THREE-DIMENSIONAL BIOMECHANICAL ANALYSIS OF THE STATIONARY AND PENALTY CORNER DRIVES IN FIELD HOCKEY

By

Michael T. Whalen

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

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ABSTRACT

The game of field hockey is one in which Canadian teams have performed exceptionally well in recent Olympic Games and World Cups. Improvement in the drive in a penalty corner situation could directly lead to increased goal scoring, which could have a significant impact in national and international competitions where games are often decided by one or two goals. Few studies have been conducted that analyze this skill and most of these were two-dimensional film analyses. The purpose of this study was to describe the kinematics of the stationary drive and the penalty corner drive and determine anthropometric, temporal and technique variables most related to ball velocity by means of multiple regression analysis. Elite field hockey players (9 male, 8 female), over half of whom have had international playing experience, were analyzed by the use of three-dimensional video techniques. Three-dimensional coordinates were calculated by direct linear transformation (DLT). The greatest resultant ball velocity for the stationary drive was 32.64 m/s (average 26.44 m/s) and for the penalty corner drive 38.93 m/s (average 28.29 m/s). Both skills were described in terms of the movements which occurred at each joint as well as an analysis of the timing of phases and events throughout the skills. Anthropometric results indicated that subjects with greater biacromial breadth, greater forearm girth, greater mass and who were taller produced greater ball velocities. For the stationary drive, of 44 technique variables measured, the following variables were most related (r^2 = .76) to producing greater ball velocity: greater ROM during the

downswing in the frontal and sagittal planes, time to contact from peak CM velocity and the time to contact from peak angular velocity between the shoulders and the hips. Of the 47 technique variables measured on the penalty corner drive, greater ball velocity was best explained (r^2 = .751) by: CM velocity at contact, time of maximal shoulder angle in the YZ-plane until contact, relative length of the final step towards the ball and peak angular velocity of the angle between the stick and the wrist.

ACKNOWLEDGEMENTS

I would like to thank my thesis committee, Dr. Thornton-Trump, Dr. Lindner and especially my advisor, Dr. Marion Alexander, for their guidance in completing this paper. Thanks again to Dr. Alexander for her assistance during my years at the University of Manitoba completing my degree.

As well, I would like to acknowledge the consultation received from the Statistical Advisory Services at the University of Manitoba, specifically to Rob Platt for his efforts.

I would also like to thank my parents for their continued support and encouragement throughout my education. You can finally see some results of my efforts. Also to Karin, who helped give me the strength to finish.

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CHAPTER ONE
INTRODUCTION

Field hockey is one of the most popular and exciting team sports for men and women throughout the world. In international competition Canada's men's and women's teams have fared well through past years. The men's team has finished among the top eleven in Olympic and World Cup competition since 1976, qualifying every year except for 1982 and 1992. From 1978 to 1989 the women's lowest finish in World Cup and Olympic games was 8th, in 1979. In 1983 they posted a second place finish at the World Cup and since 1978 were consistently among the top five in the world. At the 1990 World Cup Canada placed tenth but recently moved back into the top eight, having qualified for the 1992 Olympic Games where they finished 7th. Field hockey is very similar to soccer in terms of overall tactics and physical demands upon players; however, many different technical skills are required.

The drive or hit is one of the most basic skills in field hockey and, once the proper technique has been mastered, a player may use the drive to pass accurately to a teammate five meters (m) or fifty meters away. The drive can also be used effectively to shoot at goal, as it is the most powerful stroke in field hockey (produces the greatest ball velocities).

In field hockey, if the defending team commits a foul within their own circle (a 16 yard (14.6 m) semi-circle surrounding the net), or a deliberate foul within the twenty-five yard line (a line parallel to the goal line and twenty-five yards from it), a penalty corner is awarded to the attacking team. A penalty corner, if executed properly, produces a free shot at goal 14 - 16 yards from the goal mouth. A player with a hard, accurate drive has a fairly good chance to score on such an opportunity.

Few studies have been conducted that analyze the drive in field hockey and most of these were two-dimensional film analyses (Alexander, 1981; Alexander, 1985; Buzzell & Holt, 1979; Cohen, 1969; Hendrick, 1983). The stationary drive is described in many coaching texts but, for the most part, these are subjective descriptions of the skill (Barnes, 1969; Broderick, 1981; Broderick & van der Merwe, 1982; CFHA Coaching Committee, 1983; Heyhoe Flint, 1978; Kanjee, 1991a; Pollard, 1959; Read & Walker, 1976; Wein, 1979). Different techniques have evolved from the basic technique described in most of the literature; this is especially the case when the drive is used in a penalty corner situation (Figure 1). During a penalty corner drive many players take an approach run at the ball before hitting it, however, few authors have described the approach, except in a subjective manner (CFHA Coaching Committee, 1983; Chivers & Elliott, 1987; Kanjee, 1991a; Wein, 1979). Many options are used on the penalty corner, the direct shot at goal (utilizing the drive) is still widely used and many penalty corner options end up with a drive at goal by another player on the team. While the drive is a skill used by all players in the sport of field hockey, those players who hit the ball particularly hard in the stationary drive are usually chosen to shoot at goal in penalty corner situations.

Only one three-dimensional analysis of the drive (Chivers & Elliott, 1987) had been published. Therefore, a review of literature

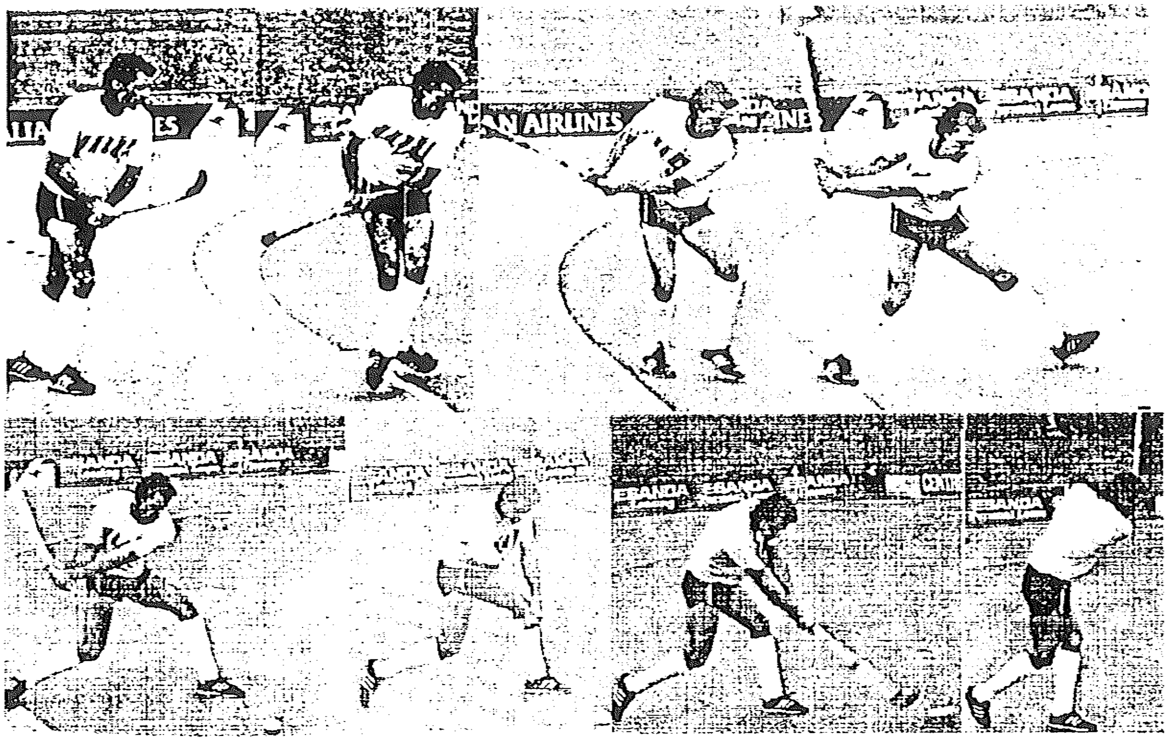


Figure 1. The drive in a penalty corner situation (Adapted from Chivers & Elliott, 1987).

on the golf drive was also undertaken. Golf is a very popular individual sport and recreational activity played throughout the world; perhaps because of its popularity it has been studied fairly extensively. The golf drive had been analyzed in somewhat greater detail by many different researchers using a variety of analysis techniques (Budney & Bellow, 1979a-c; Cochran, 1990; Cooper et al, 1974; Milburn, 1982; Nagao & Sawada, 1973; Nagao & Sawada, 1974; Nagao & Sawada, 1977; Neal & Wilson, 1985; Neal, 1990; Neal & Hubinger, 1990; Scheie, 1990). Golfers assume a stationary stance opposite to the ball, perform a large backswing, then accelerate the golf club down to hit the ball. The action of accelerating the body and the club down into the ball is quite similar to that of swinging a field hockey stick down to strike a field hockey ball.

Statement Of The Problem

The purpose of this study is to describe the basic field hockey drive, and the drive as used in a penalty corner, in terms of the sequence and timing of the major joint movements; and to develop regression models of both skills to determine which factors were important to their performance. These movements were analyzed by use of three-dimensional video analysis techniques.

Research Hypothesis

It was hypothesized that players who performed better in the stationary drive, would also perform better in the penalty corner drive and players who had greater ball velocities for the penalty corner drives would exhibit greater linear velocities of their center of mass during the approach to the ball, a longer final step towards the ball and a greater range of motion from top of backswing to contact.

Rationale Of The Study

There appeared to be a lack of objective literature describing the stationary and penalty corner drive in field hockey. Most of the objective research on the drive had been in the form of two dimensional film analysis. A three-dimensional, biomechanical analysis was used to describe the kinematics of each skill.

Regression models were developed, using anthropometric, temporal and technique variables, to indicate the relative contribution of these variables to resultant ball velocity in the stationary and penalty corner drive. They may also indicate which performance variables in the stationary drive are good predictors for performance in the penalty corner drive.

Coaches could use the results of this study to better analyze and improve performance of their athletes.

Improvement in the drive in a penalty corner situation could directly lead to increased goal scoring which could have a significant impact in national and international competitions where games are often decided by one or two goals.

Delimitations

The delimitations of the study are:

1. All subjects tested were of Canadian Senior Provincial calibre, and over half the subjects have had international playing experience.
2. All subjects were filmed for five trials of each skill.
3. All subjects were filmed under the same conditions, as filming took place indoors.
4. All subjects were given ample time to warm-up and prepare before being tested.
5. The film analysis was three-dimensional.

Assumptions

The assumptions made regarding performance were:

1) The testing situation did not affect subject's performance.

2) Subjects were able to produce their best, or near best, performance at least once during the five trials sampled of each skill.

3) The drive in the penalty corner situation was not a novel skill for those players who do not regularly take penalty corner drives for the Senior Provincial teams.

4) Ball velocity would be an accurate measure of performance.

Limitations

1) Only one subject was a current national team player.

2) Only nine male and eight female subjects were examined.

3) A filming rate of 60 frames per second was used.

4) One of the male and three of the female subjects were not normally penalty corner strikers.

Definitions Of Terms

In order to clarify the restrictive meaning of terms, the following definitions are used:

Approach: any steps taken towards the ball to put a player in proper position to strike the ball.

Backswing: movement of the stick backwards and upwards from its original resting position near the ground to a position near the shoulder level.

Circle: (refer to Figure 3a) a sixteen yard quarter circle is traced on each side of the goal, with the goal post as the center of the circle; the circle is traced through a ninety degree arc starting from the goal line, then the "circle" is completed by drawing a line parallel to the goal line connecting the two quarter circles. The rules of field hockey state that a goal may only be scored by shooting from within the circle (Hockey Rules Board, 1990).

Contact: point at which the stick first strikes the ball until the ball has left the stick; the time during which the ball and stick are touching.

Corner: see "Penalty Corner".

Downswing: movement of the stick or club from the top of the backswing until it contacts the ball.

Drive: also called the hit, is a stroke in field hockey used to pass or shoot at goal.

Follow Through: movement of the stick after impact until the end of the swing.

Hit: see "Drive".

Hitter: the player who takes a direct shot at goal on a penalty corner.

Penalty Corner: also known as a short corner or corner, is awarded to the attacking team when the defending team commits a foul within their own circle or an intentional foul within their own twenty-five yard line.

Penalty Corner Drive: the drive as seen in a penalty corner situation. It is a variation of the drive; the athlete usually approaches the ball from several yards away.

Short Corner: see "Penalty Corner".

Stick Stopper: see "Stopper".

Stopper: the player who stops the ball at the top of the circle on a penalty corner.

Striker: see "Hitter".

Stroke: a technique or skill used to propel the ball in field hockey.

Swing Weight: is the first moment of mass of a striking implement, measured about an axis of rotation at the right forefinger, and is calculated by multiplying the mass of the implement times the distance of the implement's center of mass to the axis of rotation (Daish, 1972).

Top of the Backswing: the instant during which the stick is no longer moving upwards or backwards and has not yet started moving downwards to contact the ball.

Top of the Circle: point on the circle, directly in front of the goal.

CHAPTER 2

REVIEW OF LITERATURE

Introduction

Most of the literature concerning field hockey skills and techniques was found in the form of coaching books and manuals written by coaches and players (Barnes, 1969; Broderick, 1981; Broderick & van der Merwe, 1982; CFHA Coaching Committee, 1983; Heyhoe Flint, 1978; Kanjee, 1991a; Pollard, 1959; Read & Walker, 1976; Wein, 1979). Unfortunately, the description of the skills in these books was usually based on subjective analysis by the respective authors. This led to variations and disagreement on the specifics of correct techniques; most authors failed to address some of the seemingly important aspects of the skill and there was obvious disagreement on some of the fundamental aspects of the skill (ie. whether the stick was swung through a vertical or more horizontal plane).

In undertaking the literature review it was surprising to note that the local university library's most recent field hockey publication pertaining to techniques of the game was published in 1981. The game has changed dramatically since that time, with a great many alterations in the rules which have led to changes in techniques and strategies. Technology has also played a role in changing the game. Field hockey is now played exclusively on synthetic turf at the international level which has led to the development of new techniques and an increase in skill level at which the game is played. Better construction and design of sticks and balls has also contributed to raise skill levels and the speed of the game.

Relatively few objective biomechanical studies that examined the drive in field hockey were found, and almost all of these were two-dimensional cinematographic analyses (Alexander, 1981; Alexander, 1985; Buzzell & Holt, 1979; Chivers & Elliott, 1987; Cohen, 1969; Hendrick, 1983). Therefore, literature was also reviewed for research done on the golf swing. By examination of a similar skill, variables found to be important to the performance of that skill could also be studied in the field hockey drive.

The stationary drive of a former international female player was photographed to illustrate this skill (Figure 2). For the purpose of analysis, the drive was broken down into separate, easily identifiable, phases defined as follows:

Approach: from the moment movement occurs from the players' initial stationary position until the start of the backswing

Backswing: from the instant the stick starts upwards or backwards until the instant before it starts downwards towards the ball

Downswing: from the instant the stick starts down towards the ball until the instant before impact

Contact: the instant the stick contacts the ball until the ball leaves the stick

Follow through: from the end of contact until the end of the swing of the stick

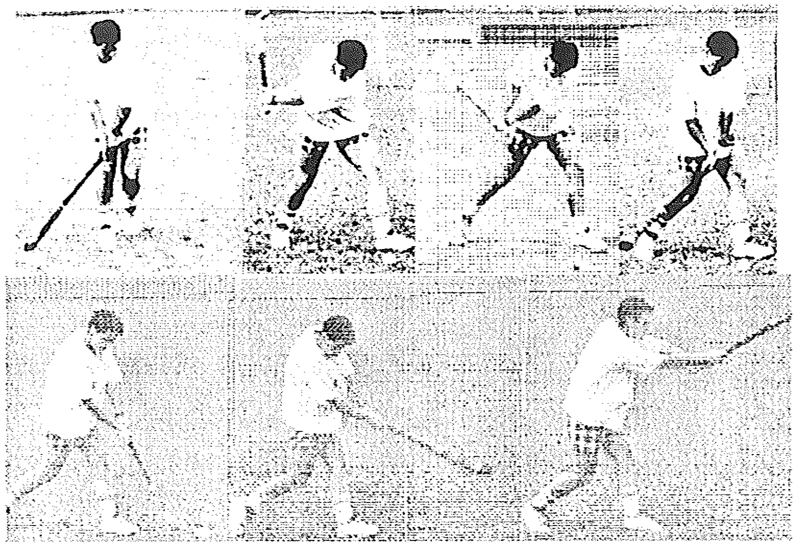


Figure 2. The stationary drive of a former international player.

It should be noted that for some subjects, possibly all subjects, the backswing may initiate movement or may occur simultaneously with the start of the approach. However, the approach phase was included as it was possible some subjects would take one or two strides towards the ball before commencing their backswing. The approach phase will not be present in the stationary drive, as all subjects will start one step behind the ball.

The literature review shall be presented in the following format: 1) general description of the drive as used in a penalty corner situation; 2) description of the drive by phase; 3) review of related skills; 4) review of the mechanics of impact; 5) review of research methods.

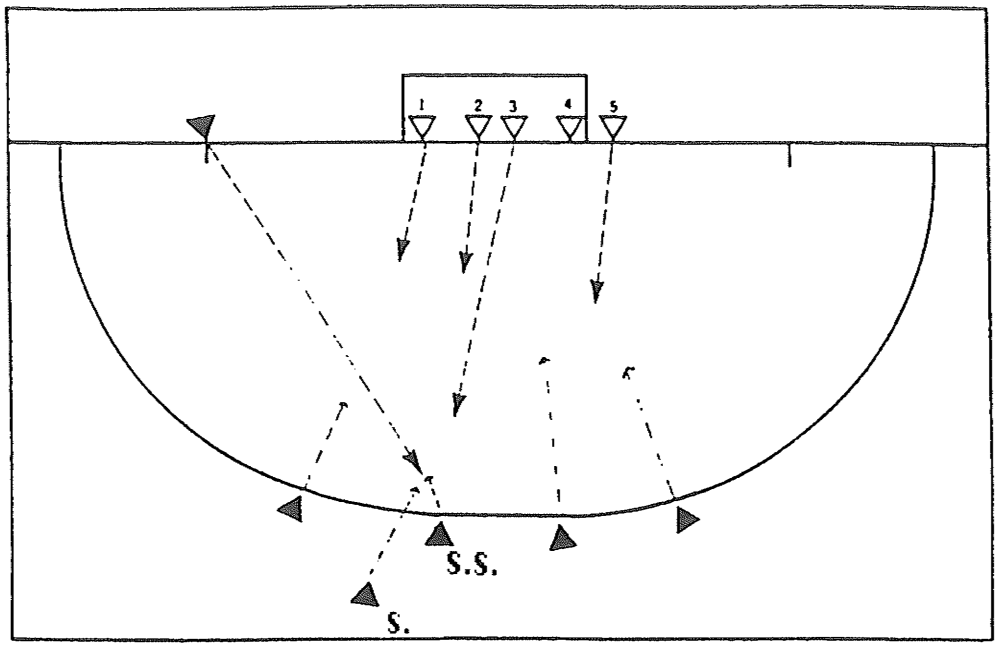
The Drive In The Penalty Corner

In field hockey, goals may only be scored by shooting from within a sixteen-yard semi-circle (the "circle") surrounding the net. The drive is often used to shoot from a penalty corner (also called a short corner, or a corner). During a penalty corner (Figure 3), the attacking team are awarded a free hit from the opponent's goal line, ten yards from either goal post. The goalkeeper and four other defenders must line up on the goal line and may not cross over it until the free hit has been taken; the remaining defenders must wait at center half until the free hit has been taken.

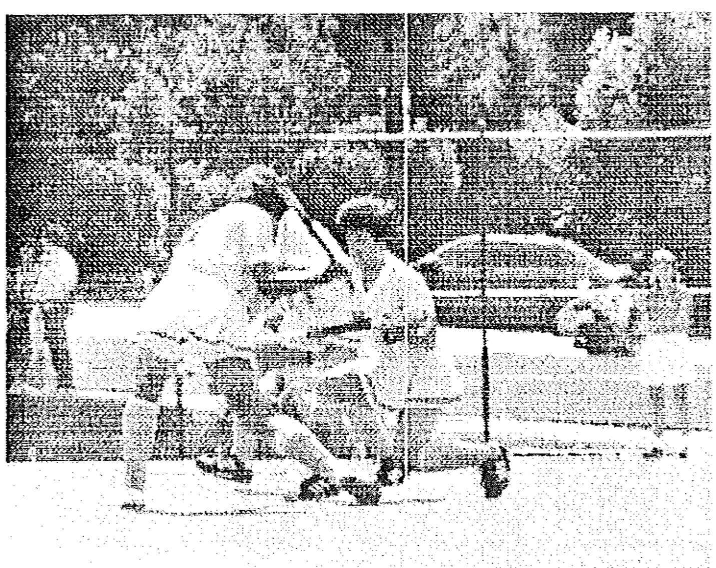
The player taking the free hit passes the ball out towards the top of the circle, 16 yards away, to a teammate, the stick stopper (**S.S.**). The ball must then be trapped outside the circle and stopped motionless; if the ball moves at all, a free hit is awarded to the defending team. The ball is then pushed into the circle for a third teammate, the striker (**S.**), to run in and drive the ball at goal.

Before the 1992 Olympics the rules allowed the stick stopper to stop the ball inside the circle. The stopper would then run in to the circle as far as possible to trap the ball. The result being that the ball was being shot at goal anywhere from 12.5 to 16 yds away.

With the present rules the ball must be stopped outside the circle before it is passed into the circle either towards the goal or parallel to the goal-line. Observation of these techniques at Canadian championships during the summer of 1992 indicated that the direct drive at goal was still a very effective option for teams to use.



a)



b)

Figure 3. a) Schematic of a standard penalty corner; the ball is passed out to the stick stopper (**S.S.**) who stops the ball outside the circle then pushes it back in to be hit. The shooter, or striker (**S.**), runs in to shoot the ball from where it has been pushed to. (Adapted from Kanjee, 1991) b) China's Junior National Team's stick stopper and striker in a game against Korea.

Klatt (1977) designed a computer simulation of the penalty corner and found that, optimally, the shot at goal should be from a point in the center of the goal mouth, 2.67 yards (2.44m) from the top of the circle. From this point the striker had a 16.67° range through which the ball could be shot on target. Shooting from the top of the circle provided a 13.9° shooting angle. A one degree change of angle equated to .86 feet (.26 m) along the goal line, therefore, by shooting from 2.67 yards (2.44m) inside the circle, the striker had 2.38 feet (.73 m) more width to shoot at. The CFHA coaching committee (1983) stated that the ball should be stopped in line with the "near" goal post or, if there is sufficient time, opposite the center of the goal.

Alexander (1985) noted that if the shot at goal was not taken within two seconds, the likelihood of success decreased immensely. Klatt (1977) stated that the time to stop and shoot the ball averaged .90 seconds, while Chivers and Elliott (1987) measured an average time of .345 seconds for the international players studied. With the new rule changes, the time from the pass out to the shot at goal will likely increase, giving defenders a better chance to break up the play.

Another rule concerning the penalty corner, is that the initial drive at goal can not be more than 18 inches high or a free hit is awarded the defending team. A backboard, 18 inches high, assists the umpire in determining whether a ball has been raised too high. Because of this rule, the strategy adopted by many goalkeepers (Player 2, Figure 3a) is to rush out two or three strides then lie down on their side, fully extended, to cover most of the backboard. The net is twelve feet wide, so one or two defenders (Player 4, Figure 3a) stand by the goal posts, protecting the parts of the goal not covered by the goalie. The other two defenders sprint out to the top of the circle; one rushes to where the ball is being stopped (Player 3, Figure 3a) to try and hurry the hitter or possibly deflect the shot at net wide, the other defender (Player 5, Figure 3a) covers any pass offs from the initial stop. If only one player guarded the posts, then the other (Player 1, Figure 3a) will move out and clear rebounds from the goalkeeper.

A penalty corner executed properly will result in a "free" shot at goal from 14 - 16 yards away. A hard, accurate shot may score. If it does not, and the shot was hard enough, the ball may rebound out in front of the goal. This would create an excellent scoring opportunity as the goalkeeper would likely be in a vulnerable position: lying on their side on the ground. Other strategies are to flick or scoop the ball at net (in which case the ball may be shot at any height) to try and catch the goalie going down, or to lay the ball off to a teammate after it has been stopped, to change the angle of the shot. If the ball were laid off, the shot at goal would still usually be a drive.

The penalty corner has traditionally been a key opportunity for teams to score goals; at the 1979 I.F.W.H.A. tournament, held in Vancouver, B C., Schrodt and Whittingham (1981) taped 60 minutes of each of nine preliminary round games. Through nine games, 148 penalty corners were awarded. Twenty-four of these penalty corners were converted into goals (conversion rate of 16.2%) accounting for 38% of the total goals in these games. One hundred and fifteen of the 148 attempted corners were direct shots at goal using the drive; this strategy produced 18 goals. Most teams were scoring on approximately 1 in 6 penalty corners. The Dutch team, the eventual tournament winners and world champions, converted about one in four corner attempts into goals.

Through the 1980's numerous rule changes have been made in the sport of field hockey, many of these pertaining directly to the penalty corner, resulting in continuous changes in penalty corner strategies on attack and defence.

To get an indication of the current importance and use of the drive in penalty corners, three games, videotaped from broadcasts by the Australian Broadcasting Corporation, at the 1990 Champions Trophy in Australia were analyzed by the author. The Champions Trophy is a competition between the top six men's teams in the world. The three games examined were: Australia vs. Pakistan; Netherlands vs. Pakistan and Australia vs. Netherlands. Twenty-four penalty corners were awarded throughout these three games with the following results: Pakistan awarded 7 corners, scored no goals; Australia 10 corners, 3 goals (33% conversion); Netherlands 7 attempts, 2 goals (35% conversion). Of the Netherlands' 7 corners, 6 were direct drives at goal and one was a lay-off attempt; both goals were scored using the drive. Australia used the direct drive twice, on one the goalie stopped the initial shot but a goal was scored on the rebound, the other one went in the goal but was called back because the ball was not stopped properly. On their other penalty corner plays the direct flick was used three times resulting in two goals, a lay-off and a drive was used once, a lay-off and a flick twice resulting in one goal, and two attempts resulted in no shot at goal because of either a poor pass out or stop.

Jay Stacie, of Australia, and Gys Weterings, of Netherlands, were the two leading goal scorers of the tournament; both are the penalty corner strikers for their respective teams. Weterings scored nine of his team's 14 goals; Australia and Germany also scored 14 goals in the tournament and, subsequently, these teams finished the tournament in the top three positions: Australia first, Netherlands, then Germany. Pakistan finished in fourth place (Rucci, 1991). Sixty-one goals were scored in 15 games, 16 as a result of a penalty corner (26%); seven of the games were decided by one goal and one game resulted in a tie (Rucci, 1991). The results of this informal analysis would indicate that the direct shot on the penalty corner was still a lethal weapon used frequently by the top teams in the world. Observations at the 1992 Canadian Men's Junior National Championships indicated that teams still used the same technique on penalty corner drives with the new rule changes.

The player selected to take penalty corner hits is usually the hardest hitter on the team. Most short corner hitters use a heavier stick, 23-26 oz., compared to that of a field player, 19-21 oz. (Kanjee, 1991b). The regulations state that the maximum stick weight is 28 oz. (Hockey Rules Board, 1990).

Alexander (1985), in her analysis of penalty corners at the Senior Canadian Women's National Championships, found that of the variables measured, the only significant difference between teams scoring and not scoring on penalty corners was the velocity of the shot at goal. The average ball velocity for goal scorers was 21 meters per second (m/s) and 15 m/s for non-goal scorers (subjects were female, Senior Provincial level players, some of whom were current or former national team players). Other studies of female players, from university to national team levels, reported ball velocities ranging from 15 m/s to 30 m/s (Alexander, 1981; Buzzell & Holt, 1979; Cohen, 1969; Hendrick, 1983). Alexander (1981), examined the running drive (hitting the ball from a forward moving dribble) of 27 national team players from several different countries and found an average ball velocity of 23.77 m/s. Kanjee (1991a) stated that male short corner hitters hit the ball from 110-120 mph (49.17-53.64 m/s), however, he did not state the source of his information.

Description Of The Drive By Phase

Approach

The drive in a penalty corner situation is a variation or progression of the stationary drive. The main difference between the two is that there is an approach phase for the penalty corner drive, consisting of two or more steps towards the ball. The approach phase of the stationary drive consists of one step forward placing the left foot next to the ball.

Wein (1979), stated that the force produced during the drive was dependent upon: the player's approach speed; the hardness and approach speed of the ball; application of the player's body weight and the speed of the downswing. Broderick and van der Merwe

(1982) added to these variables the weight and length of the stick; stiffness of the stick and muscular tension of the grip at contact.

If the ball is hit from inside the circle the hitter has to take strides into the circle such that they are in proper position to strike the ball. Players taking a short corner hit should take steps towards the ball to generate momentum (Alexander, 1985; Broderick & van der Merwe, 1982; CFHA Coaching Committee, 1983; Kanjee, 1991a; Wein, 1979). Wein (1979), noted, however, that this was a difficult skill and players must find an optimum approach speed such that they are moving towards the ball as fast as possible yet are still able to properly execute the backswing and the downswing. Kanjee (1991a) stated that the best approach would be one that achieved optimal momentum in the least number of steps. Some players wait at the edge of the circle and take the steps necessary to position themselves for the hit; while others start their approach two to three yards behind the circle such that they make three or four strides to reach the ball. The CFHA coaching committee (CFHA Coaching Committee, 1983), stated that a three step approach should be used. The first step was to move the left foot forward, the right then crossed behind the left, the left foot was then placed opposite the ball. They also noted that the line of approach should be the same line as the direction of the hit, or the hitter would have to swing across their body to strike the ball (Figure 4). Analysis of three games at the 1990 Champions Trophy showed that players almost always approached the ball such that they had to swing their stick across their approach line to the ball (Figure 4b). Only the striker for

Pakistan approached the ball along the line of the shot, and this he did only once, while shooting at the far post.

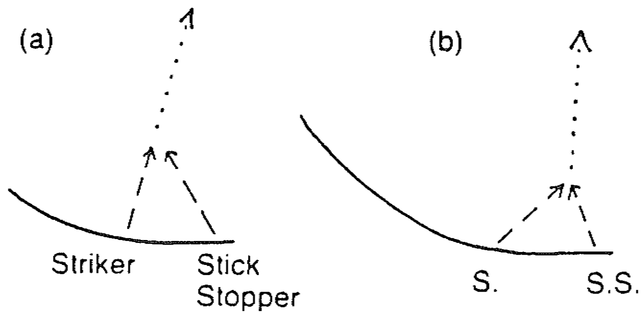


Figure 4. a) Depicts the proper approach path to ball for the striker on a penalty corner. If S. uses approach path in (b) they must swing their stick across their body to hit the ball (taken from CFHA Coaching Committee, 1983).

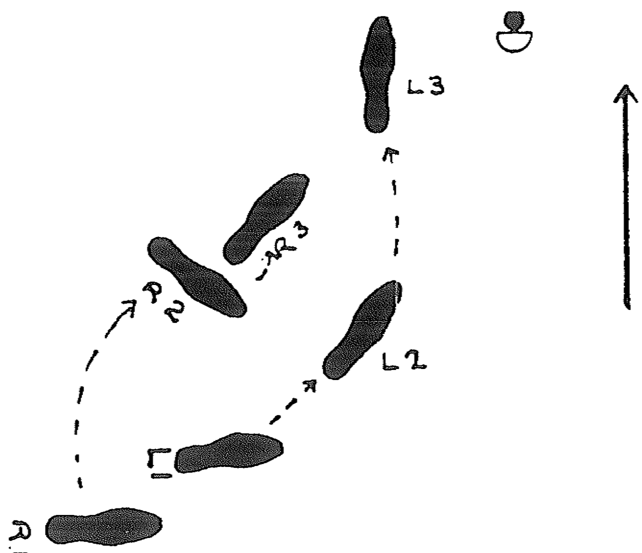


Figure 5. Striker's foot pattern to approach the ball. (taken from Kanjee, 1991a)

Kanjee (1991a) described a four step approach from the edge of the circle that started with the right foot crossing behind the left

(Figure 5). The three penalty corner strikers examined at the 1990 Champions Trophy all used a four step pattern starting with a right step forward or across the front of the body, followed by a left step forward then either the right foot crossed behind the left or the player executed a side shuffle step, then a longer left stride was taken and the left foot was placed opposite the ball. Chivers and Elliott (1987), stated that subjects who used this type of approach produced greater ball velocities than those who used only a side-stepping approach or who were stationary when they contacted the ball.

Backswing

The backswing was performed as the athlete approached the ball and had to be timed such that the downswing occurred as the player planted their left foot next to the ball (Kanjee, 1991a). Figure 6 illustrates a player at the start of the backswing during a stationary (a) and penalty corner (b) drive. In the stationary drive the athlete started behind and to the left of the ball, then took one step forward to bring the left foot next to the ball (Broderick, 1981). In the running drive, the backswing also occurred during the last step towards the ball (Alexander, 1981). In this skill, however, the player was dribbling the ball before the drive and, therefore, would probably keep their stick on the ball until the last possible instant. Kanjee (1991a) described a four step approach to the ball and stated that the backswing should start when the first right step was taken (Figure 5). During the backswing the trunk was rotated to the right and the arms and stick were brought backwards and upwards (Alexander, 1981; Chivers & Elliott, 1987; Kanjee, 1991a). The left arm was kept straight throughout the backswing and the stick was brought back in a straight line (Broderick, 1981; Broderick & van der Merwe, 1982; Read & Walker, 1976). The players' body weight was on the back foot during the backswing (Chivers & Elliott, 1987; Hendrick, 1983; Pollard, 1959; Wein, 1979).

At the top of the backswing (Figure 7), the trunk was rotated such that the right shoulder was well above the left (Alexander, 1981; Chivers & Elliott, 1987) and the left shoulder was pointed in the direction of the drive (Alexander, 1981). Kanjee (1991a) and Cohen (1969) stated that the trunk was further rotated to the right such that the back partially faced the direction of the hit. It should be noted, however, that while performing the running drive (Alexander, 1981) there may be physical limitations preventing full trunk rotation to the right as the player approaches the ball. Chivers and Elliott (1987) added that the right shoulder and the right hip were angled upwards.

At the top of the backswing the left arm was extended and almost horizontal (Alexander, 1981; Kanjee, 1991a); Chivers & Elliott (1987) stated that the left elbow was flexed at 150°. The right arm was flexed from 90° - 100° (Chivers & Elliott, 1987) to 120 - 130 degrees (angle measured between the upper and lower arm segments) (Alexander, 1981; Wein, 1979). The right elbow was about four inches from the trunk (Wein, 1979). The wrists were

a) 

b) 

Figure 6. a) Player at the start of the backswing of the stationary drive. **b)** Player at the start of the penalty corner drive, until just before the top of the backswing (adapted from Chivers & Elliott, 1987).

a)  b) 

Figure 7. Top of the backswing of the stationary (a) and penalty corner (b) drive.

cocked, the right at 153°, the left 156° (Chivers & Elliott, 1987), and the stick shaft was above and behind the right shoulder (Kanjee, 1991a).

Others, however, stated that it would be an error for the stick to go behind the right shoulder and that the swing occurred in a more vertical plane (Read & Walker, 1976; Wein,1979). This would seem to agree with Broderick (1981) and Broderick and van der Merwe (1982), as they stated that the stick was brought straight back, implying a near vertical arc path of the stick. Chivers & Elliott (1987) stated that the stick was at an angle of 85° - 91° but did not state what this angle was with respect to.

One might expect that the greater the backswing, the greater the force production possible for impact with the ball. Read and Walker (1976), however, stated that a short, fast backswing would be best and Alexander (1981), in her analysis of the running drive, found no correlation between height of the backswing and resultant ball velocity. This may indicate that during a more complex skill, proper timing and sequencing of movements may be more important than maximum force production through each phase of the skill.

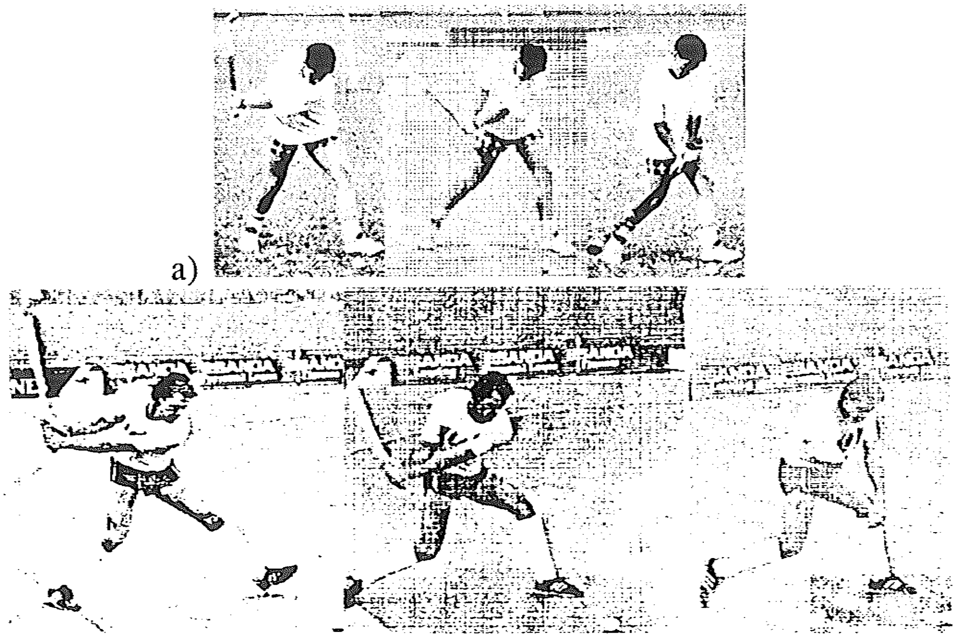
From the top of the backswing the athlete will accelerate the stick down to contact the ball.

Downswing

For the purpose of this study, the downswing (Figure 8) was defined as beginning when the stick started its downward motion towards the ball. Other definitions of the start of the downswing are presented below. The above definition was used as it clearly defined an easily identifiable point within the skill and there was disagreement in the literature on the beginning of this phase of the skill.

At the top of the backswing the athlete's center of mass was at its highest point in the skill and moved through to its lowest point which was at contact (Alexander, 1981). The player's weight during the downswing shifted from being completely on the right foot, forwards to the left foot (Alexander, 1981; Barnes, 1969; CFHA Coaching Committee, 1983; Chivers & Elliott, 1987; Hendrick, 1983; Heyhoe Flint, 1978; Pollard, 1959; Wein, 1979). Power in the drive was achieved by a combination of this weight transfer and the acceleration of the stick through the downswing (Broderick, 1981; Broderick & van der Merwe, 1982). Downswing times ranged from .15-.21 seconds (Alexander, 1981; Chivers & Elliott, 1987; Cohen, 1969).

After the left foot was planted beside the ball, the left side of the body was decelerated, which accelerated the right upper body and the stick into contact (Buzzell & Holt, 1979). Wein (1979) stated that the moment the player's body weight started to shift forward to the left foot was the beginning of the downswing; while Kanjee (1991a) stated that the downswing started by forward movement of the hips, just before the stick reached the end of the backswing. Alexander (1981) found that the downswing began with trunk rotation to the left at the hips, followed by rotation of the shoulders in the same direction. The trunk accelerated very quickly from the top of the backswing until approximately .05 seconds before impact,



a)

b)

Figure 8. Player progressing through the downswing of the stationary (a) and penalty corner (b) drive (adapted from Chivers & Elliott, 1987).

at which point it was decelerated to the point where there was no trunk rotation present at impact (Alexander, 1981). Cohen (1969) reported 80 degrees of pelvic rotation and 70 degrees of spinal rotation (measured by "fins" attached to the back) for her subjects when they performed a stationary and a running drive.

During the downswing both arms were adducted forcefully at the shoulders (Alexander, 1981). The left upper arm had maximum acceleration (90.0 radians per second squared (rad/sec^2) or 5156.0 degrees per second squared (deg/sec^2)) about .10 seconds before contact, then an even greater deceleration (-210.0 rad/sec^2 or -12032.0 deg/sec^2) until impact (Alexander, 1981). The acceleration of the left lower arm was fairly constant (Alexander, 1981). The acceleration of the right upper arm was relatively constant while the acceleration of the lower arm displayed a large acceleration then deceleration. Chivers & Elliott (1987) stated that the sequence of the segment movements were such that the left arm attained peak angular velocity, then the right arm, the left forearm, then the wrists.

The right elbow was brought down medially and adducted to add force to the drive (Cohen, 1969; Kanjee, 1991a; Wein, 1979). Chivers & Elliott (1987, p.7) stated that the right elbow flexed to between 80° - 90° early in the downswing, causing the trajectory of the stick to curve backwards' before it continued 'downwards and forward in an oblique plane'. The trajectory of the stick during the downswing was not well described: the swing should be 'low' (CFHA Coaching Committee, 1983; Kanjee, 1991a), others (Broderick, 1981; Broderick & van der Merwe, 1982; Read & Walker, 1976; Wein, 1979) stated or implied that the swing should be almost vertical.

Perhaps one of the key aspects to a successful drive is the movement at the wrists. Chivers & Elliott (1987) stated that a wrist angle of 145° - 155° during the first part of the downswing tended to delay wrist uncocking. Cohen (1969) reported that the wrist action was most responsible for movement of the stick head and that the right wrist moved through 51° - 71° during the final .04 seconds before contact, which contributed to the force of the drive. Alexander (1981) noted that the acceleration of the stick through the final 45 degrees before impact was greatest (about 15.71 rad/sec^2 or 900 deg/sec^2) and was crucial to attain maximum velocity of the stick head at contact. Kanjee (1991a) attributed most of the latter acceleration of the stick to the uncocking of the wrists. Buzzell and Holt (1979), perhaps in describing the uncocking of the wrists, stated that, prior to contact, the left wrist was decelerated, which checked the forward movement of the grip of the stick and further accelerated the head of the stick. Although 'uncocking' and 'cocking' of the wrists was not explicitly defined in the literature, one 'cocks' the wrists by abducting them. In the field hockey drive it appears that both wrists are fully abducted. When the wrists are 'uncocked' they move from a position of abduction to one of adduction.

Chivers and Elliott (1987) added that the right forearm was pronated during the downswing and they felt this movement increased the velocity of the stick head as it came into contact with the ball.

Read and Walker (1976) stated that the wrists were "bent upwards" near the end of the downswing to delay the stick swinging through the ball and this movement of the hands added power to the drive. These authors also stated that in a short corner situation the striker should be positioned perpendicular to the path of the ball, as a golfer would, choke up on the stick, then use a short swing, either from the shoulders or using just the wrists. The feet should remain stationary and the rest of the body should be fairly rigid to add power to the hit. Based upon biomechanical principles (for example use of as many body segments as possible to generate force of the most distal segment), the drive described above would probably produce relatively low resultant ball velocities.

Reported stick velocities the instant before impact ranged from 21.18 - 31.42 m/s with an average of 25.55 m/s (Cohen, 1969; Hendrick, 1983) and Alexander (1981) reported an average angular velocity of 45 radians per second (rad/sec) or 2578.3 degrees per second (deg/sec). At contact, stick velocity ranged from

20.72 - 30.72 m/s with an average of 27.84 m/s (Buzzell & Holt, 1979).

Contact

The amount of force imparted to the ball at contact (Figure 9) was dependent upon the velocity of the stick head, the strength of the grip and the stiffness of the stick (Kanjee, 1991a). For maximum force application and greatest accuracy, the stick face must contact the ball squarely (CFHA Coaching Committee, 1983; Kanjee, 1991a). Barnes (1969), however, stated that the ball should be contacted during the upswing as this would give the ball "overspin" which would increase the distance it would travel. Usually, the ball is not contacted squarely due to incorrect placement of the feet with respect to the ball (CFHA Coaching Committee, 1983; Kanjee, 1991a;

Figure 9. Contact.

Wein, 1979). The left foot was pointed forward or diagonally forward (Alexander, 1981; Barnes, 1969; Chivers & Elliott, 1987; Hendrick, 1983) and that allowed for full range of hip rotation (Alexander, 1981). The right foot was perpendicular to the direction of the drive (Hendrick, 1983). Wein (1979), stated that the toes of both feet were pointed in the direction of the body, which seemed to imply that they were either perpendicular or pointed diagonally ahead. In Cohen's study (1969), which examined two subjects driving the ball in different directions from many different positions, the subject's left foot ranged from .30 - .91 m from the ball. In Hendrick's (1983) analysis of the stationary drive, she found a range of .24 - .65 m, with an average of .47 m, from the left toe to the ball. She also reported the width of the stance (measured from the toe of one foot to the toe of the other) ranged from .46 - 1.50 m, with an average of .68 m. Unfortunately, Hendrick did not list the height of the subjects tested. Others simply stated that the feet were about shoulder width apart (Kanjee, 1991a; Wein, 1979). Placement of the ball ranged from .10 - .15 m. ahead of the left foot for the running drive (Alexander, 1981; Wein, 1979), and between the center of the body (Wein, 1979) to directly opposite the left foot (Broderick & van der Merwe, 1982; Wein, 1979) for the stationary drive. Pollard (1959), stated that the ball was ahead of the left toe and the CFHA coaching committee (1983) stated that for a penalty corner the ball was opposite the left foot. If the foot placement at contact was too far ahead of the ball there was a tendency to hit the ball into the ground, if too far behind the ball, there was a tendency to undercut the ball (CFHA Coaching Committee, 1983; Kanjee, 1991a).

Alexander (1981) noted that, in some instances, the subject's right foot had come off the ground and swung behind and to the left of the left leg at contact (Figure 10). Chivers & Elliott (1987) stated that the right foot was being dragged across the ground at contact. Penalty corner strikers at the 1990 Champion's Trophy were also seen to have their right foot swing behind the left on almost every shot. Stacie, of Australia, and Weterings, of the Netherlands, had their right foot come off the ground during the downswing and it would eventually swing forward past their left foot during the follow through. The striker for Pakistan kept his right foot on the ground when shooting at the far post or at the centre of the goal, but it came off the ground when he shot at the near post.

At contact, the player's body weight had been shifted primarily forward to the left foot (Alexander, 1981; Chivers & Elliott, 1987; Cohen, 1969; Kanjee, 1991a). Others (CFHA Coaching Committee, 1983; Pollard, 1959; Wein, 1979) stated that at contact there was even weight distribution between the left and right foot, then, during

Figure 10. The right leg in a position of extension and adduction at contact.

contact, the weight was transferred forward to the left foot. Buzzell and Holt (1979) stated that the body's center of mass, the left shoulder and the left hip worked together as a unit, and moved backwards and upwards during contact to accelerate the right side of the body through the ball. The trunk was inclined 5° - 15° (Chivers & Elliott, 1987); if erect, the player would 'top' the ball (Kanjee, 1991a). The eyes were focussed on the ball and the head was over the ball (Barnes, 1969; Broderick, 1981; Broderick & van der Merwe, 1982; Heyhoe Flint, 1978; Pollard, 1959; Read & Walker, 1976). At contact the trunk had been rotated such that the left shoulder was pointed in the direction of the drive (Wein, 1979), while others felt that the chest was facing the direction of the drive, which implied greater rotation (Alexander, 1981; Cohen, 1969). Read and Walker (1976), stated that accuracy would be maintained if a player had a "high" left shoulder over a "braced" left leg.

At contact, both arms were fully extended (Alexander, 1981; Broderick, 1981; Read & Walker, 1976; Wein, 1979); Cohen (1969), however, stated that the arms were not quite fully extended and Chivers & Elliott (1987) reported left and right elbow angles at contact of 170° and 140° respectively. The wrists were at an angle of 165° - 170° (Chivers & Elliott, 1987) and the back of the left hand was near vertical and perpendicular to the direction of the drive (Kanjee, 1991a). The stick head was in line with (Broderick, 1981; Kanjee, 1991a; Read & Walker, 1976) or just behind the hands (Chivers & Elliott, 1987; Kanjee, 1991a).

Follow Through

Essentially, the follow through (Figure 11) was seen as a continuation of the previous motions (Alexander, 1981; Chivers & Elliott, 1987) and was simply a time during which the body and stick movements were decelerated then recovered to normal playing position (Kanjee, 1991a). During the follow through the left shoulder and the path of the stick were in the direction of the drive (Barnes, 1969; Broderick, 1981; Broderick & van der Merwe, 1982; Chivers & Elliott, 1987; Heyhoe Flint, 1978).

Ball velocities of 10.60 - 29.83 m/s have been measured (with an average of 18.49 m/s) (Alexander, 1981; Buzzell & Holt, 1979; Cohen, 1969; Hendrick, 1983) and Kanjee (1991a) has reported ball velocities of 49.17 - 53.64 m/s. In an interview (Kanjee, 1991b) Kanjee stated that most international short corner strikers hit the ball at about 110 m.p.h. (49.17 m/s), while Bovelander, of the Netherlands and Fischer of Germany hit the ball at about 130 m.p.h. (58.11 m/s) and that Fischer had been clocked with a radar gun at 138 m.p.h. (61.69 m/s).

a)

b)

Figure 11. Follow through of the stationary (a) and penalty corner (b) drive.

Summary

There were several different techniques used to approach the ball, however, it was generally agreed that at least one step towards the ball should be taken during the drive, especially in a penalty corner situation. Regardless of the number of steps taken, the player approached the ball from behind and to the left of the ball. The literature stated that, on a penalty corner, the striker should approach the ball in line with the direction of the drive. However, players at the Champions Trophy tournament were seen to approach the ball from an angle to the direction of the drive. At some point during the approach the backswing was started and it was timed such that the top of the backswing was reached as the player was in the action of planting their left or lead foot near the ball.

During the backswing the trunk was rotated to the right and the arms and stick were brought upwards and backwards such that, at the top of the backswing, the shoulders had been rotated approximately 90 degrees from their original position and the left arm was in a horizontal position across the body. At the top of the backswing, the right arm was flexed at the elbow at 125°, and the stick was pointed directly up into the air.

From this position, the stick was brought forcefully downward, through a combination of weight transfer from the right to left foot, hip and trunk rotation, adduction and extension of the arms, and uncocking of the wrists. These movements brought the stick down to contact the ball and had moved the athlete through a range of motion such that, at contact, the face of the stick was positioned squarely on the ball. The hands were in line with or ahead of the stick and the shoulders. The left shoulder was pointed in the direction of the hit and the head was over the ball.

During the follow through the player's stick continued on a path in the direction the ball had gone and the athlete decelerated their movements and returned to normal playing position.

Golf Studies

The key to attaining maximal ball velocity in the field hockey drive would seem to lie in the athlete's actions during the downswing. Actions performed before the start of the downswing were done to place the athlete in the correct position to execute the downswing (Kanjee, 1991a). While the movements of the golfer before the downswing are different from the movements of the field hockey player during the approach and backswing phases, the downswing of the golf swing and the stationary field hockey drive are very similar (Figure 12). The golf swing has been studied in more detail than the field hockey drive in the past and a review of relevant articles has brought forth some interesting points to look for in the field hockey drive.

Time of the Downswing

The time of the downswing for the golf swing ranged from .151 - .288 seconds (average .226 seconds) (Budney & Bellow, 1979b;

Figure 12. Downswing of golf drive. (Taken from Hardy, 1980)

Milburn, 1982; Nagao & Sawada, 1973; Nagao & Sawada, 1977; Neal & Wilson, 1985). This was comparable to the .15 - .21 seconds reported for the field hockey drive (Alexander, 1981; Chivers, 1987; Cohen, 1969), especially considering that the golf swing was performed through a greater range of motion: approximately 270 degrees, as compared to about 180 degrees for the field hockey drive.

Golf Research Studies

As the research studies on the golf swing varied somewhat in terms of methodology and in variables examined, each study will be presented separately.

Milburn (1982), modelled the golf swing based on a two-dimensional film analysis of five subjects. The model consisted of an upper segment, composed of the left arm and shoulder, pivoted at the shoulder joint, and a lower segment, made up of the hands and the club, hinged at the wrists. Milburn identified three distinct phases of the downswing, simply labeled: Beginning Stage; Transition Stage and Final Stage. The averaged results of the best trial of each subject were reported in the results. The total time for the downswing was .23 seconds, although it was noted that downswing times were quite variable, depending upon subject's technique and stature. The Beginning Stage occurred during the first .075 seconds of the skill, Transition Stage from .075 - .125 seconds and the Final Stage was from .125 seconds until contact (about .105 seconds).

During the Beginning Stage the wrist angle remained constant, about 60° - 70° (Figure 14a); Milburn noted that this was just under the full range of wrist cocking (90°), however, based on the definition of wrist angle given in the text (angle β, Figure 12), it is unclear how

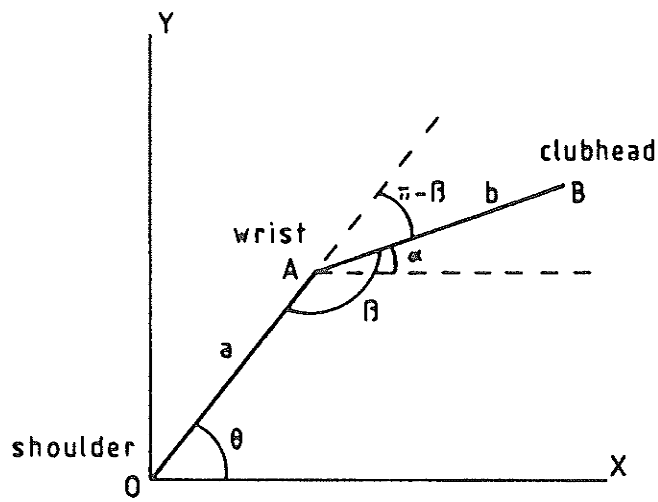


Figure 13. Definition of shoulder (θ) and wrist (β) angles. (taken from Milburn, 1982)

this angle could be less than 90° if 90° represented maximum wrist flexion.

Maintenance of this angle during this stage of the skill delayed wrist uncocking. Through this stage the shoulder angle increased 40°

- 66°, from a starting position of about 105° (taken from graph. Figure 14a). There was a steady increase in the angular velocity of the arm about the shoulder (approximately 12 rad/sec or 687 deg/sec: taken from graph Figure 14b) but almost no angular velocity of the club about the wrist. It should be noted that all velocities and accelerations for the club segment were measured relative to the arm segment. Greatest angular acceleration of the arm segment during the downswing occurred towards the end of the Beginning Stage: approximately 125 rad/sec^2 or 7162 deg/sec^2 (taken from graph, Figure 14c) at about .050 seconds.

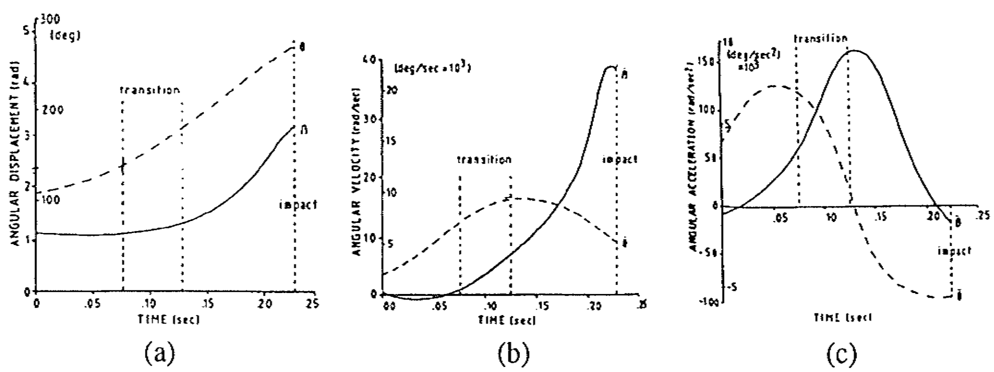


Figure 14. Displacement (a), Angular Velocity (b), and Angular Acceleration (c) of the arm segment (θ) and the club segment (β) relative to the arm segment.

The Transition Stage was marked by the start of the uncocking of the wrists. The angle at the wrist increased approximately 10° (taken from graph, Figure 15a) during this stage while the angle at the shoulder increased from approximately 132 - 180 degrees (taken from graph, Figure 15a).

The angular velocity of the arm segment increased from about 687 deg/sec (12 rad/sec) and then peaked at the end of the

Transition Stage at approximately 900 deg/sec (15.7 rad/sec; taken from graph, Figure 14b). The angular velocity of the club segment increased from near zero to about 300 deg/sec (5.2 rad/sec; from graph, Figure 14b) throughout this stage. The arm decelerated during this stage, dropping from a peak angular acceleration of about 125 rad/sec^2 (7162 deg/sec^2) to almost zero (Figure 14c). The angular acceleration of the club increased rapidly and peaked at the end of this stage at approximately 9000 deg/sec^2 (157 rad/sec^2; Figure 14c).

During the Final Stage, uncocking of the wrists continued until at contact the wrist angle was just less than 180°. Therefore, the hands were slightly leading the clubhead; the hands were also leading the shoulders at impact as the arm angle at that time was just over 270°.

During the Transition Stage, wrist uncocking increased constantly but during the Final Stage angular velocity of the wrist increased exponentially and peaked just before impact at almost 2300 deg/sec (ª40 rad/sec; Figure 14b). Angular velocity of the arm segment decreased from its maximum of about 900 deg/sec (15.7 rad/sec) at the end of the Transition Stage to approximately 500 deg/sec (8.7 rad/sec; Figure 14b) at impact. Milburn noted that even top professionals have difficulty in attaining maximal clubhead velocity exactly at contact. In this particular study maximum clubhead velocity occurred just before contact (.003 seconds before contact). At this time angular velocity of the club was greatest and angular acceleration was about zero. Maximum linear velocity of the clubhead ranged from 43.5 - 53.56 m/s.

The main purpose of this study was to determine the sequencing of segmental movements and how angular velocities produced in the proximal segments were 'summed' to produce a peak velocity at the distal end of the most distal segment (the clubhead). Several different theories were presented in Milburn's review of the literature; the findings of Milburn's study are reported below.

Delay of wrist uncocking during the Beginning Stage allowed for greater velocity of the arm segment to be reached before the club segment was moved from its 'resting' (relative to the arm segment) position. Acceleration of the club was then added to the existing angular acceleration of the arm segment. Milburn stated that the wrist joint acted as a free hinge joint once the club segment did start moving and that initial movement of the club segment (after a conscious effort to delay movement) was due to the inertial forces generated by movement of the proximal segment. The effect of the clubhead being pulled outwards was to slow the rotation of the arm segment about the shoulder joint. The slowing of the arm segment caused the club segment to straighten at an increased rate, such that, when the clubhead struck the ball it was travelling at near maximal angular velocity of the system (peak angular velocity actually occurred .003 seconds before contact).

Vaughan (1981) did a three-dimensional film analysis of the golf drive to determine the forces and torques involved in the downswing. It was found that, at the start of the downswing, movement was initiated by applying force along the shaft of the club and a counter-clockwise torque at the hands. During the first .85 seconds of the downswing the hands and the clubhead moved at the same velocity, then, .06 seconds before contact, the hands slowed and the clubhead accelerated. This was caused by a change in direction of force application along the Y-axis (horizontal axis along which the ball travelled) from positive to negative. At the end of the downswing the clubhead was brought into contact with the ball by a counter-clockwise torque about the length of the club shaft causing the clubhead to rotate and contact the ball squarely.

Vaughan found that the trajectory of the club during the downswing occurred in two different planes; one during the first .10 seconds of the downswing and another from that point until contact (approximately .10 seconds).

Neal and Wilson (1985) also performed a three-dimensional film analysis of the golf swing and calculated the kinematics and kinetics for a double pendulum model of the swing in an attempt to validate previous two-dimensional studies that used a similar model. Six subjects were filmed; the arms, forearms and hands formed one segment of the model and the club was the other segment. All results for the club segment were reported for the center of mass of that segment, not the clubhead. Average downswing time was .210 seconds and all subjects used the same club: a driver, .9 meters in length, with a mass of .394 kilograms (kg).

The three-dimensional reference frame used by Neal and Wilson defined the X-axis as the horizontal axis of the frontal plane (the X-axis was aligned such that it passed through the golfer's feet); the Y-axis as the vertical axis and the Z-axis as the horizontal axis of the sagittal plane. Displacement along the X-axis was initially in the negative direction as the club moved to the golfers right, then reached a minimum X-value as the club shaft approached horizontal (Figure 15). This was followed by wrist uncocking and movement of the club in the positive X-direction through impact. Wrist uncocking began about .100 - .080 seconds before contact; Milburn (1982) stated that wrist uncocking began about .155 seconds before contact. Along the Y-axis, the center of mass of the club travelled in a positive direction at first, then travelled downwards right through impact (Figure 15); this indicated that the club was still moving

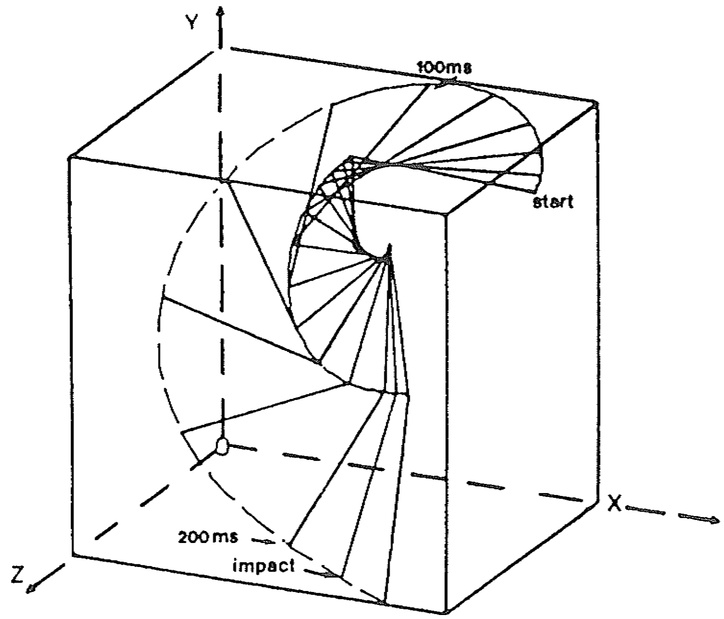


Figure 15. Three-dimensional schematic of the downswing in golf. (Adapted from Neal & Wilson, 1985)

downwards at the instant of impact. Displacement along the Z-axis showed that the club first moved in a negative direction, then in a positive direction until contact. Neal and Wilson stated that because the club was moving in a positive direction (away from the golfer) at impact, then the club approached the ball from a track inside the intended direction of the drive (Figure 15); the intended direction being along a line parallel to the X-axis. If a field hockey ball was contacted in this manner, with the stick moving downwards and away from the body, it would probably result in a mis-hit as the stick would contact the ground forcibly. It was also noted that the arc path of the downswing occurred through more than one plane. This would conflict with most previous two-dimensional models as they assumed the path of the club remained in one plane.

Starting from the top of the backswing, there was a gradually increasing negative velocity along the X-axis. As the club started to move forward, in a positive X-direction, the velocity increased rapidly, from about -18 m/s to a peak of approximately 31 m/s just after contact. This acceleration coincided with the uncocking of the wrists. The maximum resultant velocity of the club segment was approximately 63 m/s (calculated from reported angular velocity and length of the club) and the angular velocity of the CM of the club was 70 rad/sec at contact: 50 rad/sec about Y and Z axes and 0 rad/sec about X-axis. It was interesting to note that maximum linear velocity of the club was achieved after impact. Most other researchers (Cohen, 1969; Cooper et al, 1974; Hendrick, 1983; Milburn, 1982) reported decreased club or stick velocities after contact with the ball had been made.

Maximum acceleration of the club center of mass along the X-axis was 870 m/s^2 at .040 seconds before contact. The acceleration of the club then slowed until impact, although the acceleration was still positive at this time. Peak acceleration of the arm segment occurred .085 seconds before contact, while peak acceleration of the center of mass of the club occurred .025 seconds after that. This result seemed to agree with Milburn's (1982) statement that the proximal segment was accelerated first, the distal segment was then moved and acquired the acceleration of the proximal segment.

Neal and Wilson also examined the torque and force experienced at the wrist joint. They found that during the first .100 seconds of the downswing a positive torque about the Z-axis was applied by the golfer to prevent the angle between the club and forearm from decreasing. A negative torque was then applied for the next .060 seconds at the wrist joint maintaining the wrist angle and radius of the clubhead from its axis of rotation. After this time a large positive torque was applied to the club which accelerated it into contact with the ball. Initial maintenance of the wrist angle by the positive and negative torques calculated at the wrist joint agreed with Milburn's (1982) statement about conscious delay of wrist uncocking by the golfer. However, Neal and Wilson stated that torque was then applied at the wrist joint to accelerate the club into contact with the ball, and this seemed to contradict Milburn's statement that the wrist joint acted as a free hinge joint once wrist uncocking began.

Cooper et al. (1974) synchronized cinematographic and force data collection systems to study the golf swing. A two-dimensional film analysis was combined with the use of a series of force platforms. There was one platform under each foot of the golfer and these were resting upon a larger force platform which measured the forces exerted by the whole body. They compared differences in the kinematics and kinetics of five subjects, each using three different clubs: the driver, three iron and seven iron.

The following variables were tested: relationship between the position of the body's center of mass and force production throughout the swing; shift of the body weight during the swing; analysis of force components for the body and for each foot; angular displacements and velocities during the backswing and the downswing; ball and club velocity before and after impact, and the trajectory of the ball.

The sequence of the body movements during the downswing were: forward movement of the left knee, hip rotation, spinal rotation, shoulder movement, then wrist and hand movement. Minimum vertical head displacement occurred near impact.

For most of the skill there was even weight distribution between both feet; the center of mass was midway between the feet at the start of the downswing. About twenty-five percent of the force shifted forward to the left foot as the club contacted the ball. Maximal vertical force experienced was about 1.5 times body weight and occurred between the start of the downswing and the point at which the club reached the horizontal before impact. After impact, the weight shift continued, in most cases, such that at the end of the follow through 70 - 80 percent of the force was on the left foot. Rotational forces moved from a clockwise to a counter-clockwise direction from the start of the downswing until contact. The peak clockwise force occurred early in the downswing and the maximum counter-clockwise force shortly after impact (Figure 16). The change in the direction of the torque was due to the subject turning their body to better address the ball.

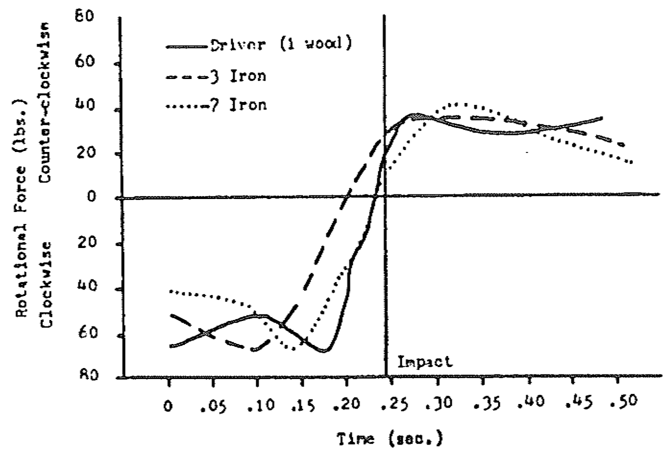


Figure 16. Ground reaction forces during the backswing and downswing. (Taken from Cooper et al, 1974)

Linear clubhead velocities increased up until the moment of contact for the driver and three iron, while peak velocity of the seven iron was reached well before contact and decreased until impact. Average resultant ball velocity for the driver was 62.59 m/s, 58.53 m/s for the three iron and 51.19 m/s for the seven iron. The authors could not explain the differences exhibited for the seven iron swing, other than to suggest that the subjects may have been trying for greater accuracy than distance with this club.

Nagao and Sawada undertook three separate studies on the golf swing (1973; 1974; 1977). The first was a two-dimensional film analysis of the swing of fourteen Japanese professionals, which compared their technique using a driver and a nine iron club. Time of the downswing with the driver ranged from .192 - .288 seconds with an average of .238 seconds; for the nine iron: .151 - .282 seconds with an average of .218 seconds. The driver was swung through an average angle of 271.4° and the nine iron through 234.3°. At the top of the backswing the driver was -1.9° below right horizontal, while the nine iron started the downswing from 24.8°

(measured from right horizontal with counterclockwise direction being positive). The driver contacted the ball at an angle of 269.5°, therefore the hands were directly above the clubhead, while the nine iron contacted the ball at 259.1° such that the hands were slightly in front of the clubhead.

It was also found that, while the downswing varied between different individuals, each individual maintained the same technique irrespective of which club they were using.

Subject's average height was 1.697 m and average stance (measured from left to right toe) was .648 m, or about 38 percent of body height, with the driver, and .443 m, or about 26 percent of body height with the nine iron.

No significant difference was found between the velocity at the grip end of the club for the driver and nine iron, however, there was a statistically significant difference between clubhead velocities. The authors felt that this difference was almost entirely due to differences in the length of the clubs. The average length of the driver was 1.09 m (43 inches) and the nine iron was .889 m (35 inches) long. Average ball velocity for the driver was 66.6 m/s at 10.82° above horizontal and 42.1 m/s at 23.50° for the nine iron.

For a follow-up study, Nagao and Sawada (1974) compared the drives of 14 Japanese professionals with two Caucasian and four Taiwanese golfers.

The golfers had a stance of approximately 42% of their body height. At contact, seven of the twenty golfers (6 Japanese and 1 Caucasian) had their "waist line" perpendicular to the direction of the hit, while the rest of the subjects' hips were open at contact (Figure

17). The left arm of 11 of the subjects was slightly bent at contact but the other nine subjects (eight Japanese and 1 Caucasian) had a fully extended left arm at contact. The forearm angles with respect to each other and with respect to the shaft of the club were measured at contact and averaged between groups. Overall, the angle between the forearms at contact was 47.97°; the average angle between the club shaft and the arms at impact was 48.93° for the right arm and .93° for the left arm. The authors noted differences between groups, but these may have been due only to differences in stature and not technique.

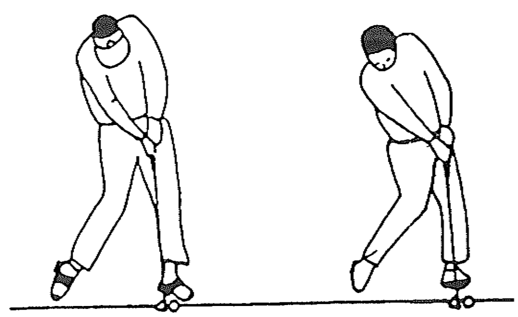
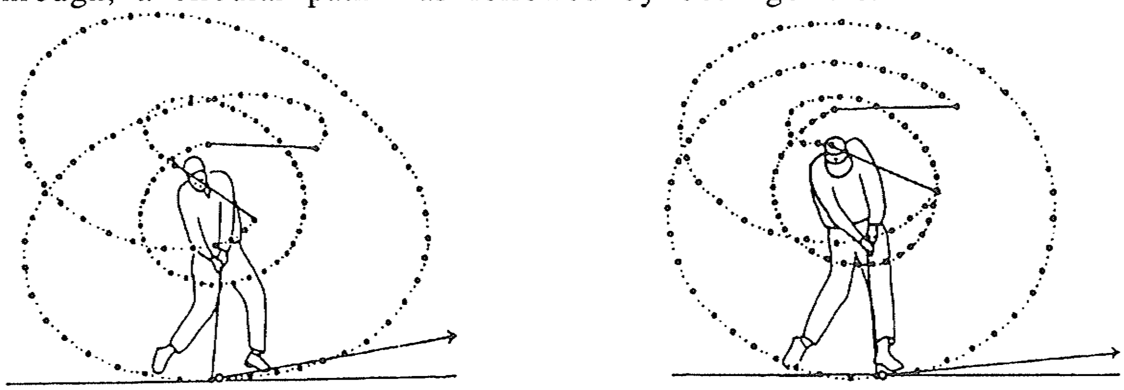


Figure 17. Comparison of golfers with 'open' and 'closed' hips at contact.

The authors concluded that the Caucasians produced greater ball velocities, took a quicker backswing and had faster grip velocity before and after contact than the other two groups. However, they failed to comment on the significance (or non-significance) of the variables reported above.

The final study by Nagao and Sawada (1977), looked specifically at the wrist action during the downswing. Two different swing patterns were found to be prevalent in all ten of their subjects (Figure 18). Subject A exhibited an oblique club path while subject B had an elliptical club path. The main difference between the two was seen within the first 180 degrees of the swing; during the final 60 - 45 degrees of the downswing, and through most of the follow through, a circular path was followed by both golfers.



(a) (b)

Figure 18. Comparison of golfers orbit of swing a) oblique for power hitters; b) elliptical for 'swing' golfers (Nagao & Sawada, 1977).

The authors stated that so-called "power hitters" tended to have an oblique swing, characterized by an almost horizontal club path during the initial stages of the downswing; while "soft swing" golfers displayed the elliptical swing pattern. This swing pattern is similar to that described by Chivers and Elliott (1987) for the field hockey downswing.

Rate of wrist uncocking was measured at .01 seconds before contact and it was found that power hitters had a faster uncocking speed at this time than did the soft swing hitters. Average angular velocity of the wrists at this time was 1234 deg/sec (21.53 rad/sec) with a range of 890 - 1690 deg/sec (15.53 - 29.50 rad/sec). The authors did not state why the oblique swing pattern would produce longer drives or how, specifically, the kinematics of the two swing patterns differed. They concluded that professional golfers with weak grip strength and muscle power may benefit from using the oblique swing pattern and gain more distance on their drives.

Budney and Bellow (1979a) developed a mathematical model of the golf swing based on a two dimensional stroboscopic analysis of six subjects. The main purpose of the study was to calculate the power attributable to arm swing motion and wrist uncocking in the downswing. They noted that other possible power sources in the swing included actions by the legs, the back and the shoulder muscles.

It was found that arm swing accounted for most of the work done during the downswing. The work done by the wrists was less for the professional golfers (negative for two of them) than the amateurs and they each exhibited negative torque at the wrists at impact (amateurs all had positive torques). Maximum arm power occurred .04 seconds before contact then decreased rapidly after that. The wrists did some positive work, then, .075 seconds before contact, performed negative work until contact. The authors stated that these results may have been due to the golfers generating such large angular velocities with the arm swing that the wrist uncocking could not be performed fast enough and therefore decelerated the club. Another explanation put forth by Budney and Bellow was that maximum tangential acceleration of the clubhead was being reached just before impact and the golfers had to apply greater grip force to the club to maintain its circular motion; increased mobility was also required at this time to accelerate the club into contact, it could not be applied because of the increased grip force and therefore the club was decelerated. They also noted that most subjects did not attain maximum clubhead speed until after impact. This result agreed with the findings of Neal & Wilson (1985); however, most other researchers (Cohen, 1969; Cooper et al, 1974; Hendrick, 1983; Milburn, 1982) reported decreased club or stick velocities after contact with the ball had been made. Club head speed at contact ranged from 42.7 m/s - 49.2 m/s with an average of 45.2 m/s.

Summary

In summary, examination of research on the golf swing revealed several variables key to successful performance of that skill and many variables that differentiated 'skilled' from 'unskilled' performers. Most researchers examined only the downswing phase of this skill, and many researchers did this through the use of a double-pendulum model. The downswing could be divided into at least two phases based upon movements of the golfer. During the first phase the golfer consciously maintained a set wrist angle, of about 65°, to delay wrist uncocking. The second phase was characterized by the start of wrist uncocking; greatest acceleration of the clubhead occurred during this phase to bring the clubhead into contact with the ball.

The hips, then the trunk, shoulders and the arms were sequentially accelerated during the downswing. Delay of wrist uncocking during the first stage of the downswing allowed for greater velocity of the arm segment to be reached before the club segment was moved relative to the arm segment. Acceleration of the club was then added to the existing angular acceleration of the arm segment during the second phase of the downswing. Initial movement of the club relative to the arm was due to the inertial forces generated by movement of the proximal segments of the golfer. The effect of the clubhead's radius of rotation increasing was to slow the rotation of the arm segment about the shoulder joint. The slowing of the arm segment caused the club segment to straighten at an increased rate, such that, when the clubhead struck the ball it was travelling at near maximal angular velocity of the system.

As impact was being reached, the golfer's weight was shifted forward onto the left foot to add momentum to the drive. Maximum clubhead velocity was reached either before, at, or after contact with the ball and the clubhead seemed to contact the ball as it was moving downwards and away from the golfer.

The downswing in golf seemed to be a similar movement pattern to the downswing in the field hockey drive. This does not imply that the kinematics of the two skills are the same or that values reported for variables in the golf drive would be representative of those of the field hockey drive. However, many of the variables found to be important to the golf swing were not evident in the literature on the field hockey drive. Because there is a similarity between the skills, it would be worthwhile to examine as many of those variables as possible in this study of the field hockey drive. The various research methods used in the golf studies could also be used in the analysis of the field hockey drive.

In summary, the following variables were examined in the golf studies and may be important to performance of the field hockey drive:

-length of the stance; absolute and as a percentage of body height

-angular displacement and velocity of the arms, wrists and club during the backswing

-path of the club during the backswing and downswing

-time and range of the backswing and downswing

-resultant and component angular displacement, velocity and acceleration of the left arm and wrist

-resultant and component angular displacement, velocity and acceleration of the club: grip, center of mass and head; both absolute and with respect to the left arm

-peak velocity, acceleration and time of peak velocity and acceleration of club, arm, wrist

-resultant and component linear and angular velocity and acceleration of the club and ball immediately before and after impact

-position and relative position of the hips, arms, hands and club at contact

-trajectory of the ball

-torques and forces at the wrist joints

-work done and power produced by the arms and wrists

-changes in grip force

-relationship between the position of the body's center of mass and force production throughout the swing

-resultant and component ground reaction force produced by the body and by each foot

-changes in kinetics and kinematics using different clubs

-changes in kinematics and kinetics for different body types

All of the above variables were studied only during the downswing unless otherwise specified. Some of these variables were measured through the use of force transducers or force platforms and therefore are beyond the scope of this particular study.

Mechanics Of Impact

The so called 'moment of truth' in the field hockey drive occurs during impact. In skills where implements are used to strike objects and propel them with as much velocity as possible or as accurately as possible, the crucial phase of the skill, the one that will determine resultant ball velocity and accuracy of the shot, is the impact phase. The main objective of the drive in a penalty corner situation is to hit the ball as hard as possible at goal. Resultant ball velocity is dependent on:

-the physical properties of the stick
-the physical properties of the ball
-the velocity of the stick head the instant before impact
-the angle between the stick and ball at contact
-the point of contact between the ball and stick

External factors that could influence resultant ball velocity include:

-the physical properties of the surface the ball is lying on
-the environmental conditions

The relationship of these variables and their role during the golf swing are well illustrated in Figure 19. Referring to Figure 19, the factors contributing to the clubhead conditions the instant before

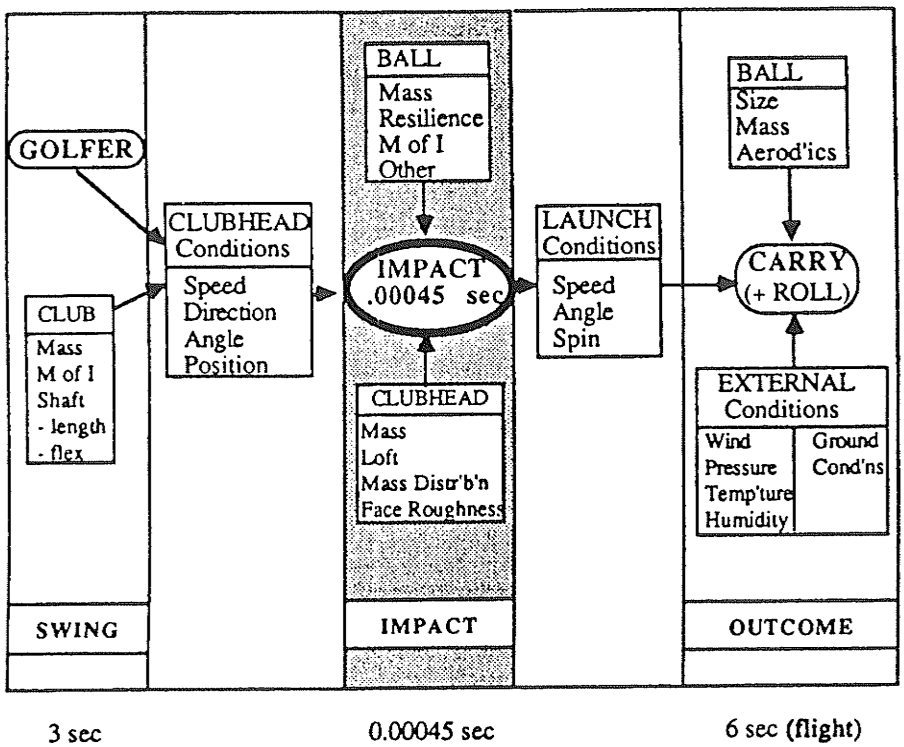


Figure 19. Factors affecting impact in the golf drive (Taken from Cochran, 1990).

contact are the movements of the golfer and the physical properties of the club itself. The factors determining the flight characteristics of the ball are the physical properties of the clubhead and the ball, the duration of contact, the 'launch conditions' (determined by the point of contact and the angle of contact between the ball and clubhead) and the clubhead conditions (or kinematics) the instant before impact. Movements of the field hockey player during the approach, backswing and downswing eventually bring the stick into contact with the ball and determine the linear and angular velocity and the position of the stick head at contact.

Impact Mechanics

Impact between a field hockey stick and ball would be classified as a partially inelastic collision. A partially inelastic collision occurs when an object is deformed upon impact with another object and then rebounds back to its original shape (Hibbeler, 1985). If the deformation of the object being struck exceeded the object's elastic limit, the object would not reform to its original form and the collision would be said to be completely inelastic or plastic (Hibbeler, 1985).

Collisions are most often analyzed using the impulse-momentum principle. Essentially, the relationship states that an objects' final momentum will be determined by its initial momentum and any impulses that act upon the object. The impulse-momentum relationship can be derived from the general case of Newton's Second Law:

$$\Sigma F = ma$$

which, in the general form is:

$$\Sigma F = d(mv)/dt$$

In this form one can see that the force, F, is equivalent to the change in momentum over time; momentum being the quantity described by an object's velocity and mass. The force applied over that time is the impulse, $\int F dt$. More specifically:

$$\Sigma\int^{t} F dt = m\int^{v} dv$$
$$\Sigma\int^{t} F dt = mv_2 - mv_1$$
$$mv_1 + \Sigma\int^{t} F dt = mv_2$$

Where F = force
m = mass
a = acceleration
v_1 = initial velocity
v_2 = final velocity
t = time

The final momentum of the object, mv_2, is equal to the initial momentum of the object, mv_1, plus the impulse applied to the object, $\Sigma\int^{t} F dt$. Considering the stick (with mass, m_s, and velocity, v_s) and the ball (with mass, m_b, and velocity, v_b) as one system, the instant before impact the momentum of the system is described by the momentum of the stick alone ($m_s v_{s1}$) as the ball is at rest.

While the ball and stick are in contact they exert forces against each other. In impact situations these forces are often called impulsive forces as they tend to be of high magnitude and act over a very short period of time. Scheie (1990), reported that the impact phase of the golf swing lasted for approximately .42 milliseconds (ms) and that the ball was accelerated from rest to a velocity of 225 ft/sec (68.58 m/s) during the first .209 ms. The average force over this time period was calculated to be about 3500 lb (15400 N); and it was estimated that the peak force was between 5200 lb - 7900 lb (22,880 - 34,760 N). These, of course, are enormous forces and if these forces were applied over any significant time period they would break the shaft of the club and probably shatter the ball.

Initially during impact the ball is deformed maximally, the force causing this deformation is called the deformation impulse, $\int P dt$. After maximum deformation of the ball has occurred, the club and ball travel at the same velocity for an instant. Then the ball will start to reform and will eventually leave the face of the striking implement. While the ball and stick are in contact with one another and the ball is reforming, the two objects exert a restitution impulse, $\int R dt$, against each other. The deformation impulse and the restitution impulse together form the total impulse of the system, $\int F dt$. The average force exerted during contact can be calculated by measuring the momentum of the system before and after contact and knowing the time of contact, as was done by Scheie (1990). After separation of the stick and ball, the final momentum of the system will be the momentum of the stick ($m_s v_{s2}$) plus the momentum of the ball ($m_b v_{b2}$).

The ratio of the deformation and restitution impulses is termed the coefficient of restitution, e. The coefficient of restitution of a ball can be determined by measuring the velocity of the ball before and after impact with an immovable object, i.e.. a hardwood floor. The coefficient of restitution would be the ratio of the ball's velocity before and after impact; e for a field hockey ball is .55 (Byrne, 1990a). The variables: e, mass and velocity, relate to each other through the following equation:

$$\frac{v_{b2}}{v_{s1}} = \frac{(1+e)}{1 + (m_b/m_s)}$$

or:

$$v_{b2} = \frac{v_{s1}\,(1+e)}{1 + (m_b/m_s)}$$

which is derived from the calculation of e and the law of conservation of momentum. From this equation it can be seen that the ratio between resultant ball velocity and the velocity of the stick just before impact varies directly with e and inversely with the ratio of the mass of the ball and the mass of the stick, (m_b/m_s). In golf v_{b2}/v_{s1} equals 1.4 (Daish, 1972); therefore the ball should leave the club face with a velocity 40% greater than the velocity of the clubhead the instant before contact. The coefficient of restitution is a constant whose value is dependent upon the physical properties of the ball (i.e.. materials and design) and will vary slightly under different temperatures and through different ranges of impact velocities. The mass of a field hockey ball and stick can vary little due to the regulations; the ball must have a mass of between 156 - 163 grams (g) and the stick can be no more than 28 ounces (.79 kg).

The absolute value of v_{b2} (resultant ball velocity) also varies directly with v_{s1} (stick velocity just before impact), and this is the only variable that the athlete has any control over during a specific impact. Stick velocity the instant before contact will vary with the strength and technique of the individual; it may also be affected by the mass and moment of inertia of the stick. The amount of force needed to accelerate the stick will vary directly with the mass and moment of inertia of the stick ($F = ma$; $\tau = I\alpha$). If one were to start with a stick of no mass and increase the mass of the stick in small increments for successive drives, one would eventually reach a point where the individual swinging the stick could not generate enough force to attain the acceleration of the previous drive. If, as one increased the mass of the stick, the distribution of the mass remained the same relative to the axis of rotation, then I (the moment of inertia) would also increase in proportion with the mass. The moment of inertia could also be altered by changing the distribution of the mass about its axis of rotation: $I = mr^2$; therefore changing the distance of the mass from the axis of rotation affects the moment of inertia exponentially. The moment of inertia will also vary according to the placement of the player's hands on the grip of the stick as this will determine the location of the axis of rotation. For example, if a player 'chokes-up' on the grip, the moment of inertia will be lowered. Assuming that each individual uses the same hand placement for each drive they take, then the properties of the stick that will affect the momentum of the system just before impact will be the mass of the stick and the moment of inertia for that particular hand placement on the grip.

What one wants to achieve during the drive is maximal velocity of the stick just prior to impact with as much mass as possible. The effects of varying m and I have been analyzed in the sport of golf using a 'mechanical golfer' and human subjects in which optimal values of m and I were calculated (Daish, 1972). In golf, swing weight is used to help describe the physical characteristics of a club; the swing weight of a club is its first moment of mass or the distance (d) of the center of mass from the axis of rotation times the mass itself (md). Letter-number combinations (i.e.. C-3) relating to a specific swing weight are stamped on the clubs. Heald (1974), assigned swing weights to a wide range of baseball bats and recommended bats of specific swing weights be used by various age groups. He also compared the effect of 'choking-up' on the bat to the resulting swing weight and time to complete the swing. It was found that swing weight was reduced by 17% by choking-up on the bat eight inches from the end, reducing the swing time from .125 seconds to .111 seconds. Choking-up on the bat four inches from the end reduced swing weight by 9% and decreased swing time by .007 seconds. A quantification such as this for field hockey sticks would greatly assist players in selecting suitable sticks and manufacturers in meeting customized orders from select customers.

Daish (1972) performed a study on varying the mass of the clubhead in golf and found the optimal mass to range from 200 to 250 g. From the following equation:

$$v_{b2} = \frac{v_{s1}\,(1+e)}{1 + (m_b/m_s)}$$

one can see that as m_s increases the ratio m_b/m_s approaches a minimum. The minimum value the denominator could assume would be a value of 1 and this would occur when m_b/m_s equaled zero. For the ratio to approach zero, m_s would have to be very massive indeed and, assuming the subject could swing a club with infinite mass at the same velocity as a 'normal' club, the increase in resultant ball velocity would only be about 1/5 of $v_{s1}(1+e)$. If the club velocity the instant before impact were 30 m/s, this increase would be approximately 9.3 m/s. In Daish's study (1972), the mass of the clubhead was incremented by 50g, from 150g to 400g, and it was found that the optimal mass of the clubhead was between 200g and 250g. However, the differences in the resulting length of the drive with each clubhead was small:

Clubhead Masses (g)	150	200	250	300	350	400
Length of Shot (m)	208	209	209	206	204	202

Two final considerations concerning stick design and impact are the stiffness of the stick and the location of the stick's center of percussion (COP). Byrne (1990), stated that, optimally, a field hockey stick should be flexible initially and get progressively stiffer as contact continues. Loss of energy transfer from the stick to the ball can occur due to deformation of the face of the stick, straightening of the shaft of the stick and the generation of heat and sound.

The COP of the stick is the point along the length of the stick where, when impact occurs, there will be maximum transference of energy from the stick to the ball and there will be no reaction at the hands (axis of rotation). Theoretically, then, contacting the ball at the COP should produce the greatest resultant ball velocities. Brody (1986)(as reported in Weyrich et al, 1989) found that greatest rebound velocity in baseball batting occurred at a point between the COP and the axis of rotation. Weyrich et al (1989) found that greatest rebound velocity occurred at COP; testing procedures were such that baseballs were 'pitched' at a stationary bat and ball rebound velocity was measured. The authors noted that in a dynamic situation the end of the bat would have the greatest linear velocity and because of this, contact at this point may produce greater relative ball velocities than were found in this study. In field hockey the ball is normally on the playing surface when contacted and therefore contact must occur at the end of the stick. Whether this point coincides with the COP or not is unknown. Weyrich et al (1989) stated that the COP was located 11.14 cm from the distal end of an aluminium bat and 14.83 cm from the end of a wooden bat of the same length.

Finally, the surface the ball is lying on may also affect resultant ball velocity. There are four possible impact situations between the stick and a stationary ball resting on the playing surface: 1) the stick contacts the ball as it is travelling in a perfectly horizontal path, 2) the stick hits the ball into the playing surface, 3) the stick contacts the surface then the ball, 4) the stick contacts the ball but in an oblique manner such that the ball is either undercut or topped. The results of these impacts will be that the ball will either rebound from the surface, roll or roll and slide along the surface, or the ball will travel through the air. It is possible the ball will travel faster in air than rolling on turf; whether the difference is significant or not and whether as much force could be imparted to the ball if trying to raise it would have to be examined. Some penalty corner strikers have been known to hit the ball such that it arcs over the prone goal keeper and comes down to contact the backboard (the rules state that the ball must be no higher than the 18" backboard for a goal to count). The results of each of these contact situations should be measured and calculated to determine the best strategy for the penalty corner striker.

The subject of impact in the field hockey drive needs further investigation. Its inclusion in this paper was to give an indication of the variables involved in impact situations; their relationship may not be exactly the same for field hockey and golf. However, based on golf impact, it was shown that the only variable the athlete could vary significantly was the velocity of the club just before impact; and this variable may be affected by strength and technique, which could the same as for the field hockey drive.

Review Of Research Methods

Three-Dimensional Filming Techniques

The field of biomechanics has undergone significant advances over the past two decades in terms of research methods and techniques. This has been due, in large part, to technological advances in instrumentation available to the researcher to collect, reduce and analyze data. The use of micro-computers and the development of software and hardware specific to researcher's needs have led to the present state where the tools used to analyze human movement are very sophisticated

The area of cinematography has also advanced significantly, from the use of single-plate methods to three-dimensional, multiple-camera set-ups. During the early 1970's many methods were developed to obtain three-dimensional data from two or more cameras. Most of these techniques required very exact measurements of the camera's orientation relative to the object space and the other cameras as well as the distance from the lens to the film plane. Many of these measurements had to be performed using surveying equipment and if the measurements were not exact, the data collected would be inaccurate.

By adapting methods used in close-range photogrammetry, it was possible to eliminate many of the tedious measurements previously required to obtain three-dimensional film data. Most notable was the use of direct linear transformation (DLT) to calculate three-dimensional coordinates from two-dimensional data collected from two or more cameras focussed on the same event (Shapiro, 1978). Essentially, the DLT method requires the filming of known points (control points) located throughout the object space. The three-dimensional coordinates of these control points relative to each other must be known or measured precisely.

Digitization of the control points from film yielded two-dimensional coordinates of each point for each camera. By knowing the three-dimensional coordinates of each point, it will be possible to develop a series of equations to transform two-dimensional coordinates from each camera into three-dimensional coordinates for each unknown point in the object space (i.e.. a point on the subject's body).

Typically, the field hockey drive has been analyzed using two-dimensional film analysis with the camera positioned either behind or to the side of the athlete, or from an overhead position. Taken separately, each of these views will have some out-of-plane movement; that is, movement either away from or towards the camera. Two-dimensional studies with multiple cameras may capture this out-of-plane movement, but, unless three-dimensional coordinates are obtained, accurate quantification of the subject's movements would be difficult. To accurately describe skills involving general plane motion in three-dimensions it is necessary to perform a three-dimensional analysis of the skill.

Regression Analysis

At a given level of ability, performance is often determined by an individuals' strength and technique, as well as some innate factors. In analyzing an athletes' performance it is often beneficial to know more precisely which variables contribute most to the performance; this must be done in a objective manner (Hay et al., 1981).

In the field of biomechanics, an athletes' performance is often recorded on film and later analysis of the film can yield almost any measure of any number of kinematic variables. The data obtained from the film analysis can then be examined statistically by either correlational or contrast methods (Hay et al., 1981). Correlational methods, such as multiple regression, can be used to identify which independent variables are highly correlated to some criterion or dependent variable (which would be a measure of performance). This would help to determine which variables are most important to performance of the skill (Hay et al., 1981). For example, ball velocity in the field hockey drive could be labelled as the criterion variable and various technique or anthropometric variables could be correlated to ball velocity to determine which of these best predict successful performance.

Hay et al. (1981) listed some weaknesses of this type of analysis as follows:

1) The selection of the independent variables is often done subjectively, with the chance for omission of relevant variables as well as the opportunity for bias by the researcher.

2) The independent variables are not ranked objectively, therefore, when the variables are entered into the regression analysis they are not entered in the appropriate order.

3) Results could also be influenced by researcher bias during post-hoc analysis of the data.

4) Procedures are often non-systematic.

5) Small sample sizes may affect results and make them non-generalizable.

6) Multi-collinearity: dependence of independent variables on each other. i.e.. the independent variables not independent of each other.

A research method often used in exploratory studies is that of multiple regression analysis. This method computes the statistically significant contribution of all identified variables to the level of some criterion variable. Multiple regression has been used fairly extensively in biomechanical research (Berg et al., 1986; Hay & Miller, 1985a; Hay & Miller, 1985b; Marino & Dillman, 1976; Yates, 1982).

Kinanthropometry

From a biomechanical perspective, the human body is viewed as a series of connected, rigid levers that are moved by muscle contractions. The parameters of these body movements that the biomechanist is interested in are the length of the levers and the amount of force the muscles can exert to move these levers; to calculate ground reaction forces, segment centre of mass (CM) and moments of inertia would also have to be measured. The length of each lever is fixed and the amount of force muscles exert is dependent upon the individuals' strength and the point of attachment of the muscles from their axes of rotation. In cases where a striking implement is used the implement is considered as another lever. The length of this lever is dependent on the implements' absolute length and the point at which the subject grips it.

Segment lengths and breadths were measured from each subject to determine the effects of variation of these anthropometric variables. Measurements were also taken to estimate the individuals' muscle mass, using a regression equation developed by Martin (1990), to estimate differences in overall strength between subjects.

All anthropometric measures were taken according to specifications listed by Ross and Marfell-Jones (1991).

Methods of Related Studies

Past analysis of the field hockey drive has been conducted through the use of two-dimensional filming using one (Buzzell & Holt, 1979; Hendrick, 1983) or more cameras (Alexander, 1981; Alexander, 1985; Cohen, 1969) and through the use of three-dimensional filming techniques (Chivers & Elliott, 1987). The filming rates used for these studies were 64 frames per second (fps) (Cohen, 1969), 80 fps (Buzzell & Holt, 1979), 100 fps (Alexander, 1981; Alexander, 1985) and 200 fps (Chivers & Elliott, 1987; Hendrick, 1983). The subjects used were all female except for Chivers & Elliott (1987) who analyzed six males and six females. Other researchers used from two to twenty-five subjects. The skill level of the subjects ranged from university (Hendrick, 1983) to provincial (Buzzell & Holt, 1979; Chivers & Elliott, 1987) to international (Alexander, 1981; Alexander, 1985; Buzzell & Holt, 1979; Chivers & Elliott, 1987; Cohen, 1969).

The variables measured in these studies are listed below:

-Temporal periods of the downswing, contact and follow through phases, both relative and absolute (Alexander, 1981; Hendrick, 1983).

-Body position and position of the center of mass with respect to the ball at contact (Hendrick, 1983) and throughout the skill (Alexander, 1981; Buzzell & Holt, 1979).

-Width of the stance, relative to the subject's height (Hendrick, 1983) and position of the feet relative to the ball (Alexander, 1981; Cohen, 1969; Hendrick, 1983).

-Position of the head with respect to the ball (Hendrick, 1983).

-Angular displacement and velocity of the wrist and elbow (Cohen, 1969; Hendrick, 1983).
-Upper and lower arm velocities and accelerations (Alexander, 1981).
-Inclination of the upper arm, lower arm and stick with respect to vertical (Cohen, 1969).
-Pelvic and upper trunk rotational displacement (Cohen, 1969).
-Stick and ball velocities (Alexander, 1981; Cohen, 1969; Hendrick, 1983).
-Shoulder position at the top of the backswing and at contact (Cohen, 1969).
-Angle between the shoulder line and the path of the ball (Cohen, 1969).
-Height of the backswing (measured as height of the stick above the shoulder) and relationship of the height of the backswing to ball velocity (Alexander, 1981).
-Relationship between anthropometric measures: height, weight, arm, leg and stick length and ball velocity (Alexander, 1981).
-Type of grip used (Alexander, 1981).

Cinematographical procedures in the relevant golf studies ranged from single-plate methods (Neal & Hubinger, 1990), to single high-speed cameras (Cooper et al, 1974: 200 fps; Milburn, 1982: 300 fps; Nagao & Sawada, 1973; Nagao & Sawada, 1974; Nagao & Sawada, 1977: filming rates not reported), to three-dimensional analysis (Neal & Wilson, 1985: 294 fps; Vaughan, 1981: 300 fps). Scheie (1990), filmed the impact between the clubhead and the ball at a filming rate of 10,000 fps. The number of subjects used ranged from 1 (Neal & Hubinger, 1990) to 20 (Nagao & Sawada, 1974).

CHAPTER 3

METHODS AND PROCEDURES

Subjects

The subjects for this study were 17 senior provincial field hockey players (9 male and 8 female) from the province of Manitoba. Four of the male subjects had previous international experience, one was a member of the Canadian National Team, two had experience with the Junior National Team and two were senior provincial players. One subject was the former penalty corner striker for Canada for four years and during this time was ranked eighth in the world (Kanjee, 1991b). Seven of the other male subjects had experience as penalty corner strikers for their respective provincial or club teams (See Subject Profiles, Appendix 1).

Four female subjects had previous international experience, the other four had played at the senior provincial level and two of these subjects had, in the past, been invited to national training camps. One subject was a penalty corner striker at the international level and five others had, at one time or another, taken penalty corner hits for their respective provincial teams. The other two subjects were chosen based on subjective analysis of their ability to hit the ball with high velocity.

Subjects were contacted, asked to participate in the study and experimental procedures were explained to them. Subjects were chosen based on subjective evaluation of resultant ball velocity in the stationary drive. These seventeen players represented the elite group of all available subjects (all senior and junior provincial field hockey players) in Manitoba.

Filming Equipment

The filming set-up is illustrated in Figure 20. Film data was collected using two video cameras; a Panasonic camcorder, model PV-460D-K/PV-A22MC-K and a Panasonic Digital camera with system camera WV-D5100, system camera kit WV-S061 with the Gen-Lock adapter and a zoom lens, model WV-LZ14/12A. The digital camera was connected to a Panasonic portable VCR, model AG-7400, and both were powered from a Motomaster Eliminator 700 amp car battery. The camcorder was powered from a standard electrical outlet using an AC adapter. Both cameras had variable shutter speeds of up to 1/500 seconds (1/2000 seconds for the digital camera). Because filming took place indoors, an additional light source of two 1500W flood lights was also used.

A time-code generator, TCG-1000 by Comprehensive Video Supply Corporation, which outputs a SMPTE time-code signal, was connected to both recording devices and placed a time-code on each. The signal was sent to the time-code in/out port of the portable VCR and recorded through the time-code channel of the VCR, then sent to the camcorder where it was recorded through the external microphone jack onto the audio track of the tape. Placing the time-code on the film allowed the computer to distinguish one frame from another and import the appropriate field for digitizing. The video

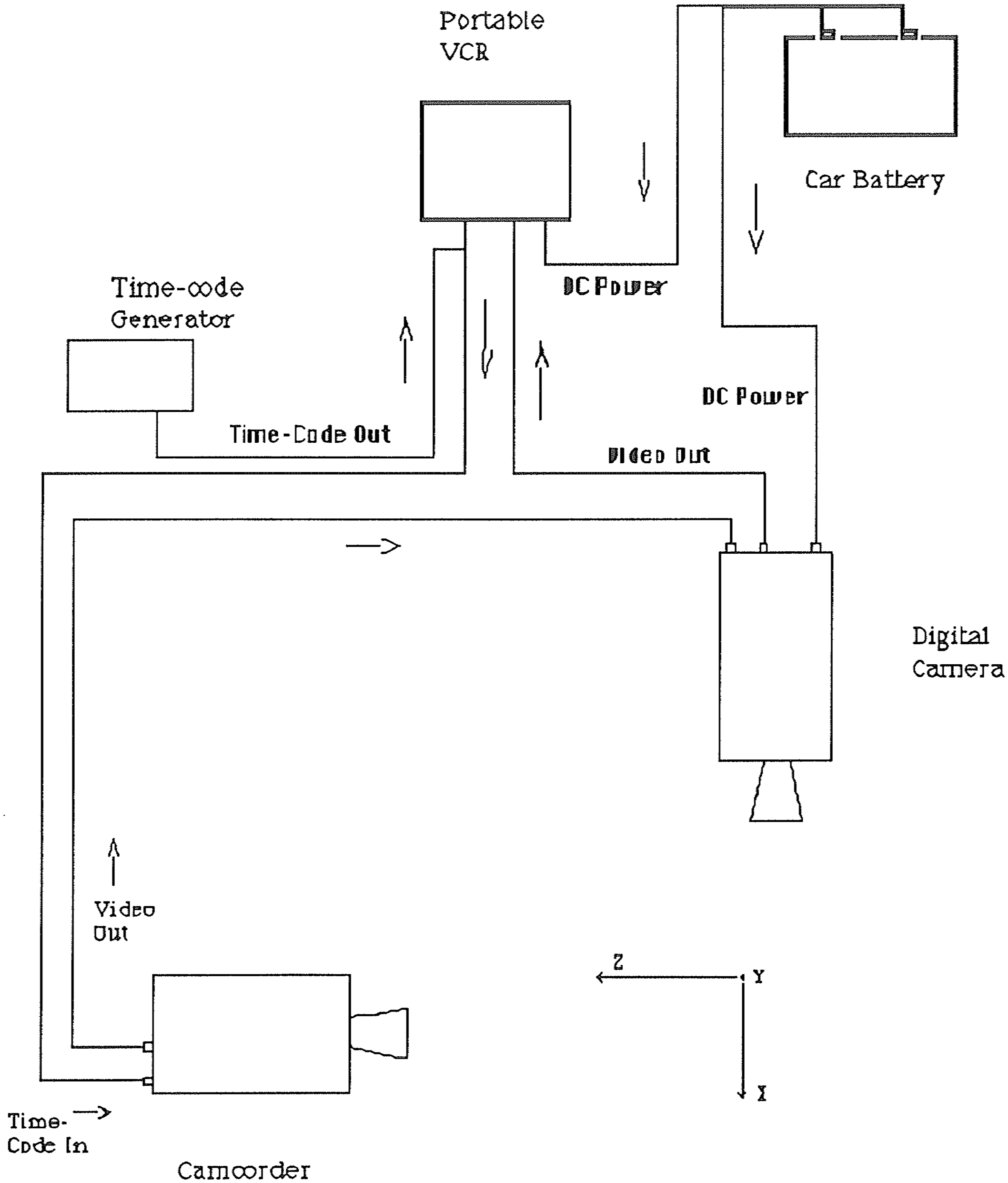


Figure 20. Overhead view of filming Set-up.

signal from the camcorder was sent to the Gen-lock adaptor on the digital camera which locked the frame advance mechanism of both recorders and ensured that each camera's shutter opened simultaneously.

After the filming equipment had been set up, the Peak calibration frame was assembled and placed within the object space, or the space in which the player hit the ball. The Peak calibration frame consists of a rectangular block, block number B-6, with eight threaded holes drilled into each corner of the block. A rod, with three white balls placed 39.4 cm; 92.0 cm and 165.1 cm, from the block end, was screwed into each corner of the block. The balls (or control points) essentially form three cubes in space and the three-dimensional coordinates of each control point had been accurately measured relative to each other, with one of the balls being the origin, (0,0,0). The reference frame used by Peak defines the vertical axis as the Y-axis and the X and Z-axes define the horizontal plane (Figure 20).

To account for possible variation due to the make and model of sticks and balls, each subject used a Slazenger "Carbo" field hockey stick, .90m in length, weighing 625 g and a regulation field hockey ball, Alfred Reader GT dimple.

Peak Analysis Equipment

The Peak analysis equipment consists of an IBM compatible 386-20 computer, a Panasonic AG-7300 VCR and a Sony Trinitron PVM-1341 colour monitor. The Peak Performance analysis system employs a 'Frame Grabber Board' in the computer which separates the video frame into its two fields and displays one field on the monitor. By dividing each frame into its composite fields, the program provides a filming rate of 60 fps, instead of the standard 30 fps. This board also displays a cursor on the monitor to allow for digitizing. The monitor screen contains 512 x 512 pixels, the cursor has a sensitivity of one-half a pixel, providing measurements well within acceptable error limits below that of the recording sensitivity; approximately ±2mm, assuming an object field of 2 m.

A project file was created for each filming session; the project file contained the direct linear transformation (DLT) equations. The DLT parameters for the filming session were established by digitizing the 24 control points on the calibration frame from the film from both cameras. The known three-dimensional coordinates of the control points on the calibration frame, relative to each other, were entered into the project file. Digitization of the control points resulted in two pairs of x,y coordinate data (one pair for each camera) in scale units; knowing the 3-D coordinates of the control points, the computer used the twelve DLT equations developed by Abdel-Aziz (reported in Shapiro, 1978) to solve for the eleven unknown DLT parameters and determine the spatial coordinates of each control point, relative to the origin (one of the control points) in real units. The program calculated the standard error in the calculated value of each DLT parameter and the residual error in the calculation of the spatial coordinates of each control point for both component and resultant coordinates. The program also output the average mean square error associated with the calculation of x, y, z and resultant coordinates of the 24 control points. Additional parameters could also be calculated to correct for lens distortion.

Testing Procedures

Subject's height, weight, segment lengths, girths and two skinfold thicknesses were recorded before they started their warm-up and joint markers were placed on the subjects at this time. Subjects were instructed in the testing procedures, then given time to warm-up. Informed consent was obtained from each subject before any testing began.

Four subjects were filmed during each filming session. When the first subject was ready, they performed five successive stationary drives at a target 10m away; the next three subjects then followed. If the ball was mis-hit during one trial, another trial was recorded for that subject. While waiting to perform the penalty corner drive, subjects were able to continue practicing in an area next to the testing area. The object space was illuminated with two flood lights and each camera was positioned as far away as possible from the object space. The cameras were then zoomed in such that the most distal control points on the calibration frame were located in the corners of the viewfinder of each camera. The shutter speed of each camera was set at 1/500 of a second and the calibration frame was then filmed for approximately one minute. After each subject had performed five stationary drives, both cameras were zoomed out, as necessary, to a position that would capture the approach phase of the penalty corner drive of each subject. The cameras were then left at that setting and the first subject performed five successful penalty corner drives, as did the other three subjects. After each subject had performed the penalty corner drives, the calibration frame was again filmed for approximately one minute so that the DLT could be performed for the trials filmed with the adjusted camera settings.

Ball velocity was determined for every trial filmed using the Peak 2-D analysis software. Using the film data collected from the side-view camera, the ball was digitized from contact until it had gone out of the camera's view. The multiplier used was the distance between two of the control points on the calibration frame. The 'best' trial, the trial representing the greatest ball velocity, on each skill, for each subject, was further analyzed using the Peak 3-D system.

Once the DLT parameters had been determined to within an acceptable error level, a 'best' trial was selected for the stationary and penalty corner drive for each subject. Each frame of film was then digitized for these selected trials. After both views of a trial had been digitized, the three-dimensional coordinates for that trial were calculated using the DLT equations and parameters stored in the project file. The 3-D coordinates of the body landmarks (28 selected points on the subject's body, the stick and the ball) could then be calculated by DLT of the two-dimensional coordinates from the two cameras. The DLT program calculates the 3-D coordinates in meters, changing the coordinates from scale units and storing the component and resultant displacement data in a data file on the hard drive. At this time the data was also smoothed, at 11 Hz cut-off frequency, using a fourth order, low pass Butterworth digital filter.

Film Data Analysis

After the 3-D linear displacement data file had been created, the linear and angular velocities and accelerations were calculated, as well as the angular displacement data, each being stored in separate files. The Peak Analysis System uses a central order difference method to calculate velocity and acceleration. This method accounts for displacement in the two fields before and after the field of interest, and velocity is calculated by interpolating the slope of the displacement curve at the time of the field of interest.

The stationary and penalty corner drives will be described, based on the averaged results of the male and female subjects, for the following variables:

1) Resultant ball velocity.
2) Temporal periods of each phase of the skill (Approach; Backswing; Downswing; Contact; Follow Through); relative and absolute.
3) Body position; position of each segment, at the beginning and end of each phase of the skill
4) Displacement of each body segment through each phase of the skill
5) Absolute and relative measures of width of stance and the length of each step; measured from the toe of one foot to the toe of the other.
6) Position of the feet relative to the ball at contact; the distance of the left toe from the ball and the orientation of the feet.

7) Movement of the right foot after the left foot has been planted.
8) Inclination of the trunk, upper arm, lower arm and stick with respect to the horizontal.
9) Hip, shoulder and stick rotational movements relative to the planted left foot from the time the foot strikes the ground until impact of the stick with the ball.
10) Height of the backswing.

Statistical Analysis

Although the field hockey drive had been described in the literature, it had not been explicitly stated which variables were most important to performance of the skill. Coaches normally select three or four of the most skilled hitters on the team and develop these players into penalty corner strikers. Of these, usually only one player will take penalty corner hits in competitions. Are there other predictors the coach should be looking for when selecting penalty corner strikers? If the coach were aware of some of the determinants of high ball velocities he/she may be able to more accurately select penalty corner strikers.

Ball velocities for each trial of the stationary drive were averaged for each subject, as were ball velocities obtained for the penalty corner drive. Simple regression was performed on these results to see if there was a relationship between performance on the stationary drive and performance on the penalty corner drive.

One of the purposes of this study was to develop a statistical model of the field hockey drive, through regression analysis of selected variables measured on the 17 subjects. The variables selected for the regression analysis fall into three areas: anthropometric variables, temporal variables and technique variables; the temporal and technique variables can be measured through video analysis.

Results of these measures were compared to stationary and penalty corner drive ball velocities to determine the factors most closely related to producing high ball velocities. Correlation matrixes containing all independent variables, as well as the dependent variables, was completed for each set of variables. The correlation coefficient between each independent variable and the dependent variable, ball velocity, was compared. As well, the correlation between each independent variable was examined to try and eliminate any multicollinearity, which occurs when independent variables are actually interdependent. If independent variables were highly related to one another only one would be kept for further analysis. Through this process a small number of variables were selected to be input into a multiple regression and a stepwise multiple regression equation. The results of these regression equations were reported for each set of variables for both the stationary and penalty corner drive.

Once the number of independent variables were reduced, multiple regression was used to analyze the relationship of these variables to resultant ball velocity. This form of analysis determines the relative contribution of each independent variable that is input and calculates a linear equation incorporating all the independent variables. This equation is of the following form:

$$y = a_1x_1 + a_2x_2 + a_3x_3 ... + a_nx_n + b$$

where: a = regression coefficients
x = independent variables
b = Y-intercept

The regression coefficients indicate the influence of that independent variable on the dependent variable (ball velocity). For example, if x_1 was the independent variable 'length of final step', measured in cm, and its regression coefficient, a_1, was +.978, that would indicate that, when the other independent variables remained constant, for each increase of length of final step of 1 cm, ball velocity increased .978 m/s. Stepwise multiple regression evaluates the contribution of each variable to explaining the variation in the dependent variable. If a variable did not make a statistically significant contribution to predicting the dependent variable it was eliminated from calculation of the regression equation.

The independent variables not eliminated previously were used in the stepwise regression analysis and an equation was developed with the variables that contribute significantly to the explanation of the dependent variable. Once the regression equation for the results of the stationary drive was determined, the same process was then performed on the data of the penalty corner drive.

All statistical procedures were carried out using the Statview II program on a Macintosh SE microcomputer. For this study, independent variables were selected based on a review of the literature. The stepwise multiple regression program used did not require a specific ordering of the independent variables to be used in the equation. The program first selected the independent variable which provided the greatest explanation of variation in the criterion variable, based on calculation of a partial F-ratio. It then passed through all the remaining independent variables to determine the next most significant variable, after accounting for the variation explained by the first variable, until no variables contributed further to the equation.

All film data was systematically treated through a series of computer programs which calculated all values of all the independent variables for each subject, which should eliminate any chance of post hoc bias by the researcher. While the sample size for this study was small (n=17) (Hay (1981) suggested a sample size of 150 subjects), it consisted of all elite field hockey players available to be tested.

A correlation matrix was developed for each set of data, anthropometric, temporal and technique for both the stationary and penalty corner drives, to determine any correlations between independent variables and between each independent variable and the dependent variable. Independent variables which were highly correlated to each other were not incorporated into the final step-wise multiple regression equation. This also reduced the ratio of independent variables to subjects.

CHAPTER 4

RESULTS

Filming Results

Seventeen subjects were examined in this study, 8 females and 9 males. The technique variables of 2 males performing the penalty corner drive could not be used in the data analysis because the calibration frame was not filmed after changing camera settings, therefore, the object field could not be scaled properly.

The direct linear transformations (DLT) to obtain the three-dimensional coordinates had an average mean square error (averaged over each filming session) of 17.24mm along the X-axis; 17.37mm along the Y-axis; and 11.27mm along the Z-axis. This resulted in an average mean square error of 26.91mm for the calculation of position. Over an object field of approximately 2.5 m, this coincides with an error of about 1%. Average standard error of the DLT parameters for each filming session for the Panasonic camcorder was .0375 and for the Panasonic digital camera was .0346.

Ball Velocity

Average ball velocity for the stationary drive was 26.44 m/s (Table 1) and average ball velocity for the penalty corner drive was 28.11 m/s. On average, the male subjects performed better than the females (Table 1). On the stationary drive four female subjects' drives were in the same range as the men while on the penalty corner drive all males hit the ball harder than every female except one.

The greatest ball velocity was attained by the same subject for each skill, S16, with a value of 32.64 m/s for the stationary drive and 38.93 m/s (87.08 mph) on the penalty corner drive.

Table 1. Average ball velocities on the penalty corner and stationary drives for all subjects. The results of the group are also displayed by gender.

		Average (m/s)	St. Dev. (m/s)	Range (m/s)
Stationary Drive	Group	26.44	3.795	19.78-32.64
	Males	28.61	2.753	23.39-32.64
	Females	23.99	3.371	19.78-29.36
Penalty Corner	Group	28.11	5.75	19.62-38.93
	Males	31.99	3.289	28.92-38.93
	Females	24.12	4.10	19.62-31.46

There was a significant relationship between the results of each skill (Table 2), indicating that subjects who performed well on the stationary drive were also better performers on the penalty corner drive.

TABLE 2. Simple Regression results of stationary ball velocity versus penalty corner ball velocity.

r^2	Adj. r^2	Probability	F-Test
.708	.688	.0001	36.289

Anthropometric Measures

The anthropometric variables are listed in Table 3 (individual anthropometric data is in Appendix A); these variables were also calculated in relative terms as a percentage of body height or mass.

With the mix of males and females in a relatively small sample (n = 17), there was an attempt to do the statistical analysis on the entire subject group. With the known anthropometric differences between males and females, simple regression was first done between the anthropometric variables and ball velocity keeping males and females in separate groups. The regression line for each variable was visually inspected; if the slope of the regression line was similar for the males and the females then that variable was included for regression analysis for the entire group. Relative muscle mass was not input into the equation as the formula to calculate muscle mass had not been verified on females (Martin et al, 1990).

Through this process a number of anthropometric variables were chosen which displayed similar relationships to ball velocity. These variables were input into a correlation matrix to eliminate those anthropometric variables which were highly related to one another. In cases where variables were related, the variable with the strongest relationship to ball velocity was kept for further analysis. These remaining variables were input into a multiple regression equation with the dependent variable ball velocity.

For the stationary drive, the following independent variables were used in a multiple regression equation: mass, arm length, thigh

Table 3. Average anthropometric measures of male and female subjects.

	MALES			FEMALES		
	$\bar{X}$	s.d.	Range	$\bar{X}$	s.d.	Range
Age (yrs)	29.2	5.74	22-39	24.25	5.89	18-33
Height (cm)	174.21	7.87	166.0-188.5	159.93	4.11	156.0-167.0
Arm Length	77.97	3.71	74.30-86.43	68.40	1.89	65.07-71.95
Leg Length	88.98	4.92	80.75-98.13	82.08	4.05	75.96-87.77
Trunk Length	52.24	3.93	45.63-57.80	48.56	2.40	45.60-51.80
Mass (kg)	72.74	8.41	61.0-86.8	61.08	6.24	49.9-68.2
Muscle Mass (kg)	38.15	5.67	31.37-47.38	Formula not validated		
%Muscle Mass	52.43	4.61	46.93-58.61	on females		
Forearm Girth	27.18	1.44	25.7-29.3	24.09	1.17	21.65-25.25
Biacr. Breadth	38.51	3.03	32.50-42.35	33.86	3.88	27.8-37.25
Biilio. Breadth	27.47	1.75	24.30-30.05	26.15	1.56	24.45-28.60
Acr./Biilio.Ratio	140.21	7.23	132.0-152.1	129.36	12.15	112.0-149.40

girth and relative biacromial breadth. The results of this multiple regression equation are detailed in Table 4. Inspection of the variable arm length indicated a negative relationship to ball velocity, when separated by gender (Appendix C). However, this relationship changed to a weak positive one when all subjects were considered together. Relative biacromial breadth was also positively correlated to ball velocity, but again, this relationship was relatively weak. Thigh girth and mass were more strongly related to ball velocity and these variables were the only two found significant in the stepwise multiple regression (Table 5). This indicates that subjects in this

Table 4. Multiple regression analysis of anthropometric variables versus stationary and penalty corner ball velocity.

Stationary Drive Ball Velocity

Variable	Probability	F-Test
All variables combined r^2 = .557 Adjusted r^2 = .409	.0330	3.766
Arm Length	.1947	1.887
Relative Biacromial Breadth	.5077	.466
Thigh Girth	.0155	7.953
Mass	.0632	4.189
Penalty Corner Drive Ball Velocity		
Variable	Probability	F - Test
All Variables combined r^2 = .655 Adjusted r^2 = .575	.0025	8.219
Forearm Girth	.0887	3.385
Biacromial Breadth	.4574	.587
Mass	.997	1.51E-5

study with greater mass and smaller thighs tended to hit the ball harder.

For the penalty corner drive, 3 independent variables were input into a multiple regression equation (Table 4). These variables were: mass, forearm girth and biacromial breadth. They provided a strong explanation for variation between subjects' ball velocities, r^2 = .655 (p = .0025). Each variable was positively related to ball velocity (Appendix C). Inputting these variables into a stepwise multiple regression equation (Table 6) it was seen that once the variable forearm girth had been accounted for the other 2 variables did not further contribute significantly to the equation.

Table 5. Stepwise multiple regression results of anthropometric variables versus stationary drive ball velocity.

Step	Variable	r^2	F - Test
#1	Thigh Girth	.24	4.733
#2	Mass	.444	5.587
			F to remove
	Variable #1		8.517
	Variable #2		5.137

Table 6. Stepwise multiple regression of anthropometric variables versus penalty corner ball velocity.

Step	Variable	r^2	F - Test
#1	Forearm Girth	.639	26.571

Muscle mass

The variable of muscle mass was examined for the male subjects and was found to relate to ball velocity (Figure 21). It can be seen from Figure 21 that most subjects closely follow the regression line, however, there was one outlier whose results affected that of the group, taking his result out of the equation gave a stronger relationship: $r^2 = .655$ for the penalty corner drive. The relationship of muscle mass to the stationary drive ball velocities remained insignificant.

The variable muscle mass was substituted for that of mass into the multiple regression equation to estimate its relative relationship to resultant ball velocity. It was found to be statistically insignificant, however, it must be noted that the sample size in this

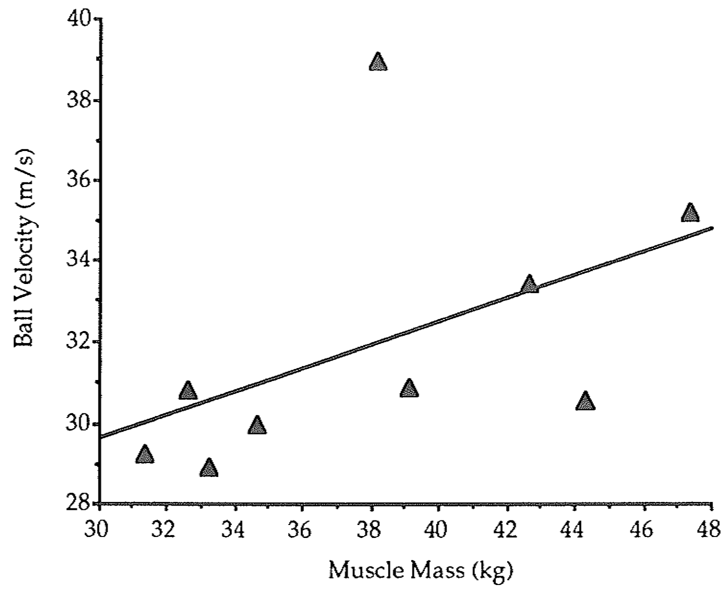


Figure 21. Scattergram of simple regression between muscle mass and ball velocity on the penalty corner drive; male subjects only.

instance was reduced to only 9 subjects as only male subjects could be used. The results of the multiple regression equation are reported in Table 7. It should also be noted that the variable forearm girth is used in the calculation of muscle mass, therefore the regression equation may be tainted by multicollinearity.

Table 7. Muscle mass substituted into the multiple regression equation of anthropometric variables versus penalty corner ball velocity. Sample size was n=9, as only male subjects could be used.

Penalty Corner Ball Velocity		
Variable	Probability	F - Test
All Variables combined r^2 = .656 Adjusted r^2 = .449	.1228	3.176
Muscle Mass	.8739	.028
Biacromial Breadth	.2378	1.797
Forearm Girth	.1814	2.408

Table 7 indicates that, combined with biacromial breadth and forearm girth, muscle mass does not contribute significantly to explaining variation in ball velocity. However, based on analysis of Figure 21, one can see that, for these male subjects, muscle mass was highly related to ball velocity.

Skill Description and Temporal Analysis

Temporal Analysis - Stationary Drive

In the literature review the drive was separated into five distinct phases: approach, backswing, downswing, contact and follow through. The approach phase was defined as beginning when the athlete first moved from their stationary starting position and ending when the backswing began. The backswing ended when the top of the backswing (TBS) was reached. It was found that, for the stationary drive, all subjects began the backswing within the first moments of the skill. Therefore, from initial movement in the skill until the top of the backswing will be termed the approach phase and during this phase the backswing was executed. The average time for the approach phase was .575 seconds, with a range from .459 - .765 seconds (Figure 22; Figure 23). After the approach the next phase was the downswing which began the instant the stick moved down towards the ball from the TBS and ended the instant before contact. The average time to complete the downswing was .221 seconds, with a range from .187 - .255 seconds. The contact phase was the period during which the stick and ball were in contact with each other. At the filming rate used for this study (60 fps) the time of contact could not be accurately quantified. For most subjects there was one frame of film in which the stick and ball were in contact with each other, however, in some instances, there were no frames depicting contact. The subjects' movements after contact were digitized as long as the ball remained in view of both cameras. Therefore, there was no common event to signify the end of the skill; the range was from four to eight frames of film digitized after contact (.068 - .136 seconds) which covered only a small part of the follow through.

Other significant events during the skill were: the moment the left foot touched back to the ground (Left heel strike - LHS) after stepping forward to be planted near the ball; the point at which the entire left foot planted on the ground (Left foot flat - LFF); and the point at which the right foot came off the ground (Right foot off - RFoff), which occurred during the downswing for all but two subjects. These two subjects kept their right foot on the ground for the entire skill and their resultant ball velocities were 26.09 m/s for the female and 26.48 m/s for the male. These ball velocities are average for the group, but are above average, by gender comparison, for the female and below average for the male. On average, LFF occurred .045 seconds after LHS (range .017 - .102 seconds) and RFoff occurred .102 seconds before contact (range 0.00 - .153 seconds).

The subjects moved towards the ball by stepping diagonally forward with the left foot during the approach phase - between the Start and TBS. Ten of 17 subjects reached top of the backswing before left heel strike, while the remaining 7 had LHS before TBS. All subjects then had LFF, right foot off and finally contact.

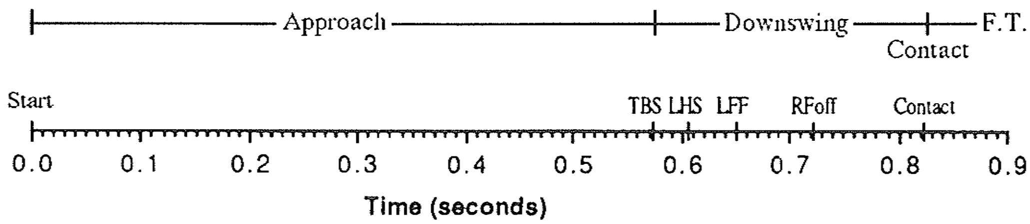


Figure 22. Phases and events of the stationary drive. The time of each phase is the average time for all subjects.

A multiple regression equation incorporating the time between each event was developed to determine if there was a specific phase of the skill which was typically performed more quickly or slowly by more skilled players. The r^2 for this equation was .414, however, the adjusted r^2 was only .089 indicating that the correlations between these independent variables and ball velocity was likely due to chance. Due to this finding a stepwise multiple regression was not done for these variables.

An attempt was made to determine if the sequence of these events was a relevant factor, however, it was found that there was no significant correlation between TBS or LHS occurring first and resultant ball velocity. In this temporal analysis it should be noted that the smallest time increment was .017 seconds, a relatively long time, possibly making it more difficult to distinguish true differences between subjects.

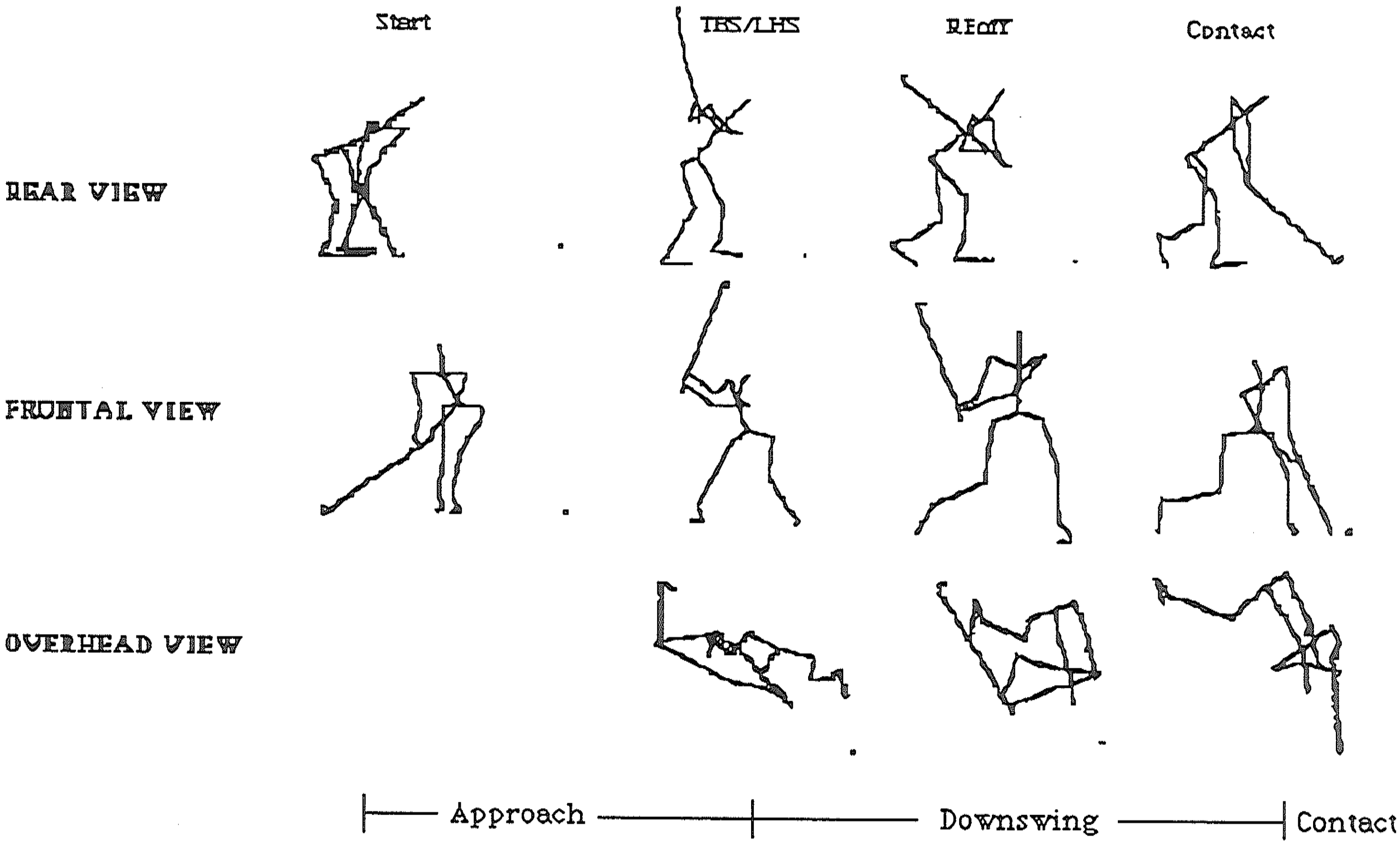


Figure 23. Body position of subject 16 at critical events during the execution of the stationary drive. The figures on the top row are a view of the subject from the rear. The middle row from a frontal view, and the bottom row an overhead view. Vertically the figures represent the same instant in time from the three different perspectives. The figures marked contact are actually the instant after contact as this phase was not captured on film for this subject.

Description of the skill - Stationary Drive

Figure 23 illustrates the standard starting position before executing a stationary drive. This is how a player would be positioned to take a free hit in a game situation. Table 8 shows the average joint angles for this position. All angles are measured between the adjoining segments at each joint, except the trunk angles and the shoulder/hip angle. The trunk angles are a measure between the angle defined by the top of the sternum, the mid-point of the hips and an axis: X, Y and Z (Figure 24a). The shoulder/hip angle is the angle between a line connecting the left and right shoulder and a line connecting the left and right hip (Figure 24b). The trunk angles give an indication of the orientation of this segment in space from three different perspectives while the shoulder/hip angle describes the relative rotation occurring about the spine.

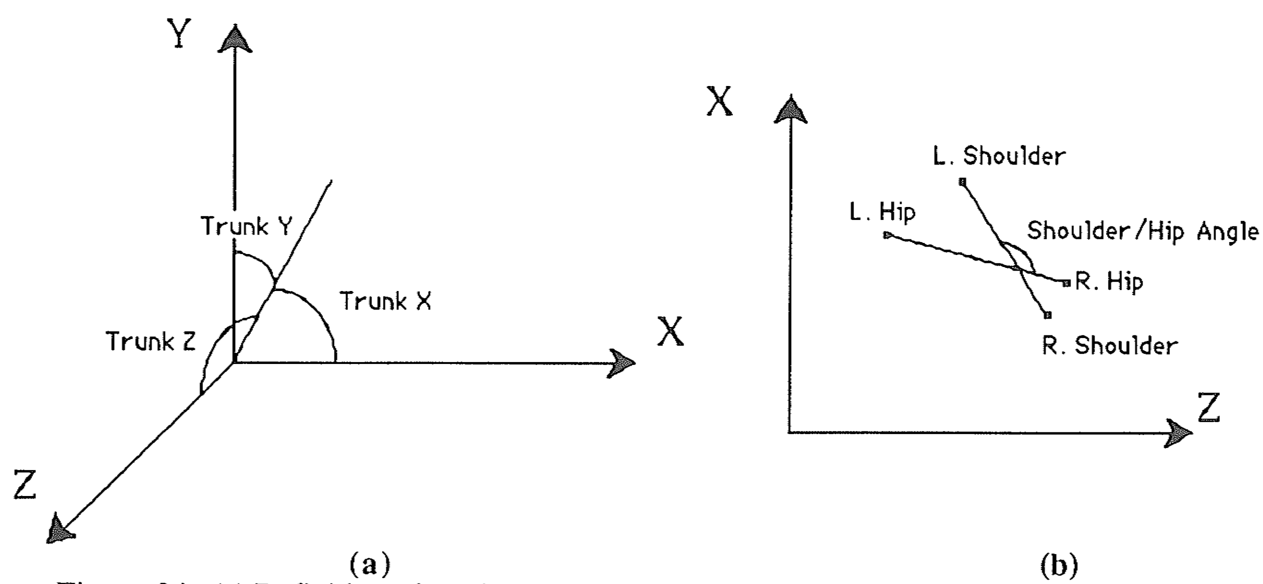


Figure 24. (a) Definition of trunk angle measurement, the reference frame originates at the mid-point of the hips and the angle measured is between an axis (X,Y or Z) and a line joining the mid-point of the hips and the top of the sternum. (b) Example of the Shoulder/Hip angle, projected onto the XZ-plane.

The Approach

Movement from the starting position was initiated by shifting the body weight toward the subjects left (towards the ball). While the hips moved left, the left heel came off the ground, then some subjects laterally rotated the right hip which produced rotation about the ball of the right foot to further move the body towards the ball; others seemed to allow their body to fall to the left, with the axis at the right foot. After the left foot had been unweighted and started moving forward the right leg appeared to push against the ground such that the length of the step towards the ball was extended (average length of step .67m; range .51 - .98m; as a percentage of body height, average 40.2% range 31.8 - 53.5%). During the step forward the body was rotated to the left about the right hip. The majority of the subjects reached TBS before the left foot contacted the ground and in the penalty corner all subjects reached TBS before, or at the same time as LHS, therefore the description of the skill will follow this sequence of events.

The stick was moved after the step had started through a combination of wrist abduction and elbow flexion. As trunk rotation approached the end of its range of motion (ROM) the left arm adducted to continue to increase the range of the back swing. As well, wrist abduction and supination of the right forearm and pronation of the left forearm assisted with this. These movements placed the subjects in a position similar to that seen in Figure 23 at TBS.

Downswing

After TBS was reached, subjects were still extending their left foot to be planted near the ball. During the step forward the body was rotated left about the right hip. As the left foot came down and contacted the ground, (LHS - Figure 23), the right knee flexed and the CM dropped, especially the upper body, as the lower body moved almost linearly forward towards the ball. As the subjects moved towards the ball and contacted the ground their left foot flattened on the ground (LFF - Figure 23) and the weight was transferred onto this foot. After LFF the rest of the body followed forward to be supported by the left leg, the left knee flexed to absorb the body weight, then extended slightly just before contact. The right foot came off the ground (RFoff - Figure 23) before contact (average .102 seconds before contact, range .034 - .153 seconds), this coincided with or occurred around peak horizontal velocity of the CM.

As the left leg extended forward, lateral rotation occurred at the left hip. This varied depending on the orientation of the left foot as it was planted. Some subjects planted their left foot almost perpendicular to the path of the ball while others planted their foot at an angle of only 22° to the ball (mean = 54.6°).

From the top of the backswing the downswing was executed to accelerate the stick down to contact the ball. Most subjects, however, seemed to maintain the stick in the same position from the TBS until LHS, letting their body fall in this position or likely allowing time for accelerations of more proximal body segments. If the stick was moved, the stickhead was usually moved posteriorly through forearm pronation and supination, and possibly also adduction of the right shoulder. The downswing was initiated by a combination of rotation about the left hip (begun by the push off from the right foot) and the lowering of the centre of mass onto the left leg, bringing the entire upper body down towards the ball. The left hip then acted as an axis about which the pelvis was rotated forward and the trunk was flexed and laterally flexed. As the left hip rotated internally, the shoulders were rotated to the left (same direction as the hips) relative to the hips. The right leg countered the trunk movement, providing dynamic balance, by abducting and flexing at the hip and knee as it swung to the left of the planted left foot. The left arm then abducted as the right adducted, bringing the stick down. Through the final part of the downswing the head of the stick was accelerated into contact (Figure 23) through adduction of the wrists combined with supination of the left forearm and pronation of the right forearm. At this point the right elbow also was extended which added to the force of the drive.

Follow Through

During the follow through the stick and upper body swung through the ball as the left knee further extended, starting the movement back to a normal playing position. As there were often wide ranges of segment angles, Table 9 shows the actual values of the top subject, S16, who had the greatest ball velocity for the stationary and penalty corner drives. This subjects' pattern of movement at each joint was described in detail to get a clearer picture of the technique of the stationary drive, and of the movements occurring between each event.

Table 8. *Average joint angles, standard deviations and ranges through each phase of the stationary drive. All measures are in degrees.

JOINT	Start	Top of the BS	Left Heel Strike	Right Foot Off	Contact
Stick-Wr Angle	**150.0** (12.20) 113.8-166.4	**133.1** (9.14) 110.8-147.1	**133.5** (8.01) 115.8-147.1	**120.5** (12.9) 101.1-136.7	**163.8** (4.79) 155.1-171.7
R. Elbow	**136.1** (7.28) 101.8-163.7	**81.8** (24.75) 51.9-136.7	**80.4** (23.93) 50.6-132.3	**86.6** (24.01) 53.7-141.2	**134.6** (15.9) 107.6-167.2
L. Elbow	**146.0** (16.77) 106.4-167.3	**144.9** (14.83) 108.5-159.5	**145.5** (14.03) 113.9-160.3	**152.4** (15.19) 119.1-171.3	**165.0** (6.40) 150.8-173.2
Sh./Hip	**15.2** (6.25) 3.0-28.8	**52.1** (13.24) 32.0-88.8	**50.2** (11.24) 32.0-73.0	**40.9** (11.43) 19.5-58.4	**23.6** (7.06) 7.5-32.8
Trunk X	**86.86** (17.71) 57.0-117.0	**94.0** (17.53) 65.0-125.7	**94.3** (17.72) 69.3-125.7	**85.3** (14.91) 63.1-108.9	**82.1** (19.90) 54.2-115.0
Trunk Y	**43.22** (16.9) 11.4-70.8	**47.7** (8.43) 33.6-58.4	**48.0** (9.24) 32.8-64.6	**49.5** (5.39) 40.1-58.8	**46.6** (7.51) 32.1-61.9
Trunk Z	**52.8** (17.17) 27.0-81.1	**47.5** (9.14) 35.7-71.7	**47.4** (9.36) 33.7-71.7	**44.3** (5.19) 88.3-108.3	**50.8** (8.34) 37.8-70.4
R. Knee	**146.9** (10.64) 124.9-160.4	**132.5** (13.47) 92.7-147.3	**136.2** (14.23) 92.7-152.0	**116.9** (12.50) 99.3-139.4	**105.6** (6.04) 90.9-113.7
L. Knee	**153.0** (12.72) 131.8-174.4	**148.7** (12.00) 127.8-172.9	**151.4** (12.37) 127.8-172.7	**139.0** (6.21) 128.3-150.2	**148.2** (8.13) 131.1-159.9

*Average joint angle is in bold on the top line, standard deviation is in brackets, and the range is listed on the bottom line. All measures are in degrees.

Table 9. Joint angles of subject #16 during the stationary drive.

JOINT	Start	Top of the Back Swing	Left Heel Strike	Right Foot Off	Contact
Stick-Wr	152.4	134.8	134.8	104.4	160.5
R. Elbow	163.7	87.5	87.5	98.1	167.2
L. Elbow	163.8	144.9	144.9	153.8	171.4
Sh./Hip	3.0	45.7	45.7	30.3	32.1
Trunk X	87.1	87.7	87.7	72.0	68.5
Trunk Y	45.9	39.1	39.1	45.2	43.8
Trunk Z	44.2	50.9	50.9	50.2	53.9
R. Knee	157.7	136.5	136.4	115.2	107.4
L. Knee	156.8	140.2	140.2	140.6	149.3

The time for S16 to contact the ball from the start of the skill was .782 seconds; his approach phase was .544 seconds and his downswing lasted .238 seconds. He reached TBS and LHS simultaneously, LFF occurred .017 seconds after LHS and RFoff .085 seconds before contact.

Stick/Wrist Angle

Stick-wrist angle was defined as the angle between the stick and the forearm. There was a gradual decrease in this angle from the start of the skill until the top of the back swing (152.4°-134.8°)(Figure 25a). During the first .119 seconds of the downswing the stick-wrist angle decreased more rapidly from 134.8° to a minimum of 102.3°, this minimum occurred .017 seconds before RFoff. The angle then increased gradually for the next .034 seconds and then opened up rapidly until contact - from 107.1° to 165.2° in .051 seconds.

Elbow Angles

Figure 25b illustrates the typical pattern of movement at the right elbow. Continuous flexion of the elbow from the start of the skill, increasing to the top of the backswing to an angle of 87.5°. The right elbow continued to flex, to a minimum 60°, during the first .085 seconds of the downswing. The elbow was then extended very quickly to an angle nearing full extension (167.2°) during the last .14 seconds of the downswing.

The left elbow remained relatively straight from the start to TBS (163.8° - 144.9°) extended about 10°, then, in the last .017 seconds before contact, extended to an angle of 171.4°.

Shoulder/Hip Angle

At the start of the skill the shoulders and hips were directly aligned (Figure 25c), then opened up to an angle of 45.7° at the TBS. This occurred as the pelvis opened up, with the body rotating to the left about the right hip and the left hip rotating laterally to orient the left foot to be planted in the correct position by the ball. At the same time the shoulders were being rotated to the right during the backswing. This subject had TBS coincide with LHS followed by LFF .017 seconds later, at which point the shoulder/hip angle was

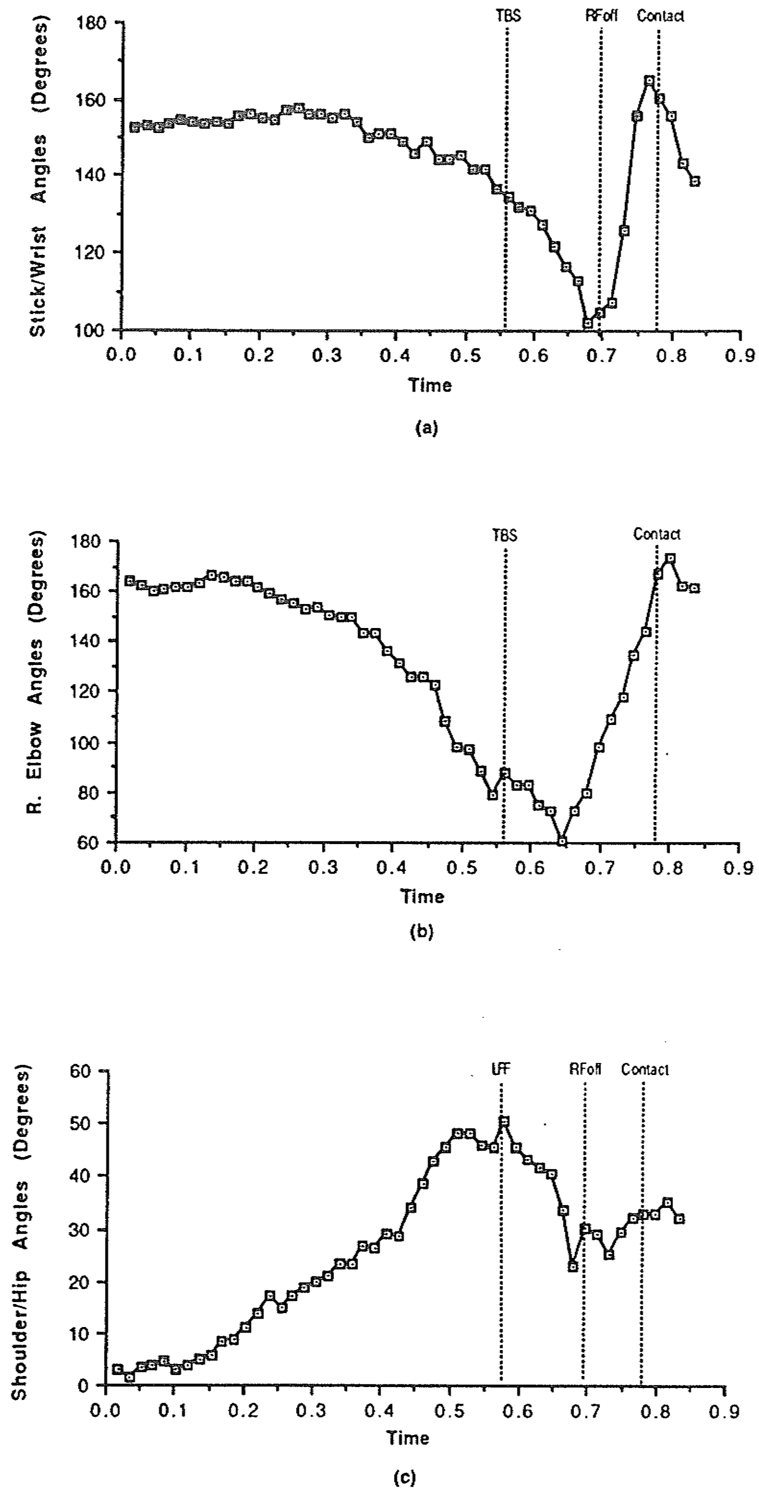


Figure 25. Angular displacements for subject 16 during the stationary drive. (a) Angle at the wrist between the stick and forearm. (b) Angle at the right elbow. (c) Angle between the shoulders and hips (definition of angle Figure 24b).

greatest - 50.5°. Once the base of support of the left foot was established and weight transfer had begun the body began to rotate to the left about the left hip.

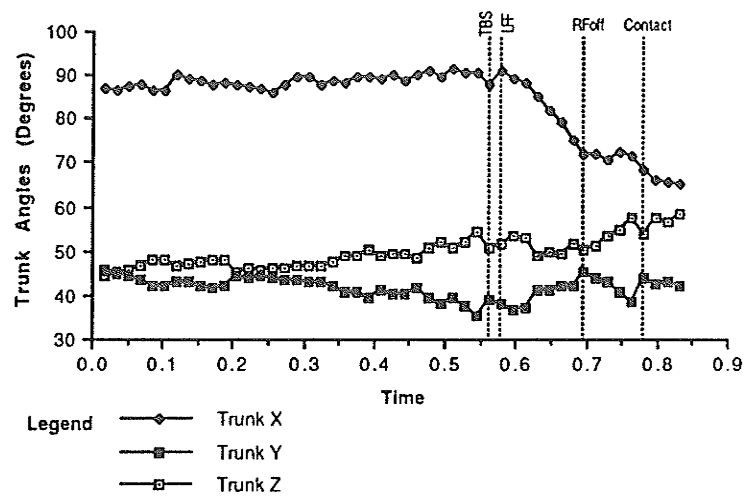
The shoulder/hip angle then decreased to 22.9° the instant before RFoff from which point it increased steadily to 32.1° at contact. When the right foot came off the ground the right leg was then free to recover under the body through hip abduction and extension. As this occurred the right hip also dropped below the level of the left hip.

Trunk Angles

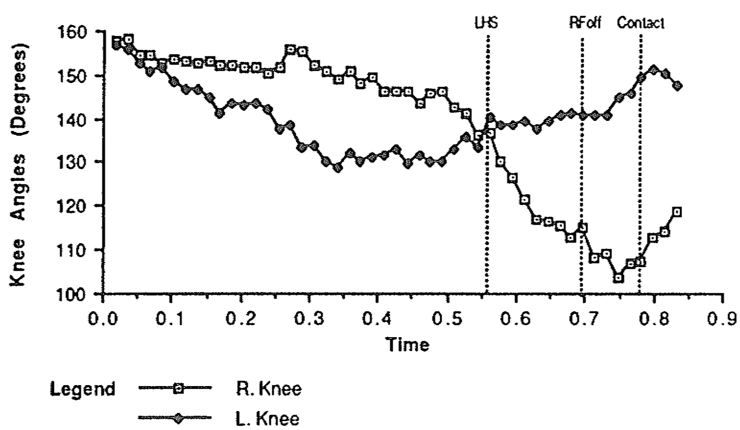
The trunk remained in a fairly fixed orientation relative to the Y and Z axes (Figure 26a), maintaining angles of about 45° and 50° respectively without much variation. Relative to the X axis the trunk moved from a position 87.7° from the X-axis at the TBS to 68.5° at contact (Figure 26a), indicating that, within the horizontal plane, the trunk was moving towards the ball.

Knee Angles

The right knee (Figure 26b) remained relatively straight from the start of the skill until .051 seconds before the TBS as the subject tended to let gravity and rotation to the left move him towards the ball. From .051 seconds before TBS to .068 seconds before RFoff the knee flexed from an angle of 142.5° to 117.0° as the CM dropped and moved towards the ball. During this time the left foot was planting



(a)



(b)

Figure 26. Angular displacements for S16 during the stationary drive. (a) Trunk angles relative to each axis. (b) Knee angles.

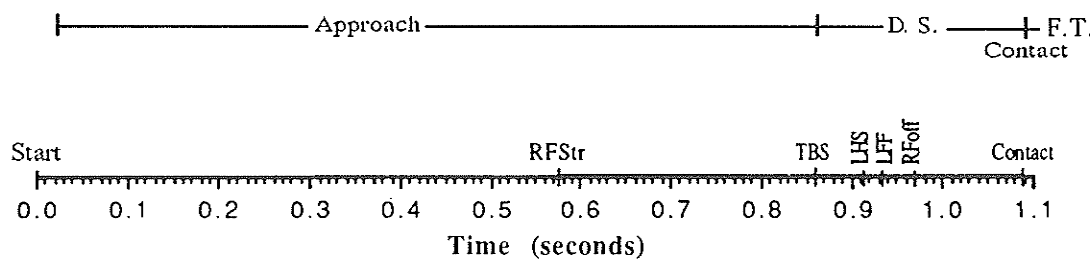
near the ball and the pelvis was starting to rotate downwards and to the left about the left hip such that RFoff occurred from a flexed knee position (115.2°).

The left knee flexed from the start of the skill as the left foot was unweighted and then stepped forward (Figure 26b). At left heel strike the knee was flexed at 140.2° then flexed further to 135° and then extended slightly to 149.3° at contact.

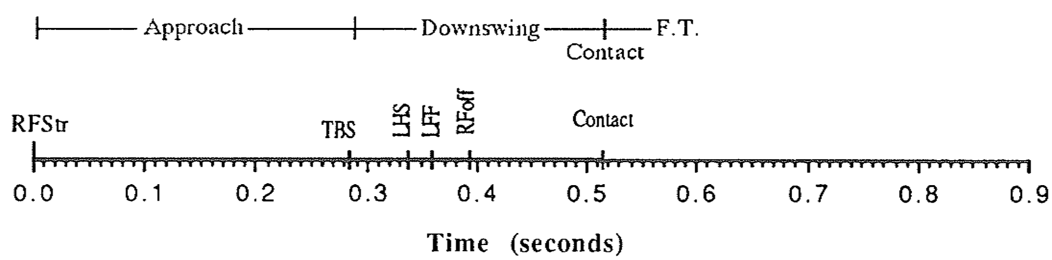
Temporal Analysis - Penalty Corner Drive

The penalty corner drive differed from the stationary drive in that there was a run up of several steps into the hit. The same phases will be used to describe this skill as were used for the stationary drive. During the penalty corner drive subjects took from two to four steps towards the ball before contact. Subjects taking more steps tended to have a distinct approach phase before starting their backswing. During this approach the stick was lifted off the ground then carried in a set position until just before the final right foot plant before contact (right foot strike). For some subjects there was no distinction between the approach and the backswing (similar to the stationary drive), so for this reason, the approach phase was defined as including the backswing and ending when the top of the backswing was reached.

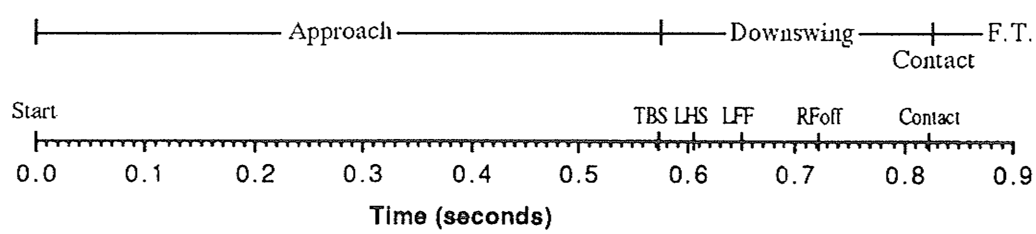
To allow for a clearer comparison to the stationary drive, the temporal analysis will start with right foot strike (RFStr) (Figure 27). At this point the subject was placing their right foot down for the last time before contact, such that they would then take one more step towards the ball with their left foot. From RFStr until contact the same events occurred as in the stationary drive, however it was more dynamic and the subject was starting with some velocity of their centre of mass which had been generated by the steps taken prior to this point in the skill.



(a) Penalty corner events from the start of the skill until contact.



(b) Penalty corner events from right foot strike until contact.



(c) Stationary drive from the start of the skill until contact.

Figure 27. Temporal analysis PC drive, (a) from initial movement; (b) from right foot strike -RFStr; (c) Stationary drive.

Average times of each event from the start of the skill are displayed in Figure 27a. Figure 27b depicts the timing of events from RFStr until contact. Average time to contact the ball from this point in the skill was .517 seconds (range .391 - .629 seconds), which was faster than that of the stationary drive (Figure 27c). Defining the approach of the penalty corner drive from RFStr until TBS resulted in average approach times of .284 seconds (range .136 - .391 seconds). Average time for the downswing was .233 seconds (range .17 - .289 seconds).

From RFStr, the sequence of events for most subjects was then TBS, LHS, LFF, RFoff, Contact (Figure 27). One subject had LHS before TBS and 2 others had these events occur simultaneously. Another subject had TBS LHS and LFF occur at the same time and one had LHS and LFF at the same instant.

The results of the multiple regression equation (Table 10) indicated that the combined effects of all the temporal variables related highly (r^2 = .741) to penalty corner ball velocity at the .05 level of significance. Analyzing the contribution of each independent

Table 10. Multiple regression of temporal variables versus penalty corner ball velocity.

Variable	r^2	Adj. r^2	Probability	F-Test
All var's combined	.741	.568	.0256	4.288
Right Foot Strike			.3142	1.136
Top of Back Swing			.1873	2.037
Left Heel Strike			.3176	1.120
Left Foot Flat			.1388	2.638
Right Foot Off			.0864	3.704
Contact			.1489	2.492

variable, however, clearly showed that no one variable accounted for much of the variability in ball velocity by itself. Further analysis through stepwise multiple regression supported this finding as no variables were entered into the stepwise multiple regression equation.

Description of the Skill - Penalty Corner Drive

The first significant event during the penalty corner drive occurred when subjects planted their right foot for the final time before contacting the ball - right foot strike (RFStr). At this point in the skill until contact the subjects took an extended step towards the ball with their left foot while executing the backswing, then as their left foot planted they began the downswing to contact the ball. These are the same events and sequence of movements that occur in the stationary drive.

At RFStr (Figure 28, Figure 29), subjects were at a point in the skill similar to that of the start of the stationary drive. The differences being that RFStr is a much more dynamic position. RFStr was also a common event that occurred for all subjects.

Until right foot strike subjects took from one to three steps towards the ball to generate momentum of their CM. Center of mass velocities at RFStr ranged from .77 m/s to 2.04 m/s (mean 1.26 m/s). However there was no significant correlation between CM velocity, at this point in time, to resultant ball velocity.

The average time to reach RFStr was .575 seconds (Range .204 - .765 seconds). Those taking longer did not necessarily have increased centre of mass velocities at this point. Body position at RFStr is illustrated in Figure 28 and Figure 29 with joint angles

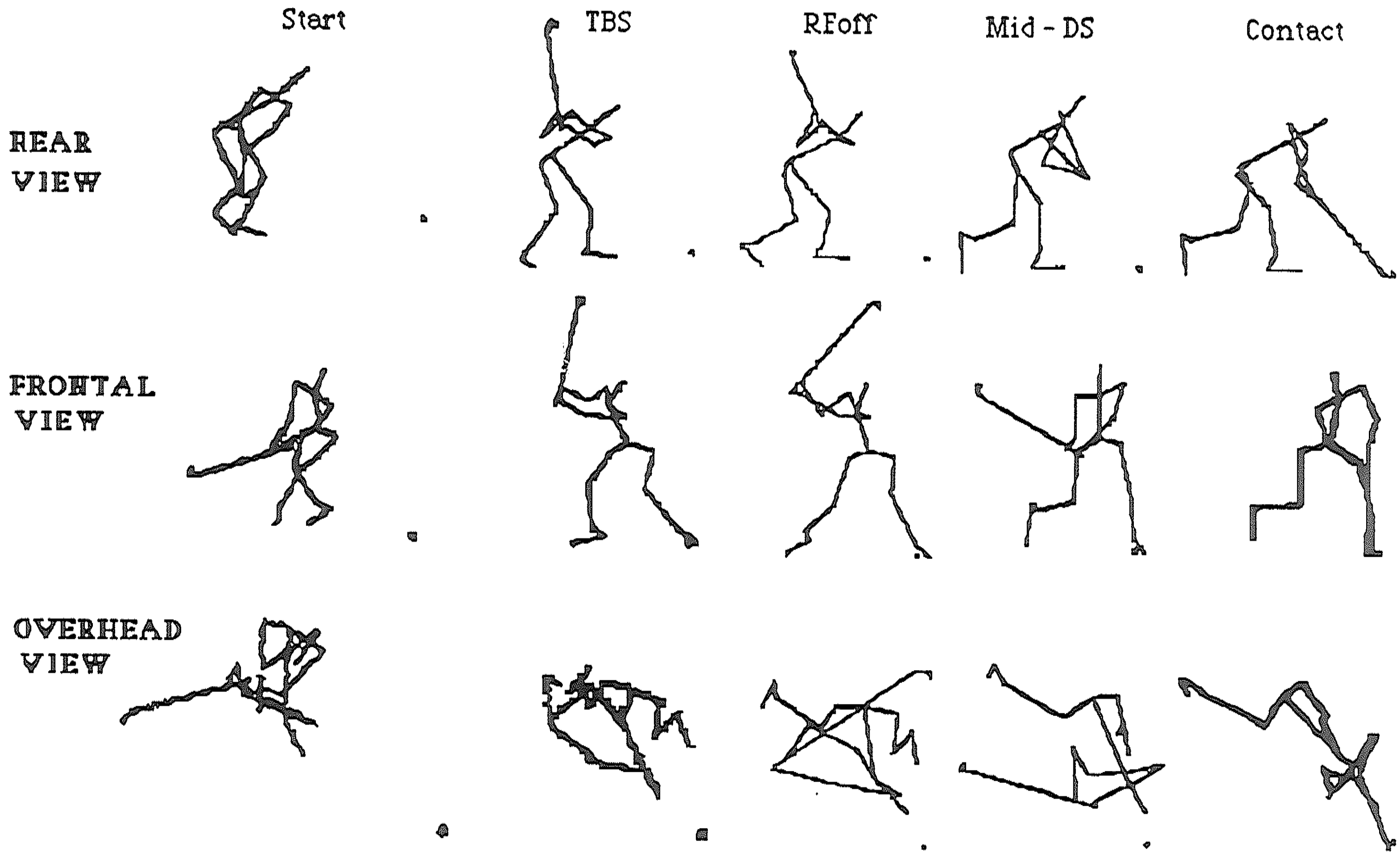


Figure 28. Body position of S16 at critical events during the penalty corner drive.

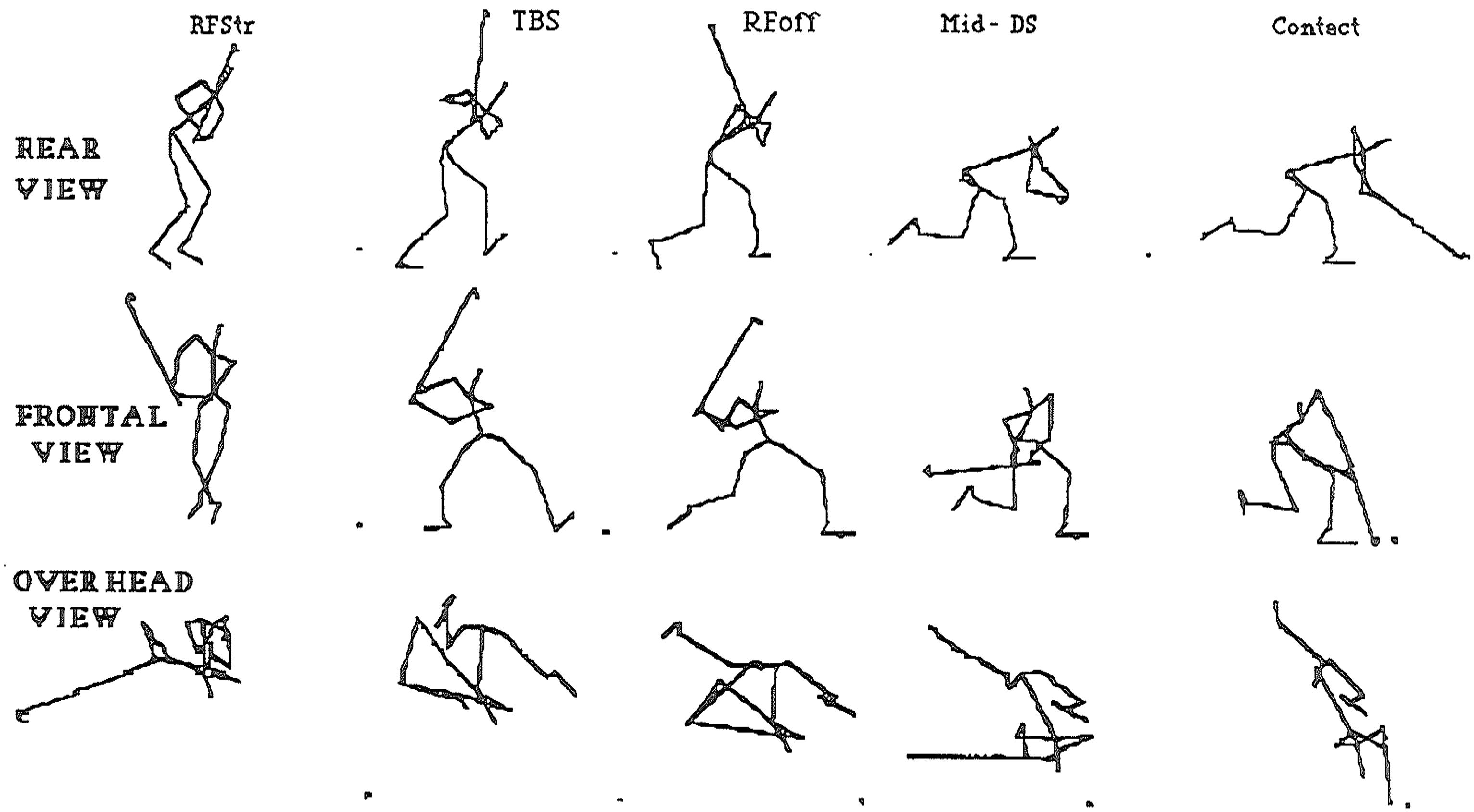


Figure 29. Body position of S17 at critical events during the penalty corner drive.

reported in Table 11. Average time to contact from RFStr was .517 seconds (range .391 - .629 seconds), which, on average, was faster than for the execution of the stationary drive (average .795 seconds; range .646 - .969 seconds).

From RFStr until contact movements were very similar to those of the stationary drive technique. The main differences between the two were the velocity and the range of motion of some of the actions. There was also greater variation between subjects on the performance of this skill, with some subjects contacting the ball from an upright trunk position while others were in a more horizontal position at contact. The average joint angles for the group at each event are reported in Table 11 while the joint angles of the top two subjects, S16 and S17, are reported in Table 12. These subjects had the greatest ball velocities, 38.93 m/s and 35.21 m/s respectively, and they also exhibited an upright position at contact, S16 (Figure 28), and a more horizontal style, S17 (Figure 29). The performance of the penalty corner drive of these two subjects will be described and compared.

Leading up to the RFStr both subjects carried the stick in a set position. From RFStr onwards the stick was brought up to the top of the backswing (TBS - Figure 28, 29). From the start of the skill until RFStr S16 took one step forward with his left foot then crossed his right leg behind his left to land at RFStr (Figure 28). Subject 17 took one step forward with the right foot, then a step with the left and then he too crossed the right behind the left to arrive at RFStr. Subject 17 had greater velocity of his center of mass at RFStr than did S16 (2.04 m/s and 1.13 m/s respectively) and executed a very

Table 11. *Average joint angles, standard deviations and ranges through each phase of the penalty corner drive. All measures are in degrees.

JOINT	Right Foot Strike	Top of the BS	Left Heel Strike	Right Foot Off	Contact
Stick-Wr Angle	**138.7** (13.65) 116.8-156.7	**135.9** (12.59) 106.1-155.7	**133.3** (12.82) 100.2-144.5	**125.0** (11.37) 102.5-144.6	**161.9** (3.57) 156.9-169.4
R. Elbow	**107.1** (22.52) 65.9-147.3	**75.5** (17.78) 54.4-114.5	**76.6** (18.95) 52.0-126.0	**74.9** (16.81) 50.0-11.0	**127.4** (9.07) 116.1-145.0
L. Elbow	**132.7** (17.55) 101.4-163.1	**137.2** (16.67) 100.7-164.8	**141.8** (14.53) 119.1-171.0	**145.6** (12.10) 119.3-163.6	**159.9** (5.99) 152.4-172.8
Shoulder /Hip	**18.9** (9.35) 0.67-33.5	**51.5** (16.17) 27.5-84.3	**54.7** (12.95) 36.8-85.2	**46.9** (11.10) 28.2-71.9	**20.7** (9.85) 1.35-32.7
Trunk X	**75.0** (21.93) 40.2-107.5	**81.4** (22.67) 49.9-114.4	**81.4** (22.94) 47.0-113.8	**78.8** (22.76) 43.8-112.4	**64.9** (23.04) 33.0-107.9
Trunk Y	**46.9** (11.57) 23.1-60.6	**53.5** (11.98) 32.9-76.3	**55.7** (13.24) 34.0-89.1	**56.4** (11.84) 39.2-88.4	**62.4** (16.00) 43.5-109.4
Trunk Z	**53.7** (9.78) 39.3-71.2	**46.0** (8.72) 33.7-62.0	**44.6** (8.32) 31.1-56.7	**44.4** (7.60) 29.9-57.1	**47.6** (11.2) 28.1-61.1
R. Knee	**128.4** (9.62) 112.9-143.0	**129.3** (11.78) 108.0-147.1	**122.9** (13.82) 91.7-140.1	**109.9** (12.37) 92.3-136.0	**96.6** (15.10) 69.8-119.8
L. Knee	**141.8** (10.46) 123.2-159.0	**151.7** (19.45) 110.8-174.7	**150.4** (10.84) 133.1-166.4	**138.7** (7.73) 125.0-154.7	**146.2** (8.10) 127.4-157.2

*Average joint angle is in bold on the top line, standard deviation is in brackets, and the range is listed on the bottom line. All measures are in degrees.

Table 12. Joint angles of subject 16 and subject 17 during the penalty corner drive.

JOINT		Right Foot Strike	Top of the BS	Left Heel Strike	Right Foot Off	Contact
Stick/Wr. Angle	S16	156.7	136.9	135.6	118.2	165.9
	S17	126.2	127.3	127.0	123.0	164.5
R. Elbow	S16	147.3	71.6	70.2	58.1	125.8
	S17	88.5	59.9	52.0	53.3	119.7
L. Elbow	S16	157.1	135.6	137.8	144.5	154.4
	S17	130.0	119.3	119.1	119.3	155.8
Shoulder /Hip	S16	23.2	52.0	52.6	48.7	29.7
	S17	31.8	52.7	59.0	52.1	28.3
Trunk X	S16	67.5	73.2	72.8	69.7	54.7
	S17	59.8	69.8	71.8	70.0	43.6
Trunk Y	S16	51.1	46.6	48.2	53.2	54.6
	S17	52.6	49.4	53.4	57.2	70.3
Trunk Z	S16	47.2	48.1	46.6	43.7	54.8
	S17	51.9	47.4	42.1	39.8	52.9
R. Knee	S16	118.9	125.6	123.9	117.1	116.6
	S17	117.8	120.0	126.9	117.3	87.8
L. Knee	S16	144.7	133.0	134.7	131.4	150.3
	S17	123.2	135.1	143.7	133.4	127.4

quick push-off from the left foot generating an airborne phase between the left foot push-off and the RFStr. Subject 16, who moved at a slower pace, took deliberate steps towards the ball, then seemed to accelerate his movements after RFStr.

Left heel strike (LHS - Figure 28 & Figure 29) which was reached after an extended step towards the ball. As the left foot was landing the right foot was pushing off and all subjects had their right foot push-off (RFoff - Figure 28 & Figure 29) occur shortly after LHS. Top of the backswing was reached before LHS and as the subjects touched down they rotated their bodies into the drive.

The approach phase for subjects 16 and 17 (from RFStr to TBS) was .289 seconds and .187 seconds respectively and the total time from RFStr to contact was .510 seconds and .459 seconds respectively. Time of the downswing for S16 was .221 seconds and .272 seconds for S17.

Stick/ Wrist Angle

The stick-wrist angle remained fairly constant for S16 (Figure 30a) up until RFStr, at which point the angle decreased from 156.7° to 136.9° at TBS. From TBS to .068 seconds before contact this angle decreased more sharply to a minimum of 101° then increased very rapidly to an angle of 165.9° at contact. Subject 17 followed a similar pattern from TBS, decreasing from 126.2° to a minimum of 113° .068 seconds before contact, then opened to an angle of 164.5° at contact.

Elbow Angles

Right elbow angles decreased from RFStr to TBS, S16 - 147.3° to 71.6°, S17 - 88.5° to 59.9° (Figure 30b); then dropped sharply for S16 to a minimum of 58.1° at RFoff. For subject 17 the right elbow angle decreased to 52.0° after TBS and maintained this position through LHS and RFoff then opened quickly as the right arm extended into

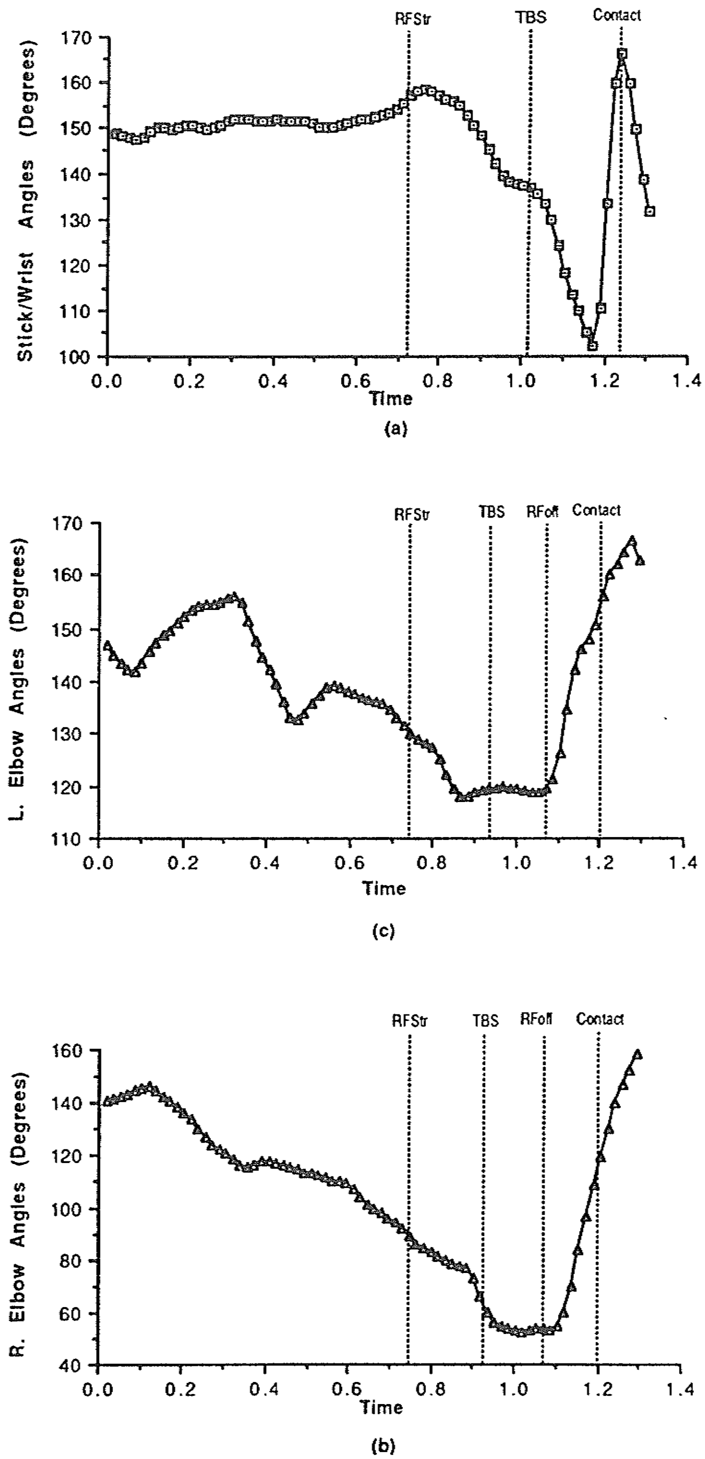


Figure 30. Angular displacements during the penalty corner drive. (a) Angle at the wrist between the stick and forearm of S16. (b) Angle at the right elbow of S17. (c) Angle at the left elbow of S17.

contact to an angle of 119.7°. Similarly S16 extended his arm at a fast rate to an angle of 125.8° at contact.

Left elbow angles were similar to those of the stationary drive; remaining relatively straight throughout the skill. The elbow flexed to a minimum angle of 135.6° for S16 at the TBS then increased to an angle of 154.4° at contact. S17 followed a similar pattern, reaching a minimum of 117.9° just before TBS, then maintained this angle up until .136 seconds before contact during which time the elbow extended to an angle of 155.8° (Figure 30c).

Shoulder/ Hip Angle

The shoulder/hip angle fluctuated slightly during the first part of the skill as the subjects took their first steps towards the ball. At .119 seconds before RFStr (Figure 31a) this angle increased as the right leg began to cross behind the left and the shoulders started to rotate to the right. As well, the left shoulder started to drop relative to the right through trunk rotation and lateral flexion. These actions continued through to TBS increasing the shoulder/hip angle to a near maximum value of 52.0° for S16. This angle was maintained until just before RFoff at which point it decreased rapidly to 16.6°, .051 seconds before contact, as the shoulders rotated to the right relative to the hips. At RFoff the pelvis was then free to rotate about the planted left leg and for the last .051 seconds before contact the shoulders and hips rotated together, then the shoulders rotated further to the left and there was lateral flexion to the right.

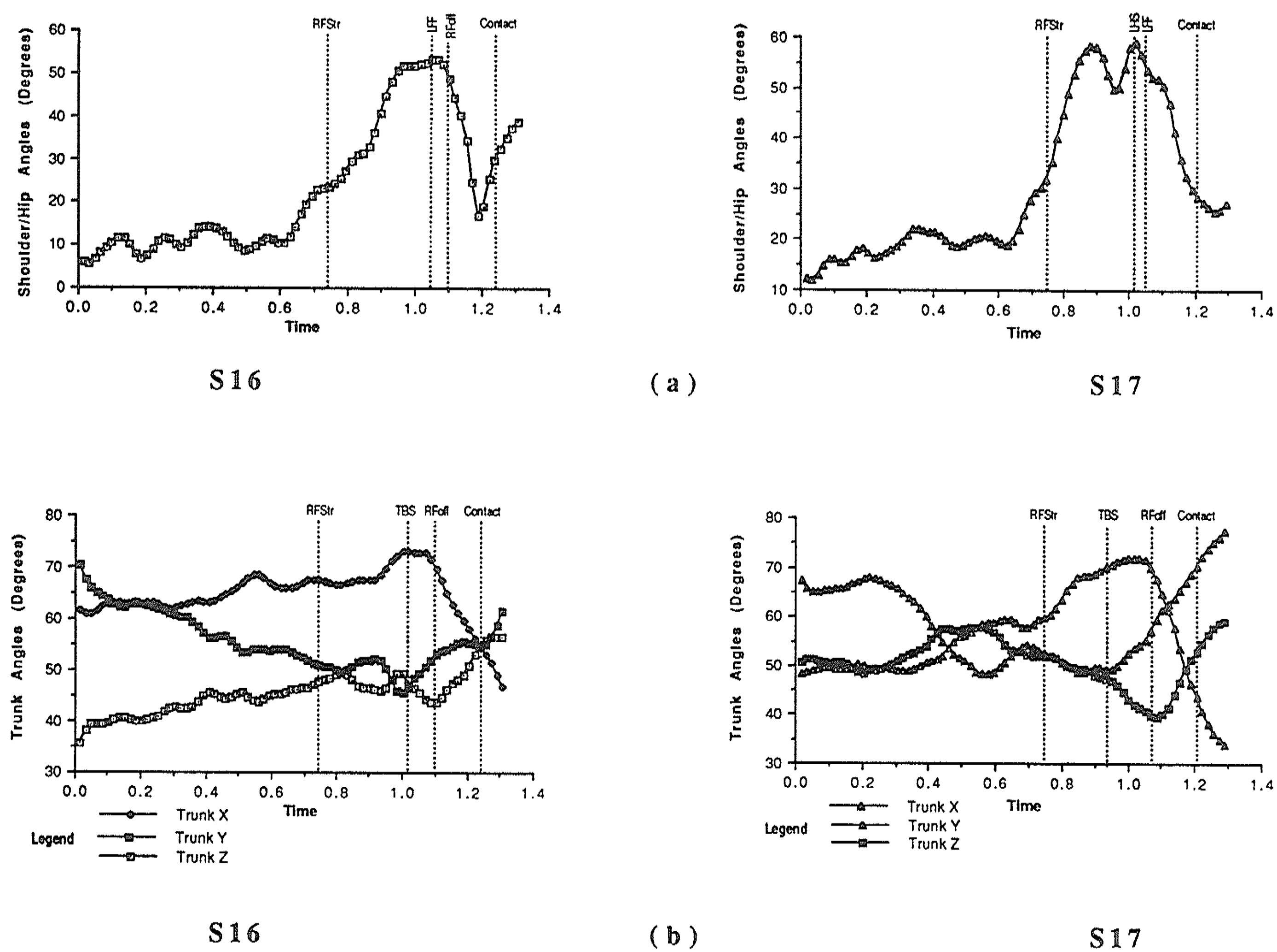


Figure 31. Angular displacements during the penalty corner drive. (a) Shoulder/hip angles of S16 and S17. (b) Trunk angles relative to each axis for S16 and S17.

Subject 17 had one maximum, 58.3°, for this angle .051 seconds before TBS (Figure 31a) through the same actions as S16. There was then a small decrease, then increase in this angle of 8.4° to 49.9° between this point and back to 59.0° at LHS. S17 took a more extended step into the hit and there was a small plateau of this angle just after RFoff where the hips and shoulders rotated together. From this point until contact (.119 seconds) this angle decreased sharply to reach 28.3° at contact. The reason the angle continued to decrease in this instance was the greater amount of rotation of the pelvis about the left hip throughout the downswing for S17.

Trunk Angles

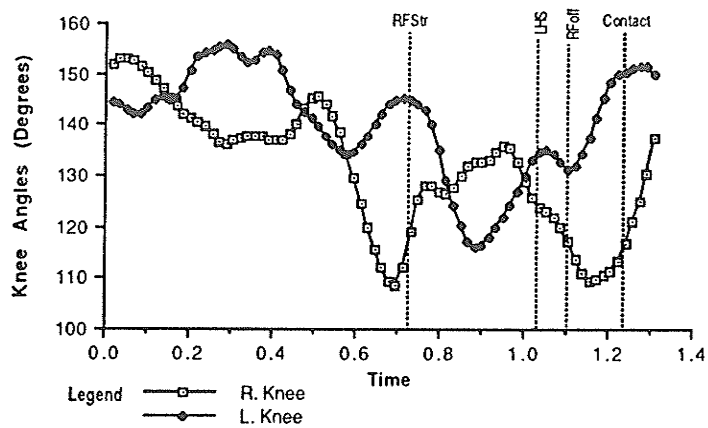
Trunk angles tended to be quite similar as those found for the stationary drive. The Trunk Z angle varied little throughout the skill and from RFStr until contact by only about 10°. There was a trend of this angle increasing from RFoff to Contact (Figure 31b; Figure 29 side view). The average increase of this angle for the group was 3.2° and about 11° for both S16 and S17.

Trunk Y angles followed the same trend, however they started to increase after TBS was reached. The average increase for the group was 9° from TBS to contact (from 53.5° to 62.4°), indicating a fairly vertical position at contact (Figure 31b; Figure 29 rear view). S17, however, had an increase of 20.9° (from 49.4° to 70.3°) from TBS to contact. This angle increased as the body fell forward onto the extended left leg. As the left leg planted and supported the body weight, the trunk continued to move downwards towards the ball.

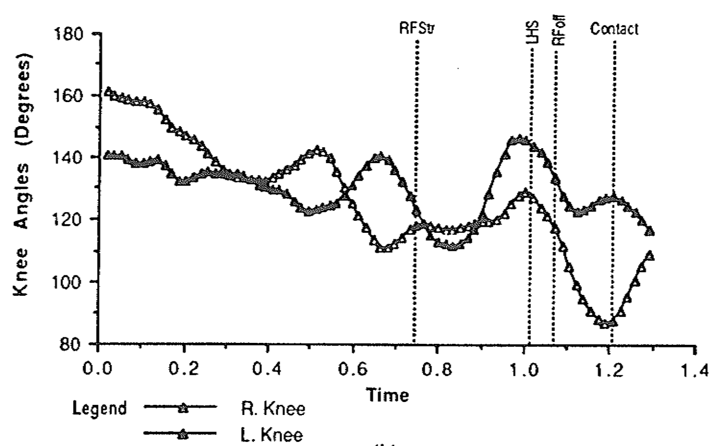
The Trunk X angle again followed the same pattern of movement as that of the stationary drive (Figure 29 overhead view) as the trunk moved towards the ball in the XZ-plane. This angle increased to a maximum around TBS, was maintained until RFoff, at which time it decreased rapidly until contact. The group average angle at RFoff was 78.8° and decreased to 64.9° at contact. Subject 16 and 17 had angles of approximately 70.0° at RFoff decreasing to 54.7° for S16 and 43.7° for S17, indicating that these subjects moved through a greater ROM through the same phase of the skill.

Knee Angles

The angles at the right knee for subjects 16 and 17 tended to follow those of the group averages, with the greatest variability between the two occurring after RFoff when the right leg was being recovered under the body. During this time some subjects flexed the knee up to 68.9° while others were flexed at 119.8° (Figure 32).
Left knee angles also followed the same patterns as those of the stationary drive, with the most significant aspect of the movement at this joint coming after LHS as the body weight was transferred onto the left leg. From LHS to contact the average knee angle decreased to 138.7° at RFoff (from 150.4° at LHS) then increased slightly to 146.2° at contact. Both S16 and S17 flexed at the left knee after LHS to a minimum of 131.3° for S16 and 122.6° for S17 between RFoff and contact, then they extended slightly to an angle of 150.3° (S16) and 127.4° (S17) at contact (Figure 32). Subject 17 had the greatest knee



(a)



(b)

Figure 32. Angular displacements during the penalty corner drive. Knee angles for subjects 16 (a) and 17 (b) throughout the skill.

flexion of the group at this point because of his horizontal body position at contact.

Technique Variables

Technique Variables - Stationary Drive

Forty - four technique variables (Appendix B) were measured for the stationary drive. These variables were chosen based on the literature review and preliminary analysis of the data. Many of these variables measured slightly different aspects of one variable; for example, length of the final step towards the ball and relative length of the final step towards the ball; peak velocity of the CM, time of peak CM velocity until contact, CM velocity at contact, drop in CM linear velocity from peak to contact.

These 44 variables, along with the dependent variable - ball velocity, were input into a correlation matrix to determine their relationships to each other. A correlation coefficient of .482 or greater (Hassard, 1991) indicated a significant relationship between two variables at the .05 level of significance. All variables with an absolute r-value with the dependent variable of .481 or less were eliminated from the analysis process. This left 8 variables (Table 13) of 44 to input into a multiple regression equation. While the results of this multiple regression equation proved to be significant at p = .0024 (Table 14), it was seen if the number of independent variables could be further reduced by inputting these 8 variables into another correlation matrix.

Table 13. Technique variables significantly related to stationary ball velocity and their associated correlation coefficients.

Variable	Correlation to Ball Vel.
Amount of shoulder rotation in the XY plane during the downswing	.742
Time to contact from peak CM velocity	.503
Amount of shoulder rotation in the XZ plane during the downswing	.483
Time of minimum shoulder angle in the XY plane until contact	-.749
Time of minimum shoulder angle in the YZ plane until contact	-.668
Amount of pelvic rotation in the XZ plane	.534
Amount of pelvic rotation in the XY plane	.667
Time of peak angular velocity at the shoulder/hip angle until contact	.698

Table 14. Multiple regression equation of technique variables versus stationary drive ball velocity.

Variable	Probability	F - Test
All Variables combined $r^2 = .903$ Adjusted $r^2 = .806$	.0024	9.32
Amount of shoulder rotation in the XY plane during the downswing	.0295	6.996
Time to contact from peak CM velocity	.7903	.076
Amount of shoulder rotation in the XZ plane during the downswing	.4219	.717
Time of minimum shoulder angle in the XY plane until contact	.3737	.888
Time of minimum shoulder angle in the YZ plane until contact	.3301	1.075
Amount of pelvic rotation in the XZ plane	.8322	.048
Amount of pelvic rotation in the XY plane	.0886	3.758
Time of peak angular velocity at the shoulder/hip angle until contact	.0078	12.415

If variables were significantly correlated (r-value of .482 or greater) the variable (s) which were less related to the dependent variable were eliminated. This left 4 variables to be input into another multiple regression equation (Table 15) resulting in slightly stronger results. These 4 variables were then input into a stepwise multiple regression equation (Table 16)

Table 15. Multiple regression equation of technique variables. Analysis of relationships between independent variables reduced the number of independent variables to 4 from the 8 used in Table 14.

Technique variables related to stationary ball velocity		
Variable	Probability	F - Test
All Variables combined r^2 = .76 Adjusted r^2 = .68	.0011	9.487
Amount of shoulder rotation in the XY plane during the downswing	.0159	7.868
Time to contact from peak CM velocity	.255	1.429
Amount of shoulder rotation in the XZ plane during the downswing	.2608	1.393
Time of peak angular velocity at the shoulder/hip angle until contact	.0894	3.414

Table 16. Stepwise multiple regression of technique variables versus stationary ball velocity.

Step	Variable	r^2	F - Test
#1	Amount of sh. rot. in the XY plane during the downswing	.55	18.32
#2	Time of peak angular vel at the sh/hip angle until contact	.71	17.156
			F to remove
	Variable #1		10.784
	Variable #2		7.749

As seen in Table 16, there were only two variables that contributed significantly to correlations between the technique variables and variation in stationary ball velocity after analysis of relationships between the independent variables. These variables were the amount of shoulder rotation in the XY plane during the downswing and the time of peak angular velocity at the shoulder/hip angle until contact.

The amount of shoulder rotation in the XY plane during the downswing was the angular displacement of a line connecting the right and left shoulders, relative to the XY plane, from the top of the backswing until contact.

The shoulder/hip angle measured the relative angular displacement between a line joining the left and right shoulder and a line connecting the left and right hip. The angular velocity at this angle was also measured, and while the magnitude of this variable was not significantly related to ball velocity, the time before contact that peak angular velocity of this angle was reached was significant as this was the second variable entered into the stepwise multiple regression equation. On average, this peak angular velocity was reached .087 seconds before contact (range .034 - .136 seconds). It was interesting to note that S16 had peak angular velocity of this angle .136 seconds before contact; this was the longest time before contact.

Technique Variables - Penalty Corner Drive

Forty-eight technique variables (Appendix B) were measured from film on each subject that performed the penalty corner drive. Displacement and velocity data could not be accurately obtained for two male subjects due to methodological errors during data collection. This left the sample size at 15 subjects. The same five step process used for the statistical analysis of the stationary drive technique data was used to treat the penalty corner drive data. The first step was the elimination of variables not significantly related to ball velocity through the use of a correlation matrix. At the .05 level of significance this required a correlation coefficient of .514 or greater with the reduced sample size. In the analysis of the stationary drive data this resulted in elimination of all but 8 variables, however, for the penalty corner drive this same step left only 4 variables (Table 17, variables marked with an asterisk *). Three of these variables were closely related to one another, therefore it was decided to reanalyze the correlation matrix, this time setting the critical level of the correlation coefficient at .10 (r-value of .441). This step resulted in the addition of five more variables which were significantly related to ball velocity (Table 17).

These nine variables were then input into a multiple regression equation (Table 18) which resulted in an r^2 value of .906. To further reduce the number of independent variables in the multiple regression equation these 9 variables plus the dependent variable, ball velocity, were entered into a correlation matrix. It was then determined which variables were significantly related (an r-value of

Table 17. Technique variables significantly related to penalty corner ball velocity and their associated correlation coefficients.

Variable	r-value to Ball Velocity
* CM peak velocity	.659
CM velocity at contact	.452
Drop in CM velocity from peak to contact	.476
Time of maximum shoulder angle in the YZ plane until contact	.453
Time of minimum shoulder angle in the XZ plane until contact	-.497
Relative length of the final step to the ball	-.485
* Peak angular velocity of the stick/wrist angle	.822
* Peak angular velocity of the stick/shoulder angle	.641
* Time of peak angular velocity at the stick/ shoulder angle until contact	-.529

Table 18. Multiple regression equation of technique variables versus penalty corner drive ball velocity.

Variable	Probability	F - Test
All Variables combined $r^2 = .906$ Adjusted $r^2 = .736$	p = .0399	5.335
CM peak velocity	.1232	3.431
CM velocity at contact	.1288	3.303
Drop in CM velocity from peak to contact	.1249	3.391
Time of maximum shoulder angle in the YZ plane until contact	.9981	5.95E-6
Time of minimum shoulder angle in the XZ plane until contact	.0555	6.174
Relative length of the final step to the ball	.0638	5.624
Peak angular velocity of the stick/wrist angle	.0284	9.51
Peak angular velocity of the stick/shoulder angle	.7645	.10
Time of peak angular velocity at the stick/shoulder angle until contact	.4019	.838

.514 at the .05 level) to the one variable which was most highly related to ball velocity. Peak angular velocity of the stick/wrist angle had the greatest r-value (.822); 5 other variables were significantly related to this one and therefore were eliminated. The remaining 3 variables were not significantly related to each other or to peak angular velocity of the stick/wrist angle and these 4 variables were used in a second multiple regression equation (Table 19). While this second equation had a lower r^2 value it resulted in a greater F-ratio and a lower probability that these results were due to chance ($p = .0045$).

Table 19. Multiple regression equation of technique variables. Accounting for relationships between independent variables reduced the number of independent variables to 4 from the 9 used in Table 18.

Variable	Probability	F - Test
All Variables combined $r^2 = .751$ Adjusted $r^2 = .652$	.0045	7.547
CM velocity at contact	.2406	1.557
Time of maximum shoulder angle in the YZ plane until contact	.6862	.173
Relative length of the final step to the ball	.4070	.749
Peak angular velocity of the stick/wrist angle	.0081	10.867

These 4 variables were then input into a stepwise multiple regression equation (Table 20). Through the stepwise multiple regression it was found that the variable of peak angular velocity of the stick/wrist angle explained most of the variation in ball velocity ($r^2 = .675$) and that, after this variable had been accounted for, the three remaining variables did not contribute significantly and were not entered into the equation.

Table 20. Stepwise multiple regression of technique variables versus penalty corner ball velocity.

Step	Variable	r^2	F - Test
#1	Peak angular velocity of the stick/wrist angle	.675	27.048

CHAPTER 5

DISCUSSION

Filming Procedures

While the average mean square error of the direct linear transformation for this study was greater than that recommended in the literature (Kennedy et al, 1989; Shapiro, 1978), the overall error was about 1% of the object field. This result seems reasonable, especially since the positional data was used only to calculate displacements and velocities, not accelerations. The calculation of acceleration from displacement data would be much more vulnerable to error in the determination of body segment coordinates as the displacement data would have to be differentiated twice to calculate accelerations.

Ball Velocity

Ball velocity results were higher for the penalty corner drive than the stationary drive, as expected. On average, there was an increase in ball velocity from the stationary drive to the penalty corner drive of 1.85 m/s (range -2.83 - 7.16 m/s; s.d. 3.016). Subjects exhibiting above average increases in ball velocity between skills tended to be more competent penalty corner hitters, however this was not always the case.

There was also a high correlation between performance on one skill, to performance on the other. Subjects who hit the ball harder on the stationary drive also hit it harder on the penalty corner drive.

The ball velocities for this group of subjects were also higher than those previously reported in the literature. This could be due to the fact that other ball velocities reported in the literature were only reported for female subjects. Velocities reported in the literature ranged from 10.60 - 29.83 m/s with an average of 18.49 m/s (Alexander, 1981; Alexander, 1985; Buzzell & Holt, 1979; Cohen, 1969; Hendrick, 1983).

In this study, the same subject produced the greatest ball velocities on the stationary and penalty corner drives. His result on the penalty corner drive was 38.93 m/s (87.08 mph) which was 2 standard deviations above the group mean. This was greater than the highest measured value published in the literature, but, not as high as the velocities reported by Kanjee (1991b), of top international penalty corner strikers. He reported that Karsten Fischer, of Germany, was recorded while hitting the ball 138 mph (measured with a radar gun) and that the average international penalty corner striker hit the ball 110 mph (Kanjee, 1991b).

The subject who produced the greatest ball velocities in this study was ranked by Kanjee (1991b) as being 8th in the world during his prime at the 1984 Olympics. However, Kanjee (1991b) still felt this subject could produce ball velocities equivalent to those of other current international penalty corner strikers (based on observations at Canadian National Championships).

The following factors could have contributed to this subject, and the other subjects, not attaining greater ball velocities:

-decrease in the stiffness of the stick with use.
-the weight of the stick was 22 oz. (.624kg), many male penalty corner strikers use a 26 - 28 oz. stick (Kanjee 1991).
-length of the stick, which was 36" (.91m).
-the surface the ball rested on was a synthetic flooring material and probably provided greater friction forces for the stick, if it contacted the ground before contacting the ball, and the ball, if it was hit into the ground.

Every player has a stick of preference with which they feel they hit the ball hardest. The biomechanical variables of the stick and ball at impact were examined in the literature review and it was decided that all subjects would use the same stick to try and eliminate variability caused by using different sticks. A new 36", 22 oz. (.91m, .624kg) Slazenger 'Carbo' stick was selected for use in the study. The rationale was that a stick of this weight would be considered moderately heavy for the female subjects and of medium weight for the male subjects. Upon later consideration, a heavier and stiffer stick may have been more appropriate, as some subjects commented that their own sticks were heavier. Most sticks are 36" (.91m) long, however, in recent years longer sticks have become more common. In Nagao and Sawada's examination of the golf swing (1973), they compared the kinematics between swinging a 43" (1.09m) driver versus a 35" (.89m) 9-iron. They reported greater ball velocity with the driver, 66.6 m/s, than the 9-iron, 42.1 m/s, and attributed most of this difference to the difference in club length. Field hockey sticks range from 35" - 38" (.89m - .96m) in length so a longer stick would increase linear ball velocity if the same angular velocity of the stick could be generated during the downswing.

Data collection took place at the Max Bell Centre, at the University of Manitoba, an indoor field house which has a synthetic rubber surface. Field hockey is practiced on the surface year round and all players had previous experience playing there. The problem with this surface was that the ball rested directly on the hard surface, as opposed to having a layer of grass or blades of artificial turf to rest on. The friction forces between this synthetic surface and the stick and ball may be greater than on grass or artificial turf, therefore, the ball rolls but does not slide, increasing the component of angular velocity. The kinetic energy (K.E.) of the ball is:

$$K.\,E. = 1/2\ mv^2 + 1/2\ I\omega^2$$

and ideally, the linear component will be maximized during impact, if not, more of the kinetic energy will be used in putting spin on the ball. If the stick contacted the surface before contact there could be more resistance than observed on normal playing surfaces, decreasing the linear velocity of the stickhead at contact.

Anthropometric Variables

Having 9 male and 8 female subjects created two small samples from an already small sample size of 17. Because these groups are from two different populations and known to differ on anthropometric measures, it was decided that the only way to analyze the two together would be if they both displayed the same trends on a particular variable. This was done by visual inspection of the scattergrams of the anthropometric variables and the dependent variables. After eliminating anthropometric variables which were closely related to one another, 4 independent variables were left for the stationary drive and 3 for the penalty corner drive. These variables were: arm length, relative biacromial breadth, thigh girth and mass, and forearm girth, biacromial breadth and mass respectively. After stepwise multiple regression was performed on these variables, the significant variables were thigh girth and mass for the stationary drive and forearm girth alone for the penalty corner drive.

These significant variables which displayed the same relationship to ball velocity for both the males and females were all absolute measures, except for relative biacromial breadth. This would indicate that variability of ball velocity related to these anthropometric variables may be more of a measure of the differences between males and females as opposed to variability of these anthropometric variables with ball velocity. Anthropometric variables had greater r-values for the penalty corner drive, possibly because of the greater difference between males and females on this skill.

For the stationary drive, subjects with longer arms, greater relative biacromial breadths and masses and smaller thighs tended to generate greater ball velocity. One would suspect that individuals with longer arms would tend to be taller and in fact arm length and height had a correlation coefficient of .922. This is a strong indication that taller subjects produced greater ball velocities on the stationary drive. Subjects with greater relative biacromial breadth would have a greater moment arm for rotations about the longitudinal axis of the trunk which would correspond to greater linear velocity of the segment at its distal end. From the literature review of impact mechanics one could conclude that players with greater mass would have greater potential to impart greater impulse to the ball at impact. This variable was also identified by Wein (1979) as contributing to ball velocity. The variable of thigh girth was found to be negatively correlated to ball velocity, which may be misleading. Several of the female subjects had large thighs but did not produce very high ball velocities, while, conversely, several of the males had small thighs, yet produced greater ball velocities than the females. For this reason, thigh girth was found to be significantly and negatively related to ball velocity. This should probably not be interpreted as a key quality to look for in players simply because it was statistically significant.

For the penalty corner drive the relevant anthropometric variables were forearm girth, biacromial breadth and mass. All were positively related to ball velocity. Mass and biacromial breadth were discussed for the stationary drive and hold the same relationships for the penalty corner drive. It is worth noting that international players tend to have large, strong forearms, this comes about due to the various techniques and demands of the game. Its importance in the drive comes about as the forearm muscles are the last to contribute to the momentum of the stick during the downswing. The forearms must adduct the wrists as well as supinate and pronate the lower arms (left and right respectively) and maintain a firm grip on the stick through the contact phase. These movements are crucial to the execution of this skill. Besides simply measuring forearm girth, it would also be advisable to measure grip strength, using handgrip dynamometers.

The variable of muscle mass, which was originally included to give some indication of strength differences, has only been validated for the calculation of muscle mass in men. Simple regression of absolute and relative muscle mass to the dependent variable indicated a significant relationship between absolute muscle mass and ball velocity. This could be an implication that players with greater general strength will produce greater ball velocities.

Results of the multiple regression models suggested that taller, heavier players with broad shoulders should hit the ball with greater velocity (assuming equal technique). It should be noted that, while these conditions applied to most subjects, the one subject who hit the ball the hardest in both the stationary and penalty corner drives had some unique anthropometric qualities. Most notably, he had broad shoulders (absolute 41.63 cm - second highest in group; and relative 24.78% - highest in group) and the greatest ratio of shoulder to hip breadth: 152.1 (average for males 140.21) while his stature was close to average (168.0 cm; group average was 167.07) and below average for the males. This subjects' mass was also above average - 78.0 kg, male average - 72.74 kg. These factors unique to this subject should also be noted by coaches when selecting penalty corner hitters.

Temporal Analysis

The multiple regression analysis of the temporal data for the stationary drive had no statistically significant findings. The variables input into the multiple regression equation were simply the times to complete each phase of the skill. For the penalty corner drive the same variables were entered into a multiple regression equation and yielded an r^2 value of .741. When these variables were used in a stepwise multiple regression equation no variable was entered into the equation, indicating that no single variable could significantly explain variation in ball velocity. One can also conclude that, for this group of subjects, no single phase of the skill was more important than the other (at least in terms of the duration of the phase).

Time of the Downswing

It was hypothesized that the time of the downswing would have been a highly relevant factor, with a high negative correlation to ball velocity. This would indicate that the quicker the downswing, the greater the ball velocity. While there were no significant trends or patterns in this data, it was interesting to note that 4 of the top 6 subjects had above average downswing times (.238 - .255 seconds, group average was .221 seconds). This included the top 2 subjects as well as the 5th and 6th subject (ranked according to resultant ball velocities). Downswing times reported in the literature tended to be shorter, range .15 - .21 seconds (Alexander, 1981; Chivers & Elliot, 1987; Cohen, 1969), on average, however, still within range of the times for these subjects; range for group .187 - .255 seconds. Differences between studies could have been due to actual differences, with subjects in this study moving through a greater ROM during the downswing, or different definitions of the TBS. However, it may be possible that some subjects perform the actions at each joint or segment more completely and/or more efficiently, thereby actually taking longer to perform these ballistic movements. They would have a longer preparatory phase during which the more proximal segments would move through a greater ROM and acquire a greater angular velocity before the next segment (distal segment) was moved. This would account for subjects having a longer downswing time. This does not imply that subjects with longer downswing times necessarily had lesser angular velocities of their segments through the downswing. They simply may take longer to generate this angular velocity, and in some cases this led to greater angular velocities during the downswing and greater ball velocities.

Downswing times for the penalty corner drive averaged .233 seconds (range .17 - .289 seconds), .012 seconds longer than the stationary drive and covering a greater range than that of the stationary drive downswing times (range .187 - .255 seconds). This implied that the downswing times for individuals for each skill were virtually identical as the smallest increment of time measurable at the filming rate used was .017 seconds. Both subject 16 and 17 had differences of only .017 seconds in their downswing times for each skill.

Approach Phase

The total time to complete the penalty corner drive was longer than the time to perform the stationary drive, as this involved a longer approach phase. When comparing each skill by phase it was only the approach phase which differed significantly. From the start of the penalty corner drive to TBS the approach phase was longer, however, when considering the penalty corner drive from the point of RFStr, the equivalent starting point of the stationary drive, the approach phase was shorter. This was due to the fact that subjects reached this point in the skill with some linear velocity, generated by the earlier steps taken, and executed the rest of the skill more quickly.

Sequence of Temporal Events

Five temporal events were identified as potential critical points through the execution of each skill: top of the backswing; left heel strike; left foot flat; right foot off; and contact. These events occurred for each subject for each skill, however, the sequence of these events varied between subjects, especially for the stationary drive. All subjects concluded both skills with the following sequence of events: LFF/ RFoff/ Contact. Variation was seen between subjects reaching TBS before or after LHS. Some subjects reached these at the same time and others had LHS and LFF occur at the same instant. Statistically there seemed to be no relationship between one event occurring before, or at the same time as, the others and ball velocity.

It was interesting to note, however, that four of the top 6 subjects on the stationary drive had TBS before LHS, the same 4 which exhibited the longer downswing times. This would mean that they had reached TBS while the left foot was still extending out towards the ball and the bodies' CM was falling towards the ground. Also at this time the right leg was propelling the body forward, the pelvis was rotating to the left about the right hip and in many cases the left leg was rotating laterally about the left hip. These actions set up the base from which trunk and upper body movements could occur.

Swing Plane of the Stick

In the literature review, top of the backswing (TBS) was defined as the moment that the stick began its movement down towards the ball and was identified for each subject using this definition. What was observed was not a direct upwards then downwards movement of the stick, rather the stick reached a peak vertical point (TBS) then was moved posterior to the frontal plane of the body (Figure 33). Several sources in the literature, however, stated or implied that allowing the stick to move posterior to the right shoulder was incorrect technique (Broderick, 1981; Broderick & van der Merwe, 1982; Reed & Walker, 1976; Wein, 1979).

In this study, subjects moved the stick posterior to the shoulders through a combination of left forearm pronation, right forearm supination and possibly some wrist abduction and internal rotation of the left shoulder. These movements produced a swing

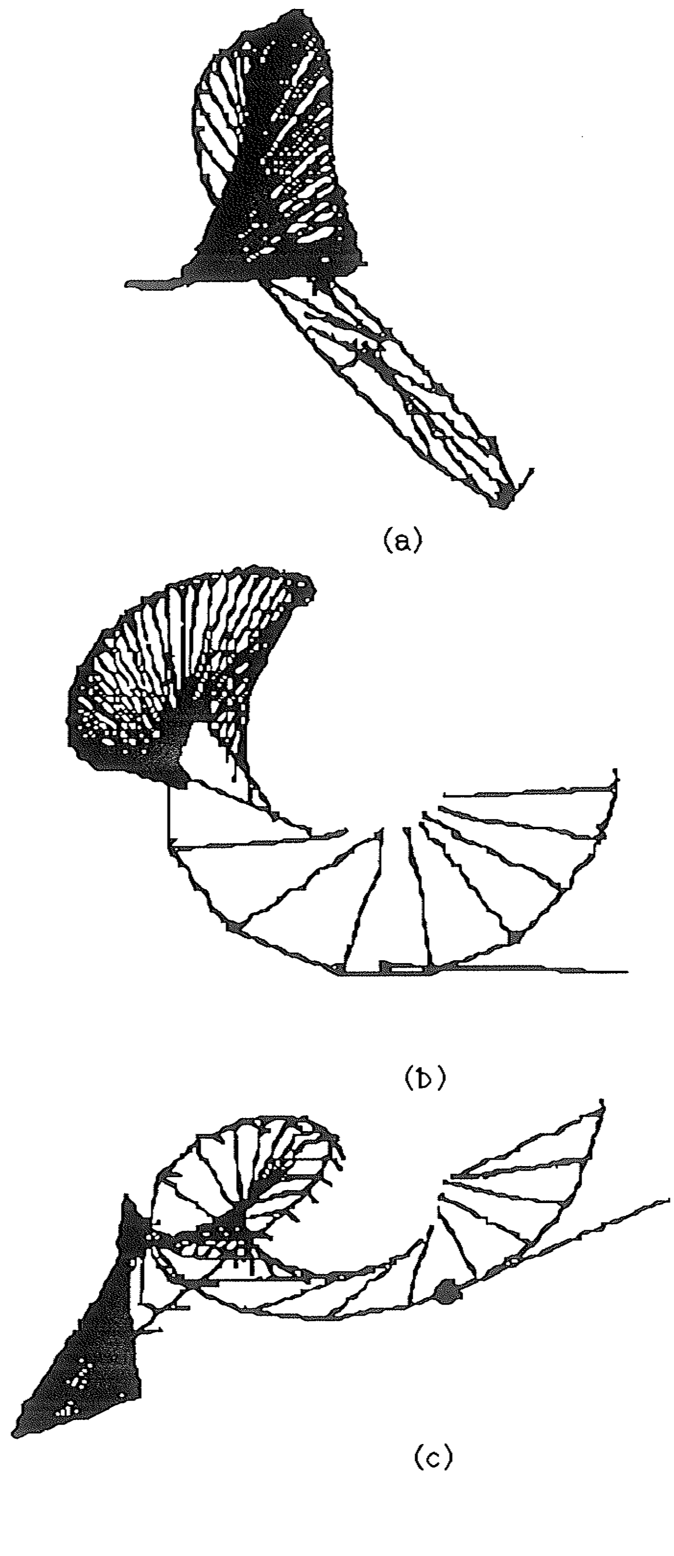


Figure 33. Typical swing plane for the stationary drive. (a) Rear view; (b) Frontal view; (c) Overhead view.

plane that had a phase where the stick had already reached TBS but was still being moved into a position that would allow for greater ROM through the downswing. From the overhead view of the downswing plane (Figure 33c) one can see that the displacement of the stick from one instant to the next does not start to increase significantly until some time after TBS. This can be seen as each successive image of the stick is drawn almost on top of each other producing an indistinguishable black area, then, as the stick was accelerated, one can clearly distinguish the image of the stick at each instant in time. This would indicate that the stick segment was still in a preparatory phase, even after the identified point of TBS. As stated earlier, this may be done to allow more proximal segments to move through a greater ROM and attain a greater angular velocity before the distal segments were moved, relative to the proximal segment. This movement pattern was also presented by Milburn (1982) in his analysis of the golf swing and is a theory of movement pattern put forth by many other biomechanists.

Reaching TBS before LHS may actually allow for the downswing to begin from a more posterior position and, therefore, through a greater ROM. If TBS was reached after LHS, and the timing of the movements of the more proximal segments remained the same, then the downswing would have to begin more quickly, and, therefore, probably not through as great a ROM.

Because the sequence of events was not proven to be statistically significant, it would be possible to argue for either TBS or LHS to occur first, however, for the penalty corner drive TBS did occur before LHS for all but one subject which may be an indication that this event should occur first for both skills.

Left foot flat and RFoff were also relevant events, especially with regard to rotations of the pelvis and trunk. Once LFF was reached the body weight could be fully supported by the left leg, which would allow for the CM to move further forward and for rotations of the pelvis to occur about the left hip. Right foot off would also be a critical point where, once reached, the right leg would be free to move with the pelvis and movement of this free body segment provided dynamic balance for the athlete and may have also provided additional force to the drive. Two previous studies reported the right foot moving from its planted position before contact: Chivers and Elliott (1987) and Alexander (1981). This was also a movement observed of penalty corner strikers at the 1990 Champions Trophy for men, however, neither researcher commented further on this. Several variables were measured concerning RFoff, timing during the skill, ROM the right leg travelled before contact, the velocity of the right leg as it was moved - peak velocity and velocity at contact, but none were found to be statistically significant.

Several golf studies had segmented the downswing into 2 to 3 separate phases (Milburn, 1982; Nagao & Sawada, 1977; Neal & Wilson, 1985; Vaughan, 1981), each with distinct events occurring throughout. These studies also tended to focus on the uncocking of the wrists and the plane through which the downswing occurred. It was felt that at the filming rate used for this study the beginning and end of these phases would not be accurately identified and therefore may lead to erroneous conclusions. Identifying and measuring these same phases for the downswing of the field hockey drive and accurately describing the plane through which the stick moved would provide for an excellent future research study. It had been proposed that this study would examine the plane of the stick during the downswing; this variable could not be quantified but it was discussed earlier in this paper.

Technique Variables - Stationary Drive

When this study was at the proposal stage a small number (14) of technique variables had been chosen to be measured on each of the 17 subjects. These variables were chosen based on the literature review and there was also an effort to restrict variables to ones that could be measured directly from video. Analysis of the data through the Peak Technologies Analysis System provided linear measures of each digitized point (end-points of each segment) along each axis (X, Y, Z) as well as resultant measures for each frame of film. The Peak System also calculated angular displacements at each joint and angular velocities of each body segment plus other defined angles, such as the shoulder/hip angle, for each frame of film. This produced a large amount of information and several means for measuring most of the 14 identified variables from the literature review.

Further analysis of the data revealed other potentially significant variables; these were identified by reviewing the raw data for each variable and noting if there was a peak or a minimum occurring around the time of contact. This was checked for several subjects and if a trend in the data was found, then this variable was also retained for further analysis. These steps resulted in the inclusion of 44 technique variables for the stationary drive and 47 variables for the penalty corner drive into a multiple regression equation (these variables are listed in Appendix B). The additional variables for the penalty corner drive were measures of athletes kinematics at RFStr, the equivalent starting point of this skill. These variables were all input into correlation matrixes and the variables significantly related to ball velocity were put into a multiple regression equation. This process determined if any of these variables were significantly related to one another, thereby reducing the number of independent variables. The remaining independent variables were then input into both a multiple regression and a stepwise multiple regression equation.

For the stationary drive, 8 variables were found to be significantly related to ball velocity (Table 14): the amount of shoulder rotation in the XY plane during the downswing; the amount of shoulder rotation during the downswing in the XZ plane; time of minimum shoulder angle in the XY plane until contact; time of minimum shoulder angle in the XZ plane until contact; amount of pelvic rotation in the XY plane; amount of pelvic rotation in the XZ plane; time of peak angular velocity at the shoulder/hip angle until contact; time to contact from peak CM velocity. These variables were input into a multiple regression equation with a resulting r^2 value of .903; adjusted r^2 = .806 (p=.0024). These results were significant, however, there were still a large number of independent variables for the number of subjects in the sample, therefore, these independent variables were reduced in number by eliminating any variables closely related to one another. This left 4 independent variables to be used in a second multiple regression equation: the amount of shoulder rotation in the XY plane during the downswing; the amount of shoulder rotation during the downswing in the XZ plane; time of peak angular velocity at the shoulder/hip angle until contact; time to contact from peak CM velocity. These variables combined produced an r^2 value of .76, adjusted r^2 = .68 (p=.0011).

The amount of shoulder rotation in the XY and XZ planes defined the ROM of the shoulder from the top of the backswing until contact, by measuring the angle between a line connecting the left and right shoulder, relative to a plane. Both of these measures were positively related to ball velocity, indicating that an increase in these angles would result in an increase in ball velocity. Therefore, greater ROM of the shoulders in these planes, presumably through a greater backswing, would lead to increased ball velocities of .053 m/s for each additional degree of rotation in the XY-plane and .035 m/s for each additional degree of shoulder rotation in the XZ-plane. Shoulder rotation in the XZ-plane described shoulder tilt, or the difference in height between the left and right shoulder. Movement of the shoulders in this plane was observed by Alexander (1981) and Chivers and Elliott (1987) but their significance was not described.

It should be noted that regression analyses of this type are only valid through the range of values measured. Increases in these angles past the greatest measured value may have no effect on resultant ball velocity, i.e.. increasing the shoulder angle in the XY plane to 120° would not increase ball velocity and would result in a very extreme body position.

Time of peak velocity of the CM was also positively related to ball velocity. Peak velocity of the CM tended to occur between LHS and RFoff; for 14 subjects it occurred within .034 seconds of LFF. During this time the athletes added to their linear momentum by pushing against the ground with their right leg, the CM then decelerated after the weight was transferred onto the left leg. As an increase in this time related to an increase in ball velocity, and peak velocity tended to occur around LFF, this finding may relate to allowing the athlete time to transfer velocity more completely through to the stick by allowing time for motion to occur at proximal segments. The range of values for this variable were relatively small: range .102 - .221 seconds, average .142 seconds.

For all subjects, the rotation of the shoulders relative to the XY plane described a similar pattern in which this angle was at some maximum value at TBS, decreased to a minimum (around 0.0°) some time before contact, then increased again until contact. Through the statistical analysis, it was found that the time from minimal angle until contact was a significant factor and a smaller time was related to higher velocities. This may indicate that subjects reaching this position in the downswing had greater angular velocity of the shoulders in this plane, and therefore, contacted the ball sooner. Another possibility was that subjects who took longer to contact the ball after reaching this point in the downswing contacted the ball at a greater angle and possibly rotated too far and contacted the ball in an incorrect position (range of time 0.0 - .136 seconds).

As with the previous variable, the shoulder angle in the YZ plane went through a similar pattern of maximal and minimal angles in which the timing of the maximal angle before contact was found to be a significant factor. Subjects with greater ball velocity attained this angle closer to contact and three subjects attained this angle at contact at 180°. This indicated that these subjects' shoulders were aligned parallel to the Y-axis at contact.

Pelvic rotation in the XZ-plane went through a pattern of a minimal angle at the TBS as the hips were fairly level, then increased significantly as the left leg supported the body and the right knee dropped. The right foot then came off the ground and the right leg was adducted and extended, this lowered the right hip relative to the left and increased this angle for most subjects. This variable was positively correlated to ball velocity, therefore the greater this angle the better. Essentially, this angle represented the difference in height of the left and right hip joints, which was observed by Chivers and Elliott (1987) and they stated that the right hip was angled upwards. The greater this difference in height, the greater the angle. Subjects who exhibited this were doing what Nagao and Sawada (1974) referred to as closing the hips (Figure 17). However, they did not state whether this position at contact was more advantageous than having the hips in a more 'open' position. The variable of pelvic rotation in the XY-plane is also a measure of the angular displacement of a line joining the hips from the original frontal plane of the body. During the execution of the skill the pelvis rotated to the right about the left hip (after LFF), and more skilled subjects had greater displacement of this angle.

The final variable included in the multiple regression equation was the time of peak angular velocity between the shoulders and the hips until contact. The shoulder/hip angle measured the angular displacement between a line connecting the left and right shoulder and a line connecting the left and right hip. This angle was greatest around TBS, then decreased until contact. This variable was positively related to ball velocity which indicated that if this peak angular velocity was reached sooner in the downswing, ball velocity would increase more. It must be kept in mind that this angle measured the relative velocity between two segments that were both moving in the same direction to contact the ball. Peak angular velocity was reached near RFoff, after this event the angle between these segments did not vary as much. The point of peak velocity of this variable may indicate the time at which the angular velocity of the more proximal segment was being transferred to the more distal segment. If subjects performed this movement too close to contact, it could have decreased the ROM through which the more distal segment, and subsequent distal segments, could be accelerated.

Several variables which had been hypothesized as being critical to performance of this skill were not included in the multiple regression equation. Some of these were not included because they were significantly related to variables which were used in the equation. Several of the variables measuring rotations of the shoulder line and the pelvis were significantly related to each other and all indicated that greater ROM during the downswing would result in greater ball velocities. Other variables worth noting were stick displacement, which measured the displacement of the stick head from the ball at the TBS. This was related to shoulder displacement in the XZ-plane (r = .512). Also hand displacement and relative hand displacement were related to pelvic rotation in the XZ-plane (r = .518 and .572 respectively). These 3 variables were included as a measure of the height of the backswing, as the greater the ROM through the downswing would lead to increased ball velocities. It is reasonable that measurements of shoulder and pelvic rotations would be a better indicator of ROM of the downswing. It may be that a more sensitive measure of the ROM of the downswing was needed, as Alexander (1981) also found no relation between ball velocity and height of the backswing, as measured by the vertical displacement of the stick head at the top of the backswing.

The distance of the left toe from the ball was related to shoulder rotation in the XY-plane (r = .526) and pelvic rotation in the XY (r = .653) and XZ-planes (r = .637). With all subjects using the same length stick, and subjects being of varying heights, the distance the left foot was placed from the ball would eventually determine many of the characteristics of the body position at contact. To contact the ball properly, a taller person would either have to flex at the hips more to reach the ball, or move the ball closer to the left foot. The positive relationship would indicate that subjects who hit the ball harder tended to have the ball further from the left foot. This could imply that they also take a more horizontal position at contact.

Step length towards the ball was also significantly related to the time of peak shoulder/hip angle until contact (r = .495) and to pelvic rotation in the XY-plane (r = .472). It was hypothesized that subjects who took a longer step towards the ball would have greater peak linear velocity of their CM and would be able to generate greater ball velocity. Hendrick (1983) reported an average step length of .68 m for subjects in her study with a range of .46 - 1.50m, but did not comment on variability of step length to ball velocity.

Trunk angles at relevant events during the skill were measured to describe the performance of the skill and were reported in the results section of this paper. The trunk positions of all subjects at contact were regressed against ball velocity to further examine the implication that a more horizontal trunk position at contact may be critical to performance of this skill. Figure 34 shows that the Trunk - Y angles at contact were significantly related to ball velocity ($r = .583$) and indicated that a more horizontal position produced greater ball velocities for these subjects. Simple regression between trunk-Y angles at contact and ball velocity produced an r^2 value of .34, adjusted $r^2 = .296$ ($p = .014$). Greater trunk lean would mean that the moment arm along the longitudinal axis of the trunk would be increased. If equivalent angular velocity of this segment could be achieved in this position it would result in greater linear velocity at the distal end of the segment. Greater trunk lean would also indicate an increase in the ROM through which this segment travelled, increasing the impulse of the system and the power of the drive. If striking the ball from an upright position, the axis of rotation for the trunk is primarily about the spinal column and therefore there would be a smaller moment arm about this axis.

Chivers and Elliot (1987) reported trunk angles of 5° - 15° but did not describe the measurement of this angle. Kanjee (1991a) stated that if the ball was contacted from an erect position there was a good chance the player would top the ball, but did not define 'erect'. It is interesting to note that subject 16 was relatively upright and produced the greatest ball velocity, however, he was also one of the shortest subjects and this may have allowed him to still be effective from this position.

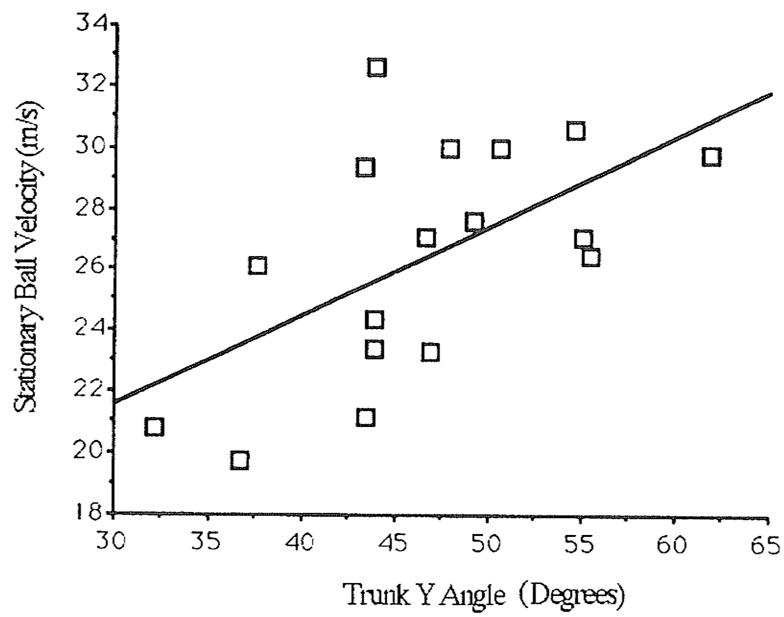


Figure 34. Relationship of the Trunk-Y angle, the angle between the vertical axis and the trunk, at contact and ball velocity.

Technique Variables - Penalty Corner Drive

Following the same steps that were used in the analysis of the stationary drive data, the independent variables measuring components of the penalty corner drive were decreased to 9 (Table 17) through a correlation matrix. Four of these variables were related to ball velocity at a .05 level of significance: peak CM velocity;

peak angular velocity of the stick/wrist angle; peak angular velocity of the stick/shoulder angle and time of peak angular velocity of the stick/shoulder angle until contact. Because this was a small number of variables and three of the four were highly related to one another it was decided to include variables that were related to ball velocity at the .10 level of significance. These variables were: relative step length; minimum shoulder angle in the XZ-plane; maximum shoulder rotation in the YZ-plane; CM velocity at contact and drop in magnitude of CM velocity from peak until contact.

The results of the multiple regression analysis using these 9 variables was an r^2 value of .906, adjusted r^2 = .736; p = .0399. The removal of related independent variables from this equation increased the strength of the statistics. The 4 variables, relative step length, CM velocity at contact, peak stick/wrist angular velocity and maximum shoulder rotation in the YZ-plane, produced a regression equation with an r^2 value of .751, adjusted r^2 = .652, p = .0045.

Center of mass velocity at contact was not significantly related to any other independent variables; including peak velocity of the center of mass. All subjects had a drop in CM velocity from peak until contact, however, more skilled subjects were able to maintain their linear velocity of their CM through to contact. The average drop in CM velocity from peak until contact was 55.4%, however, this ranged from 37.7% to 79.6% and there was a tendency for more skilled players to experience less of a drop in velocity. More skilled subjects also had greater peak velocity of their CM and therefore their velocity at contact tended to be greater than that of the less skilled players.

The greater velocity of the CM at contact also resulted in greater linear velocity of the stick head at contact, all other things remaining equal. While the measure of CM linear velocity at contact remained in the regression equation, it should be noted that peak velocity of the CM during the skill was more highly related to ball velocity (r = .659) indicated that, for these subjects, it was more important to generate this peak velocity during the approach to the ball than it was to maintain the magnitude of this velocity through the skill. This finding was in agreement with Wein's statement that the force of the drive was partly dependent on the athletes approach speed (Wein, 1979). The variable of peak CM velocity was eliminated from the regression equation because it correlated highly with the angular velocity of the stick/wrist angle. This does not necessarily mean that the two were a measure of the same thing, rather, that more highly skilled subjects tended to have larger values of each variable and less skilled subjects tended to have lower values for these variables.

Relative step length was the length of the final step towards the ball, measured from the position of the right toe at RFStr to the position of the left heel at LFF, divided by the subjects height. Relative step length ranged from 38.5% to 63.7% (average was 46.9%) of the subjects height and the actual length of the step ranged from .664m to 1.15m, average .792m. These values are quite a bit higher than those of the stationary drive (range .557 - .987m, average .673m; relative measures average was 39.8%, range 31.88% - 53.51%) and higher than those reported in the literature for the stationary drive (average .68m, Hendrick, 1983). Relative step length was also significantly related to some other independent variables: hand displacement from the ball at the TBS, the distance of the left toe to the ball, the velocity of the right foot after RFoff and, of course, to the actual length of the step.

The relationship between relative step length and ball velocity was negative, which implied that a decrease in the length of this step would result in an increase in ball velocity. This was the opposite finding to that which had been hypothesized earlier in this paper. This negative relationship may be explained by the fact that some of the less skilled and less experienced subjects may have mis-judged their starting position for this skill and therefore, to compensate, had to take too long a final step towards the ball, placing themselves into an improper body position from which to contact the ball.

The two top performers on this skill both had above average final strides to the ball (S16 - .814m; 48.45%BH; S17 1.15m; 62.35%BH). It is also possible that subjects who did perform well on this skill, did so mostly by generating large angular velocities of their upper body segments as opposed to building on the movements of the lower body. Wein (1979) stated that the penalty corner drive was a difficult skill and that an individual must find the optimal approach to the ball such that they generate maximal velocity of their CM and place themselves in the correct position to execute the downswing. It is difficult to achieve optimal CM velocity and coordinate foot movements to place oneself in the ideal position to contact the ball from. This is most noticeable in game situations where the ball is not passed out on target or the stop is not made correctly. The striker then must adjust at the last instant which usually results in lower ball velocity of the drive.

In a closer analysis, by scattergram (Figure 35a), of the relationship between relative step length and ball velocity, two distinct patterns emerged. Those subjects who hit the ball with above average velocity tended to have a positive correlation between these two variables (Figure 35b), while those who did not hit the ball as hard tended to have a negative relationship between these two variables (Figure 35b).

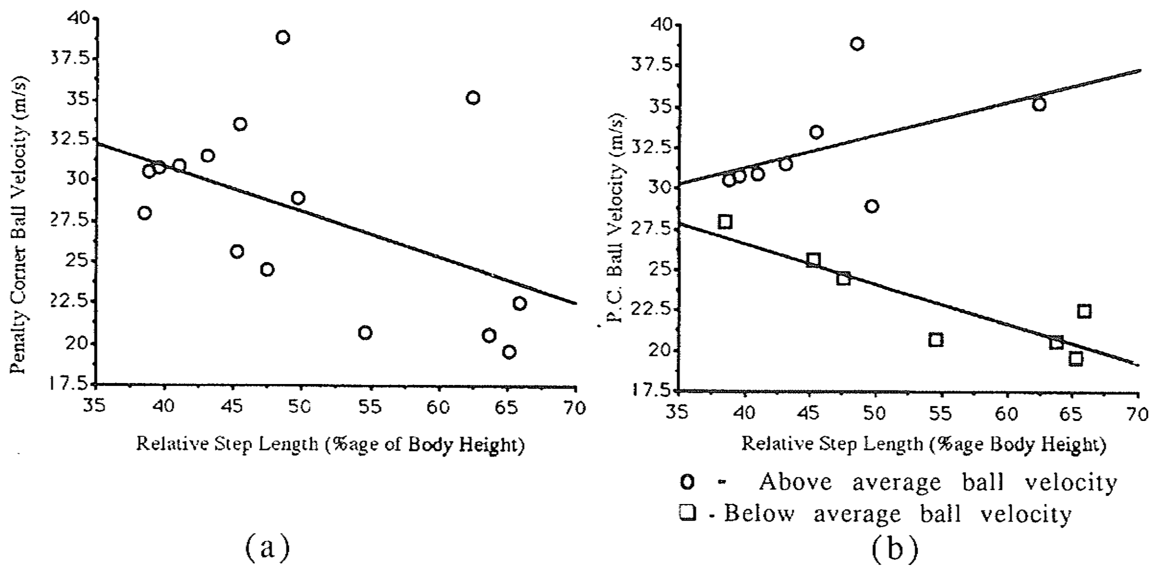


Figure 35. Relative step length versus penalty corner ball velocity (a) all subjects; (b) separate regression lines for those subjects with above average and below average ball velocities.

Patterns such as this were noted in some of the other variables which may have been an indication that either the subjects were part of two separate populations i.e. skilled and unskilled, or that the variable of gender affected more than the expected differences seen in the anthropometric data as most of the subjects with above average ball velocity were male.

Maximum shoulder angle in the YZ-plane was highly related to pelvic rotation in the YZ-plane and XY-plane, and also to minimum shoulder rotation in the XY-plane. This maximal shoulder angle was reached, on average, .065 seconds before contact.

Stick/wrist angular velocity had the greatest correlation to ball velocity (Table 17) and a number of variables were also related to it. The following variables: stick/shoulder peak velocity, time of peak stick/shoulder velocity before contact, time of minimum shoulder angle in the XZ-plane, CM peak velocity and drop in CM velocity from peak until contact were removed from the regression equation because of their strong relationships to stick/wrist angular velocity. Another variable which was also significantly related to stick/wrist peak angular velocity was the angular velocity of the stick/shoulder angle at contact.

The peak angular velocity at the stick/wrist angle was the dominant variable in this analysis. This was a rather obvious result and would have been expected in the stationary drive analysis as well. This result may not have been statistically significant in the stationary drive because there was less variation in resultant ball velocity for that skill. The subject with the greatest angular velocity of their stick during the downswing will hit the ball with the greatest linear velocity, providing the lengths of the segments are equal. Measures of the angular velocity between the stick segment and the shoulder segment essentially measured the same thing as the stick/wrist angular velocity and do not reveal any new information. The strong correlation between CM peak velocity and stick/wrist peak angular velocity implied that subjects who generated greater

CM velocity while approaching the ball also had greater angular velocity at the stick/wrist angle.

Summary, Conclusions and Recommendations

This research project was exploratory in nature and attempted to determine key anthropometric, temporal and technique variables in the execution of the stationary and penalty corner drive through regression analysis methods. Variables were identified from the literature, from interviews with elite coaches and from analysis of the research data. Several measures of each identified variable were taken from three-dimensional film analysis of 17 elite players (9 males; 8 females). These measures were regressed against resultant ball velocities of each skill, resulting in multiple regression equations for the anthropometric, temporal and technique variables.

The results of this study were particular to the subjects sampled, the sample was relatively small, there was a mix of gender and there appeared to be a mix of skill level. Therefore, generalization of these results to other populations and interpretation of relationships between variables past the bounds of those measured here must be done with caution. It would be best to interpret these results as the identification of variables key to the performance of these skills (using ball velocity as the criterion variable). Comparison of these identified variables between groups, such as skilled and unskilled, would better reveal the nature of these relationships.

It was hoped that the key variables found from this study could be measured from subsequent two-dimensional film analyses. However, it was found that, for this subject group, variables significantly related to ball velocity could only be measured through three-dimensional analysis.

The key technique variables found in this study involved the rotational components of the skill, which can only be quantified accurately through three-dimensional methods. Therefore, future studies should all be three-dimensional in nature and interpretation of previous two-dimensional studies should be done with care. Future research must attempt to identify variables related to performance which can also be measured from two-dimensional methods to simplify the process of identifying and correcting performance factors.

Conclusions

Analysis of the 17 elite field hockey players in this study revealed several factors related to the ball velocities they produced during the execution of the stationary and penalty corner drives. The following conclusions appear justified:

1. The variable of gender was the dominant variable in the multiple regression analysis of the anthropometric data in that males tended to produce greater ball velocities and most body measurements were greater in males.

2. Several absolute anthropometric measures were highly related to ball velocity, including forearm girth and muscle mass.

3. Temporal analysis of each skill did not reveal any statistically significant findings; so the duration of any particular phase was not found to be significantly related to ball velocity.

4. Four of the technique variables selected for the multiple regression equation were able to explain variation in stationary ball velocity. These represented different facets of the ROM of the downswing, and all essentially indicated that the greater the ROM, the greater the resultant ball velocity.

5. Three of the technique variables significantly related to stationary drive ball velocity measured the timing of pelvic and shoulder rotations during the downswing and indicate that greater ball velocities can be produced if the timing of movements from the proximal to distal segments allows for maximal displacement of the proximal segment before movement of the distal segment.

6. The final technique variable which was significantly related to stationary drive ball velocity was the time of peak velocity of the CM before contact. Higher ball velocities were produced when this time was higher.

7. Relative length of the final step, the velocity of the CM at contact, the maximum angle of the shoulders in the YZ-plane during the downswing and the angular velocity at the stick/wrist angle were the most significant technique variables related to penalty corner drive ball velocity. Each was positively related to ball velocity, which indicated that increases in these variables would increase ball velocity.

Recommendations

1. It is recommended that future studies analyze these specific variables that were found to be statistically significant as well as the more general components of the skill that they were designed to measure. For example, it would be useful to find a more general method of measuring the ROM of the downswing.

2. Attention must also be focussed on variables identified from a review of research done on the golf drive. These included precise timing of movements during the downswing and a breakdown of the downswing into 3 separate phases, which would require filming speeds of 200 fps or more for the field hockey drive.

3. It is recommended that the impact between the stick and ball be analyzed in detail, this would greatly assist in the design and specification of equipment and would require filming speeds of up to 2000 fps.

4. It is recommended that a much larger sample of subjects be used and that subjects be of the same gender and of the same skill category, i.e. only current national team members.

5. Finally, future studies should use three-dimensional techniques to describe and analyze these skills.

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APPENDIX A.

SUBJECT PROFILES

SKILL LEVEL AND EXPERIENCE.

Subject/Gender	Highest Level Played	P.C. STRIKER
S1/F	International	yes/international
S2/F	Senior Provincial	no
S3/M	Jr National Squad	yes/provincial
S4/M	International	yes/provincial
S5/M	International	no
S6/M	International	yes/international
S7/F	International	yes/provincial
S8/F	Sr. National Squad	no
S9/F	Senior Provincial	yes/provincial
S10/M	Senior Provincial	yes/provincial
S11/M	International	yes/provincial
S12/F	Jr. Squad	yes/provincial
S13/F	Jr. National	no
S14/M	International	yes/international
S15/F	Squad	yes/provincial
S16/M	International	yes/international
S17/M	Senior Provincial	yes/provincial

SUBJECT/SEX	AGE	LEG LENGTH	LEG L/HT	TRUNK L.	TRUNK L/HT	ARM LENGTH	ARM L/HT	HEIGHT	ACR. BR.	ILIO. BR.	TROC. BR.
S1/F	28	87.77	52.56	79.23	47.44	69.15	41.41	167	37.25	28.6	33.9
S2/F	18	78.6	49.28	80.9	50.72	65.07	40.8	159.5	33.5	25.97	30.67
S3/M	23	98.13	52.06	90.37	47.94	86.43	45.85	188.5	40.87	30.05	33.15
S4/M	30	89.77	51.59	84.23	48.41	77.65	44.63	174	37.5	28.4	33.35
S5/M	39	80.75	48.64	85.25	51.36	75.15	45.27	166	39.05	28.35	32.3
S6/M	29	87.05	50.76	84.45	49.24	78.45	45.74	171.5	37	27.7	30.25
S7/F	33	75.96	48.23	81.54	51.77	67.65	42.95	157.5	35.75	27.45	33.25
S8/F	31	82.45	50.27	81.55	49.73	71.95	43.87	164	36.55	24.45	31.95
S9/F	24	86.45	53.2	76.05	46.8	68.75	42.31	162.5	35.33	25.8	31.63
S10/M	22	90.75	51.42	85.75	48.58	79.83	45.23	176.5	36.67	25.73	32.85
S11/M	24	84.5	50.9	81.5	49.1	74.3	44.76	166	32.5	24.3	29.8
S12/F	18	84.43	53.95	72.07	46.05	68.43	43.73	156.5	27.9	24.9	28.55
S13/F	19	81.75	52.4	74.25	47.6	68.35	43.81	156	27.8	24.5	26.8
S14/M	36	90	52.02	83	47.98	75.52	43.65	173	39.05	26.45	31.7
S15/F	23	79.25	50.64	77.25	49.36	67.9	43.39	156.5	36.8	27.57	31.3
S16/M	29	87.5	52.08	80.5	47.92	75.43	44.9	168	41.63	27.37	32
S17/M	31	92.4	50.09	92.05	49.91	79.05	42.86	184.5	42.35	28.9	33.2

SUBJECT	FOREARM GIR	THIGH GIR.	CALF GIR.	SF/THIGH	SF/CALF	MASS	AcrBr/Ht	IlioBr/Ht.	TrocBr/Ht	ShHipRatio	M. Mass	M.M.%Wt
S1/F	24.95	56.85	37.7	1.95	1.82	67.5	22.31	17.13	20.3	130.24	37.23	55.16
S2/F	23.35	50.15	34.7	3	1.43	56.7	21	16.28	19.23	128.99	25.58	45.12
S3/M	27.55	52.65	36.7	1.6	0.78	86.8	21.68	15.94	17.59	136.01	42.63	49.12
S4/M	26.15	47.75	35.35	1.91	0.52	69.5	21.55	16.32	19.17	132.04	32.61	46.93
S5/M	26.05	48.3	34.7	1.63	0.9	65.7	23.52	17.08	19.46	137.74	31.37	47.75
S6/M	25.95	47.5	34.7	0.77	0.36	61	21.57	16.15	17.64	133.57	34.62	56.76
S7/F	25.25	58.75	36.2	2.14	1.48	62.5	22.7	17.43	21.11	130.24	36.23	57.97
S8/F	23.75	52.45	35.55	1.41	0.6	58	22.29	14.91	19.48	149.49	33.7	58.19
S9/F	24.8	58.75	38.9	3.19	2.77	68.2	21.74	15.88	19.46	136.94	33.66	49.36
S10/M	29.3	54.6	36	1.28	0.59	76.9	20.78	14.58	18.61	142.52	44.29	57.6
S11/M	26.5	56.35	35.15	1.53	0.96	70.7	19.58	14.64	17.95	133.74	39.12	55.34
S12/F	24.2	57.03	37.95	2.22	2.28	66	17.83	15.91	18.24	112.05	33.19	50.3
S13/F	21.65	48.93	32.75	2.05	1.25	49.9	17.82	15.71	17.18	113.47	24.63	49.37
S14/M	25.7	47.6	33.05	0.9	0.93	65.3	22.57	15.29	18.32	147.64	33.2	50.89
S15/F	24.8	54.2	35.6	2.25	1.23	59.9	23.51	17.62	20	133.48	31.49	52.58
S16/M	29.3	52.5	38.55	2.22	0.9	78	24.78	16.29	19.05	152.1	38.14	48.9
S17/M	28.2	53.85	38.3	0.75	0.45	80.9	22.96	15.67	18	146.54	47.38	58.61

APPENDIX B.

TECHNIQUE VARIABLES

Hand Displt- resultant distance of the hands from the ball at TBS

Rel HndDisplt- hand displacement divided by subjects' height

Stick Displt- resultant distance of the head of the stick from the ball at TBS

Rel Stick Displ- stick displacement divided by subjects' height

Step Length- length of the final step towards the ball, distance in metres from the right toe (stabilized after RFStr) to the left heel at LFF.

Rel Step L.- step length divided by subjects' height

Rt Foot Displt- resultant displacement of the right toe from RFoff until contact

Rel Rt Ft Displt- Rt foot displacement divided by subjects' height

T. of RFt Plant- time elapsed from RFStr until RFoff in the penalty corner drive

Rt Ft Vel @ C.- resultant velocity of the right foot at contact

Pk Rt Ft Vel- peak resultant velocity of the right foot between RFoff and contact

PRFV t b/f C. -time from Pk Rt Ft Vel until contact

Lt Toe/ Ball- resultant distance, in metres, between the left toe and the ball at LFF (same distance as at contact with the ball)

ReldistLTBall- Lt toe/ ball distance divided by subjects' height

Stick X XZ DS - angle between the stick and the X-Axis, projected onto the XZ-plane

Stick Y XY DS- angle between the stick and the Y-Axis, projected onto the XY-plane

Stick Z YZ DS- angle between the stick and the Z-Axis, projected onto the YZ-plane

Sh Rotn XZ DS- range of motion of the angle between a line connecting the left and right shoulder, relative to the XZ plane, from TBS until Contact

ShRot XZDSmin - magnitude of the minimum Sh.Rotn XZ DS angle during the downswing

ShRotXZDS tC - time from whence ShRot XZDSmin was reached until contact

Sh Rotn XY DS- range of motion of the angle between a line connecting the left and right shoulder, relative to the XY plane, from TBS until Contact

ShRot XYDSmin - magnitude of the minimum Sh.Rotn XY DS angle during the downswing

ShRotXYDS tC - time from whence ShRot XYDSmin was reached until contact

Sh Rotn YZ DS- range of motion of the angle between a line connecting the left and right shoulder, relative to the YZ plane, from TBS until Contact

ShRot YZDSmax - magnitude of the maximum Sh.Rotn YZ DS angle during the downswing

ShRotYZDS tC - time from whence ShRot YZDSmin was reached until contact

PRot XZ DS- range of motion of the angle between a line connecting the left and right hip, relative to the XZ plane, from TBS until Contact

PRot XY DS - range of motion of the angle between a line connecting the left and right hip, relative to the XY plane, from TBS until Contact

PRot YZ DS- range of motion of the angle between a line connecting the left and right hip, relative to the YZ plane, from TBS until Contact

CMvel@RFoff - resultant velocity of the centre of mass at right foot off

CM Peak Vel.- peak resultant velocity of the CM

CM Vel. @ C. - velocity of the CM at contact

M-N - drop in CM velocity from peak until contact

L Ft/Ball Pth - angle between the path of the ball after contact and a line connecting the left toe to the left heel.

CM/ Ball Path - angle between the path of the ball after contact and a the path of the CM during the approach to the ball.

Sh/ Ball Pth- angle between the path of the ball after contact and the shoulder line, projected onto the XZ or horizontal plane.

Rt Elbow PkVel- peak angular velocity of the right elbow during the downswing

Time b/f C. - time of peak elbow velocity until contact

St/WrAng Pk - peak angular velocity at the stick/wrist angle

St/WrAng t b/fC - time of peak angular velocity at the stick/wrist angle until contact

St/WrAng @ C - angular velocity at the stick/wrist angle at contact

Sh/HipAng Pk - peak angular velocity at the shoulder/hip angle

ShHipAng t bfC - time of peak angular velocity at the shoulder/hip angle until contact

ShHipAng@C - angular velocity at the shoulder/hip angle at contact

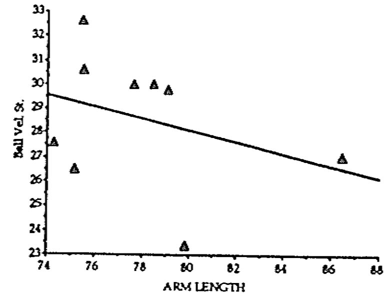
St/Sh Pk - peak angular velocity at the stick/shoulder angle

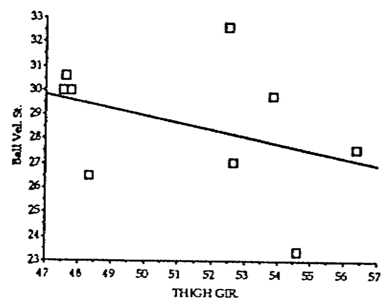
St/Sh t b/f C -time of peak angular velocity at the stick/shoulder angle until contact

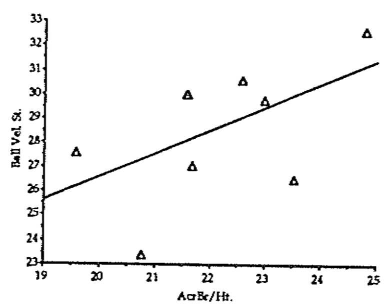
St/Sh @ C -angular velocity at the stick/shoulder angle at contact

APPENDIX C.

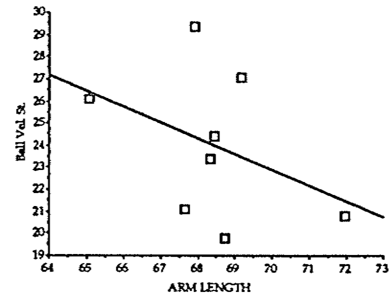
REGRESSION SCATTERGRAMS FOR MALE AND FEMALE ANTHROPOMETRIC DATA

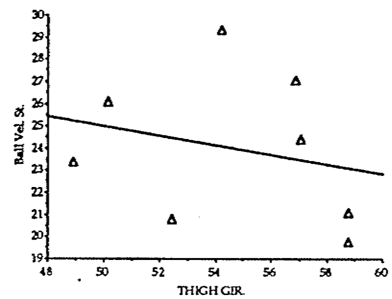

Ball Vel. St.
ARM LENGTH

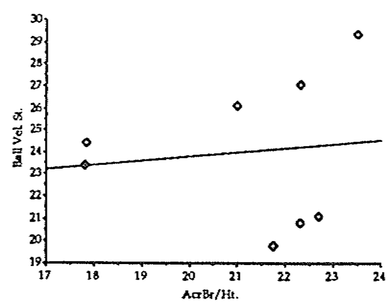

Ball Vel. St.
THIGH GIR.


Ball Vel. St.
AcrBc/Ht.

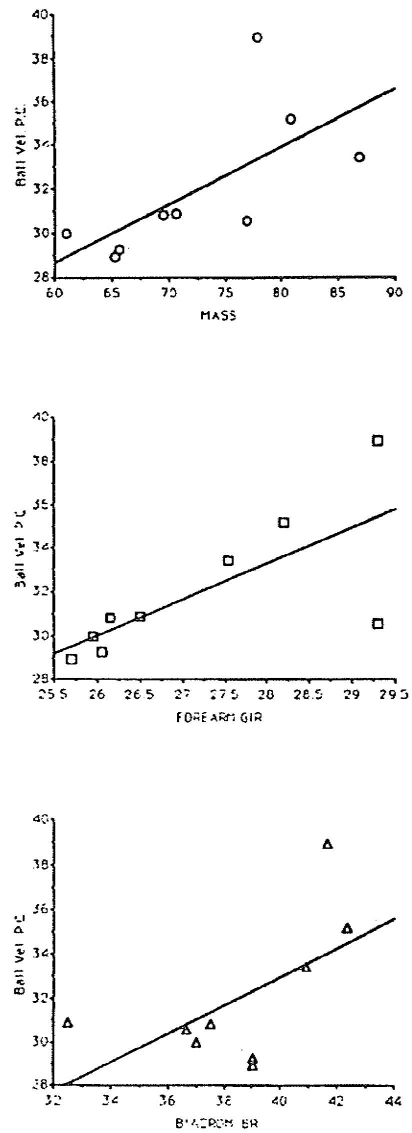
MALES


Ball Vel. St.
ARM LENGTH

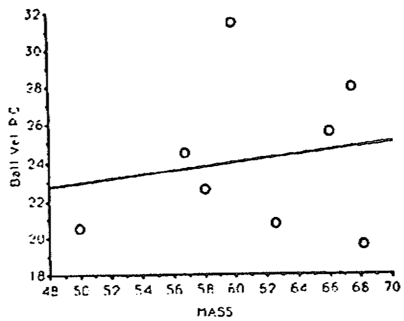

Ball Vel. St.
THIGH GIR.

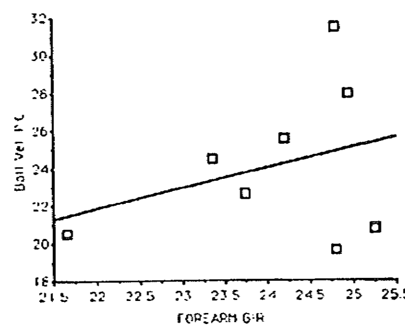

Ball Vel. St.
AcrBr/Ht.

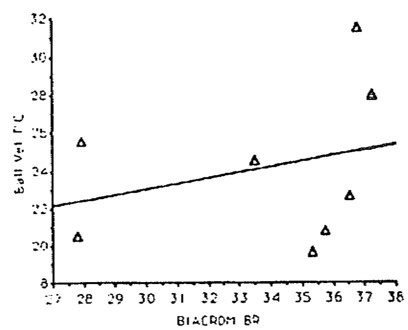
FEMALES



MALES


Ball Vel PC
MASS


Ball Vel PC
FOREARM GIR
25.5


Ball Vel PC
BIACROM BR

FEMALES