-through implies that the latissimus dorsi and pectoralis muscles are primary contributors to force production in the quarterback pass. This was evident in both athletes, however subject 2 was not able to score accuracy points and therefore his total score was decreased for that particular throw.

CONCLUSION

The primary limitation of these results was the size of the sample. A larger sample size would allow for more obvious trends while minimizing the effects of outliers on the results. The subjects had a variety of formal training with subject 2 in had just finished his last year of high school football while Subject 1 has played 2 years as a back up at the university level. A larger and more diverse study would be able to incorporate a larger variety of skill levels among university and high school aged athletes.

The test used in this study appears to be adequate in differentiating between accurate and inaccurate passers. Some limitations to the study that could be controlled for in future studies are strength and flexibility. Both of these factors could affect mechanics as an athlete with greater strength may be able to throw faster without proper mechanics. An athlete with limited flexibility may also make adjustments to his technique to accommodate his flexibility issues. Other confounding variables that should be accounted for in the future include wind, temperature and time of day. Weather conditions such as wind can affect the flight of the ball. Time of day may be useful to determine if the sun may be a factor in the athlete's vision. The scoring system for throwing velocity also appears capable of finding skill differences among quarterbacks. Each athlete was informed that pass velocity was a factor in scoring and were instructed to throw with high velocity to increase their total score. The scoring of the throwing test is evenly weighted between pass accuracy and velocity to encourage the athletes to be proficient in both aspects of the skill in order to perform well in the test. The current study was successful in distinguishing between skill levels and determining primary differences between groups, and can be used in future studies in assessing quarterback skill level.

Appendix

Pilot Study Raw Data

Subject 1

Phase	Variable	9 meter	18 meter	27 meter
Backswing	Right Shoulder Abduction (deg)	91	95.6	95.2
	Right Knee Flexion (deg)	25.7	39.8	32.8
	Right Elbow Flexion (deg)	95.7	94.2	91.6
	Left Knee Flexion (deg)	53.8	45.3	39.8
	Maximum Lateral Shoulder Rotation (deg)	144.4	143.3	156.5
Force Production	Internal Shoulder Rotation Velocity (deg/sec)	1781.82	1693.94	1990.91
	Right Shoulder Abduction @ MER (deg)	107.4	108.9	108.3
	Step Length (cm)	80	88	92
	Percent Standing Height	41.67	45.83	47.92
	Right Knee Flexion (deg)	25.6	31	27.6
	Left Knee Flexion (deg)	45.7	46.5	34
	Elbow Extension Velocity (deg/sec)	1642.42	1984.85	1512.12
	Left Shoulder Abduction (deg)	42.2	46.5	45.2
Critical Instant	Right Elbow Flexion (deg)	34.8	33.1	27.6
	Right Knee Flexion (deg)	49.9	43.3	51.2
	Left Knee Flexion (deg)	36.9	35.3	16.6
	Forward Trunk Lean (deg)	29.2	27.6	24.7
	Ball Velocity (m/s)	22.44	21.44	22.37
	Ball Velocity (km/hr)	80.784	77.184	80.532
	Lateral Trunk Lean (deg)	13.9	18	17.8
	Right Shoulder Abduction (deg)	101.2	106.6	107.3
	Throw Time (sec)	0.266	0.2	0.2
	Relative Release Height (percent)	104.69	103.65	114.58
Follow-through	Minimum Elbow Flexion (deg)	36.2	38.8	40.8
	Shoulder Adduction (deg)	39.5	38	37.9
	Shoulder Medial Rotation (deg)	85	78.8	78.2
	Forearm Pronation (deg)	45	33.1	27.6
	Shoulder Internal Rotation Velocity (deg/sec)	2575.76	2387.88	2369.7

Subject 2

Phase	Variable	9 meter	18 meter	27 meter
Backswing	Right Shoulder Abduction (deg)	79.8	79.3	79.7
	Right Knee Flexion (deg)	26	29.6	33.3
	Right Elbow Flexion (deg)	106.5	113.3	119.4
	Left Knee Flexion (deg)	39.6	48.8	41
	Maximum Lateral Shoulder Rotation (deg)	170.9	174.6	187.7
Force Production	Internal Shoulder Rotation Velocity (deg/sec)	1766.667	2175.758	1060.606
	Right Shoulder Abduction @ MER (deg)	95.8	94.8	93.6
	Step Length (cm)	78	81	71
	Percent Standing Height	41.94	43.55	38.17
	Right Knee Flexion (deg)	25.2	26.1	34.2
	Left Knee Flexion (deg)	40.5	43	37
	Elbow Extension Velocity (deg/sec)	136.364	536.6	506.061
	Left Shoulder Abduction (deg)	35.5	35.9	29.7
Critical Instant	Right Elbow Flexion (deg)	63.7	48.8	44.4
	Right Knee Flexion (deg)	44	38.7	45
	Left Knee Flexion (deg)	31.6	40	29.7
	Forward Trunk Lean (deg)	24.1	22.8	12.9
	Ball Velocity (m/s)	15.22	18.46	17.07
	Ball Velocity (km/hr)	54.792	66.456	61.452
	Lateral Trunk Lean (deg)	10.2	12.6	10.6
	Right Shoulder Abduction (deg)	73.2	79.6	82.6
	Throw Time (sec)	0.3	0.25	0.216
	Relative Release Height (percent)	103.23	101.61	105.91
Follow-through	Minimum Elbow Flexion (deg)	27.9	33.7	45.8
	Shoulder Adduction (deg)	29.7	44	35.1
	Shoulder Medial Rotation (deg)	48	69.6	80
	Forearm Pronation (deg)	15	10.5	20
	Shoulder Internal Rotation Velocity (deg/sec)	1454.545	2109.091	1600

Appendix D

Subject Characteristics

Subject Characteristics

Subject	**Variables**		
High School	**Age (years)**	**Height (cm)**	**Weight (kg)**
HS1	18	184	80.3
HS2	16	185	71.2
HS3	17	189	102.1
HS4	17	177	65.8
HS5	16	187	71.7
HS6	17	202	74.3
HS7	18	179	83.3
HS8	18	184	67.6
HS9	15	185	70.3
HS10	17	189	110.5
Mean HS	16.9	186.1	79.71
University			
U1	19	191	111.3
U2	27	186	106.8
U3	24	177	90.9
U4	20	191	90.0
U5	30	187	98.2
U6	20	183	83.8
U7	19	176	91.9
U8	20	180	91.0
U9	22	192	114.5
U10	24	183	85.4
Mean U	22.5	184.6	96.38

Appendix E

Reliability Test Raw Data

Reliability Test Data

	Backswing			Force Production				Critical Instant		
Date	**Right Elbow Flexion (degrees)**	**Right Shoulder Abduction (degrees)**	**Left Knee Flexion (degrees)**	**Max. Ext. Shoulder Rotation (degrees)**	**Left Knee Flexion (degrees)**	**Right Knee Flexion (degrees)**	**Step Length (cm)**	**Forward Trunk Flexion (degrees)**	**Left Knee Flexion (degrees)**	**Right Knee Flexion (degrees)**
Sept. 11, 2008	111.7	84.5	30.5	152.6	34.7	35.7	71.0	15.8	29.6	47.7
Oct. 4, 2008	111.1	80.1	28.6	151.2	35.5	37.1	71.0	16.6	28.6	47.9
Oct. 14, 2008	111.4	81.0	30.3	152.5	34.0	35.2	71.0	17.0	31.1	46.4
Oct. 28, 2008	112.1	81.3	30.3	153.6	32.7	37.7	71.0	17.7	31.2	48.4
Oct. 31, 2008	113.3	81.1	32.5	154.5	33.7	38.5	71.0	16.9	29.6	45.8
Mean	111.92	81.60	30.44	152.88	34.12	36.84	71.00	16.80	30.02	47.24
SD	0.86	1.69	1.38	1.24	1.05	1.37	0.00	0.69	1.11	1.09
Minimum	111.1	80.1	28.6	151.2	32.7	35.2	71.0	15.8	28.6	45.8
Maximum	113.3	84.5	32.5	154.5	35.5	38.5	71.0	17.7	31.2	48.4
Range	2.2	4.4	3.9	3.3	2.8	3.3	0	1.9	2.6	2.6

Appendix F

High School Players Raw Data

High School Players (Backswing)

	Variables				
Subject	Right Shoulder Abduction (degrees)	Right Knee Flexion (degrees)	Right Elbow Flexion (degrees)	Left Knee Flexion (degrees)	Max. Ext. Shoulder Rotation (degrees)
HS1	95.80	28.80	108.60	26.73	172. 1
HS2	84.43	45.67	131.13	35.50	170.97
HS3	114.20	18.23	109.23	25.77	171.70
HS4	94.87	30.93	102.30	37.67	183.10
HS5	97.03	23.33	124.43	32.30	184.87
HS6	86.93	29.07	117.57	36.93	179.10
HS7	84.57	40.13	113.70	57.47	168.13
HS8	114.17	21.83	112.07	27.67	171.83
HS9	107.27	32.90	73.30	25.17	185.13
HS10	109.33	32.80	112.67	25.77	139.40

High School Players (Force Production)

	Variables							
Subject	Internal Shoulder Rotation Velocity (deg/sec)	R. Shoulder Abduction @' MER (degrees)	Step Length (cm)	Percent Standing Height	Right Knee Flexion (degrees)	Left Knee Flexion (degrees)	Elbow Extension Velocity (deg/sec)	Left Shoulder Abduction (degrees)
HS1	1132.00	108.67	91.67	0.50	23.30	35.60	1781.82	80.27
HS2	1201.67	97.77	76.67	0.41	18.03	30.63	1843.43	38.07
HS3	918.00	99.53	75.67	0.40	25.43	23.47	2328.28	46.70
HS4	1277.33	107.63	73.00	0.41	33.27	44.40	997.98	56.57
HS5	1148.00	112.13	73.00	0.39	34.43	23.47	1473.74	125.70
HS6	1244.00	96.30	98.00	0.49	15.63	29.63	1538.38	52.43
HS7	1570.00	85.87	85.33	0.48	24.50	39.00	1927.27	63.73
HS8	909.33	96.50	72.67	0.39	31.80	31.53	1951.51	52.87
HS9	1240.67	103.27	83.00	0.45	25.43	18.57	1321.21	77.17
HS10	1060.08	94.37	86.67	0.46	23.13	34.50	1346.46	37.80

High School Players (Release)

	Variables											
Subject	Right Elbow Flexion (degrees)	Right Knee Flexion (degrees)	Left Knee Flexion (degrees)	Forward Trunk Lean (degrees)	Ball Velocity (m/s	Ball Velocity (km/hr)	Lateral Trunk Lean (degrees)	Right Shoulder Abduction (degrees)	Throw Time (sec)	Back Foot Unweight (Y=1; N=0)	Release Height (cm)	Relative Release Height (%)
HS1	13.47	30.03	30.67	30.73	21.43	77.15	24.37	118.40	0.17	0.00	207.33	113.00
HS2	43.43	27.47	24.73	20.27	19.33	69.60	23.53	104.37	0.18	0.00	208.33	113.00
HS3	16.67	26.73	4.73	13.33	18.96	68.26	20.43	106.13	0.26	0.00	209.00	111.00
HS4	14.70	37.97	35.93	19.97	17.71	63.76	16.03	111.57	0.21	0.33	183.67	104.00
HS5	8.30	35.03	14.67	17.03	17.82	64.16	7.53	120.83	0.21	0.00	199.67	107.00
HS6	11.37	21.40	30.57	29.20	23.21	83.56	22.13	115.47	0.15	0.00	218.00	108.00
HS7	33.40	26.90	27.17	20.93	20.75	74.69	18.20	91.17	0.23	0.33	198.00	111.00
HS8	25.50	47.67	18.57	20.20	19.18	69.06	12.90	100.77	0.22	0.33	191.67	104.00
HS9	11.83	40.63	19.80	24.20	20.03	72.12	19.20	114.10	0.22	0.67	224.00	121.00
HS10	44.33	14.33	16.40	27.07	18.36	66.08	13.10	102.40	0.28	0.33	205.67	109.00

High School Players (Follow-through)

	Variables				
Subject	Minimum Elbow Flexion (degrees)	Shoulder Adduction (degrees)	Shoulder Internal Rotation (degrees)	Forearm Pronation (degrees)	Pronation Velocity (deg/sec)
HS1	13.90	49.33	22.23	68.77	1879.49
HS2	38.00	25.87	15.47	80.97	1619.33
HS3	35.63	41.43	18.77	65.10	1476.46
HS4	26.97	55.30	36.27	89.57	2032.77
HS5	44.87	47.40	26.47	62.27	1682.18
HS6	15.17	42.40	43.90	91.93	2464.06
HS7	15.93	25.57	13.90	60.87	1844.44
HS8	93.93	72.60	24.87	77.93	1803.54
HS9	11.40	43.93	13.63	90.27	1805.33
HS10	20.43	37.07	19.97	90.40	1807.33

Appendix G

University Players Raw Data

University Players (Backswing)

	Variables				
Subject	**Right Shoulder Abduction (degrees)**	**Right Knee Flexion (degrees)**	**Right Elbow Flexion (degrees)**	**Left Knee Flexion (degrees)**	**Max. Ext. Shoulder Rotation (degrees)**
U1	89.67	35.50	125.73	31.20	153.90
U2	83.17	32.70	118.83	32.03	150.53
U3	110.83	32.03	88.90	30.90	157.37
U4	95. 13	29.30	112.03	43.43	169.57
U5	77.43	29.93	121.37	28.37	157.27
U6	117.47	15.40	83.73	35.90	153.03
U7	103.27	29.00	123.60	26.70	159.23
U8	74.60	22.43	131.67	36.47	141.27
U9	98.33	24.07	119.60	39.07	154.80
U10	94.23	32.03	119.33	41.70	159.07

University Players (Force Production)

	Variables							
Subject	Internal Shoulder Rotation Velocity (deg/sec)	Right Shoulder Abduction @' MER (deg)	Step Length (cm)	Percent Standing Height	Right Knee Flexion (deg)	Left Knee Flexion (deg)	Elbow Extension Velocity (deg/sec)	Left Shoulder Abduction (deg)
U1	1136.00	96.10	90.33	0.47	26.20	29.47	1796.97	46.63
U2	788.00	88.23	82.67	0.44	23.50	26.87	1488.89	29.53
U3	1288.00	111.10	87.67	0.50	21.43	42.97	1169.69	39.63
U4	1065.33	105.67	76.33	0.40	30.07	45.67	2043.43	39.53
U5	1130.00	87.50	72.67	0.39	39.97	36.30	1314.14	52.10
U6	960.67	105.30	77.67	0.42	25.13	31.33	1281.82	67.47
U7	1258.67	112.17	69.67	0.40	42.97	22.40	1437.37	58.90
U8	1356.24	88.43	76.33	0.42	37.37	24.97	1800.00	48.27
U9	930.67	104.83	89.33	0.47	35.27	39.70	1876.77	55.17
U10	736.00	110.37	82.67	0.45	36.17	36.80	1857.57	77.33

University Players (Release)

Subject	Variables											
	Right Elbow Flexion (degrees)	Right Knee Flexion (degrees)	Left Knee Flexion (degrees)	Forward Trunk Lean (degrees)	Ball Velocity (m/s	Ball Velocity (km/hr)	Lateral Trunk Lean (degrees)	Right Shoulder Abduction (degrees)	Throw Time (sec)	Back Foot Unweight (Y=1; N=0)	Release Height (cm)	Relative Release Height (%)
U1	30.80	37.07	32.20	17.23	20.56	74.00	16.70	104.90	0.16	0.67	217.00	114.00
U2	26.33	27.00	14.60	20.23	18.89	67.99	19.57	110.80	0.17	1.00	212.00	114.00
U3	41.73	18.37	35.57	23.33	18.82	67.75	27.73	114.00	0.18	0.00	195.33	110.00
U4	34.60	39.23	34.73	15.37	19.88	71.58	13.03	106.57	0.21	1.00	197.67	103.00
U5	33.27	50.20	32.30	12.33	19.73	71.02	11.20	98.00	0.16	1.00	195.00	104.00
U6	20.13	28.33	17.33	20.77	21.07	75.86	21.10	109.20	0.21	1.00	209.33	114.00
U7	52.37	47.70	21.03	17.63	18.11	65.21	11.90	118.20	0.18	0.67	193.67	110.00
U8	30.67	36.87	22.37	15.47	20.01	72.05	14.37	96.10	0.13	0.00	185.00	103.00
U9	21.33	59.10	30.70	22.83	21.54	77.56	19.30	115.67	0.16	1.00	211.00	110.00
U10	20.83	58.50	20.93	14.47	19.12	68.83	15.10	124.13	0.16	1.00	207.67	113.00

University Players (Follow-through)

	Variables				
Subject	Minimum Elbow Flexion (degrees)	Shoulder Adduction (degrees)	Shoulder Internal Rotation (degrees)	Forearm Pronation (degrees)	Pronation Velocity (deg/sec)
U1	21.67	58.87	25.70	73.13	2216.16
U2	13.27	38.90	17.47	85.83	1993.47
U3	40.47	51.90	28.50	79.37	1785.84
U4	37.93	37.37	22.00	66.43	1979.80
U5	45.17	34.27	19.20	83.33	1868.95
U6	26.37	56.03	14.30	80.20	2137.39
U7	34.83	35.57	36.17	67.30	1555.15
U8	43.23	42.80	13.93	74.83	1954.81
U9	32.67	45.50	22.40	82.07	2486.87
U10	34.90	42.00	10.43	75.30	2281.82

Appendix H

Quarterback Pass Checklist

Quarterback Pass Checklist
(Assuming a right handed athlete)

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Grip:

- Athletes will differ slightly how they grip the ball depending on individual hand size and comfort.
- Athletes with smaller hands will grip closer to the back of the ball, but results in less contact with the laces.
- Larger hands allow the athlete to grip closer to the middle of the ball, allowing more of the fingers to grip the laces. This also allows the athlete to apply more torque to the ball at release and can improve the rate of spin of the ball in the air, improving it's stability in flight.
- Fingers are spread to ensure a large surface area of contact for maximum friction. This prevents slippage and increases torque.
- The thumb and index finger should form a "V" with both fingertips being equal distance from the tip of the ball.
- The ball should not touch the palm of the hand, being held only by the fingertips.

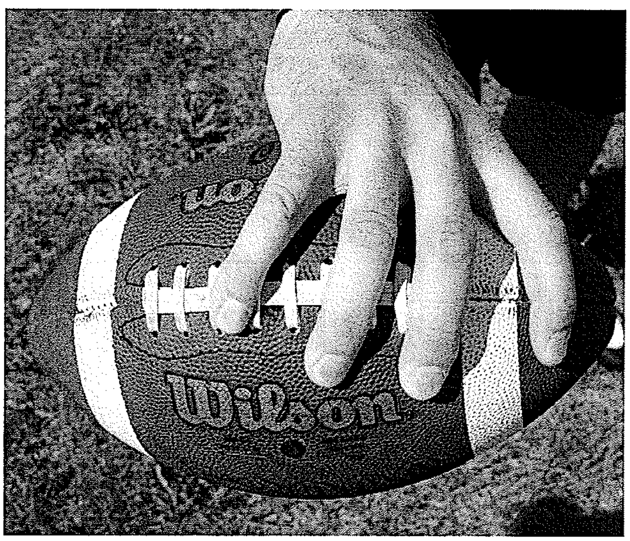

Figure 1: Fingers are spread to increase area of contact and increase friction

Drop Back:

- The number of steps used will depend largely on the length of the pass with a three step drop used for shorter passes and a five or seven step drop used for longer passes.
- Regardless of the length of drop back the technique is similar. The last two steps of the drop back are short, quick steps to allow the quarterback to gather and plant to get into the ready position.

- The previous steps are used to gain depth with a three step drop using just one depth step while a five step drop uses three depth steps followed by the gather and plant.
- The initial step should be close to 180 degrees from the front foot to rotate the quarterback away from the line of scrimmage.
- During the first step the athlete should be leaning away from vertical to allow a larger step and create more distance from the line of scrimmage.
- The last two short steps bring the athlete back to a vertical position and into a set position.
- If the second step is too long the athlete will gain too much distance and the right knee will be outside of the right ankle.
- The final step stops backward momentum and puts the athlete in a ready position to throw without needing to take any extra steps.

Ready Position:

- Both knees should be bent slightly to allow an aggressive drive step during the throw.
- Feet should be perpendicular to the target and shoulder width apart with most of the weight over the back foot to allow for a large step. If the stance is too wide the athlete may be forced to take a false step to reset his feet before throwing.
- The athlete should be facing perpendicular to the target and should stay on the balls of the feet to allow for sudden change in direction.
- The ball is held close to the body at shoulder height to protect it from nearby defenders. Keeping the ball at or just passed the midline of the chest towards the throwing shoulder also shortens the length of the backswing and allows for a quicker release.
- The right elbow should be pointing downward, but some shoulder abduction is acceptable, however excessive abduction will decrease ball protection.
- The left hand should not leave the football prior to the athlete starting backswing. This protects the ball and will assist in trunk rotation.

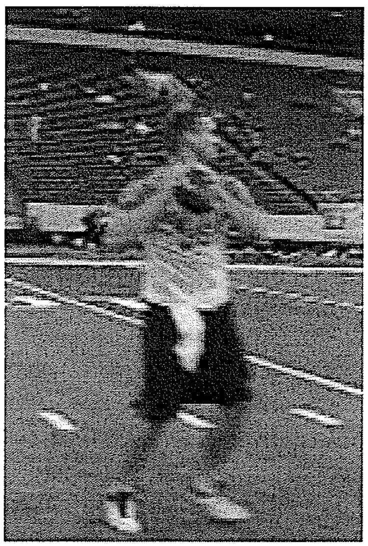

Figure 2: Ready position in an elite quarterback.

Backswing:

- As the athlete takes a step towards the target the right arm should abduct close to 90 degrees as the shoulder begins to externally rotate.
- The left shoulder also abducts to elevate the shoulder girdle and allow greater shoulder rotation.
- At peak backswing the shoulder should externally rotate until the lower arm is approaching parallel to the ground.
- The step should be close to half the standing height of the athlete to ensure a powerful step onto the front foot. A long step could result in locking out the front knee and limiting weight transfer.
- The knees should remain flexed throughout the entire step.
- The left toe should point towards the target with the shoulders still rotated back to their maximum position at foot contact.
- The step should land just left of the target to allow the hips to open and increase the range of motion for trunk rotation. A step too far left will open the hips too far and cause the athlete to rotate away from the target through release. If the athlete fails to open the hips enough hip rotation will be reduced and force production will decrease.
- The trunk remains relatively vertical during backswing to maximize rotation of the shoulders and hips. Excessive trunk lean will limit hip and trunk rotation.

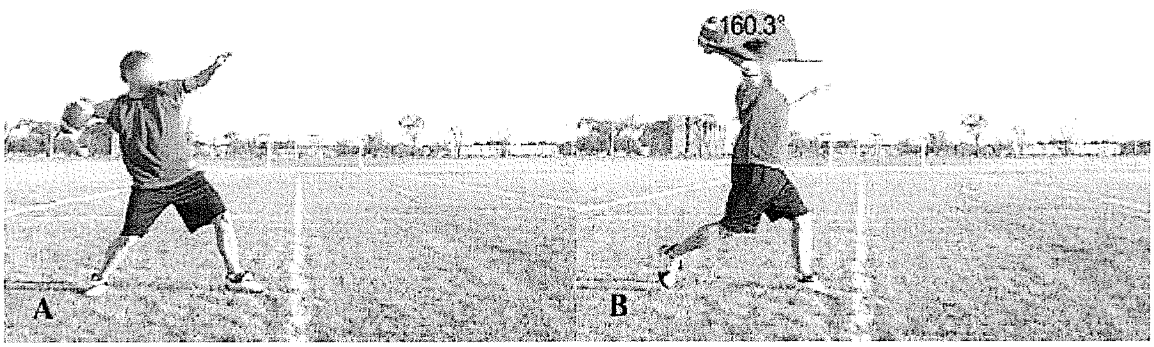

Figure 3: During the step both shoulders abduct and the right shoulder goes into external rotation and is assisted by inertial lag created by hip and trunk rotation.

Force Production:

- During the step the athlete extends the right hip to transfer weight onto the front foot.
- The hips are rotated to face the target with the trunk and shoulders remaining rotated away creating a stretch in the trunk muscles.
- The trunk and shoulder girdle rotate to face the target while the shoulder is thrown into maximum external rotation.

- The left shoulder should drive down and back to assist in trunk rotation. This also drops the left shoulder and raises the throwing shoulder to increase release height.
- The trunk rotates to face the target and should stabilize and stop rotating as the throwing shoulder continues to internally rotate and the elbow extends through release.
-The throwing shoulder also horizontally adducts during force production as the ball is released just in front of the head.
- Rotation to face the target should be segmented with the larger, slower limbs initiating movement and transferring momentum to the smaller and faster distal limbs.
- The step should be initiated with right hip extension rather than right knee extension to allow full weight transfer and unweighting of the front foot at release.
- The front knee should remain flexed during the throw. This allows the athlete to transfer all weight over the front foot and level the shoulder girdle by release to prevent high passes.
- The athlete should avoid excessive forward trunk flexion in order to assist weight transfer as it will cause a lowered release height and could result in pulling down on the ball at release.

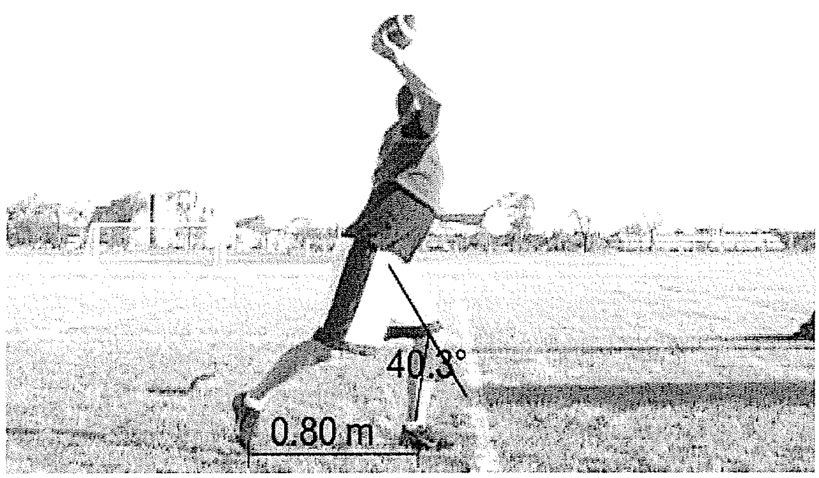

Figure 4: The front knee remains flexed as the athlete steps onto the front foot. The trunk stops facing the target as the shoulder internally rotates.

Figure 5: The free arm drives down and back, raising the throwing shoulder as the shoulder internally rotates and the elbow extends.

Release:

- At release the ball should be released at maximum height to allow the athlete to throw over the defenders. This will also increase throw distance by increasing initial height as well as accuracy by allowing a flatter trajectory.
- The throwing shoulder should remain abducted approximately 90 degrees. If the shoulder is abducted much greater than 100 degrees the risk of shoulder impingement is increased. There should be very little change in shoulder abduction through force production and release.
- The elbow should be flexed close to 20 degrees to allow increased release height, yet avoiding full extension which increases the risk of injury to the biceps tendon.
- The time from front foot touchdown to release of the pass should be approximately 0.2s. Rushing the motion too much can result in reduced range of motion for force production. It also makes it difficult to stabilize the trunk and hips and stop rotation prior to release.
- The athlete should be flexed laterally and forward at the trunk to increase release height and assist in weight transfer.
- Weight should be fully transferred onto the front foot at release with the back foot fully unweighted when the ball is released.
- The left knee should remain flexed close to 30 degrees to allow the athlete to fully transfer his weight onto the front foot and allow the shoulders to become level.
- The ball rolls off the fingers with the index finger being the last to leave the ball and points to the target briefly after release.
- The little finger initiates spiral rotation as it pulls down on the side of the ball and each finger follows in succession.
- The wrist flexes and the forearm pronates to rotate the fingers and wrist outward. A tight spiral provides stability to the ball in the air.

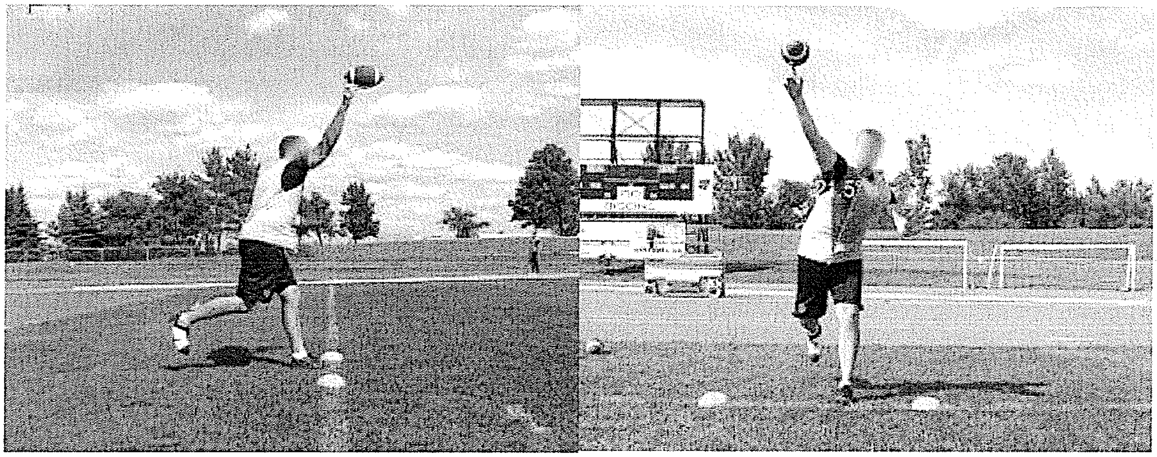

Figure 6: At release the athlete has fully transferred his weight onto the front foot and has maintained close to 100 degrees of shoulder abduction in the throwing shoulder.

Follow-through

- The main purpose of the follow-through is to decelerate the arm over a large range of motion to reduce risk of injury.
- The forearm continues to pronate as the shoulder internally rotates, extends and adducts.
- The thumb of the throwing arm should end up pointing towards the opposite hip. The arm ends close to the body and protects the arm from impact with potential defenders.
- The athlete should continue to rotate to face the target in case he is forced to react.

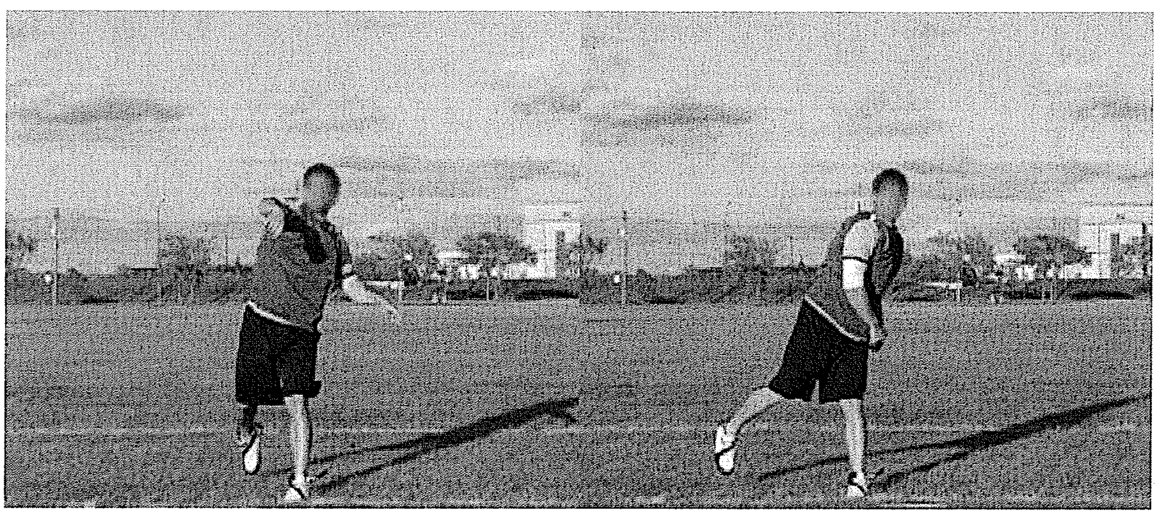

Figure 7: During follow-through the athlete continues to pronate the forearm, internally rotate and adduct the throwing shoulder to decelerate the arm.