Ice hockey stick and puck biomechanical predictors of wrist shot accuracy

By

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Abstract

The purpose of this study was to identify the movement patterns of the ice hockey stick from a wrist shot that corresponds to the accuracy of puck trajectory. A total of twenty five subjects participated in this study; each performed 10 successful wrist shots on four targets. Performances were evaluated by simultaneously recording the movements of the stick's shaft and blade and of the puck with infra-red based motion capture (Vicon®) system (240 Hz) Kinematics of the shaft and blade of the hockey stick were examined using a multiple regression analysis using the accuracy score as the dependant variable. The results indicate that accurate shooters tended to alter release parameters (puck release orientation and velocity), loading mechanics and blade orientation to achieve proper puck trajectory explaining 40% and 76% of the accuracy variances for the bottom and top corners respectively. Shooters were more accurate shooting at bottom corners than at the top corners (67% vs 45%). These analyses helped to identify key stick usage variables that predict accuracy during the execution of stationary wrist shots. Further studies are needed to identify the whole body kinematic patterns associated with the hockey stick kinematics.

Résumé

L'objectif premier de cette étude était d'identifier les mouvements caractéristiques du bâton de hockey correspondant à la précision de tirs du poignet stationnaire à travers différents niveaux d'habiletés. Un total de vingt-cinq sujets ont fait parti de l'échantillon. Chacun d'eux ont dû réussir correctement dix lancers dans chacune des quatre différentes cibles. La performance des sujets a été évaluée en mesurant le déplacement du bâton et de la rondelle à l'aide de marqueur réfléchissants qui était filmé à l'aide d'un système d'analyse du mouvement composé de caméra infrarouge (Vicon®), le tout étant enregistré à 240 Hz. La cinématique du manche et de la palette du bâton de hockey ont été analysées par le biais d'une analyse de régression multiple en utilisant le niveau de précision comme étant la variable dépendante. Les résultats démontrent que les joueurs les plus précis ont tendance à modifier les paramètres de projection (orientation et vitesse de la rondelle), le mécanisme de mise en charge du bâton ainsi que l'orientation de la palette pour obtenir la trajectoire de rondelle désirée avec des modèles de prédiction pouvant expliqué respectivement 40% et 76% de la variabilité de la précision pour les cibles inférieures et supérieures. Les sujets étaient plus précis pour les cibles inférieures que pour les cibles supérieures (67% vs 45%). Cette analyse a permis d'identifier les variables clés pour effectuer un lancer du poignet stationnaire précis mais d'autres recherches doivent être effectuées pour

identifier les mouvements du corps qui sont associés avec la cinématique du bâton de hockey.

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Chapter 1: Introduction

1.0 Introduction

In ice hockey the primary tool for puck control and shooting is the ice hockey stick that is required to put the puck in the opposing team's net. The wrist shot is generally accepted as a more accurate technique for puck projection (Pearsall et al, 1999). Though numerous coaching manuals present general guides for technique development (Gendron, 1957; Randy, 1956; Haché, 1970; Dowbiggin, 2001), beyond the emphasized repetitive practice drills to improve both accuracy and speed of the shot, the ability to define the underlying mechanics of the stick's behavior is relatively unknown.

In the NHL all star weekend, the accuracy contest is one of the most difficult events to perform. Raymond Bourque won the event seven times over ten years from 1990 to 2000 (www.NHL.com). This however, begs the question, of how is this skill performed? What is the difference between Bourque and a recreational player?

In the never-ending search for a more competitive edge, there has been a push to use new equipment designs, materials and construction methods to enhance sport performance. In most sports, both kinematics and kinetics are rarely measured although they are most relevant to increase the desired performance of the equipment used. Biomechanical analysis of how the equipment is used may lead to an optimization of performance. Part of the answer can be revealed by a detailed 3D kinematics analysis. Given that there is a desire for players, coaches and trainers to understand the parameters involved in an accurate wrist shot, and furthermore the desire to develop superior equipment, studying the 3D kinematics of a wrist shot is both relevant and important.

1.1 Nature and scope of the problem

The hockey industry has grown considerably over the past few decades to become a multi-million dollar industry not only in Canada but worldwide. In their 2007 annual report, Hockey Canada discussed the social impact of the national sport. In this report it was estimated that 4.5 million Canadians are involved in hockey as coaches, players, officials, administrators and direct volunteers. These numbers do not take into account spectators, parents and occasional volunteers. In 2006-2007, Hockey Canada had more than 500 000 players registered across their different organization and leagues. In light of the extent of involvement of Canadian citizens in ice hockey, applied research is important because the design and manufacture of improved hockey products and ice hockey has both commercial and societal value.

It is evident that the caliber of offensive players is based in large part on the success of shots leading to a goal. Equally evident is projection, speed and accuracy of the puck which are emphasized by coaches. It is known that high caliber players are more accurate shooters than low caliber players. However little is known about how a player uses the stick to perform an accurate wrist shot. In an ice hockey task analysis, Montgomery et al. identified the wrist shot as the most accurate type of shot in hockey. In addition, the wrist shot is being used in 23 to 37% of all shots taken depending on the player position (Montgomery et al., 2004). A better understanding of stick behavior during shooting may have important implications for stick design and help us to better understand the skill of shooting. For example, if a relationship between blade displacement in the three planes and accuracy were identified, it could lead to the design of blade patterns that are advantageous to players regardless of skill level by optimizing/recreating the kinematics of an accurate shot. The way the stick is used could also lead to better teaching and coaching strategies to improve a player's shooting accuracy.

1.2 Rationale

The hockey stick is a passive implement (Minetti, 2004) used to extend one's arm reach and to create a longer lever to project of the puck. The primary objective of a wrist shot is to project the puck with maximal velocity and accuracy so as to beat the opposing goalie and to score. There have been several studies that have determined which of the different types of shots are most commonly used in ice hockey (slap, snap, backhand, wrist shots) and more particularly the maximal velocities that players generate during the execution of each of these types of shots. (Alexander et al.,1963, 1964, Cotton, 1966, Furlong, 1968, Chau et al., 1973, Roy & Doré, 1974, 1976, Doré &

Roy, 1976, Simm & Chau, 1978, Pearsall et al., 1999, Meng & Zhao, 2000, Wu et al., 2003, Villasenor et al., 2006).

However to date, there has been little attempt to compare the stick behavior with the performance outcome during shooting. The research literature treating the mechanical properties and behavior of the hockey stick has generally addressed these issues qualitatively (Roy & Doré, 1975,1978, Roy & Delisle, 1984). Only recently, quantitative research on the mechanics of the hockey stick has outlined differences in terms of the stick behaviors across skill levels and shooting technique (Wu et al.,2003, Villasenor et al., 2006).

Skills using the stick, particularly shooting, are determined by many interrelated variables (fig 1.1). From that deterministic model, many dependant measures are identified has beeing relevant factors for the displacement and accuracy of the puck .However, the extent to which these variables influence the resulting shooting performance is not well known given the limited research specific to ice hockey (Pearsall et al, 2000). In particular, the studies that have measured the wrist shot have not investigated the factors that influence the accuracy of a wrist shot (Doré, 1976; Wu et all., 2003; Naud 1975; Meng & Zao., 2000).

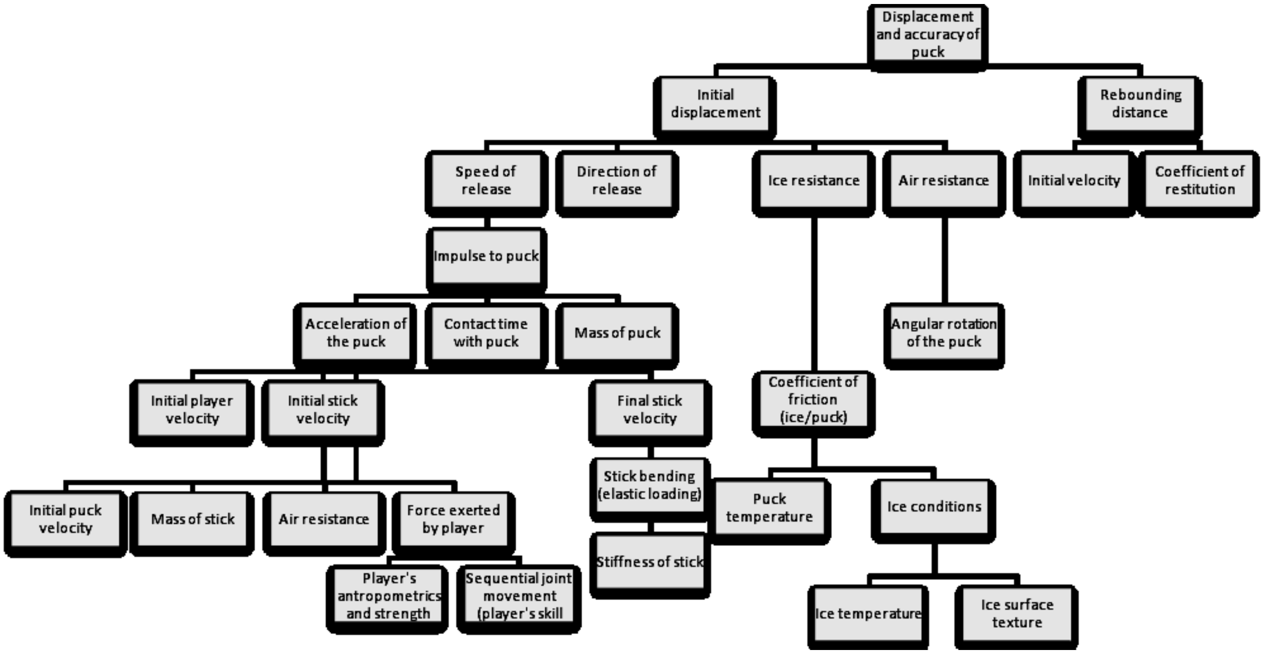

Fig. 1.1: Interacting factors that affect the displacement and accuracy of the puck (adapted from Pearsall et al., 2000)

Recent studies have demonstrated that in throwing or striking tasks, the projection angle at which a projectile is released is crucial for the accuracy outcome of the specific task (Martin et al., 2001, Hore et al., 1996, Mueller et Loosch, 1999, Button et al., 2003, William et Sih, 2002). These studies also found that the release velocity of the projectile and/or the end effectors (hand, golf club, field hockey stick) is another decisive factor contributing to the accuracy in such tasks. But once again, to date there has been no attempt to identify ice hockey stick's behavior variables that account for accurate shooting in ice hockey wrist shots.

1.3 Objectives and hypotheses

The purpose of this study is to identify the movement patterns of the ice hockey stick from a wrist shot that correspond to the accuracy of puck trajectory. These movement patterns will be quantified by measuring stick and puck kinematic variables and compared to outcome measures of shooting accuracy for players of varying skill levels. The goal of this study is not to identify cause and effect relationships but rather to sort out the variables that best predict accuracy.

The following research hypotheses are based on previous work completed in this laboratory. In this study, it was hypothesized that players that shoot accurately use the stick and its blade in a different manner compared to less accurate shooters. The kinematics of the blade and the shaft of the stick are expected to be different when comparing players of different shooting proficiency. We expect to see differences in the maximal angular displacement of the blade orientation (pitch and yaw) for the successful shots compared to inaccurate shots and we also expect higher overall values on these variables in the high caliber players.

Also, different dispersion patterns (i.e. scatter distribution) at target contact are expected when comparing the four targets at which the subjects are shooting. These differences should be different in terms of horizontal and vertical displacement from the center of each target window.

1.4 Limitations

1- All experiments were conduced at room temperature (22 to 24º C);

2- Experiments were conducted under laboratory conditions with a ground surface covered by lubricated polyethylene sheets used to simulate ice skating;

3- The experiment was not performed under a real game situation;

1.5 Delimitations

Delimitations of the study include:

1- Experimental tasks studied include the wrist shots only;

2- Only male subjects were used in the present study;

3- Only stationary (i.e. standing) wrist shots were evaluated;

4- Only one blade pattern was used (Nike/Bauer ®P106– Gagne)

5- Only one stick per shooter side was used (Nike/Bauer® Vapor XXX-Lite Composite stick, length =148 cm) ;

6- Four targets were defined within the target net (the 4 corners);

7- The target net was set 4m away from the puck's initial location;

8- Subject stood at 90 degrees with reference to the net's plane;

9- The subjects used their own skates and gloves;

1.6 Independent (IV) and dependant variables (DV)

The DV in this study is the accuracy level (i.e. accuracy score along a continuum from the lowest accuracy score to the highest accuracy score). The IV's, and their respective abbreviations, are presented below in Table 1.1 and Table 1.2.

Table 1.1: Puck independent variables list

Variables	Per trial	Per target, per subject	By subject	By target (all target)
Accuracy score	*Dependant variable* Successful/unsuccessful	Accuracy (%)	Overall accuracy (%)	Overall accuracy (%)
	Independent variables			
Puck	Off target displacement (z-axis)(Z-Dis)	Mean ± SD	Mean ± SD	Mean ± SD
	Off target displacement (y-axis) (Y-Dis)	Mean ± SD	Mean ± SD	Mean ± SD
	Radial dispersion (Radial)	Mean ± SD	Mean ± SD	Mean ± SD
	Path during contact	y,x displacement, graph by time		y,x displacement, graph by time
	Release velocity (v_{p-r})	Mean ± SD		Mean ± SD
	Release angular velocity - Spin (ω_p)	Mean ± SD		Mean ± SD
	Time of puck contact (Ct)	Mean ± SD		Mean ± SD
	Puck contact distance (Cd)	Mean ± SD		Mean ± SD
	Puck to blade position (P_2B)	Mean ± SD		Mean ± SD

Table 1. 2: Stick independent variables list

Variables	Per trial	Per target, per subject	By subject	By target (all target)
Shaft	*Independent variable*			
	Shaft bend (θ_{SB})	Mean ± SD		Mean ± SD
Blade	*Independent variables*			
	Yaw at release (Ψ_r)	Mean ± SD, graph by time		Mean ± SD, graph by time
	Pitch at release (Φ_r)	Mean ± SD, graph by time		Mean ± SD, graph by time
	Roll at release (β_r)	Mean ± SD, graph by time		Mean ± SD, graph by time
	Linear velocity of blade toe (v_t)	Mean ± SD		Mean ± SD
	Linear velocity of blade heel (v_h)	Mean ± SD		Mean ± SD

1.7 Nomenclature

Events defining the wrist shot

Initial contact (IC): When the wrist shot is initiated; i.e. the puck and the blade first contact.

Release (R): The puck and the blade begin to follow independent trajectories and are no longer in contact.

Target contact (TC): The puck ends its trajectory and intercepts the targets plane

Phases defining the wrist shot

Blade/puck contact phase: Defined as the phase between IC and R

Flight phase: Defined as the phase between R and TC

Spin: Angular velocity of the puck

Stick blade: Lowermost, curved portion of the hockey stick, which is used for puck control and projection.

Blade curve (pattern): Refers to the shape of the curve in the blade provided during manufacturing. Blade curve are classified (e.g. heel-, mid-, or toe-curve) based on the location of the origin of the curve when the blade is laid flat on the ice and viewed directly from above (Fig. 1.2)

Stick shaft: The straight, handle portion of the hockey stick (Fig 1.2)

Angular orientation and displacement of the blade in the three planes (Fig 1.3)

Yaw (Ψ): angular rotation around the Z-axis

Pitch (Φ): angular rotation along the X-axis

Roll (β): angular rotation along the Y-axis

Contra side: Refer to the opposite/contra lateral side to the subject shooting side (Fig. 1.5) e.g. Right side of the net for a left handed shooter

Ipsi side: Refer to the same/ipsi lateral side as the subject shooting side (Fig. 1.5) e.g. Left side of the net for a left handed shooter

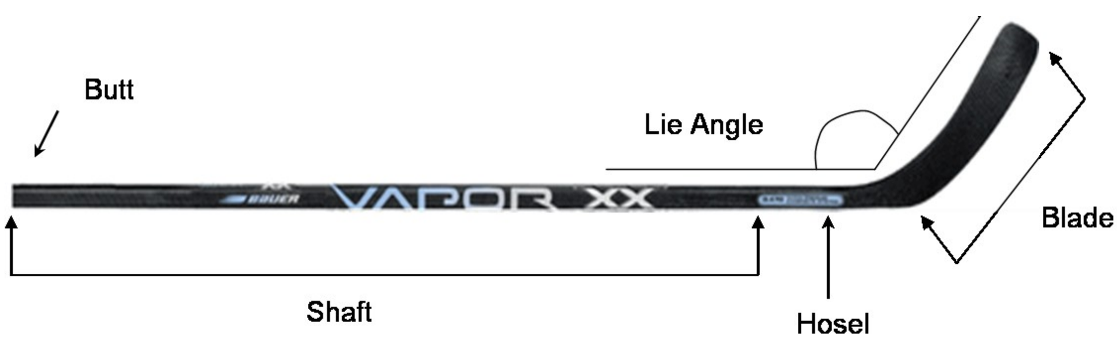

Fig. 1.2 : The basic components of a hockey stick

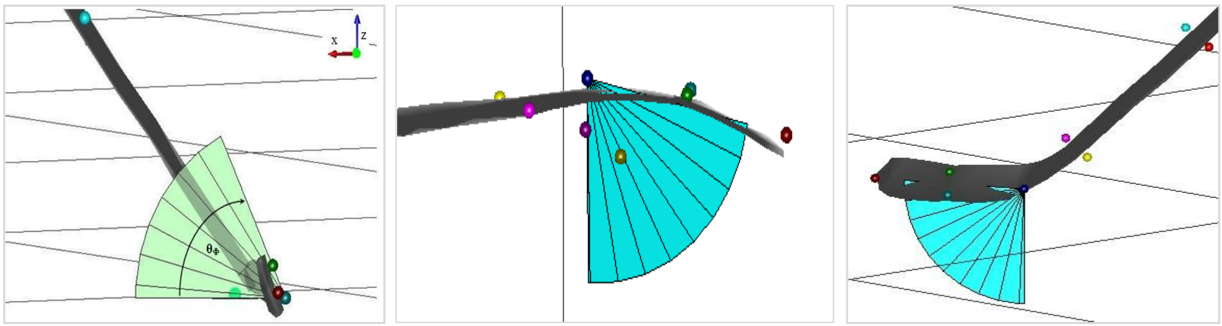

Fig 1.3: Blade's pitch, yaw and roll.

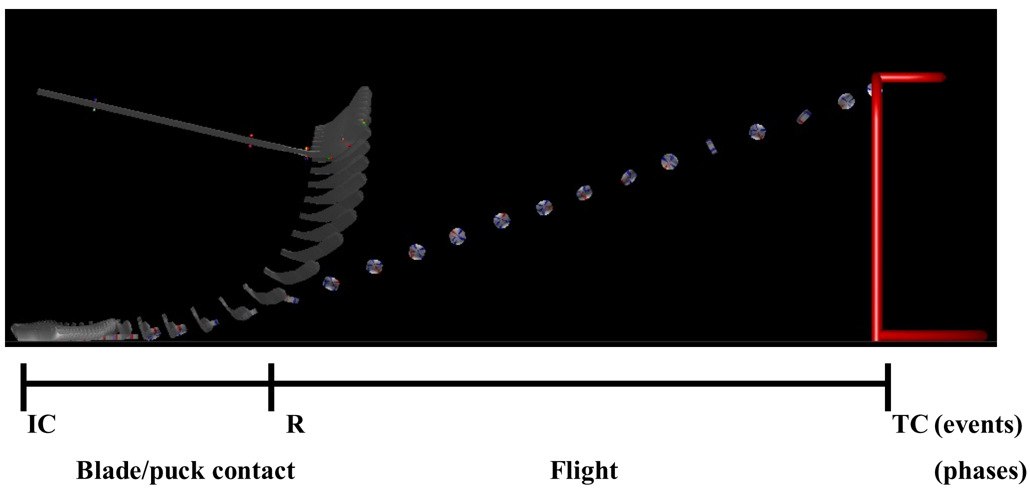

Fig 1.4: Wrist shot phases and events

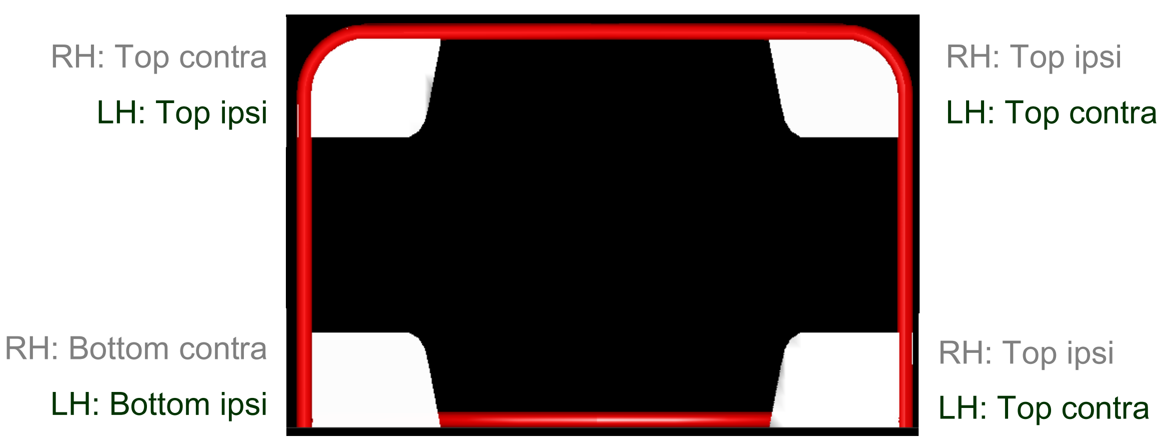

Fig. 1.5: Hockey net with the four different targets and the corners identification relative to the subject shooting side (RH – Right handed, LH – Left handed

Chapter 2: Review of literature

2.1 Ice hockey

Since the origins of ice hockey, the game and the equipment have consistently evolved. It has been common for both coaches and players to initiate changes in equipment to enhance performance, prevent injuries, and improve aesthetics. Often these modifications were made in an effort to raise the technical level and performance of the game of ice hockey (Pearsall & Turcotte, 1999; Pearsall et al., 2000). Not only the game and equipment have evolved but players' physiological and anthropometric characteristics have also changed in the past few decades. The average player size has increased and on average players today are 17 kilograms heavier and 10 centimeters taller than players from the early 1900's (Montgomery, 2006). In addition to this size increase, physiological profiles of today's professional ice hockey players have also evolved. Montgomery observed that compared with values from players in the early 1980s, the VO2 max of today's players has increased significantly with the improvements being independent of body mass and overall strength. Also in parallel, presumably to prevent potential injuries, protective equipment has increased in size, without affecting the mobility of the players.

Because the game of ice hockey is played on a surface of low friction a very specific set of skills is needed for performance and this skill set is distinct from other team sports (figure 2.1). Thus, to describe the level of skill possessed by a player, several qualities defining the efficiency and effectiveness of movement must be taken into account, such as timing, anticipation, speed, agility, and reaction time (Pearsall et al., 2000).

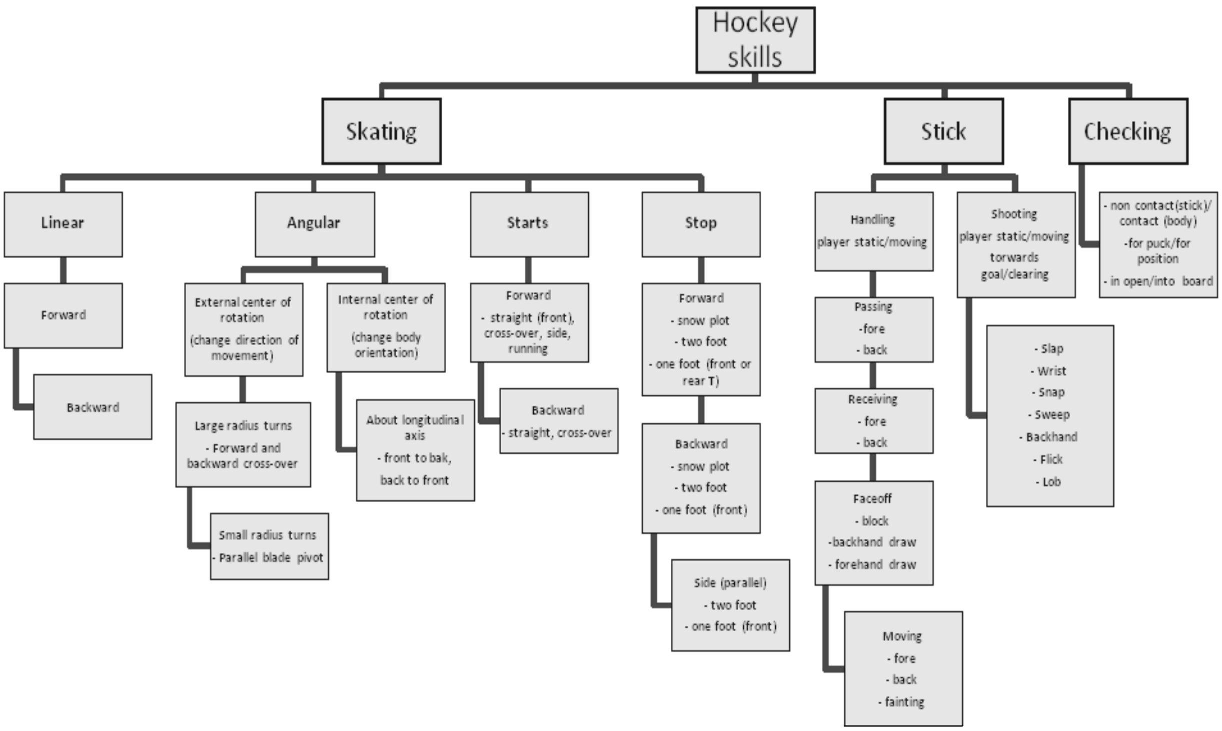

Fig. 2.1: Hockey's fundamental skills (adapted from Pearsall et al., 2000)

The ice hockey stick is an essential piece of equipment to the game of ice hockey. It is used to shoot, pass, catch/intercept and maneuver the puck as well as for checking in order to push opponents off the puck and in the legal acts of body checking and illegal acts as well (crosschecking, slashing and hooking). One extensively studied skill is shooting technique. Previous studies have observed that the slap shot results in the greatest puck velocity while the most accurate type of shot is the wrist shot (Alexander, 1963; Doré et Roy, 1976, 1974, 1973).

2.2 Wrist shots

The wrist shot is the most accurate type of shot, and is used in 23 to 37% of shots that are taken during a game. However, its use varies as a function of player position (defensemen vs forward) (Montgomery et al., 2004). In addition, since scoring/shooting is one of the most important task requirements for the success of a hockey player (Renger, 1994), the ability to shoot the puck with maximal velocity and precision is a decisive factor in the overall performance of a player (Hoerner, 1989; Larivière et Lavallée, 1972). Having more skilled, larger players and goalies increases the difficulty of scoring goals and further emphasises the importance of accuracy in order to shoot successfully. Although the wrist shot has a lower shot velocity than the slap shot, its greater accuracy makes it an important shooting technique in ice hockey (Wu et al., 2003).

One operational definition of the wrist shot is that it begins when the player draws the stick along the ice. Subsequently, the stick is brought forward with the puck in a rapid motion and the shot is terminated by a vigorous pronation (wrist snap) of the lower hand which is moving forward with a simultaneous backward movement of the top hand (Naud, 1975). Unfortunately, only limited work has been done on wrist shot mechanical properties.

Among the other types of shots used in the game of ice hockey, the slap shot involves the greatest angular and linear stick displacement and the highest impact forces of all shot types and most research has focused on the slap shot mechanical properties (Villasenor et al., 2006).

2.3 Blade function

The construction of the ice hockey stick has changed drastically since the 1960's when the curved blade stick was introduced. Today, all NHL players, including goalies use a curved blade (Haché, 2002). Taking out his frustation on a broken stick, former NHL player Stan Mikita has been credited with accidentally discovering the benefits of a curved blade (Dowbiggin, 2001). Even if the curved blade became a standard for the hockey stick, there have been relatively few attempts to quantify the performance benefit of such blade curvature. Examining the blade's effect on shot velocity and accuracy comparing the straight and curved blade during slap shots and wrist shots, Nazar (1971) demonstrated significant differences in terms of shot velocity and accuracy between the two blade patterns. The author claimed that a curved blade stick allowed greater shot velocity and accuracy for both types of shots (i.e. slap and wrist shots) but accuracy measures were not reported. In addition, the authors confirmed previous results (Alexander et al., 1963) by establishing the skating wrist shot as being a slower but more accurate shot. Although curved blades are now the standard in professional hockey, strict regulations exist restricting the amount of curvature permissible for blades. In the National Hockey League's (NHL) rulebook it is stated that the curvature of the blade of the stick shall be restricted in such a way that the distance of a perpendicular line measured from a straight line drawn from any point at the heel to the end of the blade to the point of maximum curvature shall not exceed one-half inch (1/2") (http://www.nhl.com/rules/index.html).

Hache (2002) describes a more theoretical analysis of the advantages of the curved blade over a straight blade in the "Physics of Hockey". During a straight blade's impact with the ice, the blade tends to bend forward, hence that bend affects the angle of release of the puck leaving the blade and therefore the overall accuracy of the shot. On the other hand, pre-curved blades do not bend as much as the straight blades upon ice contact and consequently it has been proposed that the curved blades have less influence on the puck release angle and ultimately on the accuracy of the shot. Haché (2002), described the advantage of the curved blade stating that the puck naturally rolls toward the toe end of the blade and is released at the same point on every shot, allowing more shooting consistency. Conversely, when executing a backhand shot accuracy can be diminished with a curved blade.

2.4 Hockey stick properties

Biomechanical studies of ice hockey sticks have not been widely published. Most of the stick related tasks and the mechanics of the hockey stick have generally been examined only qualitatively although there are a few studies that have quantitatively investigated these issues. Doré and Roy (1978) investigated the effect of stick shaft stiffness on slap shot performance in six pee-wee age players (mean age = 12.3 years). Twelve strain gauges (ten on the shaft and two on the back of the blade) and a single high-speed camera (200 Hz) were synchronized to record both sweep and slap shots for each shaft stiffness model. Maximum forces tended to occur when the puck left the blade, at the top and bottom hands, and were determined to be 13 to 33% less in the flexible shaft stick for each respective hand. The authors suggested that younger players should use flexible sticks; since, they require less force exertion to achieve the same puck velocity as stiffer sticks.

Roy and Delisle (1984), investigated the geometric and dynamic characteristics of the hockey stick in regard to their performance using fourteen models of hockey sticks. These sticks were distributed among 45 Midget AA players in a random manner. Each player had to use the sticks to perform slap shots until the stick would break. This work confirmed findings from a previous study of Roy and Doré (1975) which demonstrated a high level of homogeneity in their geometrical characteristics of the sticks but a lot of heterogeneity in their dynamic characteristics. Through a multiple regression analysis, it was shown that the width, the thickness and the rupture coefficient of the shaft as well as the module of rigidity of the shaft contributed significantly to the durability of the hockey stick.

The effect of the stick's construction and the player's skill on the slap shot and wrist shot performance, were evaluated by Wu and colleagues (2003) using high speed filming and ground reaction forces using a force plate. Two groups of ten subjects (i.e. ten skilled and ten recreational players) performed slap shots and wrist shots with three hockey sticks of different stiffness. The shaft bend and the stick movement were determined by the high speed filming (480 Hz). The shot mechanics were determined by the force plate data combined with the high speed footage while the puck speed was measured with a radar gun. The results indicated that the slap shot corresponded to greater vertical loading force, stick bending, faster puck velocity and width of the hand placement when compared to the wrist shot. In addition, the puck velocity was influenced by skill level and body strength but not stick stiffness, while skilled players were able to generate more vertical force and bend of the stick, in part, by adjusting their hand position on the stick.

In 2006, Villasenor et al. studied the recoil effect of the hockey stick during slap shot testing in five recreational and four elite hockey players. The players' performance was evaluated by recording stick movement and internal bending simultaneously from high-speed digital video (1,000 Hz). Puck acceleration was acquired using a triaxial accelerometer positioned inside the puck. The results indicated that blade-puck contact time was greater for the elite than for recreational players (38 +/- 9 ms and 27 +/- 5 ms); however, measures for puck acceleration were essentially the same (63.8 g +/- 9.9 and 61.8 g +/- 19.5). Furthermore, the elite players were able to generate greater puck velocities (120 +/- 18 km/h and 80.3 +/- 11.6 km/h) while the recoil timing was found to be greater for elite players (59.8% of blade-puck contact).

Worobets and colleagues (2006) expanded on this work by examining the influence of shaft stiffness on potential energy and puck speed during wrist and slap shots. Thirty left handed composite hockey sticks from eleven hockey stick manufacturers were subjected to a mechanical cantilever bend test to determine the shaft stiffness of each stick. From these thirty sticks, eight were chosen representing the entire spectrum of stiffness. Infra-red high speed digital video cameras (480 Hz) were used to record wrist and slap shots taken by five elite hockey players with all eight sticks. The high speed footage was used to measure shaft deformation and puck speed. The force-deformation data was acquired by the shaft stiffness bench testing and the associated potential energy storage and return of each stick. The results showed that during a wrist shots, the puck speed was higher with a stick that stored a more potential energy in the shaft ($r = 0.83$, $p < 0.05$). In general, flexible sticks were found to store the most energy ($r = -0.71$, $p < 0.05$). Energy considerations did not explain changes in puck speed for the slap shot. It seems that for that type of shot it is the athlete and not the equipment that influences puck speed but the underlying physiological mechanisms have not yet been documented.

2.5 Three-dimensionnal analysis in sports

Three dimensional analyses in sports are becoming more common with the advances in both hardware and software technologies that have made it more accurate and less time consuming. In 2004, Woo et al, compared the upper body and stick kinematics of 5 elite and 5 recreational ice hockey players during a static slap shot (i.e. slap shot taken without skating in). Fifteen electromagnetic markers were placed on the subjects' upper limb, on the stick and on the puck and these markers were tracked by an Ultratrak system and the markers' 3-D coordinates were obtained. Subjects were asked to perform 5 slap shots attempting to hit a 1.3m x 1.13m target located 3.3m away from the puck's starting position. From this protocol, a significant difference ($p < 0.05$) was found between the stick velocity of elite and recreational players with a peak velocity of 29.14 m/s versus 26.46 m/s in the elite and recreational shooters respectively. This difference could be explained by a different joint coordination pattern and global stick movement.

Three-dimensional analysis was also used to improve spectators' safety during ice hockey games. In order to determine what increase in the height of the safety glass would be necessary to reduce the risk of severe injuries to spectators in ice hockey rinks; Böhm et al. (2007) simulated puck flights towards the safety board based on initial take-off conditions of the puck. Three high caliber players shot the puck against a vertically positioned force plate to record the impact forces while six Vicon-MX460 cameras (400 Hz) captured three 6mm spherical reflective markers that were fixed on the puck. All shots were taken and recorded in laboratory conditions on a low friction synthetic material sheet called "Nierolen" as on ice capture was not ideal for the camera set-up. The simulations showed that increasing the security glass from board height without any protective glass of 117 cm to a total height of 380 cm with the plexiglass would lower the relative frequency of shots with a potential to hit a spectator by 80%. With these changes in board height, the maximum velocity of potentially dangerous shots would slighty decreased from 28.4 $m{\cdot}s^{-1}$ to 25.2 $m{\cdot}s^{-1}$.

Bretigny and colleagues (2006) used 3-D motion capture analysis to investige the upper-limb kinematics and coordination of the short grip and classic drive in field hockey. The advantage of the classic drive seems to be in power, whereas the potential advantage of the short grip drive lies in its short duration. In field hockey, one of the principal factors that determine which type of shot to use is a tactical consideration in response to temporal pressure. Ten female elite field hockey players performed ten shots (5 for each type) mimiking a game situation as though they were passing the ball 10 m away. The trials were recorded using a Vicon optoelectronic system (5 cameras) at a sampling rate of 50 Hz. Reflective markers were placed on subjects on both the acromio-clavicular joints, and on both epicondylis of the arms, on the right and left styloid radius, on the head of the stick and 45 cm away from this first on the shaft of the stick. From their results, the shorter total time to perform the short grip drive could be explained by the position of the hand on the stick. The hands were placed lower on the stick hose in the short grip drive, so they were closer to the ground resulting in a smaller overall amplitude. The kinematics parameters revealed differences in the short grip and classic drives that justify their use in different contexts in relation to tactical intentions.

Golf swing and the biomechanics of golf have been widely investigated over the past decade and the technology available is one of the important factors that contributed to these studies. One of the primary focuses of golf research has been to understand the golf club design factors relating to increased launch velocity of the ball.

William and Sih (2002) studied the impact of the changes in the golf club orientation following ball impact. Using three Motion Analysis video cameras sampling at 200 Hz, they tested 28 right handed golfers with handicaps ranging from 0 to 36. Each participant had to perform 14 shots with a driver and a 5-iron. Markers were placed along the club's shaft and on the face of the club so that its orientation could be calculated throughout the whole swing. Direct linear transformation algorithms were used to determine the markers 3-D coordinates. The orientation angles of the club face were defined as the lift, the pitch and open/closed angles (fig 2.2). Based on their analysis, there were three factors that influenced the final direction of the ball after impact: the travelling direction of the clubhead, the orientation of the clubhead relative to that travel direction and the frictional interactions between the clubface and the ball during impact. In addition, golfers who showed a high degree of variability in clubface orientation and impact location on the clubface were likely to show high variability in shot direction and spin.

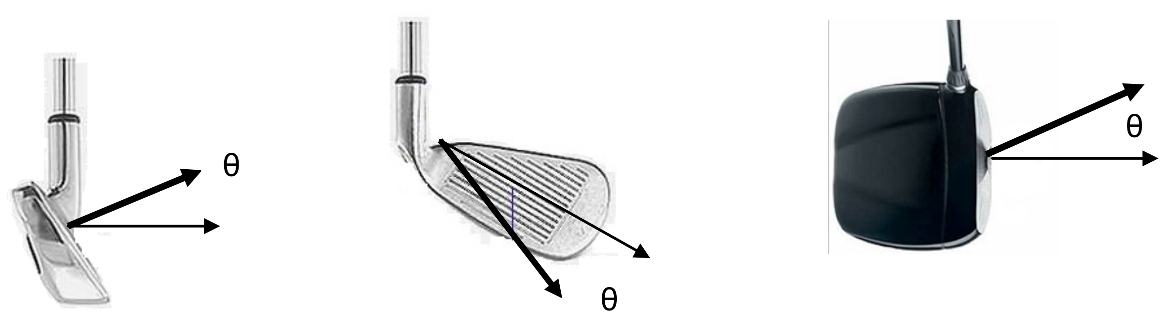

Fig. 2.2: Definition of clubface loft (A), tilt (B) and open/closed (C) angles

2.6 Accuracy

The accuracy of the different types of hockey shots (slap, snap, sweep, wrist shots) has been poorly documented in the literature. Although there is a lack of research documenting accuracy in shooting, many studies have looked at the parameters that affect accuracy in many other throwing tasks (dart throwing, overarm throw, basketball free shot) and in other sports where a projectile is shot with the use of an implement (golf shot, pistol shooting). The outcomes of these investigations that are relevant to this thesis are to be presented in the following section.

In a study investigating throwing accuracy, Martin and colleagues (2001) reported that proficiency of complex movements such as an over arm throw, comprising several body/joint segments moving at high acceleration and velocities is critically dependant on movement timing. Given the complicated nature of movement, humans become exceptionally accurate only after they practice tasks such as overhand throwing. Therefore, it has been hypothesized that three variables could account for the inaccuracies: hand location in space at ball release, hand speed, and hand orientation at ball release. However, the video based motion analysis in this study showed that modifications to both position and speed of the hand play an important role in the resulting accuracy of the throws when subjects are forced to compensate for a vertically shifting prism perturbation during a dart-like throw. Regression analyses showed that these factors contribute approximately 30% (16.3 cm of the 50 cm adaptation) of the adaptation in subjects for which these variables were statistically significant ($p < 0.05$) and thus become an important variable to consider when looking at throwing accuracy.

Hore and colleagues (1996) evaluated the kinematics of accuracy during over arm throws when using the non-dominant arm. Joint rotations at the shoulder, elbow, wrist, and fingers, and arm translations were calculated during these over arm throws and were related to accuracy from the center of a target. The authors concluded that although rotations were in general more variable at both proximal and distal joints of the non-dominant arm, the major cause of decreased throwing accuracy was increased variability at the distal joints. From these findings, it can be hypothesized that for this type of multisegment coordination task, practice is crucial for minimizing movement variability from trial to trial and therefore increasing the accuracy outcomes. In addition, since the distal joint is responsible for the final trajectory of the projectile, the release orientation is of great importance in determining the end point of that projectile on the target plane.

Mueller & Loosch, 1999, developed a simple model (dart throwing task) where the dart final location was tracked only in the vertical direction (up and down) and speed, angle of release and the upper body kinematics were recorded. Velocity was treated as a continuous variable that changed with time. As the angle of the elbow changed from trial to trial, the hand velocity also changed. Changes in angle of release affected both the speed of release and the object trajectory which determined the final position of the dart on the target. From these findings, the authors concluded that the speed and the orientation of the hand and therefore of the dart prior to release are related to the final accuracy outcome. This model also predicted that a variety of release speeds and orientations could lead to the same final location on the target. (Davids et al., 2006)

Another factor affecting the final path of the projectile trajectory has been defined by Kreighbaum and colleagues (2006) exploring dart throws. The distance between the aimed target and the location where the projectile is released directly affects the parabolic profile of the projectile trajectory. A parabolic trajectory implies that the shooter needs to take into account the vertical drop of the dart that increases with the increasing distance of travel before it intercepts the target (dart board). Two strategies might be utilized in order to compensate for this vertical drop: 1) the shooter could shoot the dart with a greater linear velocity in order to give to dart greater kinetic energy and therefore delay the vertical drop or 2) release the dart higher with respect to the aimed target so that the dart intercepted the dart board during its downward trajectory. In addition, the authors defined the angle of incidence as the angle between the target plane and the shooting location. That angle becomes important when considering the margin of error to hit a particular target. As represented in fig 2.3, with a more perpendicular shooting location from the target plane, the shooter receives the benefit of a greater margin of error when attempting to be accurate. On the other hand, the more parrallel to the target plane, the smaller the margin of error becomes.

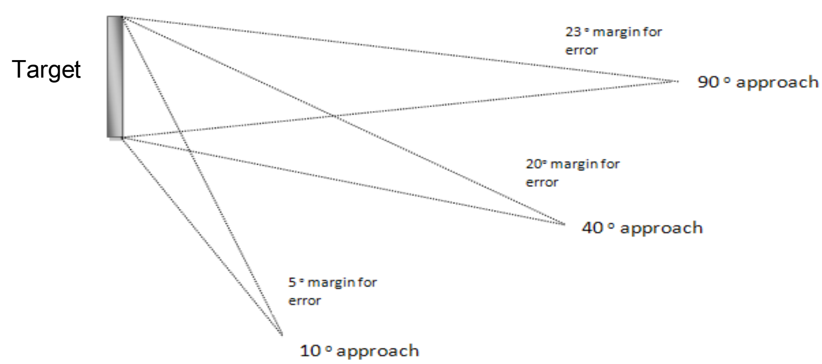

Fig. 2.3: Margin of error to hit the target according to the angle of incidence (90, 40 and 10 degrees) (adapted from Kreighbaum & al., 2006)

Although the speed of release is important for a parabolic trajectory, Fitts's laws (Fitts, 1957) describes a non-linear relationship between the release speed and the accuracy outcomes. This law describes a model of human movement which predicts the time required to rapidly move to a target area as a function of the distance to the target and the size of the target. Even if most of Fitts's work was done investigating arm pointing tasks, it introduces a very important notion for accuracy outcome which is the variability (intra-inter subjects) in the motor domain. Variability can be defined from a statistical standpoint as being the variance of data about a mean and is usually quantified by the size of the standard deviation (Riley and Turvey, 2002). From a dynamic perspective, variability can be seen as an index of fluctuation necessary to allow the movement system to adapt to changing constraints from one situation to the next (Button et al., 2003). Looking at the basketball free-throw, Button and colleagues have defined the learning process as a gradual release of the rigid control of degrees of freedom and their incorporation into a dynamic controllable system. Some anecdotal evidence from Bernstein (1967) was outlined where novice movement patterns appear to be stiff while expert movement patterns are more fluid and unconstrained. In situations where the release in degrees of freedom occurrs in many tasks and where accuracy of an end-effector is a primary goal, humans tends to show increasing constraints over degrees of freedom with practice. Participants learn how to suppress movement variability with a better control over a greater amount of degrees of freedom to improve accuracy as a function of practice. In addition, learners who practiced a precision throwing task exhibited little change in the standard deviation of overall release parameters (position, angle, speed) over 150 trials (Button et al., 2003). Investigating the space-time accuracy of rapid movement, Newell and al. (1993), found that not all aspects of movement become more variable with increased speed. In rapid-timing tasks, which require moving through a fixed distance in a specified time, variability in timing decreases with increased movement speed. When the movement time is fixed, increasing the distance of movement, and hence increasing the speed of movement, substantially reduces variability in timing.

Scholz and colleagues (2000) have investigated the control structure of multi-joint coordination during pistol shooting. Their analysis was performed based on an intuitive consideration that accurate shooting relies primarily on two angles (pitch and yaw) at the time of shooting but not the roll (fig. 2.4). Since pistol shooting implies a percussion mechanism in order to provide the translational projectile velocity, the roll angle could have a different role in a task where movement coordination and a tool are used to propel a projectile.

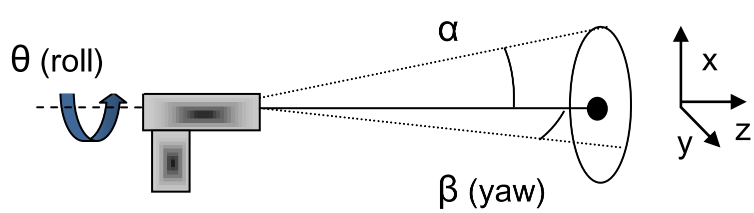

Fig. 2.4: Important and unimportant errors in pistol's position during shooting. Errors in pitch and yaw lead to inaccurate shooting, whereas in roll and coordinate of the pistol along the shooting line (z) do not. (adapted from Scholz & al., 2000)

In light of findings from these studies, it is evident that many release parameters are important to accurately hit a target/intented result. The speed, location in space and orientation of the end-effector prior to release are crucial for determining the projectile trajectory. Therefore different release speeds and orientations can lead to the same results as experience shooters/throwers showed increased variability in degrees of freedom at release point to adapt to any inaccuracy/variability in the events prior to release.

Chapter 3 Methods

3.1 Test sticks

Two new carbon-fibre, composite hockey Vapor XXX-Lite® sticks (Nike\Bauer Inc, St-Jérome, Canada), with a unique blade pattern, were used in the testing protocol. The P106® blade pattern specifications are listed in Table 3.1.

Table 3.1 Blade pattern specifications

Pattern	Length	Toe	Lie angle	Curve	Face
P106 Gagné	CCM	Round	6	Heel	Open

Each test stick was fitted with a series of 14 mm diameter reflective markers (Vicon, Oxford, UK) on the back of the blade and along the shaft, which were glued to the stick and the blade surface (fig 3.1). A layer of black hockey tape was then applied to the sticks to prevent any undesirable light reflection. For reference, the stick markers were numbered according to their position on the stick with S1 located on top edge of the shaft and S10 on the blade's toe. All the others markers were labelled with respect to their distance from S1 as shown in figure 3.1.

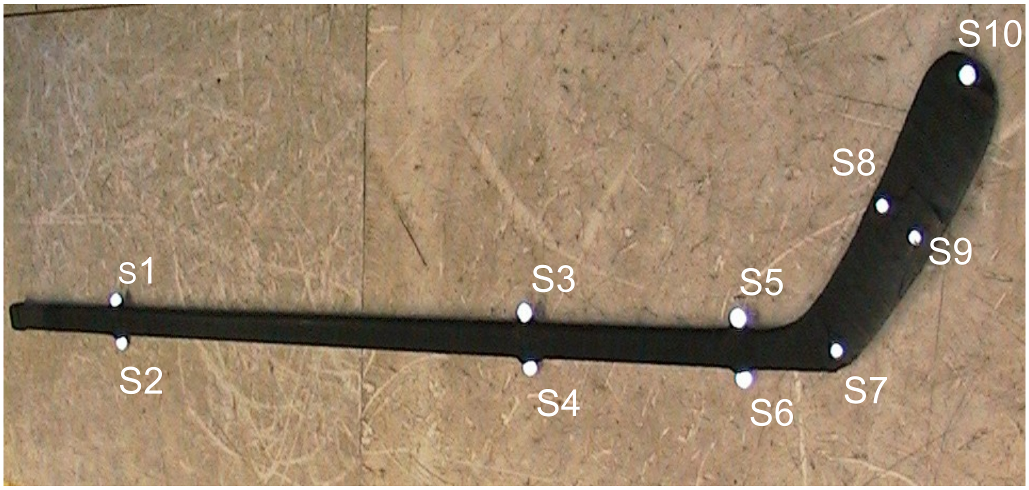

Fig. 3.1: Example of the right handed test stick's marker location

3.2 Subjects

Twenty-five male subjects were recruited to participate in this study. All the subjects were recruited from the university student population and included varsity level ice hockey players and recreational players. The sample was representative of a range of high to low caliber skill levels (Appendix I). At the time of testing, all subjects were healthy and did not present any physical injuries that could prevent them from performing the shooting tasks. Fifteen subjects were left handed shooters while ten subjects were right handed shooters. All right handed shooters data was subsequently transformed to make them left handed shooters for later data analysis.

Prior to the testing session, all participants read and signed an informed consent form (Appendix II) in accordance with the Tri-Council Policy Statement on Ethical

Conduct for Research Involving Humans. The Ethics Committee of the Faculty of Education, McGill University, approved the study (Appendix III).

3.3 Testing apparatus

Six digital optical motion infrared camera (Vicon MX® system, Oxford,UK) were used to record marker displacement. The cameras were on tripods and into fixed locations around the subject in such a way that the entire field of view of interest could be captured. The experimental setup included a sheet of low friction glice (high-density polyethylene) of 4.45m by 1.85m to simulate an ice surface. The cameras were positioned around the glice so that every marker could be seen by at least two cameras at all times during trial captures to calculate 3-D coordinates (fig. 3.2). In order to optimize camera resolution for the high speed projectiles, the cameras' sampling rate was set at 240 Hz. The capture environment volume was delimited to 3 x 2 x 2 meters so that the stick could be captured during the entire shot as shown in fig. 3.2. A digital video camera (Canon Optura 200 Mc, Canon Inc, USA) was used as a film log of every trial to confirm that the trials were "successful". The visual logs were used to verify the end puck locations on the target plane. Both types of cameras were linked to a single trigger channel, which allowed simultaneous and synchronous recording.

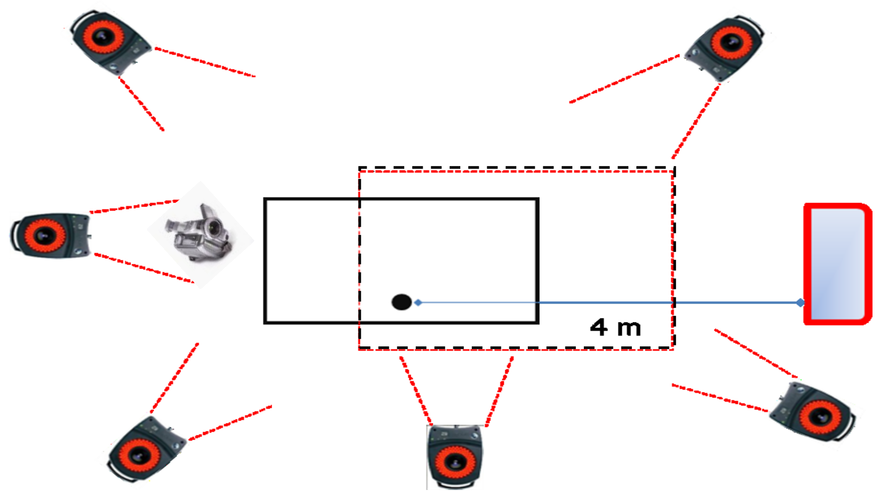

Fig. 3.2: Experimental set-up representation. The capture zone is delimited by the dashed-line box

Two, 14 mm diameter, reflective markers were fastened to the puck so that the trajectory could be recorded (fig. 3.3). As stick kinematics have not been widely reported, the location of the markers described in figure 3.3 were determined *a priori* by the investigator.

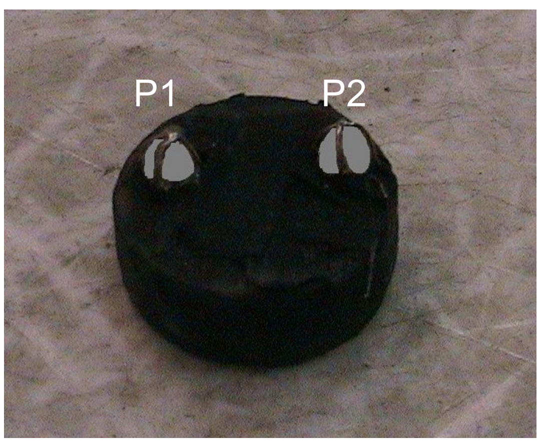

Fig. 3.3: Example of markered puck

A standard target training screen (Shooter tutor®) composed of a sheet of leather and plastic composite material was attached to the hockey goal covering the entire net except for the four corners (fig. 3.4). The target dimensions were 0.35m x 0.40m. These four corners were used as the targets for the subjects’ shots.

Fig. 3.4: Hockey net implemented with the shooter tutor creating the four targets

3.4 Testing protocol

3.4.1 System calibration

Prior to each testing session, each of the six cameras of the motion capture system were calibrated in order to capture every marker separately and to discriminate markers that were close to each other that would have been circle fit as only one marker. The 3-D capture volume was dynamically calibrated using a 14 mm diameter marker wand (fig. 3.5) provided by the manufacturer. This wand was waved in the entire capture environment so that it could be seen by all cameras. The dynamic calibration was considered successful only if the residual error of marker locations was less than

0.20 mm. A static calibration was then performed in order to determine the floor plane's orientation. A 30 mm diameter reflective marker L-Frame (fig. 3.5) was placed on the floor in the middle on the capture volume in order to determine that plane. The L-Frame position would determine the origin of the global coordinate system and was standardized so that all subjects performed in the same coordinate system.

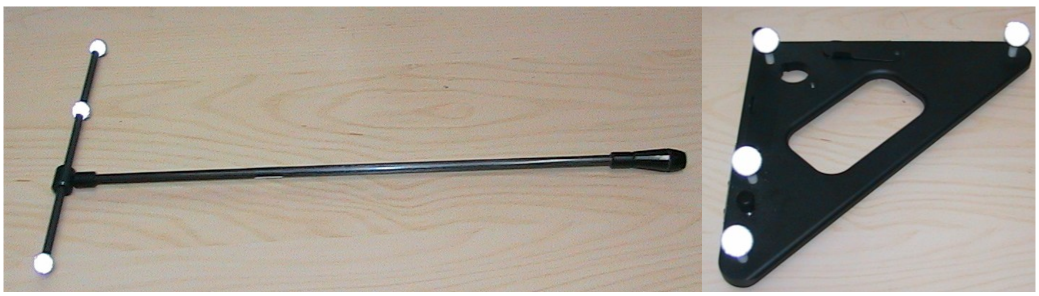

Fig. 3.5: a) 14 mm markers dynamic calibration wand b) 30 mm markers L-Frame for origin calibration

3.4.2 Experimental task

During tests, subjects wore their own shirt, shorts, skates and hockey gloves while standing on the shooting surface. The shooting surface's polyethylene sheets were sprayed with a silicon spray to simulate low friction ice surfaces, as pictured in Figure 3.2 (Pearsall et al. 1999; Wu et al. 2003) The puck starting position was set 4 meters away from the hockey net. The order of target identification was randomized as subjects were asked to complete ten successful wrist shots at each target, with the marker implemented puck. A maximum of twenty shots per target were allowed in order to establish an accuracy performance rank order.

3.5 Data reduction and processing

Data from the raw marker coordinates were exported into ViconIQ 2.5 (Vicon Mx®, Oxford,UK) (fig. 3.6) in order to obtain three-dimensional spatial coordinates of each stick and puck markers during the wrist shots. When reconstructed, the markers formed a series of linked segments (e.g. Figure 3.7). These data were used in various combinations to calculate velocity (v_{p-r} , ω_p , v_t , v_h), shaft flexion angles (θ_{SB}), and a series of gross blade projection angles (Ψ_r, Φ_r, β_r) measured with respect to the blade local coordinate system, in order to quantify the behavior of the ice hockey stick during the execution of the stationary wrist shot. The data from the puck markers was used to calculate the trajectory of the puck; linear velocity (v_p) and puck angular velocity (ω_r i.e. spin). Visual inspection of every trial was used to determine the start (e.g. start point) of the shot and the point where the puck was released (release point) from the blade.

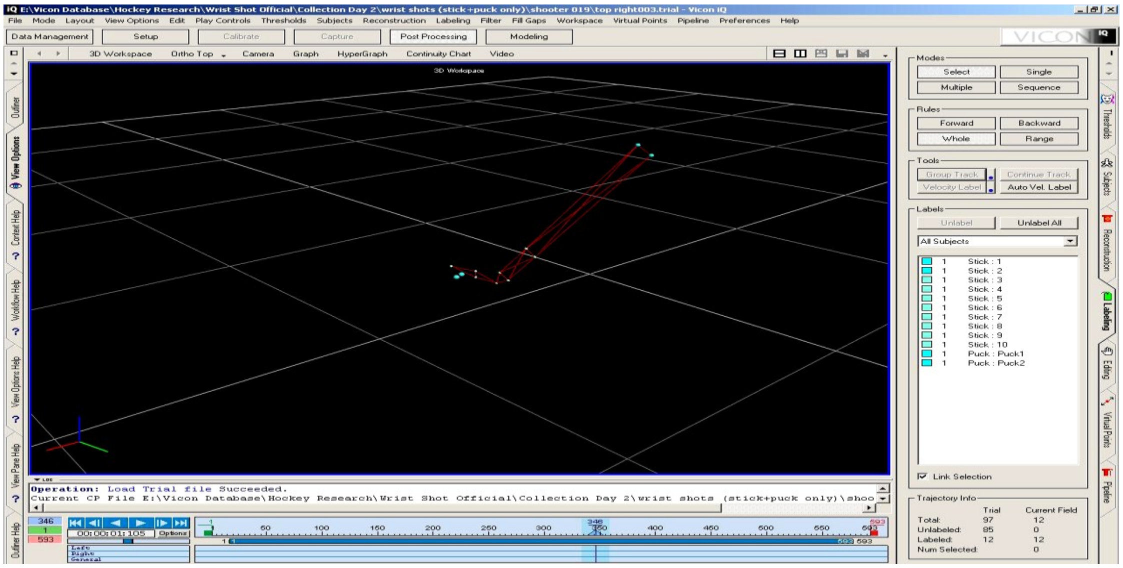

Fig. 3.6: Screenshot of Vicon IQ 2.5 software

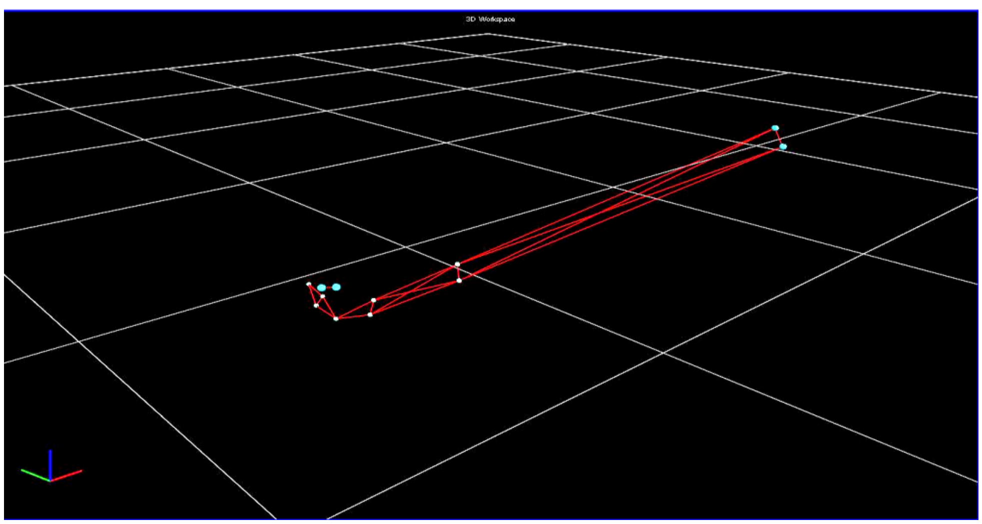

Fig. 3.7: Example of segments formed by the digitized markers

3.6 Data analysis

3.6.1 Angle measures

Angles were measured with respect to planes defined in the global coordinate system. Three global angles were calculated in order to represent the general orientation of the blade throughout the shot. First, a local coordinate system was created with the origin located at the blade's heel marker as displayed on fig. 3.8. A first vector (*j*) was calculated from the S7 and S10 markers defining the local Y-axis. A second vector (*i'*) was created from the S7 and S8 markers and the cross-product of *j* and *i'* was calculated to obtain the orthogonal unit vector *i* defining the local X-axis. The local Z-axis was obtained by the cross-product of unit vectors *i* and j, which is defined as *k*.

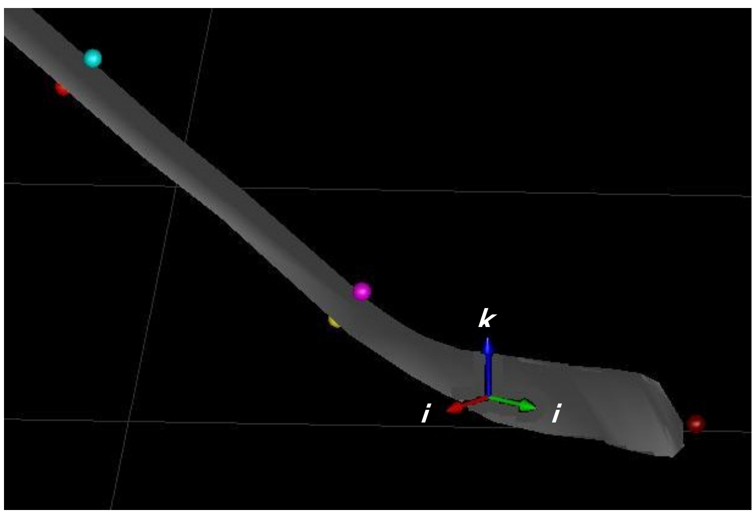

Fig. 3.8: Blade local coordinate system definition

The orientation of the blade local coordinate system relative to the global coordinate system was obtained throughout the contact phase of every trial to define the yaw (Ψ), pitch (Φ) and roll (β) angles. As displayed in figure 3.9, the yaw angle was defined by the angle between the global coordinate system's Y-axis and *i*, the pitch angle was defined by the angle between the global X-axis and *k* and finally the roll angle was defined calculating the angle between the global Y-axis and *j.*

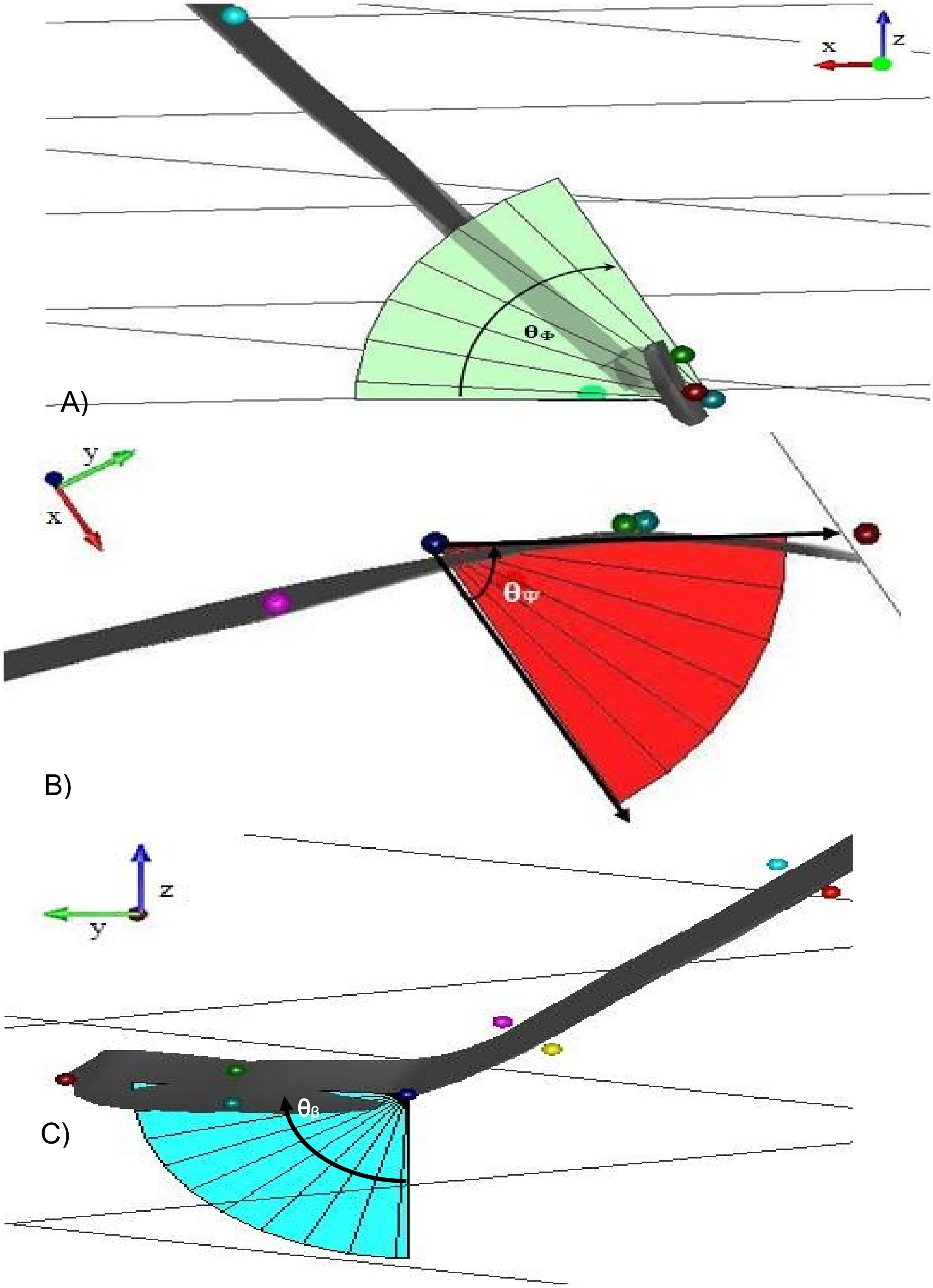

Fig. 3.9: Blade's a) pitch, b) yaw, and c) roll angles definition

In addition to the blade orientation angle, the shaft bend (θ_{SB}) was calculated. A first vector was created using S1 and S3 defined as S_{v1} and a second vector S_{v2}, using S3 and S5. With the angle between S_{v1} and S_{v2} being 180^o when the stick is in an unloaded condition, the shaft bend was calculated with the equation 3.1;

Shaft bend (o) = 180 - (Sv1 ˚ Sv2) equ. (3.1)

Fig. 3.10: Shaft bend representation

3.6.2 Velocity measures

Velocities were calculated from the raw markers displacement data using the same methods. For the heel velocity, v_h, S7 coordinates from frames F_i and F_{i+1}were used to calculate the vector *v*. Then the magnitude of *v* was measured to obtain the marker displacement, d_h, from frames F_i to F_{i+1} in cm. Finally, d_h was divided by the sampling rate to obtain a velocity in km/h. Equation 3.2 was also applied to the blade's toe marker and the puck to obtain their respective velocities.

Velocity (km/h) = ((magnitude (v)) x sampling rate)*3600/100000)   equ. (3.2)

The puck spin (angular velocity) was calculated from the 3-D coordinates [x, y, z] of the puck markers P1 and P2 (fig 3.11). The vector p was created from P1 to P2 at frame Fi and at frame Fi+1. Having the angle θ from the orientation difference between the vectors Fi and Fi+1 calculated with both puck markers, the equation 3.3 was applied.

Puck spin (o/s) = θ/sampling rate   equ. (3.3)

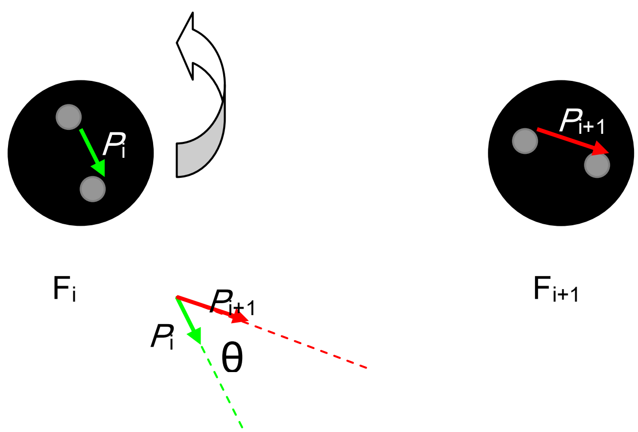

Fig 3.11: Puck spin calculation representation

3.6.3 Target dispersion

Since the recorded capture volume did not allow recording of the puck trajectory from the initiation of the wrist shot to the point where the puck hit/missed the target, the puck trajectory was extrapolated until it reached the target plane. The equations 3.4 were used to measure extrapolated [x,y,z] coordinates of the puck at every frame outside the capture zone to obtain the entire puck trajectory. The coordinates of the center of all four targets were used to obtain the vertical and horizontal errors of every shot according to the puck's final location on the net (fig 3.12). The horizontal error (Y-dis) was calculated from the distance between the center of the target to the center of the puck along the global Y-axis while the vertical error (Z-dis) was measured from that same distance, but along the Z-axis. The radial distance (Radial) was calculated using the equations 3.5.

$$x = x0 + v0x\,(t)$$
$$y = y0 + v0y\,(t) \qquad \text{equ. (3.4)}$$
$$z = z0 + v0z(t) - ½\, g(t)2$$

$$\text{Radial}= \sqrt{Ydis^2 + Zdis^2} \qquad \text{equ. (3.5)}$$

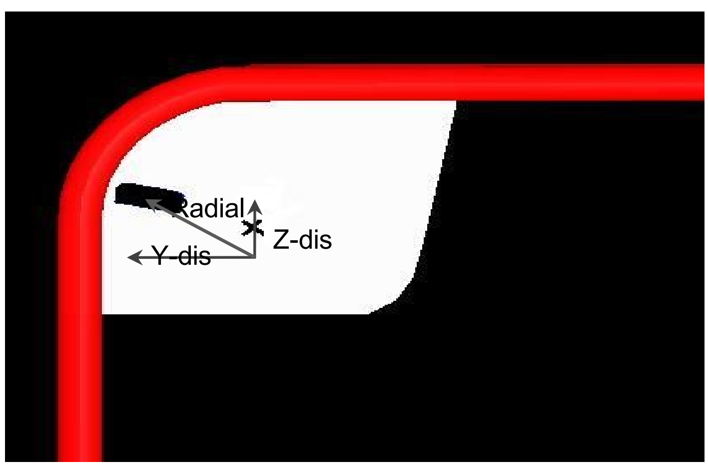

Fig. 3.12: Target dispersion's Ydis, Zdis and Radial representation

3.6.4 Statistical analysis

A statistical analysis including a one-way ANOVA ($p < 0.05$), with Bonferonni post-hoc tests, was performed to determine accuracy score differences across the four corners. The one-way ANOVA was also used to investigate the target dispersion patterns across the targets. All statistical analyses were performed with SPSS© 15.0 (SPSS Inc., Chicago, Illinois, USA) and MatLab® (version R2006b) (MathWorks Inc., Natick, MA, USA) software.

Descriptive statistics, including mean, standard error, minimum, maximum and range were carried out on the IV previously listed in Table 1.1 and Table 1.2. The means of the IV at release were compared within and between independent stick variables and puck variables. The independent variables and their abbreviations have been previously summarized in Table 1. A MANOVA analysis was performed on these variables based on shooting conditions. Multiple regression analysis was applied to the independant variables and the accuracy scores to determine which of the above mentioned variables best predict accuracy.

Chapter 4 Results

The forthcoming sections present the data obtained through the testing protocol. The accuracy score results are discussed first, followed by a detailed description of the target dispersion variables from all subjects (n=25) for all shooting conditions (i.e. corners, n=4). The chapter concludes witha representation of the multiple regression models that best describe shooting accuracy in the present experimental set-up.

4.1 Accuracy scores

Accuracy scores were calculated for all subjects (n=25) for all shooting conditions. In addition, an overall accuracy score was also calculated for all subjects and was used to represent the accuracy level of subjects. Pearson product - moment correlation coefficients (one-tailed) were calculated to determine associations between overall accuracy and the accuracy scores for the four different targets are listed in table 4.1. The accuracy scores descriptives statitics are also displayed in table 4.1.

Table 4.1: Descriptive statistics for the accuracy scores: Mean, standard error, maximum, minimum and range for the four shooting conditions and overall accuracy. Pearson's product - moment correlation coefficients (r) between corners' accuracy scores and overall accuracy.

Subject	Bottom Contra (BC)	Bottom Ipsi (BI)	Top Contra (TC)	Top Ipsi (TI)	Overall
Mean	68.3	66.0	45.0	45.0	54.2
SE	4.3	3.1	4.0	4.0	3.2
Max	90.9	83.3	83.3	83.3	80.0
Min	35.0	50.0	5.0	10.0	26.6
Range	55.9	53.3	78.3	73.3	53.1
r	0.82	0.72	0.90	0.92	N/A
R^2	0.67	0.52	0.80	0.85	N/A
P	0.00	0.00	0.00	0.00	N/A
Sign. differences	TC, TI	TC, TI	BC, BI	BC, BI	N/A

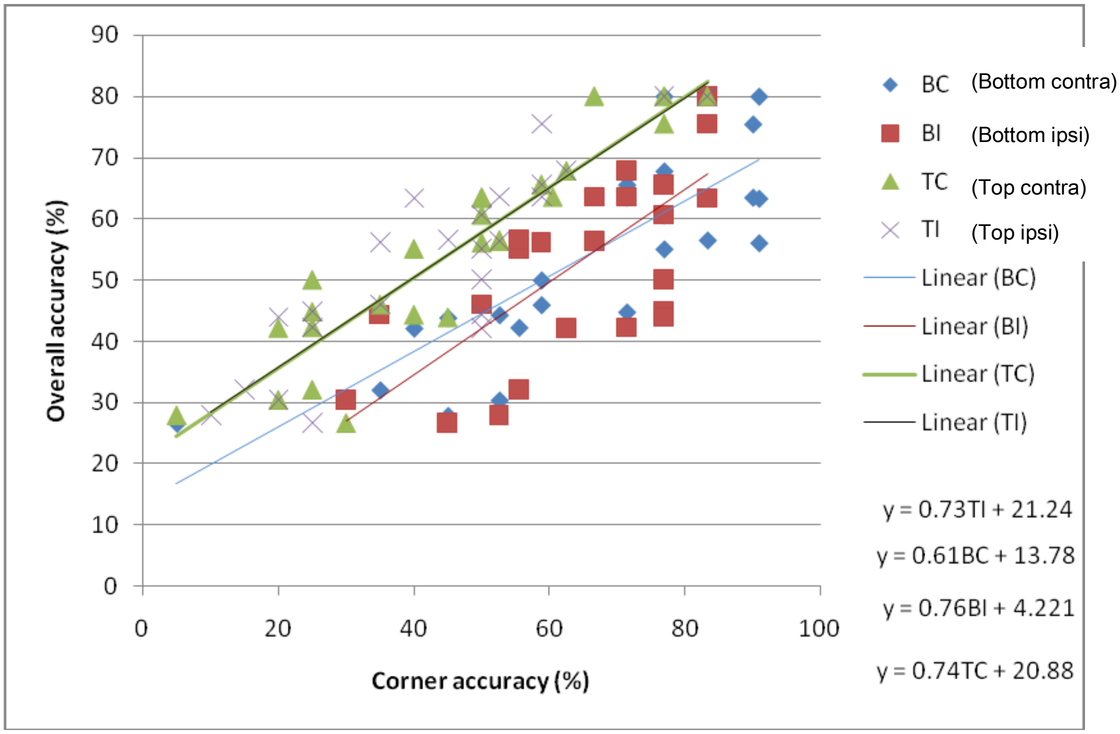

Fig. 4.1: Correlations between overall accuracy and the four shooting conditions accuracy. The linear regression equations and their respective representation are displayed for all targets.

Results of the one-way ANOVA comparing accuracy scores across shooting conditions showed a shooting height main effect as significant differences ($p < 0.01$) were observed between the bottom corners condition and the top corner. On the other hand, no significant differences were observed across shooting side as displayed in figure 4.2.

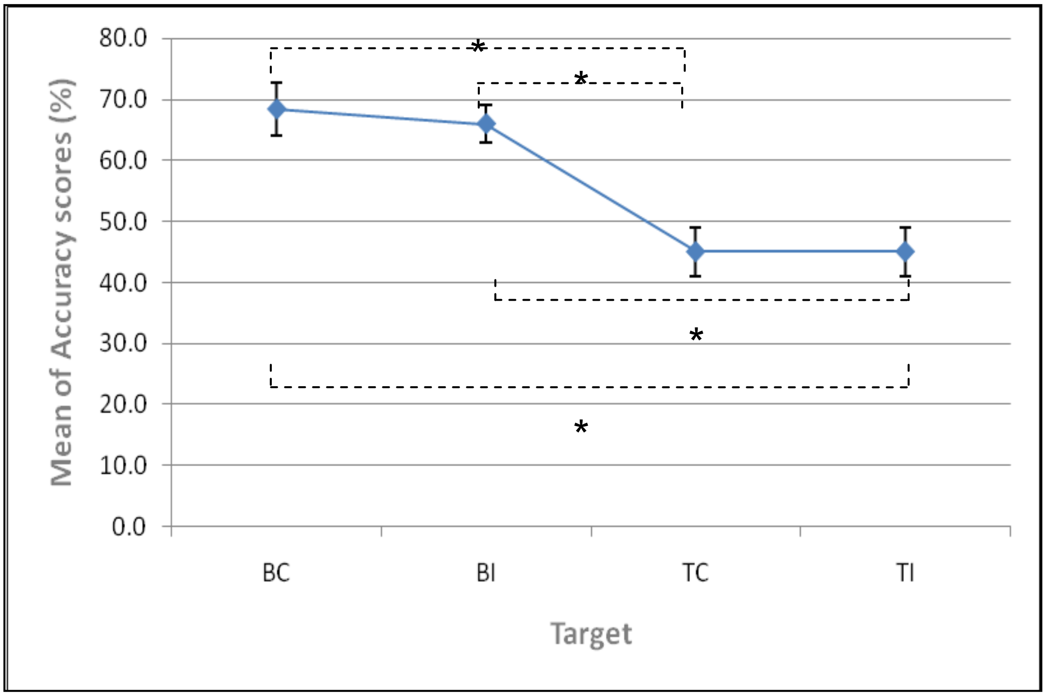

Fig. 4.2: Mean of Accuracy score for the four shooting conditions. Statistical significance is denoted by * ($p < 0.05$)

4.2 Kinematics

In order to identify relevant release parameters and other kinematics variables that could account for increased overall accuracy, the yaw, pitch and roll profiles were plotted for a high accuracy (subject 1 – 80% overall accuracy) and for low accuracy shooter (subject 25 – 42% overall accuracy). Since TI accuracy had the highest correlation with the overall accuracy scores, six shots were taken in a random manner for the TI corner and the graphs are displayed in figure 4.3. Visual inspection of the general projection angle patterns for both shooters allowed for the identification of additional important independent variables (IV). Noticeable differences were found in the range of projection angle from initial contact to release point; these variables are the ΔRoll, ΔPitch and ΔYaw (figure 4.3). These IV were entered into the multiple regression model along with the previously listed IV (Table 1.1) presented in chapter 1.

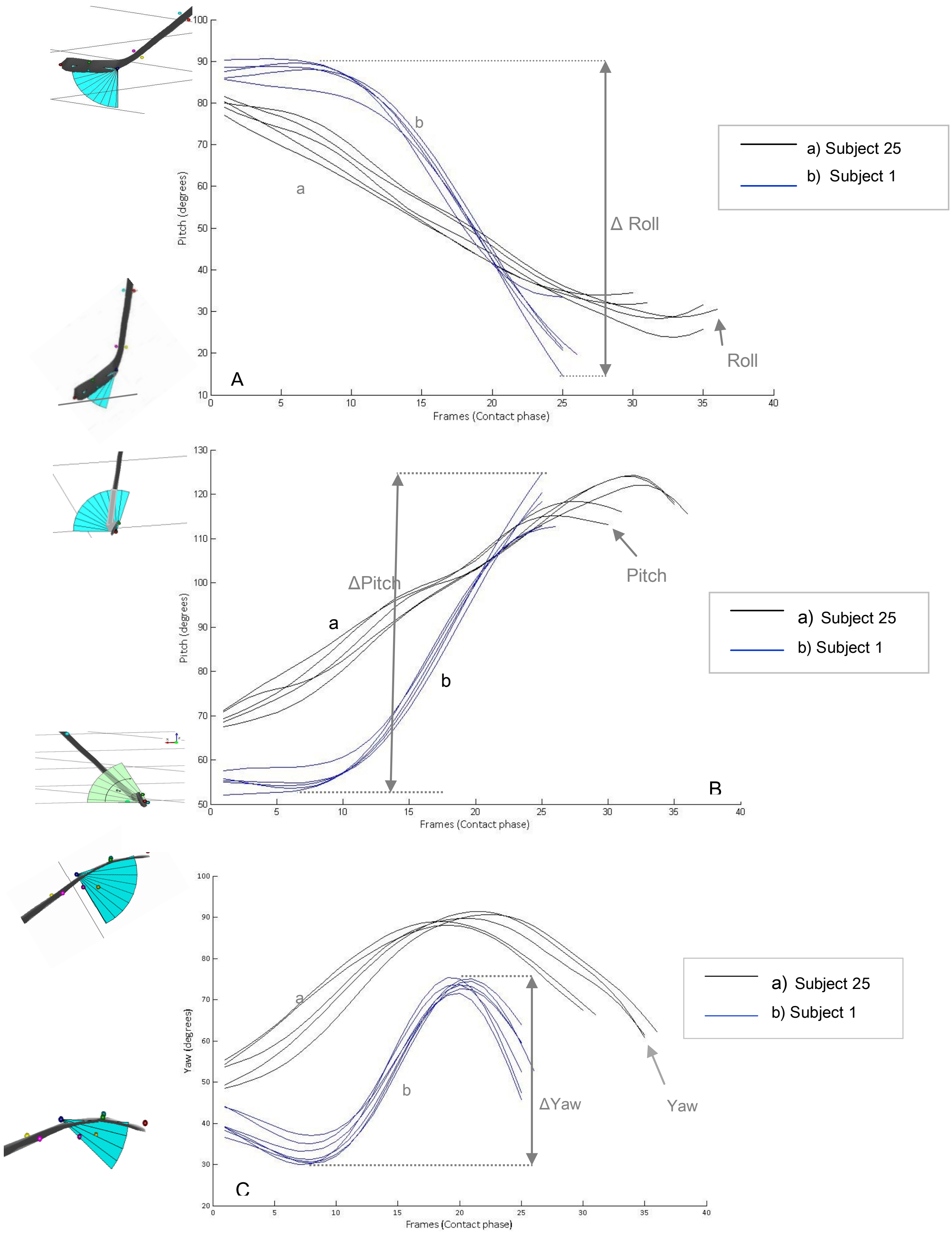

Fig 4.3 Projection angle profiles (a) Roll b) Pitch c) Yaw) for a low accuracy (42%) and a high accuracy(80%) shooter for the top ipsi corner.

In addition to the blade's orientation, the puck trajectory profiles of a high accuracy subject (subject 1 – 80% overall accuracy) and for low accuracy shooter (subject 25 – 42% overall accuracy) were plotted and observed from a x-y axis perspective. As displayed in figure 4.4, noticeable differences were found during the contact phase of the wrist shot which is defined by initial contact (IC) and puck release (R)

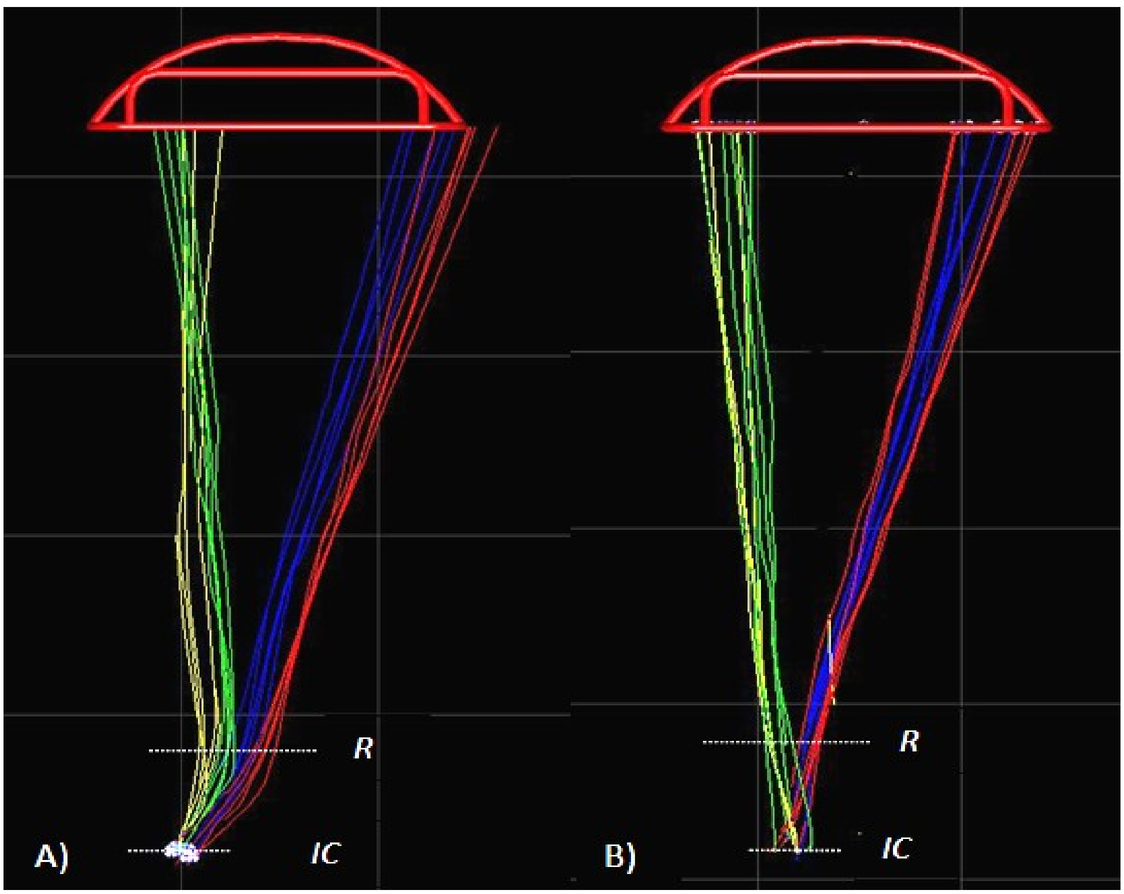

Fig. 4.4: A) Puck trajectories for a high accuracy shooter (i.e. Shooter 1 – 80% accuracy) from X-Y axis perspective B) Puck trajectories for a low accuracy shooter (i.e. Shooter 25 – 42% accuracy) from X-Y axis perspective

4.3 Target dispersion

The distance between the end location of the puck relative to target center was defined by the variable Y-dis, Z-dis and the radial distance. One-way ANOVAs were performed on these three variables across the four shooting conditions. The means and standard errors are presented in table 4.2. First, for the Y-dis, which represents the horizontal error, significant differences were found between shooting conditions (figure 4.5). The BC Y-dis and the TC Y-dis, 15.49 ± 0.75 and 18.59 ± 0.96 respectively, were found to be significantly different ($p<0.05$) as displayed in figure 4.5. In addition, the BC Y-dis was found to be significantly different ($p<0.05$) with the TI, 19.32 ± 0.94. That difference suggests a main effect of shooting height for the ipsi side. Furthermore, that main effect was also found for the ipsi side as the difference between BI, 11.42 ± 0.68, and the top corners' Y-dis reached significance ($p<0.05$).

Table 4.2: Descriptive statistics for the Y-dis, Z-dis and radial dispersion for the four shooting conditions

	Bottom contra	Bottom ipsi	Top contra	Top ipsi	Significant differences
Y-dis (cm)	15.49 ± 0.75	15.50 ± 0.76	18.59 ± 0.96	19.32 ± 0.94	BC-TI; BC-TC; BI-TI; BI-TC
Z-dis (cm)	11..43 ± 0.60	11.42 ± 0.68	24.26 ± 1.27	21.68 ± 1.42	BC-TI; BC-TC; BI-TI; BI-TC
Radial (cm)	21.15 ± 0.76	21.39 ± 0.81	33.36 ± 1.34	32.19 ± 1.44	BC-TI; BC-TC; BI-TI; BI-TC

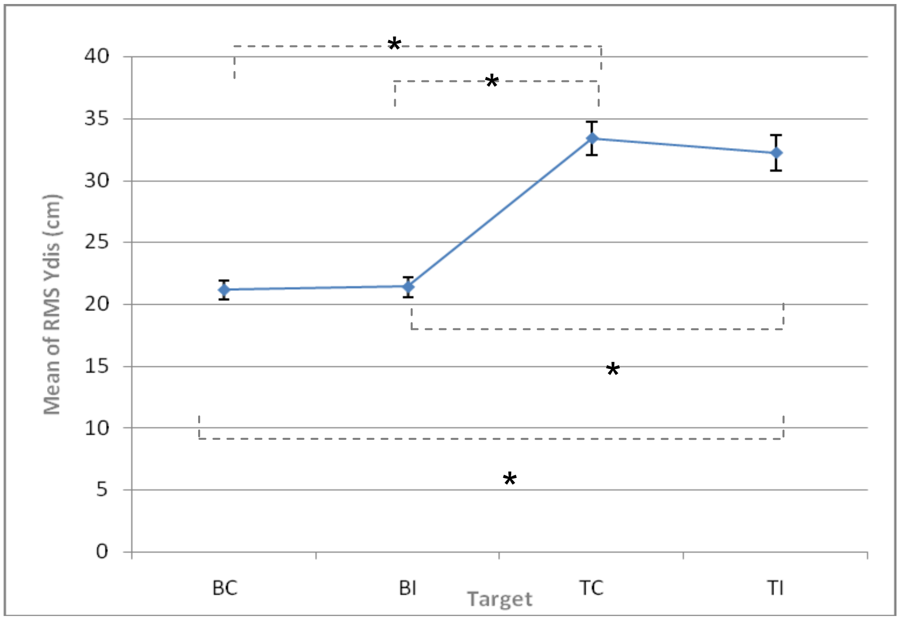

Fig. 4.5: Mean of Y-dis for the four shooting conditions

Statistical significance is denoted by * ($p < 0.05$)

In terms of shooting side, no significant difference ($p<0.05$) between TC and TI was found, 18.59 ± 0.96 and 19.32 ± 0.94 respectively, nor between BC and BI, 15.49 ± 0.75 and 15.50 ± 0.76. These results suggest that there was no main effect of shooting side for the horizontal errors.

Furthermore, for the vertical error from the center of the target, Z-dis, the bottom contra condition showed a significant difference ($p<0.05$) with the top contra and top ipsi conditions. The same shooting height main effect was found on the ipsi side as the bottom ipsi condition showed significant difference ($p<0.05$) with the top contra and top ipsi conditions. Neither significant main nor an interaction effect for shooting side were found as the differences between the bottom contra and bottom ipsi and between top contra and top ipsi did not reach significance. The means of each shooting condition are displayed in figure 4.6.

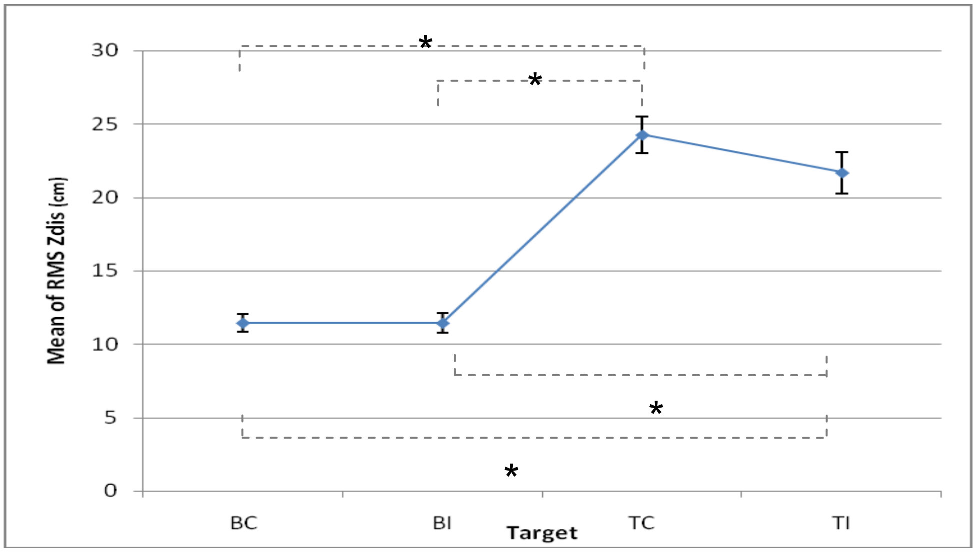

Fig.4. 6: Mean of Z-dis for the four shooting conditions

Statistical significance is denoted by * (p< 0.05)

Likewise, a main effect of shooting height was observed for the radial dispersion as significant differences ($p<0.05$) were observed between the bottom ipsi condition and the top corners and between the bottom contra and top contra and top ipsi conditions. There was no main effect of shooting side on the radial dispersion and there was no interaction effect of shooting side and shooting height on radial dispersion. The means of each shooting condition are displayed in figure 4.7.

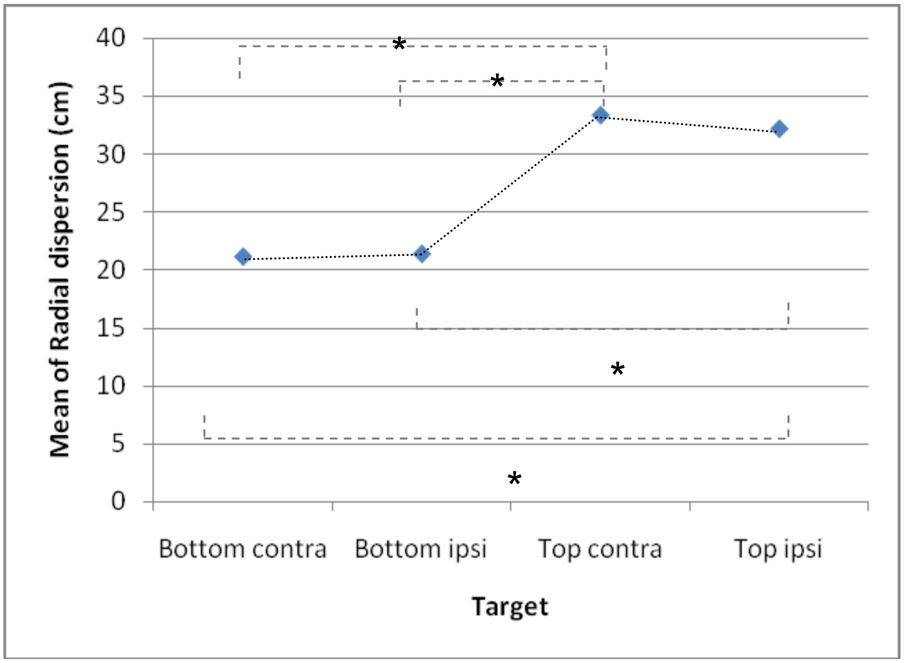

Fig.4. 7: Mean of Z-dis for the four shooting conditions. Statistical significance is denoted by * ($p < 0.05$)

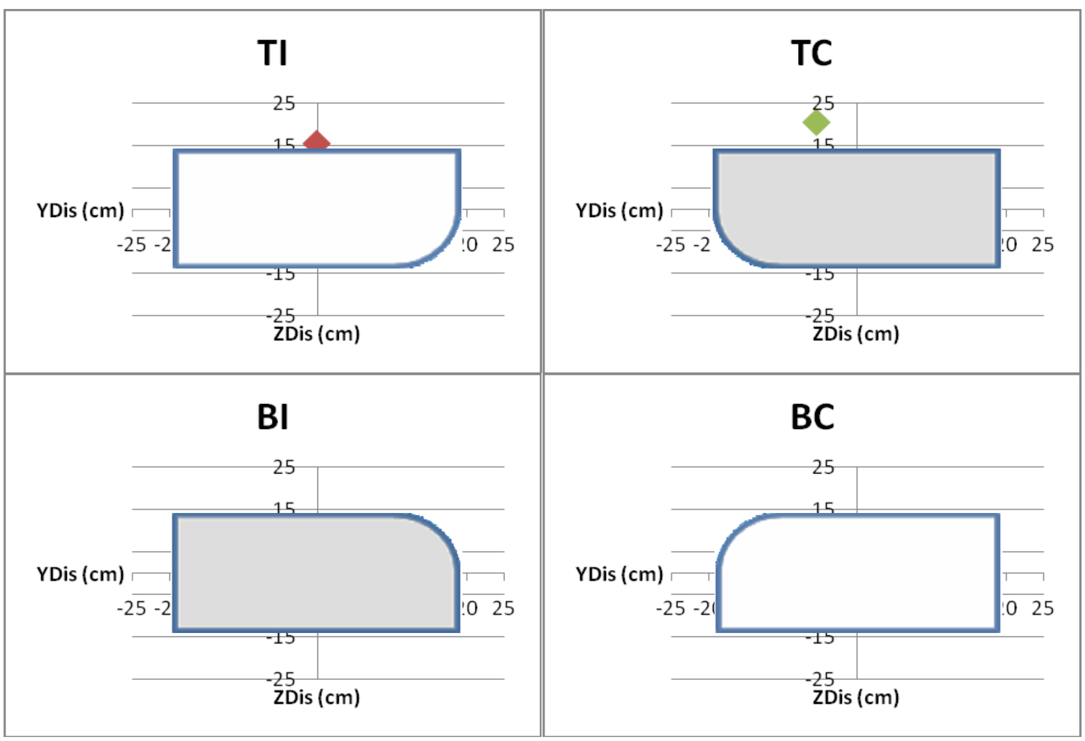

Fig. 4.8: Mean puck locations on the four targets, the marker size represent both Ydis and Zdis standard error

Table 4.3 Descriptive statistics for the selected release parameters for all four shooting conditions and significant differences between shooting condition from MANOVAs :

	TC			TI			BC			BI			
	$\overline{X}$	*SE*	*Range (Min-Max)*	$\overline{X}$	*SE*	*Range (Min-Max)*	$\overline{X}$	*SE*	*Range (Min-Max)*	$\overline{X}$	*SE*	*Range (Min-Max)*	*MANOVA Significant differences ($p< 0.05$)*
Contact time (ms)	180	.00	110 290	180	.01	110 250	170	.01	100 250	150	.01	80 220	N/A
Contact distance (cm)	123.1	4.26	87.1 170.0	116.88	3.98	83.8 159.9	124.7	4.23	97.6 179.4	115.9	3.82	87.7 165.1	N/A
Max shaft bend (^{o})	3.06	.13	1.69 4.40	3.11	.15	1.88 4.50	3.73	.22	1.35 5.55	3.93	.25	1.31 6.05	BI-TC, BI-TI
Blade's heel velocity (km/h)	52.5	1.76	35.7 73.0	51.04	1.74	36.5 68.9	51.53	1.96	30.2 78.0	50.09	2.10	28.4 78.2	N/A
Blade's toe velocity (km/h)	72.6	2.10	54.5 92.8	72.05	2.08	54.3 91.5	69.55	2.63	43.1 100.9	67.57	2.82	40.3 99.7	N/A
Puck to blade position (cm)	22.0	.58	15.5 27.4	23.0	.59	17.2 28.5	18.5	.64	12.8 25.9	18.7	.77	12.4 27.1	BC-TI, BC-TC, BI-TC, BI-TI
Puck linear velocity (km/h)	66.6	1.82	47.8 86.0	65.6	2.01	48.1 90.4	67.28	2.25	43.7 93.4	65.93	2.27	40.4 91.7	N/A
Puck angular acceleration – Spin (^{o} /s)	6130.88	226.94	3792.35 - 8086.99	6120.86	225.34	4081.98 - 8381.24	5139.84	246.52	2998.72 – 7345.04	4884.52	246.20	2400.68 - 7450.61	BC-TI, BC-TC, BI-TC, BI-TI
Yaw (^{o})	62.42	1.05	50.16 73.40	80.80	1.07	71.66 90.37	47.32	.85	39.75 56.91	66.77	.81	59.91 73.31	All corners
Pitch (^{o})	117.89	1.90	89.57 131.70	119.01	1.50	96.64 128.74	99.47	.93	92.70 107.93	99.93	.84	93.63 111.72	N/A
Roll (^{o})	22.07	1.26	9.82 31.82	21.81	1.30	12.39 34.70	47.95	1.12	37.37 59.60	47.45	1.03	34.75 56.54	BC-TI, BC-TC, BI-TC, BI-TI
Δ Yaw (^{o})	33.54	1.86	12.39 50.19	35.59	2.54	8.88 53.42	15.60	1.83	-4.59 33.98	14.03	1.96	-3.92 34.17	BC-TI, BC-TC, BI-TC, BI-TI
Δ Pitch (^{o})	58.18	2.52	24.32 85.94	56.95	2.96	19.04 84.63	38.58	1.36	26.15 52.97	35.17	1.60	12.42 48.75	BC-TI, BC-TC, BI-TC, BI-TI
Δ Roll (^{o})	-1.71	.328	-8.76 -0.15	-1.73	.34	-7.49 0.63	-2.17	.39	-5.78 1.39	-1.65	.30	-6.50 1.41	N/A

4.4 Release parameters

Pearson product - moment correlation coefficient tests (two-tailed) were carried out to determine associations between accuracy score and the selected release parameters for the four shooting conditions. Statistical significance was set at $P < 0.05$. The following results are presented corner by corner. Selected parameters' descriptive statistics are presented in Table 4.3. The results from the MANOVAs are also presented in Table 4.3. Pearson's product - moment correlation coefficients for the top contra condition between the release parameters and accuracy scores are listed in Table 4.4. Six of 13 release parameters investigated for the top contra condition were significantly associated with overall accuracy scores.

Table 4.4 Descriptive statistics for the four shooting conditions: Pearson's product - moment correlation coefficients (*r*) between selected release parameters and accuracy score.

	BC	BI	TC	TI
	r	***r***	***r***	***r***
Contact time	0.149	0.151	0.049	0.304
Contact distance (m)	0.235	0.164	***0.401**	***0.495**
Max shaft bend (deg)	***0.386**	***0.453**	0.226	0.153
Blade's heel velocity (km/h)	***0.381**	***0.440**	0.332	0.270
Blade's toe velocity (km/h)	0.317	***0.391**	***0.367**	0.250
Puck to blade position (cm)	***-0.448**	***-0.546**	-0.106	-0.237
Puck linear velocity (km/h)	0.327	***0.395**	***0.552**	***0.499**
Puck angular acceleration – Spin (^{o} /s)	-0.011	0.072	***0.398**	0.274
Yaw (^{o})	-0.136	0.011	0.071	0.103
Pitch (^{o})	-0.193	-0.333	-0.060	-0.102
Roll (^{o})	0.158	0.210	-0.461	***-0.505**
Δ Yaw (^{o})	0.082	0.322	***0.497**	***0.518**
Δ Pitch (^{o})	0.323	0.123	0.279	***0.443**
Δ Roll (^{o})	0.011	-0.094	0.328	-0.206

Statistical significance is denoted by * ($p < 0.05$)

For the top ipsi condition, Pearson's product - moment correlation coefficients between the release parameters and accuracy scores are listed in Table 4.4. Five of 13 release parameters investigated were significantly associated with overall accuracy scores for the top ipsi condition.

Pearson's product - moment correlation coefficients for the bottom contra condition between the release parameters and accuracy scores are listed in

Table 4.4. Three of 13 release parameters investigated for that condition were significantly associated with overall accuracy scores ($p<0.05$).

For the bottom ipsi condition, Pearson's product - moment correlation coefficients between the release parameters and accuracy scores are listed in Table 4.4. Five of 13 release parameters investigated for the bottom ipsi condition were significantly associated with overall accuracy scores.

Multiple linear regression analysis was used to investigate the relationships between accuracy and stick/puck mechanics. The following analyses include four prediction models that were built upon the regression analyses corresponding to the four shooting conditions. Entry into the regression was set at $P < 0.05$, while the overall significance of the best-fit multiple regression model was established at $\alpha = 0.10$ (SPSS, Inc., version 15.0). Although the relationships between key variables when correlated directly one-to-one were generally poor, a statistically significant ($p<0.05$) model was built to predict accuracy for each corner. The variables placed into that model could be interpreted in terms of speed, technique and orientation. First of all for the bottom contra corner, four wrist shot release parameters accounted for 36.7% of the variance in accuracy score: puck to blade position at release, release heel velocity of the stick's blade, yaw and pitch. These variables and their respective explanation of the variance are listed in Table 4.8. The ΔR^2 values (Table 4.5, 4.6, 4.7, 4.8) show the individual contributions of the release parameter entered at that level of the model to the explanation of wrist shot accuracy.

Table 4.5 Results of multiple stepwise regression analysis of the between selected release parameters and accuracy score.

Model	Bottom contra	R^2	ΔR^2	P
Note: The four technique parameters associated with accuracy explained 36.7% of the variation in the overall accuracy scores.				
1	Puck to blade position	0.200	0.200	0.025
2	Release heel velocity	0.300	0.100	0.020
3	Yaw	0.326	0.026	0.037
4	Pitch	0.367	0.041	0.048

The regression suggests that 40.6% of the accuracy can be explained by the three technique parameters listed in Table 4.6 for the bottom ipsi target: puck to blade position at release, release heel velocity of the stick's blade and the delta pitch.

Table 4.6 Results of multiple stepwise regression analysis of the between selected release parameters and accuracy score.

Model	Bottom ipsi	R^2	ΔR^2	P
Note: The four technique parameters associated with accuracy explained 40.6% of the variation in the overall accuracy scores.				
1	Puck to blade position	0.299	0.299	0.047
2	Release heel velocity	0.399	0.100	0.004
3	Delta pitch	0.406	0.007	0.001

The same multiple regression method was applied for the top corners' release parameters. First of all, for the top contra target, six wrist shot release parameters accounted for 76.0% of the variance in accuracy score: puck velocity, roll, release heel velocity of the stick's blade, maximum bend, delta yaw and delta pitch. These variables and their respective explanation of the variance are listed in Table 4.7.

Table 4.7 Results of multiple stepwise regression analysis of the between selected release parameters and accuracy score.

Model	Top contra	R^2	ΔR^2	P
Note: The six technique parameters associated with accuracy explained 76.0% of the variation in the overall accuracy scores.				
1	Puck velocity	0.279	0.279	0.007
2	Roll	0.411	0.132	0.003
3	Release heel velocity	0.548	0.137	0.001
4	Max bend	0.663	0.115	0.000
5	Delta yaw	0.691	0.028	0.000
6	Delta pitch	0.760	0.069	0.000

The multiple regression analysis suggests that 76.0% of the accuracy can be explained by the eight technique parameters listed in Table 4.8 for the top ipsi target: puck velocity, roll and release heel velocity of the stick's blade, maximum bend, delta yaw, delta pitch, release puck spin and puck to blade position.

Table 4.8 Results of multiple stepwise regression analysis of the between selected release parameters and accuracy score.

Model	**Top ipsi**	R^2	ΔR^2	P
Note: The eight technique parameters associated with accuracy explained 76.0% of the variation in the overall accuracy scores.				
1	Puck velocity	0.249	0.249	0.000
2	Roll	0.427	0.177	0.000
3	Release heel velocity	0.624	0.197	0.000
4	Max bend	0.661	0.036	0.000
5	Delta yaw	0.681	0.020	0.001
6	Delta pitch	0.684	0.003	0.002
7	Release puck spin	0.738	0.054	0.002
8	Puck to blade position	0.760	0.022	0.001

Table 4.9 Results of multiple stepwise regression analysis of the between selected release parameters and accuracy score; Summary

	BC	BI	TC	TI
	ΔR^2	ΔR^2	ΔR^2	ΔR^2
Contact time				
Contact distance (m)				
Max shaft bend (deg)			0.115	0.036
Blade's heel velocity (km/h)	0.100	0.100	0.137	0.197
Blade's toe velocity (km/h)				
Puck to blade position (cm)	0.200	0.299		0.022
Puck linear velocity (km/h)			0.279	0.249
Puck angular acceleration – Spin (º /s)				0.054
Yaw (º)	0.026			
Pitch (º)	0.041			
Roll (º)			0.132	0.177
Δ Yaw (º)			0.028	0.020
Δ Pitch (º)		0.007	0.069	0.003
Δ Roll (º)				
Total R^2	**0.36**	**0.40**	**0.76**	**0.76**

The unstandardized Beta coefficients (B) were calculated for the release parameters that accounted for the variance explanation for all shooting condition's models. The β coefficients are listed in Table 4.10. From these coefficients, regression equations were built for every shooting condition and these equations are displayed in equations 4.1, 4.2, 4.3 and 4.4.

Table 4.10 Unstandardized B coefficients for selected release parameters that predict accuracy scores and the constant for the four shooting conditions

	BC	BI	TC	TI
	B	B	B	B
Contact time				
Contact distance (m)				
Max shaft bend (deg)			-0.134	-0.069
Blade's heel velocity (km/h)	0.006	0.006	-0.020	-0.020
Blade's toe velocity (km/h)				
Puck to blade position (cm)	-0.029	-0.019		-0.011
Puck linear velocity (km/h)			0.031	0.020
Puck angular acceleration – Spin (º /s)				$4.64E10^{-5}$
Yaw (º)	-0.012			
Pitch (º)	0.012			
Roll (º)			-0.015	-0.010
Δ Yaw (º)			0.008	0.003
Δ Pitch (º)		-0.002	-0.005	0.004
Δ Roll (º)				
Constant	**0.154**	**0.678**	**0.362**	**0.523**

$$BC = 0.006\ vh - 0.029P2B - 0.012\ \Psi r + 0.012\ \Phi r + 0.154 \qquad \text{equ. (4.1)}$$

$$BI = 0.006\ vh - 0.019P2B - 0.002\ \Delta\ \Phi r + 0.678 \qquad \text{equ. (4.2)}$$

$$TC = -0.134\ \theta SB - 0.020\ vh + 0.031\ vp\text{-}r - 0.015\ \beta r + 0.008\ \Delta\ \Psi r - 0.005\ \Delta\ \Phi r + 0.362 \qquad \text{equ. (4.3)}$$

$$TI = -0.069\ \theta SB - 0.020\ vh - 0.011P2B + 0.020\ vp\text{-}r - 4.64E10\text{-}5\ \beta r + 0.008\ \Delta\ \Psi r - 0.005\ \Delta\ \Phi r + 0.523 \qquad \text{equ. (4.4)}$$

Chapter 5 Discussion

The primary purpose of this study was to identify the movement patterns of the ice hockey stick during the performance of a wrist shot and to relate these to shooting accuracy. First, the subjects that were part of the sample had average overall accuracy scores of 54%, ranging from 27% to 80%. These scores were normally distributed and represented a cross section of high to low caliber players based on their accuracy level (Appendix I). Looking at the accuracy scores by target, a height main effect was observed regardless of caliber, with significant differences ($p>0.05$) found between top and bottom corners accuracy scores (65% and 45% respectively). In addition, the relationship between the overall versus target specific accuracies showed greater scores for the top versus bottom corners, with r^2 values of 0.85 and 0.80 for TC and TI respectively compared to 0.66 and 0.52 for BC and BI respectively (Fig. 4.1). Although, a main effect of shooting side (ipsi vs contra) on accuracy score was expected, no significant differences were observed ($p>0.05$). Potentially, other test configurations such as shooting further from the net and/or greater left and right oblique shot orientations to the net could reveal different effects on accuracy.

From the above, across most subjects, accuracy scores for the top targets were approximately 20% lower than bottom corners. This top target accuracy “handicap” is consistent with the greater complexity of the task; that is, shooting at the top targets requires a three-dimensional trajectory that must account for all variables of forward distance (constant at 4m), vertical (pitch, Φ) and horizontal (yaw, Ψ) orientation of the target. In contrast, shooting at bottom targets is a simpler two-dimensional task; that is, only the forward distance and Ψ location are relevant trajectory variables. Hence, given more release parameters for high shots increases the source of potential error in hitting the target.

This latter point was confirmed when considering the variables of shooting precision (i.e. distance from the center of the target to the actual puck impact point).Y-dis, Z-dis and radial distances were found to be significantly different between the bottom and top corners ($p>0.05$). As displayed in Figure 4.8, the radial distance from the center of the targets was greater for the top targets primarily due to the larger vertical error (Z-dis). Since the bottom corners could be hit by virtually sliding the puck on the ground, the mean vertical off target center distance (Z-dis) was substantially lower than the top corners Z-dis.

Given the shooting tasks were constant for all subjects, what were the higher caliber players doing fundamentally different (in terms of stick usage and release parameters) to score more accurately than the lower caliber players? To put the task difficulty in perspective, consider the size of each target (35 x 45 cm) with respect to the release point 4m away. For a puck to hit the target, the trajectory vector must fall within a scope of ± 2.5° Φ and ± 2.85° Ψ. To investigate this question, kinematics parameters were observed with respect to accuracy scores. Furthermore, regression models were developed to predict accuracy from selected kinematics parameters. For the bottom corners, the principal predictors of accuracy were the blade's heel velocity (km/h) and the position of the puck relative to the blade heel. These derived regression equations explained 36% and 40% of the variance in overall accuracy for BC and BI respectively. For the top corners, six parameters were found to be significant predictors of accuracy: puck release velocity ($v_{p\text{-}r}$), blade heel velocity (v_h), shaft bend (θ), release roll (β) and changes in blade orientation angles: ΔΦ and ΔΨ. These six parameters explained 76% of the accuracy variance for both TC and TI.

Surprisingly the regression equations derived to predict BC and BI accuracy did not explain the variance in shot outcome very well with few stick kinematic parameters strongly related to scoring. One may have presumed blade orientation to be an important variable, since it should determine the puck's angle of release similar to golf shot drives where the resultant ball trajectory and velocity vector depends on golf club face orientation at impact (William and Sih, 2002). However, in comparison the time duration for impact between the stick's blade and the puck (~180 ms), which is much larger than that of a golf club's head and ball (~10 ms). In the latter case, a near instantaneous impact of the club's face orientation is dominant in determining the ball's trajectory vector (disregarding slicing induced flight dynamics). In the case of the wrist shot, the impulse to the puck represents the cumulative gain in momentum during which the blade orientation changes throughout puck-blade contact. Hence, the end blade orientation at puck release does not predict shot trajectory, and in turn accuracy outcome. The puck in a sense is not impacted so much as guided forward by means of steering with the stick's shaft and cradling in the blade's concave front profile. This interpretation is supported by the observation that the strongest predictor of bottom target accuracy was the position of the puck relative to the blade heel, wherein HC players had the puck rest on average 18 cm from the heel, or effectively at the blade's curve apex (center of curvature), where as LC players had the puck closer to the blade's heel. Puck-blade position was adjusted by control of the blade's Ψ and speed throughout the contact phase, by means of upper limb kinematics especially in terms of the wrist and forearm (supination/pronation) motions. Further whole body kinematics studies are warranted to identify specific technique traits (i.e. limb kinematics and their coordination) of HC shooters.

In contrast to the bottom targets, the accuracy scores for top targets were approximately 20 % lower across all subjects. This decrement is related to the third dimension (i.e. height) of the task, necessitating precision in Φ of the puck at release. Shooting at top targets requires the player to lift the puck at the optimal pitch vector accounting for the target vertical position and gravitation drop of the puck during flight. Considering the average puck release velocity (65 km/h), the puck drops approximately 25cm over a 4m distance. Since the range of puck velocity at release was from 47 to 86 km\h for the top corners, the puck drop that the shooters had to deal with was ranged from 13 to 46 cm. HC players exhibited less variance in vertical projection around the top targets (Z-dis) and therefore must have had better precision in both pitch angle projection and estimation of gravitational puck drop for given speeds than LC players. This interpretation is supported in part by the findings of Newell (1975) that showed that in learning a projectile task visual flight feedback (seeing the puck trajectory) provides redundant information for response selection on the next trial when the end result knowledge is available. When examining data for the top corners, one of the strongest predictors of accuracy was the puck linear release velocity (Table 4.9).

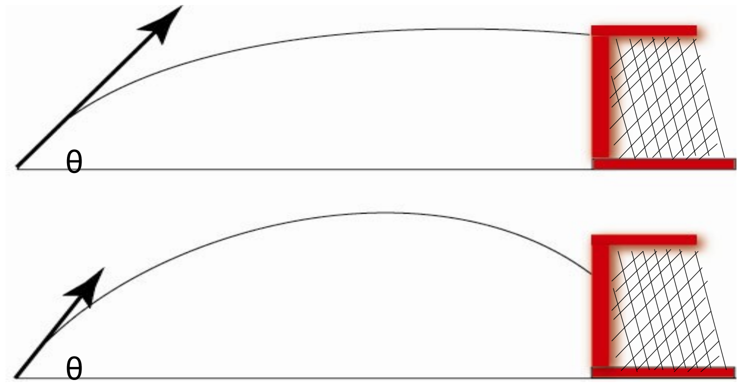

Fig. 5.1: Difference in end location for two projectiles shot at the same angle of projection θ, but with different release speeds, that difference is imputable to the puck “drop” effect cause by gravity.

Looking at different projectile related tasks and sports, Kreighbaum et al. (2006) reported that an increase in a projectile release velocity for a given angle would “flatten” the object trajectory over a fixed distance (i.e. less drop due to gravity over the flight distance). Since we have already established that aiming at top targets involves dealing with such a parabolic trajectory, over a 4 m distance releasing the puck with a greater velocity would result in a more “flattened” puck trajectory as pictured in Fig. 5.1.

Taking a wrist shot at one of the top targets will require the shooter to “scoop” under the puck (i.e. moving the blade under the puck to permit application of a vertical force component to the puck) in order to lift it and provide the optimal puck's velocity vector to intercept the target window. Therefore, a substantial amount of change in the pitch angle ($\Delta\Phi$) throughout the contact phase is needed for the blade to "scoop" under the puck. Thus, the player must account for both release magnitude and direction. According to Muller's model, any projectile travelling in a parabolic trajectory can accurately hit a target with many angle of release/speed of release combinations (Davids et al., 2006). Thus, the shooter could potentially adjust these two parameters ($\Delta\Phi$ and puck velocity) to obtain the intended puck trajectory. The latter variable was shown to be an important variable in predicting top target shooting accuracy (Table 4.9). In relation to puck speed, greater shaft bend was a characteristic also displayed by HC players. Presumably, these greater shaft bends were utilized to store and subsequently release elastic energy to aid in obtaining greater puck speed. This phenomenon was shown previously to exist for slap shot by Villaseñor et al. (2006). Furthermore, Worobets and colleagues (2006) suggested that puck speed was highly correlated ($r = 0.81$) with the amount of potential energy stored in an ice hockey stick while performing a wrist shot.

In addition to the "scoop" mechanism, the wrist shot is characterized by a rapid "flick" during the end contact phase between the blade and puck. This descriptive term "flick" corresponds to the fast change in blade orientation ($\Delta\Phi$ and $\Delta\Psi$) and concurrent stick bend recoil ($\Delta\theta$). Taken together, these parameters were shown to be strong predictors of shooting accuracy for the top targets. These are associated with wrist flexion and forearm pronation of the limb with lower hand gripping the stick (hence it is named the "wrist" shot). From a biomechanical perspective, the ability of the wrist to move through a large range of motion while grasping a passive tool (Minetti et al., 2004) greatly increases the impact power that can be delivered with the tool (Wolfe et al., 2006). Future studies focusing on the upper limb joint movements and their respective coordination of both intra-limb and between left and right limbs is warranted to identify how the stick's spatial orientations are produced and sequenced.

Though the overall contact time was not related to accuracy, several velocity (at release) variables significantly correspond to accuracy (Tables 4.4, 4.9). In particular, greater speed of the blade's heel (at release of the puck) strongly correlated with improved accuracy scores for all targets (Table 4.4). As well, in several instances the amount of blade's $\Delta\Phi$ and $\Delta\Psi$ and shaft θ also corresponded to higher accuracy scores. The combinations of greater stick end speed, greater blade angular rotation and shaft recoil culminating at release is congruent with the descriptive "flick" phenomenon as a desirable technique for better shooting accuracy. Though not derived in this study, a higher rate of blade's $\Delta\Phi$, $\Delta\Psi$ and $\Delta\beta$ may well follow with this argument, as interpreted from angular-time profiles (e.g. Fig 4.3).

Another variable strongly correlated with upper corner accuracy was the blade's roll (β) angle at release. Qualitative inspection of the video logs showed that most HC players would drag (or "draw in") the puck and the stick's blade closer to their base of support during early puck contact (Fig. 4.4). In order to bring the stick closer, HC shooters would need to flex their elbows more. This technique may permit greater freedom for the wrists to manipulate the stick to in turn permit enhanced puck guidance. In effect, HC player's tended to bring the puck to a set distance with respect to his body, to a predetermined optimal point of release (in the global reference frame). LC shooters would more often than not push the puck forward with little regard to the puck's point of release with respect to the body. As a consequence, their stick motion profiles tended to be more pendulum-like throughout, rotating about the shoulder. Greater wrist involvement has been shown to improve accuracy, as seen in other skills such as the basketball free-throw. Button et al. (2003) reported that experienced players would show greater variability at the distal joints (wrists and fingers) than less skilled players who instead would use the elbows and shoulders to determine the ball trajectory, resulting in a lower success rate. To confirm these deductions with shooting in ice hockey, tracking of upper body kinematics are required in future studies. A second negative consequence of more pendulum stroke motions is a decrease in window of opportunity for release of the projectile for successful interception with the target. The more linear or "flattened" the swing motion during contact, as noted earlier, the better guidance of the projectile towards the intended target. This favorable technique is shown in other sport activities; for example, investigating movement control in golf putting, Delay et al. (1997), reported that expert players showed longer and more linear swing patterns than the novice players both before and after ball contact.

With regard to yaw (Ψ) and $\Delta\Psi$, these kinematic profiles were somewhat different between HC and LC players (Figure 4.3). In particular, $\Delta\Psi$ was a strong predictor of top corner accuracy. Consistent with observed blade "flick", greater $\Delta\Psi$ may assist in rolling the puck to an optimal position on the blade: optimal in the sense that the puck would be cradled in the concave front face of the blade thereby inhibiting unpredictable wandering of the puck. Hence the puck would faithfully follow the trajectory defined by the end stick's movement, and in turn minimize the margin of error in terms of Y-dis accuracy as pictured in Figure 5.2.

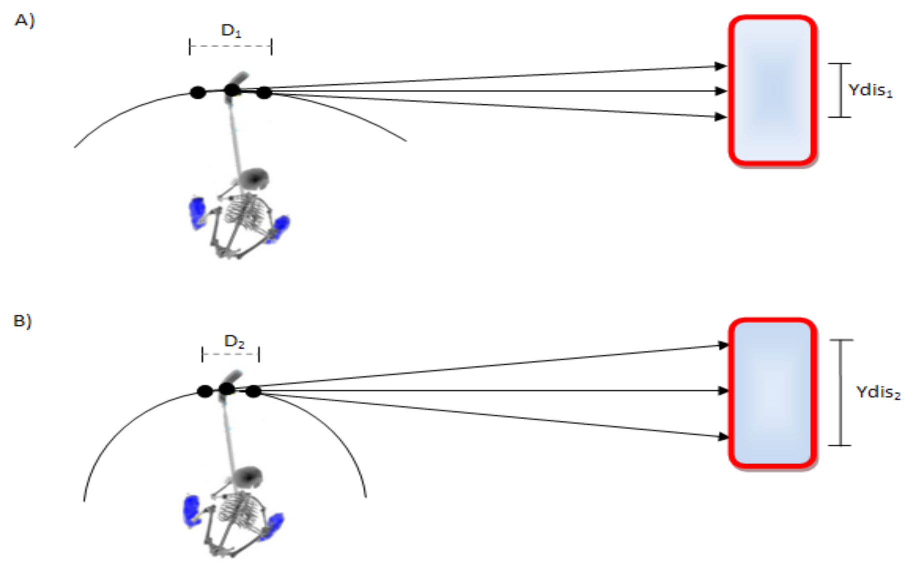

Fig. 5.2: Linear movements of the stick (from a top view) (A) allows for a greater margin for error as well as increased accurate projection of the puck as opposed to the more curvilinear motions of the stick (B) as $D_1 > D_2$ and $Ydis_1 < Ydis_2$ (adapted from Kreighbaum and Barthels 1996)

As noted several times already, future analysis of whole body kinematics is necessary to identify fundamental motor control coordination strategies for this challenging task. As well, other shooting scenarios must be addressed; for instance, in this study we used a stationary shooting protocol and thus it is not necessarily possible to extrapolate these findings to other game situation such as different shooting angles and distances relative to the net. This study provided unique insight into the movement technique of the blade and shaft of the hockey stick associated with the accuracy of a stationary wrist shot. As such, these findings shed some light on the previously largely unexplored function of the hockey stick and provoke a series of additional research questions within this field of study thereby, providing valuable information for future hockey stick design and development and coaching strategies.

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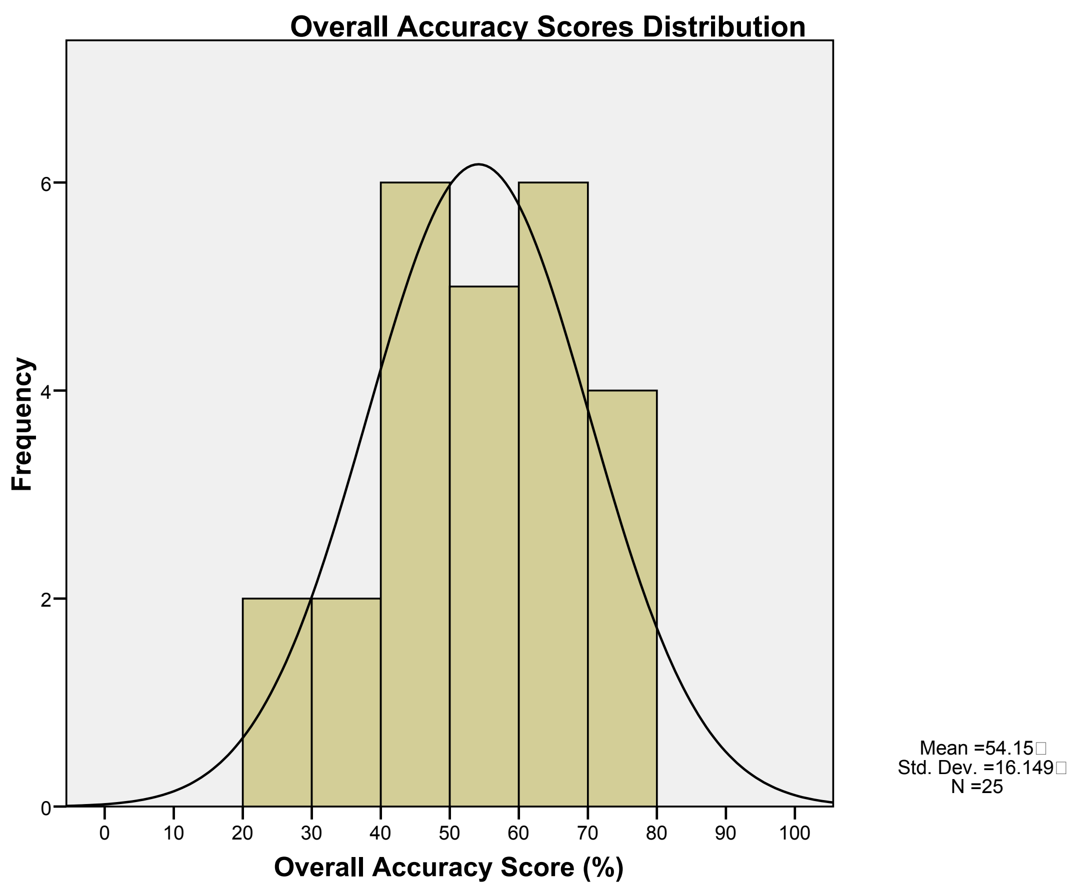
http://www.nhl.com/rules/index.html

http://www.hockeycanada.ca/6/6/9/8/index1.shtml

Appendix

Appendix I - Accuracy scores distribution

	N	Minimum	Maximum	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
Overall Accuracy Score	25	26.58	80.00	54.1524	16.14875	-.023	.464	-.810	.902
Valid N (listwise)	25								



Appendix II

MCGILL UNIVERSITY
FACULTY OF EDUCATION

RESEARCH SUBJECT CONSENT FORM

Mechanical and biomechanical evaluation of ice hockey skates and sticks:

Physics of projectile accuracy in wrist shots

Participation in this study consists of performing shooting tasks common in ice hockey. You will be asked to perform these shooting tasks under controlled conditions within the lab. The risk of injury is minimal. In order to insure your safety, the exact tasks will be explained verbally and demonstrated to you.

All personal information collected will be confidential. The use of a number code will maintain anonymity of yourself when data are presented in abstracts, publications or reports presented at conferences or in journals. The only personal information required will be the height, weight and the extent of ice skating experience.

Your participation in this study is voluntary and not mandatory. You are free to withdraw from participating in any part or all of the study at any time.

During testing, you will wear your own shirt, short, skates and hockey gloves (if available) while standing on a sheet of glice (high-density polyethylene). You will be asked to complete three wrist shots at all four targets. Successful trials will include those shots that faster than 50 km/hr. For each task, performance measures will include high-speed near-infrared video recording.

I, ______________________________, have both read the above testing conditions and have had the testing conditions verbally explained and demonstrated to me. I understand that my participation in this study is voluntary and that I may withdraw from participating in any part or all of the study at any time. I understand that all personal information collected will be confidential. If I have any questions or concerns regarding the above tests, I should contact Dr. David J. Pearsall, Associate Professor, of the Department of Kinesiology & Physical Education (Room 404, Currie Memorial Gym, phone: 398-4184 ext. 09976, or email: david.pearsall@mcgill.ca)

Participant's signature_________________________________ date ______
Tester's signature _______________________________

Appendix III - Ethics certificate

McGill

Faculty of Education – Ethics Review Board
McGill University
Faculty of Education
3700 McTavish; Room 230
Montreal H3A 1Y2

Tel: (514) 398-7039
Fax: (514) 398-1527
Ethics website: www.mcgill.ca/rgo/ethics/human

Faculty of Education – Review Ethics Board
Certificate of Ethical Acceptability of Research Involving Humans

REB File #: 713-1006

Project Title : ***Physics of projectile accuracy in wrist shots***

Applicant's Name: David Pearsall **Department**: KPE

Status: Faculty **Supervisor's Name: n/a**

Granting Agency and Title (if applicable): NSERC

Type of Review: Expedited _✓ Full ____

This project was reviewed by: Hoover/Starke-Meyerring

Approved by

R. Bracewell Oct 16, 2006
Signature/Date
Robert Bracewell, Ph.D.
Chair, Education Ethics Review Board

Approval Period: Oct/16/06 to Oct. 16/07

All research involving human subjects requires review on an annual basis. An Annual Report/Request for Renewal form should be submitted at least one month before the above expiry date. If a project has been completed or terminated for any reason before the expiry date, a Final Report form must be submitted. Should any modification or other unanticipated development occur before the next required review, the REB must be informed and any modification can't be initiated until approval is received. This project was reviewed and approved in accordance with the requirements of the McGill University Policy on the Ethical Conduct of Research Involving Human Subjects and with the Tri-Council Policy Statement on the Ethical Conduct for Research Involving Human Subjects.

10/16/06

Appendix IV - Accuracy score sheet

Shooter: ____06______

Handedness: __Left___

Top left

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
M	**X**	**X**	**X**	M	M	**X**	M	**X**	M	**X**	**X**	M	**X**	**X**	**X**				

Top right

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
X	M	**X**	M	M	M	**X**	**X**	**X**	**X**	**X**	M	M	**X**	**X**	**X**				

Bottom left

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
M	M	**X**	M	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**							

Bottom right

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
M	M	**X**	**X**	**X**	M	**X**	**X**	**X**	**X**	M	**X**	**X**	**X**						

X = Successful

M= Miss

Appendix V - Accuracy scores

		Wrist Shot Accuracy Scores				
Shooter	*Handedness*	*Top left*	*Top right*	*Bottom left*	*Bottom right*	*Total shots*
1	Right	83.3	66.6	83.3	90.9	80.0%
2	Left	25.0	15.0	35.0	55.5	32.1%
3	Left	20.0	20.0	52.6	30.0	30.4%
4	Left	5.0	10.0	45.0	52.6	27.9%
5	Left	50.0	50.0	76.9	76.9	60.6%
6	Left	62.5	62.5	76.9	71.4	67.8%
7	Right	35.0	50.0	58.8	90.9	56.1%
8	Left	25.0	50.0	58.8	76.9	50.0%
9	Left	50.0	40.0	90.9	83.3	63.3%
10	Left	58.8	58.8	71.4	76.9	65.6%
11	Left	83.3	76.9	76.9	83.3	80.0%
12	Left	76.9	76.9	83.3	83.3	80.0%
13	Right	50.0	40.0	55.5	76.9	55.1%
14	Right	35.0	35.0	50.0	58.8	45.9%
15	Left	30.0	25.0	5.0	45.0	26.6%
16	Left	25.0	25.0	71.4	76.9	44.8%
17	Right	45.0	52.6	55.5	83.3	56.5%
18	Right	20.0	50.0	40.0	62.5	42.1%
19	Right	50.0	40.0	35.0	52.6	44.3%
20	Left	45.0	20.0	45.0	76.9	43.8%
21	Right	58.8	50.0	66.6	90.9	63.5%
22	Left	52.6	52.6	55.5	66.6	56.3%
23	Left	60.5	52.6	71.4	71.4	63.5%
24	Right	58.8	76.9	83.3	90.9	75.5%
25	Left	25.0	25.0	55.5	71.4	42.3%