Three-Dimensional Blade Position and Orientation during a Stationary Ice Hockey Slap Shot

By

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ABSTRACT

The purpose of this study was to examine the three-dimensional movement profile of the blade during a stationary slap shot, as a function of blade construction properties and player skill level. A total of fifteen subjects participated in this study; eight were classified as elite and the remaining seven were recreational. Performances were evaluated by simultaneously recording the movements of the stick's lower shaft and blade with high-speed video (1000 Hz), the time and duration of stick-ground contact with two uniaxial forceplates, and time of blade-puck contact with a uniaxial accelerometer mounted within the puck. Data were analyzed with a two-way ANOVA for several dependent variables, including: linear kinematics, temporal phase data, and global angles. The results indicated that elite shooters tended to alter timing parameters (i.e. phase length), magnitude of linear variables (i.e. displacement, etc.), and the overall blade orientation to achieve a higher velocity slap shot. These analyses helped to identify a unique rocker phase within the execution of the slap shot in both groups. Further studies are needed to discern the precise role and function of the rocker phase, in order to advance the cause of hockey stick, specifically blade design and development.

RÉSUMÉ

Le but de cette étude était d'examiner les déformations tri-dimensionnelles de la lame d'une bâton dehockey pendant un lancer frappé stationnaire; relativnent à la fonction de la construction de la lame, les caractéristiques de la lame et du niveau du joueur. Un total de 15 sujets ont participé à cette étude, avec huit classifiés comme joueurs d'une niveau élite (ELITE) et les sept autres classifies comme sujets d'un niveau récréatif (REC). Les performances ont été évaluées par enregistrement simultané du mouvement du manche inférieur du bâton et de la lame avec une caméra vidéo a haute vitesse (1000Hz), le temps et durée de contact avec le sol avec deux platformes de force uni axiales, et le temps de contact de la rondelle et la lame avec un acceléromètre uni axial montée a l'intérieur d'une rondelle. Les données on étre analysées avec une approache d'analyse de variance bi-directionnelle pour plusieurs variables dépendantes, incluant : cinématique linéaire, données de phase temporelle, et les angles globaux. Les résultats ont indiqué que les sujets de niveau élite avaient tendance à modifier leurs paramètres de timing (e.x. longuer de phase), les amplitudes de variables linéaires (e.x. déplacement, etc.), et l'orientation de la lame pour atteindre un lancer frappé de plus haute vélocité. Ces analyses ont aidé à identifier une phase rocker unique dans l'exécution du lancer frappé dans les deux groupes de sujets. Des études supplémentaires sont requises pour discerner le rôle précis et la fonction de phase rocker afin d'avancer la cause du baton de hockey, spécifiquement la lame, le plan et le développement.

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CHAPTER 1 – INTRODUCTION

In the increasingly technology-driven world of sport equipment design, there is a constant search for a competitive edge and ice hockey is no exception. In an attempt to enhance performance, there has been a dramatic shift to new equipment designs, materials, and construction techniques. Nowhere is this shift more apparent than in ice hockey's most important implement – the stick. Throughout the game's history the stick has evolved in geometric dimensions, materials, manufacturing, and technical innovations (Dowbiggin 2001).

Initially, hockey sticks were constructed entirely of wood, with the preference being for white ash. In fact, this design remained primarily unchanged until the 1950's, when manufacturers began constructing separate shafts and blades, joining them together later in the manufacturing process. In the mid-1960's Chicago Blackhawk's forward Stan Mikita is thought to have further revolutionized hockey stick design by adding a curve to his blade; thus, improving player's forehand stick handling and increasing slap shot velocity and accuracy (Dowbiggin 2001; Nazar 1971). Through the seventies, with the intent on reducing stick weight and the amount of wood used, manufacturers experimented with a wide variety of fibre-glass and plastic layers over the wooden core of the stick. Eventually, manufacturers were able to incorporate stronger, more light-weight materials, such as carbon-fibres, aluminium alloys, and fibreglass in varying combinations. As such, today's high end sticks are stronger, lighter, more expensive, and easily reproduced (Dowbiggin 2001).

Yet, other determinants of player's stick preference include brand and model loyalty and the kinaesthetic feel of the stick. To this end, elite hockey players are notoriously meticulous in their choice and preparation of sticks. Players tend to have individually preferred taping strategies and some even reshape the butt end; however, the blade of the stick is where player preferences are most apparent (Dowbiggin 2001; Hoerner 1989).

The blade is a key component of the stick because it is the final contact point between the stick and the puck. The properties of the blade are perceived to affect velocity, accuracy, and location of shots and passes, as well as the ability to receive passes. Players use numerous combinations of shape (within league regulations), contour, material, stiffness, and lie angle in the blades of their sticks (Dowbiggin 2001), all determined by the athlete's perception of the "feel" of the stick during shooting and stick handling tasks.

Each stick is subjected to a wide variety of tasks during the course of a game; for instance: shooting the puck towards the opposition's goal, passing and receiving passes between players, stick-handling, and in checking (Hoerner 1989). Of these tasks, the most spectacular is shooting (Lariviere & Lavalle 1972; Renger 1994), which is influenced by a wide variety of factors, including: puck impulse, puck acceleration, puck mass, blade-puck contact time, initial puck velocity, initial/final stick velocity, stick mass, forces exerted by the player, stick stiffness, and stick bending (Pearsall et al. 2000).

Nowhere is the appropriate combination of the aforementioned variables more important than in hockey's most popular and prolific shot – the slap shot. This particular shot is employed 26% of the time by forwards and 54% of the time by defence players (Montgomery et al. 2004). The distinguishing feature of the slap shot is the increased puck velocity, as compared to other shots (i.e. wrist, snap, sweep) (Pearsall et al. 1999).

1.1 Nature & Scope of the Issue

Ice hockey has grown from a recreational pastime into a multi-million dollar industry; with many major manufacturers still based out of Canada. In addition to this economic value, the game also has substantial social value in Canada, with an estimated 4.5 million Canadians involved in organized ice hockey annually (*Hockey Canada Report* 2003). As such, applied ice hockey research aids the design and manufacture of improved hockey products and has both commercial and societal value in this country.

It is equally important to educate the general public, particularly coaches and athletes, by providing practical information on the fundamental behaviours of the stick, beyond the obvious or biased views, to aid in distinguishing between fact and marketing fiction. As a case in point, the pervading wisdom in hockey suggests that composite sticks allow for faster shots as compared to conventional wood sticks (Trainor 2004); however, research has failed to find any significant difference in slap or wrist shot velocity between sticks of different materials (Wu et al. 2003).

To date, there have been several attempts to quantify both kinematic and kinetic parameters of the player in terms of successful shot performance (e.g. Alexander et al. 1963; Marchiori et al. 1987; Woo 2004). From these data, it is apparent that the individual athlete's strength (Fergenbaum & Marino 2004; Pan et al. 1998; Pearsall et al. 2000) and movement patterns (Woo 2004) are principal determinants of puck velocity, as compared to shaft stiffness or construction material (Pearsall et al. 1999; Wu et al. 2003). There have also been some analyses of the mechanical properties of the shaft (Marino & VanNeck 1998; Villaseñor-Herrera 2004) and blade (Nazar 1971), with respect to slap shot performance. However, the relationships between various mechanical factors (e.g. puck-blade contact time, blade deformation, and relative motion between shaft and blade) remain poorly understood.

1.2 Rationale

The primary objective of the slap shot is projecting the puck with maximal velocity and accuracy as a means to out-manoeuvre the opposing goalie and ultimately score. To this end, there has been constant pressure from athletes, coaches, and stick manufacturers to better understand how this velocity is generated. For instance, several studies have indicated, not surprisingly, that skilled athletes are able to generate higher puck velocities than their unskilled counterparts during the slap shot (Alexander et al. 1964; Alexander et al. 1963; Pearsall et al. 1999; Wu et al. 2003). Slap shot velocity has also been correlated with upper body strength and stick displacement (Woo 2004; Wu et al. 2003). However, neither stick shaft stiffness nor construction (i.e. wood versus composite) has been found to significantly influence slap shot velocity (Pearsall et al. 1999; Wu et al. 2003).

Since recent studies have demonstrated that puck-blade contact time is significantly correlated with puck velocity in the slap shot (Villaseñor-Herrera 2004), it is possible that certain blade properties and constructions can alter contact time in this critical period. However, to date there has been no attempt to correlate the material or mechanical properties of the blade with its performance during shooting.

Purpose

The purposes of the present study are as follows:

1. Examine the differences in timing of certain key events of the stationary slap shot between recreational and elite hockey players, and between various brands of ice hockey stick blades;

2. Quantify the vertical and horizontal linear displacement of various brands of ice hockey stick blades during the stationary slap shot in both recreational and elite hockey players;

3. Examine the three dimensional bending properties of various brands of ice hockey stick blades during a stationary ice hockey slap shot;

4. Quantify the global angle of various brands of ice hockey stick blades with respect to the frontal and transverse planes in recreational and elite hockey players;

5. Determine whether differences exist in the linear velocity and/or acceleration of the blade between various brands of ice hockey stick blades or between recreational and elite hockey players.

1.3 Hypotheses

This study hypothesizes that:

H1. The elite group will demonstrate a longer period of time between initial stick-ground contact and initial stick-puck contact (loading phase) than their recreational counterparts;

H2. The elite group will have a longer total blade-ground contact time than the recreational group;

H3. The elite group will produce a higher puck velocity than the recreational group;

H4. The recreational group's shaft and blade will experience a greater overall Z displacement than in the elite group;

H5. The elite group will produce higher blade and shaft velocities and accelerations than the recreational group in all phases, and;

H6. Blade constructions with high density cores will provide similar deformation characteristics as blades with low density core constructions; however, since they have increased mass, they may allow the shooter to achieve a higher shot velocity.

1.4 Limitations

Limitations of this study include:

1. All experiments will be conduced at room temperature (22 to 24° C) instead of ice rink temperature;

2. Experiments will be conducted under laboratory conditions with a ground surface covered by lubricated polyethylene sheets used to simulate ice friction;

3. Only stationary (i.e. standing) slap shots will be studied;

4. Participants will not be wearing full hockey gear (i.e. skates, shoulder pads, elbow pads, hockey pants, shin guards, etc.); however, hockey gloves will be worn, and;

5. Shaft kinematics will only be analyzed for the lower 15 cm of the shaft.

6. Only commercially available sticks, which must fall within narrow, NHL-defined construction parameters, were considered in this study.

1.5 Delimitations

Delimitations of the study include:

1. Experimental tasks only included the slap shot;

2. Subjects only included males.

1.6 Independent (IV) & Dependent (DV) Variables

The IV in this study are skill level (i.e. elite and recreational hockey players) and stick model (i.e. Easton Stealth, Easton Si-core, CCM Vector, Bauer Vapor XX, Bauer Vapor XXX, Bauer Vapor I CTC). The DV, and their respective abbreviations, are presented below in Table 1.

Table 1 - List of proposed DV (* variables diagrammed in Section 3.5)

Abbreviation	*Variable Definition*
V_{puck}	puck velocity
P_{zone}	puck contact zone
$*\Delta t_1$	time from initial toe contact (TC) to initial heel contact (HC)
$*\Delta t_2$	loading phase (initial toe contact (TC) to initial blade-puck contact (PC))
$*\Delta t_3$	total blade-ground contact time(from initial toe contact (TC) to final stick-ground contact (S-OFF)
*Face Angle	global blade angle (2-1 to 2-3) with respect to the frontal plane
*Tilt Angle	global blade angle (2-1 to 2-3) with respect to the transverse plane
*Loft angle	global blade angle (1-2 to 3-2) with respect to the transverse plane
2-2x, 2-2y, 2-2z	linear displacement of blade marker (2-2) in the X, Y, and Z directions, respectively
v2-2x, v2-2y, v2-2z	linear velocity of blade marker (2-2) in the X, Y, and Z directions, respectively
a2-2x, a2-2y, a2-2z	linear acceleration of blade marker (2-2) in the X, Y, and Z directions, respectively
S1x, S1y, S1z	linear displacement of shaft marker (S1) in the X, Y, and Z directions, respectively
vS1x, v2S1y, vS1z	linear velocity of blade marker (S1) in the X, Y, and Z directions, respectively
aS1x, aS1y, aS1z	linear acceleration of blade marker (S1) in the X, Y, and Z directions, respectively

1.8 *Nomenclature*

Specific terminology related to the ice hockey stick exists (Figure 1 & Figure 2). These include the following:

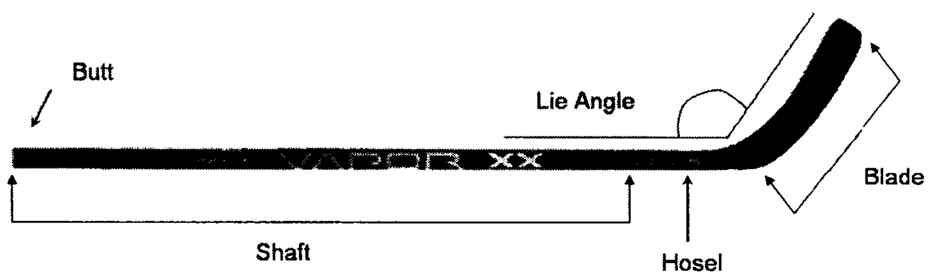

Figure 1 - The basic components of a hockey stick

Blade – Lowermost, curved portion of the hockey stick, which is used for puck control and projection (Figure 1).

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 (Figure 1).

Butt end – The top (proximal) end of the shaft; towards where the player's top hand is located (Figure 1).

Full-wrap – Refers the outer layers of the blade wrapping around the core of the blade. This is thought to give blades increased torsional stiffness.

Fused stick (two-piece stick) – A popular variant in carbon-fibre sticks, where the blade and shaft are actually two separate pieces that have been joined together during the manufacturing process and superficially appear as a one-piece stick. Since separate blades are inserted into the shafts, the hosel portion of a fused stick is a more solid, continuous structure that has increased torsional stiffness than a "true one-piece" stick.

Heel – The angled portion of the hockey stick where the blade meets the shaft; the beginning of the blade (Figure 2).

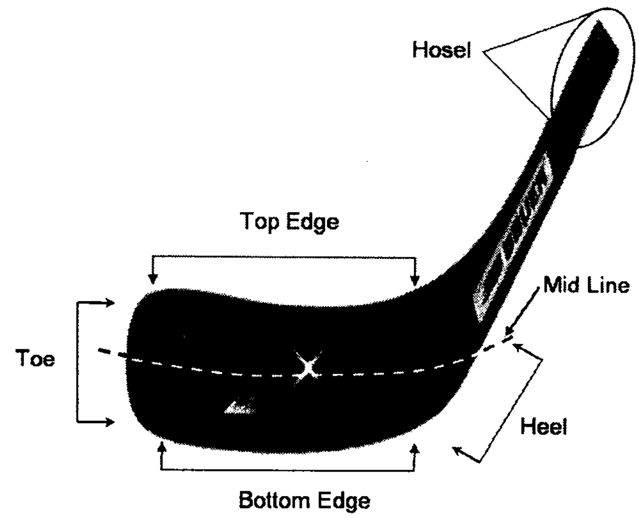

Figure 2 - The basic components of a hockey stick blade

Hosel – The socket or neck portion of the lower shaft of a hockey stick, into which the blade is inserted (Figure 1).

Left-handed shot – A player holds the stick with the right hand towards the top of the stick and the left hand near the middle.

Lie – The angle formed between the blade and the shaft when the blade is flat on the ice. Lie angles typically are rated on a scale from 4 to 8; however, the most common lie angles are between 5 and 6. Higher numbers indicate a smaller angle between the blade and the shaft, while smaller numbers indicate a larger angle (Figure 1). For instance, a lie angle of 5 corresponds to approximately 45°.

Mid-line – The line that runs the length of the blade approximately equidistant from the top and bottom edge (Figure 2).

Pre-Preg (pre-impregnated) – A material used in the manufacturing process. Carbon or fibreglass fibres are already impregnated with resin. This material is placed into a mold to make blades and/or sticks. The material uses less resin than the RTM blades, which can make pre-preg blades lighter.

Right-handed shot – A player holds the stick with the left hand towards the top of the stick and the right hand near the middle.

RTM – Resin transfer molding. A manufacturing process used in the construction of some blades & shafts, whereby dry fibres are placed and compressed in the blade mould while resin and a catalyst are injected under low pressure. Since resin & catalyst are added directly into the mold, this process tends to use excess resin; thus, making RTM blades slightly heavier than those made with pre-preg.

Sandwich structure – A blade construction technique whereby fibres are layered over both sides of a core and outer layers do not wrap around the edges of the blade.

Shaft – The straight, handle portion of the hockey stick (Figure 1).

Toe – The furthermost end of the blade (Figure 2).

True one-piece stick – A carbon-fibre stick which is one continuous structure from shaft to blade. The hosel portion of this type of stick hollow which is thought to give it less torsional stiffness.

CHAPTER 2 - REVIEW OF LITERATURE

2.1 Ice Hockey

The origins of ice hockey date back to the 1880s in Canada; since then, it has evolved into a fast-paced game with international appeal (Dowbiggin 2001). In addition to increasing popularity, hockey has become increasingly sophisticated in terms of technological innovations, equipment design and improvements in training, coaching, and game strategies (Pearsall et al. 2000). However, due to the specialized environmental conditions (e.g. low surface friction), ice hockey requires a unique skill set. These skills can be subdivided into general categories of skating, shooting, and checking. Each category includes a subset of specific skills, the hierarchy of which is demonstrated in Figure 3.

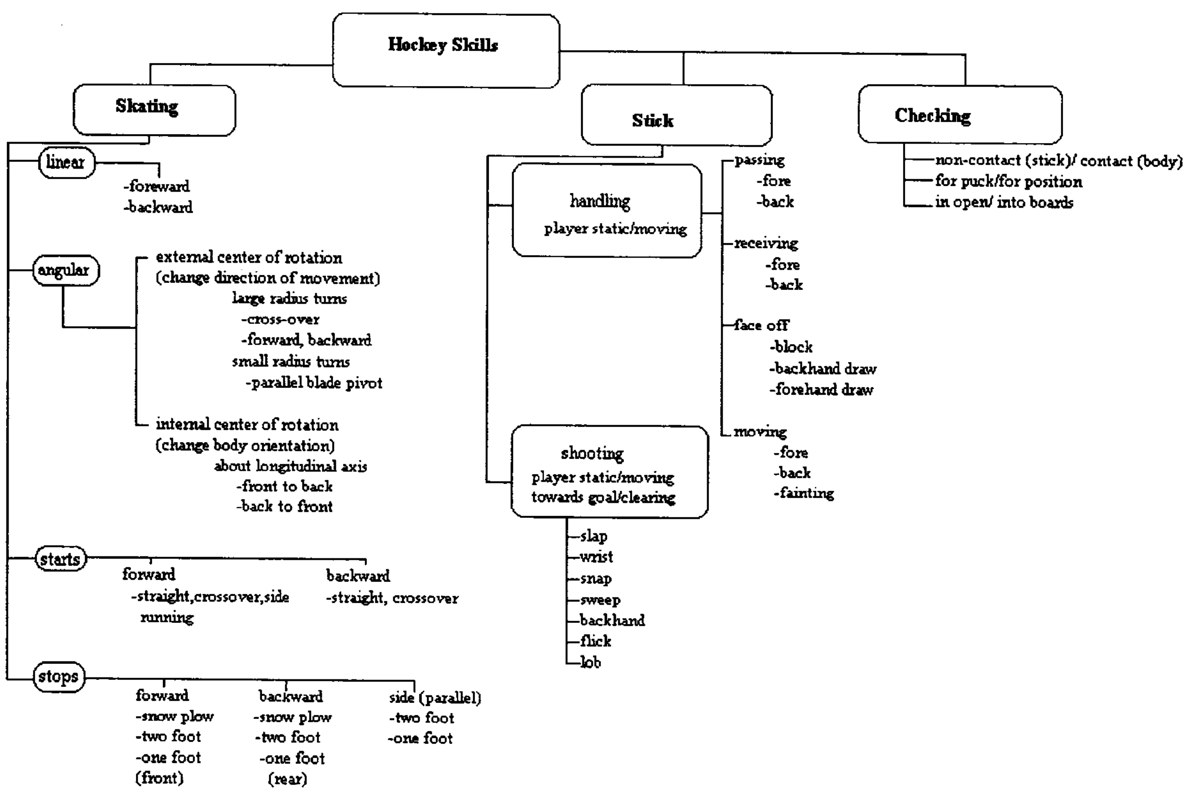

Figure 3 - Classification of fundamental ice hockey skills (adapted from Pearsall et al, 2000)

2.1.1 Slap Shot

Since the primary objective in ice hockey is scoring goals against the opposing team, ice hockey skills are predominately goal-oriented, with the timing and organization of movements a secondary function of this pursuit (Pearsall et al. 2000). As such, the function of the hockey stick and the skills associated with it are of great importance to the overall success of a player or team. In fact, a survey of over 900 NHL scouting reports ranks three skills associated with the stick (i.e. shooting/scoring, puck control, and passing) in its top ten list of skills/attributes in both forwards and defensive players (Renger 1994). Of these skills, shooting and scoring was ranked most important in forwards, while puck control was ranked most important in defensive players.

Players commonly utilize a wide variety of shots during a typical game situation. Since the ability to shoot with optimal velocity is a decisive factor in the overall performance of a player, the distinguishing feature between shots is often their velocity (Lariviere & Lavalle 1972). To date, at least six different approaches have be used to quantify shot velocities; they are: impact velocity (Alexander et al. 1964; Alexander et al. 1963), average velocity (Doré & Roy 1976; Roy 1974; Roy & Doré 1976; Roy et al. 1974), instantaneous velocity (Simm & Chau 1978), maximal velocity (Doré 1978), radar (Pearsall et al. 1999; Wu et al. 2003), integration of accelerometer data (Villaseñor-Herrera 2004). Based on these analyses, the slap shot consistently demonstrated the highest shot velocity, while the wrist shot was deemed the most accurate shot (Alexander et al. 1963; Nazar 1971; Pearsall et al. 1999; Wu et al. 2003).

As with most preliminary analyses of sports techniques, early investigations into the slap shot were primarily qualitative (Lees 2002). For instance, Hayes (1965) provided a qualitative description of the slap shot as well as a list of common errors in technique. Additionally, the author postulated that while a heavier stick would increase striking mass, it would ultimately decrease stick velocity at impact; therefore, a lighter stick might increase shot velocity.

Later, Emmert (1984) described the slap shot as being a powerful scoring technique that can be optimized with a full-body training program. The slap shot is discussed with reference to three unique phases – preparatory, action, and follow though. The preparatory phase includes the backswing, while the action phase includes: downswing, pre-loading, and loading (Pearsall et al. 1999; Wu et al. 2003).

Falconer (1994) provided a similar description of the slap shot as part of a coaching manual; however, the author describes the shot as comprising five unique phases. These phases are: preparation, wind-up, downswing, loading the stick, impact, and follow-through. Preparation involves orienting the body with respect to the puck (e.g. pointing the lead shoulder in the direction of the shot). Wind-up is also commonly referred to as backswing; it involves drawing the stick back by raising the trail arm and rotating the trunk, hips, and shoulders. Downswing occurs as the shooter rotates his or her hips, shoulders, and trunk such that the stick accelerates forward and downward until it contacts the ice (~ 10 cm behind the puck). Loading the stick occurs as the shooter continues to apply a force to the mid-shaft of the stick, causing the shaft to deflect and store energy. Impact occurs as the blade of the stick contacts the puck, releases its stored energy and accelerates the puck toward its intended destination. Finally, follow-through occurs as the shooter continues to allow the body to rotate and move forward, so that the stick moves forward and upward in front of the body; thus allowing the shooter to move forward and maintain his or her balance.

2.1.1.1 Shot Velocity

While the abovementioned studies provide insightful descriptions of the slap shot's movement pattern, they do not offer any quantitative data to support their hypotheses. However, as the slap shot gained popularity in the late 1950's and early 1960's, researchers began to examine its technique in greater depth. For instance, Alexander and colleagues (1963) examined the differences between slap and wrist shot in terms of speed, accuracy, and grip strength in thirty hockey players from professional and amateur teams. As demonstrated in Table 2, both Alexander et al (1963) and Cotton (1966) found that the skating slap shot produced the highest velocity (127 km/h and 100 km/h, respectively); whereas the standing wrist shot demonstrated the lowest velocity (97 km/h and 81 km/h, respectively). However, the skating wrist shot was deemed to be the most accurate shot tested and there was no significant correlation between static grip strength and shot velocity (Alexander et al. 1963).

Table 2 - Summary of puck velocities (km/h) reported in various studies (adapted from Pearsall et al, 2000)

				Slap		Wrist	
Author(s)	**Method**	**Velocity**	**Age**	**Skate**	**Stand**	**Skate**	**Stand**
Alexander et al, 1963	Ballistic	Impact	Adult	127	111	117	97
Alexander et al, 1964	Ballistic	Impact	Varsity	121		114	
Cotton, 1966			Adult	100	90	90	81
Furlong, 1968	Stop watch	Average	Professional	175		163	
Chau et al, 1973	Cine	Instant	Adult	132	110	143	132
Roy et al, 1974	Cine	Average	Junior B	89	92	81	64
Roy & Doré, 1976	Sound	Average	Pee-wee		69		
			Adult		96		
Doré & Roy, 1976	Sound	Average	Adult	104	97		
Simm & Chau, 1978	Cine	Max	High school	150			
			Adult	200			
Pearsall et al, 1999	Radar	Max	Varsity		108		
Meng & Zhao, 2000	Cine	Instant	Elite Adult	87			
Wu et al, 2003	Radar	Max	Varsity		105		
			Recreational		95		
Villaseñor-Herrara, 2004	Accelerometer	Max	Varsity		121		
			Recreational		80		

Furlong (1968) observed mean skating slap and wrist shots of 175 km/h and 163 km/h respectively. These values represent some of the highest shot velocities observed in ice hockey; however, they were calculated using manual stopwatches, which may introduce some inherent error.

The 1970's saw the advent of more advanced and precise technology in the field of biomechanics, and as such researchers were able to examine the slap shot in greater detail. For instance, Chau and colleagues (1978) utilized high speed camera technology to obtain kinematic information in various hockey skills in two adults and one juvenile player. Variables including: puck velocities, stick kinematics, push-off kinematics and kinetics, various skating speeds, and puck impact forces were examined using two cameras (filming at 400 Hz and 750-1000 Hz). Peak skating slap and wrist shot velocities were recorded at 132 km/h and 143 km/h, respectively; thus, contradicting earlier suggestions that the skating slap shot is always the highest velocity shot (Alexander et al. 1964; Alexander et al. 1963; Cotton 1966; Furlong 1968).

Roy and colleagues (1974) expanded on this work by examining: mean puck velocity, puck-blade contact time, shaft deflection properties (e.g. duration, maximum, velocity, etc), horizontal blade linear velocity, and percentage of velocity of the puck. The authors studied used high-speed filming (200 to 500 Hz) to examine the skating and standing slap and wrist shots of four junior B calibre players. Maximum slap shot velocity was found to be 89 km/h, which was comparable to values obtained by Cotton (1966), but lower than those in Alexander and colleagues (1964; 1963). The average slap shot impulse reported was 35 ms. Standing and skating slap shots had mean deflection duration of 63 and 82 ms and mean angular velocity of 17 to 13 radians per second respectively. Maximum shaft velocity of angular deflection correlated with the puck leaving the blade; however, the angular velocity values obtained did not compare well with those of Chau and colleagues (1978).

The authors attributed 40 to 50% of puck velocity to shaft deflection in the slap shot trials; whereas only 25 to 34% and 8 to 10% of puck velocity was attributable to shaft deflection in the wrist and backhand shots. Therefore, the Roy and colleagues (1974) suggest that shaft deflection is primarily caused by friction between the blade and ice rather than the blade and the puck. However, the precise contribution of blade flexion was not investigated.

Horizontal blade velocity was reported to have reached its maximum of 20 m/s prior to contacting the ice. During ice contact the blade's horizontal velocity decreased until the strain energy stored in the shaft (due to its deflection) was released, resulting in the blade once again achieving a maximum horizontal velocity of 20 m/s. Overall, Roy and colleagues (1974) suggested that proper shaft stiffness is an instrumental factor in slap shot performance.

In a later study, Roy and Doré (1976) used a digital time counter, triggered by a magnetic cell embedded in the ice and stopped by the impact sound as recorded by a microphone, to record average puck velocity in adult and pee-wee hockey players. Average standing slap shot velocities were 69 and 97 km/h for the pee-wee and adult groups respectively; thus, closely corresponding with those values reported by Cotton (1966) and Roy and colleagues (1974). The authors also noted a higher correlation between morphologic and strength variables and shot velocity in the younger subject group, suggesting that younger players rely more heavily on these attributes than older players. This suggests that younger players should select a more flexible hockey stick shaft, in order to make better use of their size and strength characteristics.

More recently, Meng & Zhao (2000) used a high-speed camera (72 Hz) to analyze four different shooting techniques in ice hockey (i.e. pulling shot, reflection shot, flick shot, and hitting shot). These terms appear to be unique to ice hockey in China; however, based on the descriptions provided of each shot, the hitting shot appears to be analogous to the slap shot. The authors describe this shot as consisting of an advanced waving stage, waving forward stage, deformation stage, and batting stage. This description loosely corresponds with earlier definitions of the slap shot which included backswing, down swing, loading, and follow-through phases (Emmert 1984; Falconer 1994). The authors report a mean 37 cm displacement in the center of gravity; however, temporal descriptions of changes in center of gravity were not provided. The mean total motion time and the mean puck-blade contact time were 65 and 40 ms, respectively, for the hitting shot; thus, corresponding to values reported earlier by Roy and colleagues (1976). Puck velocity at departure from the blade was reported to be 87 km/h, which is substantially lower than values reported in a similar study by Chau and colleagues (1978), but comparable to Roy and colleagues (1974) results with Junior B calibre players.

Woo (2004) was the first to examine the three dimensional kinematics of the stationary slap shot in both elite and recreational hockey players. An electro-magnetic tracking device (60 Hz) was used to determine the kinematics of the players' torso, arms and hockey stick. As expected, the elite group demonstrated a higher shot velocity than the recreational group (104.91 km/h and 95.29 km/h, respectively). Increased shot velocity was attributed to an increased translational acceleration of the stick by the elite group; as compared to the recreational group, who used more rotational acceleration see (Table 3). The elite group also demonstrated less variation in stick movement path than the recreational group. Finally, elite subjects demonstrated a more proximal-to-distal kinematic chain sequence.

Table 3 - Stick velocities of elite and recreational subjects deconstructed into their rotation and translation components (adapted from Woo, 2004).

Skill Level	**Velocity Attributed to Rotation (km/h)**	**Velocity Attributed to Translation (km/h)**
Elite	57.60	47.30
Recreational	62.57	32.69

Recently, Polano (2003) also examined three dimensional kinematics (60 Hz) of a standing slap shot in a group of varsity hockey players. Mean shot velocity was reported to be 108 km/h for the three subjects. The author also quantified some descriptive parameters of the slap shot, including average the average distance the stick contacts the ice behind the puck (~38 cm) and the total puck-blade contact time (~35 ms). The author also characterized the sequencing of a standing slap shot as a combination of a throw-like and push-like, as opposed to following a conventional kinetic chain model.

2.1.1.2 Strength Effects

Hockey is a multi-dimensional game with a variety of strength and skill requirements. Players require a unique balance of anaerobic and aerobic training to develop stamina, and full-body resistance training in order to complete all of the necessary skills (Emmert 1984). In particular, shooting, passing, and stick-handling require strength in the trunk, shoulders, arms, and wrists (Emmert 1984). Nowhere are these strength demands more apparent than in the powerful slap shot. In fact, Wells and Luttgens (1976) estimated that the slap shot requires 25% of the trunk, 40 to 45% shoulder, and 30 to 35% elbow and wrist involvement. As such, several researchers have focused on determining the exact relationship between player size, strength, training program and slap shot velocity.

For instance, early work by Alexander and colleagues (1963) indicated that there was no correlation between grip strength and slap shot velocity. However, the authors did suggest that: "...perhaps a combination of neuromuscular action and wrist strength is the salient factor governing the velocity of the shot..."; which alludes the importance of joint coordination later described in the literature (Fergenbaum & Marino 2004; Woo 2004).

More recently, Wu and colleagues (2003) examined the relationship between height, mass, bench press, and grip strength in skilled and unskilled, male and female subjects. The authors used a radar gun and a high-speed vide camera (480 Hz) to examine puck velocity and stick kinematics. As indicated in Table 4, all sub-groups mean peak puck velocity correlated most strongly with subject characteristics (e.g. height, mass, bench press, and grip strength) for slap and wrist shots. While it is not possible to establish a causal relationship from this data, it does suggest the importance of both size and strength in slap and wrist shot performance.

Table 4 - Correlation between subject characteristics and peak shot velocity (adapted from Wu et al, 2003); *p < 0.05

Variable	Shot	
	Slap	Wrist
Velocity	1.00	1.00
Height	*0.64	*0.56
Weight	*0.88	*0.83
Bench	*0.79	*0.75
Right Grip	*0.67	*0.66
Left Grip	*0.59	*0.61

However, it is important to note that while significant differences ($p < 0.05$) were found between the skilled and unskilled group, there were no significant differences between these groups in terms of strength measures (i.e. bench press and grip strength). That is, the skilled group produced higher shot velocities despite having similar physical strength to the unskilled group. Therefore, it appears that differences in performance must be attributed to differences in technique; such that the skilled subjects strike imparts a greater impulse on the puck than their unskilled counterparts.

The potential relationship between strength and slap shot velocity has also generated several studies that attempt to improve shot velocity through strength training. For instance, Alexander et al (1964) examined the effect of strength development on shot velocity. Four varsity hockey players were filmed with high-speed cameras from the frontal and sagittal views while performing skating slap and wrist shots. After completing a resistance training program, that emphasized upper body strength, players demonstrated an increased mean shot velocity as compared to a control group for both the slap and wrist shots (6.7 km/h and 8.7 km/h increases, respectively).

Later, Pan and colleagues (1998) also examined the effects of a specialized upper body strength training program on slap and wrist shot velocity. The authors used a 16-channel surface electromyography (EMG) system and six high-speed digital video cameras (240 Hz) to determine muscle activation patterns, puck velocity, and point of puck contact/release before and after a six week training program in ten collegiate hockey players. There were significant ($p < 0.05$) increases in shot velocity in both the slap and wrist shots in the magnitude of 16.79 and 15.55 km/h, respectively.

Additionally, specific muscle activation patterns were observed. For instance, at the point of puck contact, the slap shot utilizes: latissimus dorsi, anterior deltoid, triceps, wrist extensors, and wrist flexors of the dominant arm and trapezius, biceps brachii, triceps and wrist flexors in the non-dominant arm. Whereas, at the same point in time during a wrist shot only the wrist flexors and extensors of both arms, the triceps of the dominant arm, and the latissimus dorsi on the non-dominant side are involved. However, the authors did not quantify muscle activation levels or discuss eccentric/concentric loading properties.

Most recently, Fergenbaum & Marino (2004) examined the effects of upper-body plyometrics training on upper-body isometric strength, stick velocity and puck velocity during a slap shot over ten weeks of in-season hockey training in 21 collegiate hockey players. Surprisingly, isometric strength did not correlate with puck or stick velocity; however, the authors speculated that the isometric tests used were too static to relate to the dynamic, high velocity slap shot.

The authors were able to establish a relationship between changes in off-ice stick velocity (increasing 13%) and on-ice puck velocity (increasing 4.2%); suggesting that off-ice slap shot training could offer some on-ice benefits. Fergenbaum & Marino (2004) went on to postulate that improvements in off-ice stick velocity may be the result of improved ballistic coordination between the upper and lower limbs. That is, coordination may be improved due to improved synchronicity of the motor units between the upper and lower limbs (as a result of repetitive slap shot training with light weights). However, exhaustive investigation into the coordination between the upper and lower limbs during the slap shot has yet to be reported.

2.1.1.3 Stick Properties

Some of the mechanical factors that are proposed to be important during the slap shot are: (1) lower (distal) shaft velocity prior to puck contact, (2) pre-loading of the stick, (3) stick stiffness characteristics, and (4) puck-blade contact time (Doré & Roy 1976; Hoerner 1989; Marino 1998). However, the precise relationships between these mechanical properties of the stick and shot performance have only recently been investigated. For instance, Roy & Doré (1973; 1975; 1976) completed some of the first kinetic analyses of various shots in ice hockey (e.g. slap, wrist, and sweep shots) with high-speed film (200 Hz) and several strain gauges attached to the shaft and blade of the stick. Using multiple strain gauges placed along the shaft the authors calculated forces exerted by the top and bottom hands and back side of the blade during the impulse (i.e. loading) phase.

Roy and Doré (1975) evaluated various shots based on three categories: (1) geometric, (2) static, and (3) dynamic. Geometric characteristics included length, minor axis dimension, major axis dimension, blade length, blade thickness, lie angle, and center of mass. Static characteristics included various stiffness measures, including: blade stiffness, shaft stiffness through minor axis, shaft stiffness through major axis, and shaft torsional stiffness (Figure 4). Dynamic characteristics were obtained using high-speed filming and a series of eight strain gauges placed along the shaft and blade; values obtained included: impulse phase, shaft deflection during impulse, puck velocity, and blade velocity during impulse.

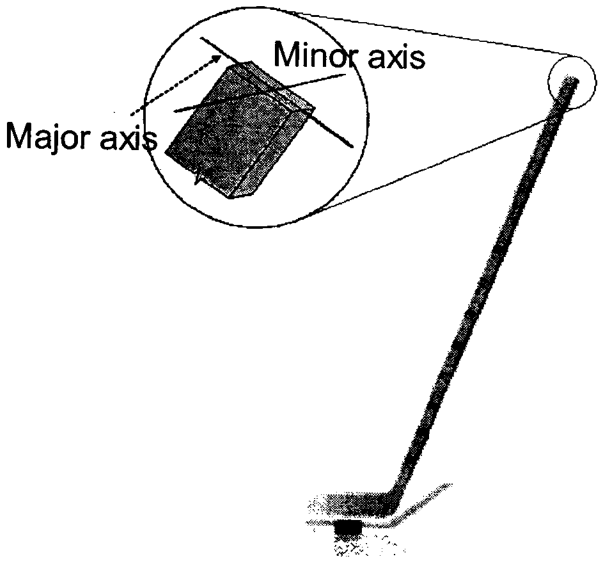

Figure 4 - Shaft major & minor axes (adapted from Pearsall, et al, 1999)

Using this configuration the authors were able to calculate the location of the forces exerted on the stick during a slap shot, (Figure 5); however, these locations could not be determined precisely. The authors presented recorded forces of approximately 2 to 3 kg at the blade locations (G1 & G2, respectively), from 3 to 6 kg at each of the top hand locations (G4 and G5, respectively), and from 5 to 8 kg at each bottom hand location (G'4 and G'5, respectively) for one subject. However, there was a substantial amount of inter- and intra-subject variability during the slap shot trials. Finally, the authors report that the values of G3 and G'3 could not be obtained accurately.

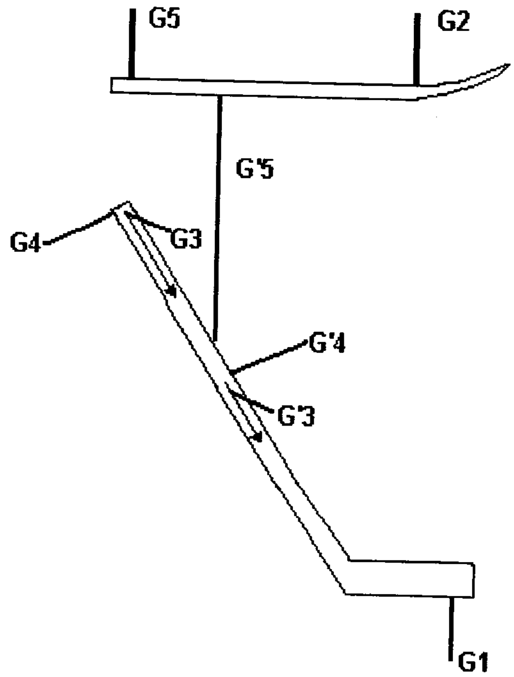

Figure 5 - Force applied to a hockey stick during a slap shot. G1 and G2 represent the reaction of the ice and of the puck on the blade; G3, G4, and G5 are the three components of the action of the upper hand on the handle; and, G'3, G'4, and G'5 represent those of the lower hand (adapted from Roy & Doré, 1975)

An extension of the previous study was resented by Roy and Doré (1976), whereby sixteen strain gauges were placed on a hockey stick (eight below the top hand, six below the bottom hand, and two on the back of the blade) and force-time histories were observed during the sweep, wrist, and slap shots of nine amateur players. The forces along the length of the shaft and the upper and lower hand positions were not recorded precisely. In fact, the authors acknowledge that the kinematic data were not synchronized with the force-time histories, so the two data sets cannot be directly linked. Puck velocity was not directly related to maximum force exerted by the lower hand, which further emphasizes the importance coordination in a successful slap shot.

Doré and Roy (1978) expanded on the previous study in their examination of 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. As such, the authors suggest that younger players should use flexible sticks; since, they require less force exertion to achieve the same puck velocity as stiffer sticks.

Simm and Chau (1978) used cinematographic motion analysis to measure puck velocity, stick angular velocity. The authors also embedded force plates into the ice to measure vertical ground reaction forces during the skating slap shot, although no details were provided as to how this was accomplished. Puck velocities ranged from 150 km/h for high-school aged players to 200 km/h for college and professional players. Angular stick velocity ranged from 20 to 40 radians/s and vertical ground reaction forces ranged from 1.5 to 2.5 times player body weight.

Pearsall and colleagues (1999) also examined the role of stick shaft stiffness in six elite male hockey players. Initial ground reaction forces, stick deformation, and puck velocity were measured using an AMTI strain gauge force platform, high-speed filming system (480 Hz), and radar gun, respectively, for shafts with four different stiffness properties (i.e. medium, stiff, extra, and pro stiff). Vertical ground reaction forces were relatively low compared to those of Simm and Chau (1978), ranging from 120 to 130 N (approximately one-fifth of body weight), while anterior-posterior forces were substantially less (16 to 25 N). The highest peak vertical force was recorded for the extra stiff shaft, while the lowest peak vertical force was recorded in the medium stiff shaft. Total contact time was 60 ms, as compared to 90 ms reported by Roy & Doré (1976). Puck velocities ranged from 105.9 to 108.2 km/h. However, the highest puck velocity was associated with the medium stiff shaft (108.2 km/h), while the lowest velocity was associated with the extra stiff shaft (105.9 km/h). Peak stick deflection angle reached 20 degrees. Highest peak deflection angle and greatest time to peak was observed in the medium stiff shaft.

From the above study, significant ($p < 0.05$) differences existed in peak vertical and anterior-posterior forces, time to peak forces, peak deflection, and time to peak deflection between subjects; however, previous studies suggest that these differences may also be attributed to various factors (e.g. skill level, stature, strength, technique) (Pan et al. 1998; Roy & Doré 1979). So, the authors conclude that subject parameters are likely more influential over slap shot performance than shaft stiffness. This supposition is further supported by subsequent work by Wu and colleagues (2003), which concluded that player skill and technique are primary determinants of slap shot performance.

Baroud and associates (1999) conducted a preliminary investigation to determine the amount of mechanical energy stored and returned in the shaft during pre-loading and impact and the influence on puck velocity. A three-dimensional finite element model of a wooden hockey stick was created to quantify the deformation and displacement of the stick. This data and the corresponding stresses were used to calculate strain energy density. Overall, the stick exhibited non-symmetric bending behaviours in the z- and y-directions due to different bending stiffness and acting forces. The maximum displacement occurred just under the lower hand and generated total deformation energy of 11 J. This deformation energy translated into an 11.3 m/s increase in puck velocity for the particular stick modeled. As such, the authors speculate that stick performance could be substantially improved by altering stick shape and construction material so as to maximize the kinetic energy return to the puck.

Most recently, Villaseñor-Herrera (2004) also examined the energy storage and transfer during the pre-loading and impact stages (i.e. "recoil" effect) of the stationary slap shot. Both elite and recreational subjects had their slap shots evaluated through the simultaneous recording of high-speed video (1000Hz) and a tri-axial accelerometer embedded into a hockey puck. Puck velocity proved to be influences by skill level, blade-puck contact time, and stick bending energy, but not puck acceleration. The elite group demonstrated a mean puck velocity of 120.8 km/h and 16.6 J of stick elastic (bend) energy, as compared to the recreational group whose puck velocity was 80.3 km/h and strain energy was 2.1 J. This translated into significant differences between the amount of kinetic energy transferred to the puck between the elite and recreational groups (152.25 and 66.93 J, respectively). Puck velocity was highly correlated to both stick bending energy ($r^2 = 0.81$) and total puck contact time ($r^2 = 0.82$).

2.1.1.4 Blade Function

In the mid-1960's, the appearance and construction of the hockey stick changed dramatically as players began to use curved blades. Today, all NHL players, including goalies use a curved blade (Hache 2002). Stan Mikita has been credited with accidentally "discovering" the benefits of the curved blade while taking out his frustration on a broken stick (Dowbiggin 2001); however, there have been relatively few attempts to quantify the benefits of this modification. Nazar (1971) compared the use of straight and curved blades during wrist and slap shots and examined the blade's effect on shot velocity and accuracy. The curved blade demonstrated significantly higher shot velocity and was significantly more accurate than the straight blade. Furthermore, the author confirmed previous results (Alexander et al. 1963) by establishing the skating slap shot as the fastest and least accurate shot, regardless of player stick preference.

In an examination of the "physics of hockey", Hache (2002) offers a more theoretical analysis of the advantages of the curved blade over conventional straight blades. For instance, during a straight blade's impact with the ice, it will bend forward slightly (the amount of bend will depend on where it contacts the puck); thus, influencing the angle at which the puck leaves the blade and overall accuracy of the shot. However, if the blade is curved, this forward bend has less influence on shot accuracy. Similarly, wrist shots also benefit from a curved blade, as the puck will naturally roll toward the bottom of the curve (i.e. toe end) and depart at the same point every time, allowing a more consistent shot. Conversely, on a backhand shot accuracy can suffer if the blade is curved excessively.

2.1.1.5 Summary

Investigation into the mechanics of a successful slap shot remains a relatively recent phenomenon; evolving from preliminary qualitative analyses to more sophisticated quantitative techniques. Historically, researcher first endeavoured to define hockey's many skills. As such, the slap shot was quickly recognized as the fastest, and often least accurate weapon for most hockey players, with more skilled players demonstrating a significantly faster shot (Table 2) (Alexander et al. 1964; Alexander et al. 1963; Cotton 1966). Since these early definitions, research has primarily focused on the role of the player in creating a successful slap shot. As such, most investigators have focused on player kinematics (e.g. joint angles, strength effects, movement coordination, etc) (Emmert 1984; Fergenbaum & Marino 2004; Hayes 1965; Meng & Zhao 2000; Pan et al. 1998; Woo 2004; Wu et al. 2003) and kinetics (e.g. ground reaction force, forces exerted by the hands, etc.) (Doré & Roy 1976; Roy & Doré 1975; Roy et al. 1974). These authors have noted some correlation between slap sot performance (i.e. velocity) and variables such as: player strength (Fergenbaum & Marino 2004; Pan et al. 1998; Roy & Doré 1976; Wu et al. 2003), joint coordination (Polano 2003; Woo 2004), and vertical ground reaction force (Pearsall et al. 1999; Simm & Chau 1978).

However since the world of sport equipment design has grown into a multi-million dollar industry, manufacturers and designers are under constant pressure to deliver state-of-the-art products that use technology to improve performance. In an attempt to meet these demands, the last tend years have seen dramatic shifts in stick design, materials, and construction techniques. This trend has corresponded with an increase in research examining the specific contribution of the stick (particularly the carbon-fibre variety) in hockey's most prolific shot, the slap shot. Early indications are that despite player perceptions of faster shots, changes in shaft construction do not play a role in improving slap shot velocity (Marino 1998; Pearsall et al. 1999; Roy & Doré 1976; Wu et al. 2003). Thus, begging the question: "Are player's perceptions of higher velocity slap shots entirely unfounded, or is there another mechanism within the stick contributing to improved velocity?"

There have been some indications of a strong positive correlation between puck-blade contact time and slap shot performance (Polano 2003; Villaseñor-Herrera 2004). Nazar (1971) has also suggested that the industry shift from straight to curved blades increased slap shot velocity and accuracy. However beyond these efforts, the role of blade in general during a slap shot remains largely unknown. Additionally, to date there has been no examination whether or not the actual material construction of the blade changes or improves its function during this skill. Theoretically, it might be possible that certain blade constructions might marginally increase puck-blade contact time and consequently increase shot velocity. However, this remains a subject for future investigation.

2.2 Kinematics

Kinematics refers to the study of motion characteristics, more specifically, the analysis of motion from a spatial and temporal perspective without considering the forces producing the motion. Combinations of camera and marker systems are most frequently used to obtain both two- and three-dimensional kinematic data.

The simplest configuration for three-dimensional data collection uses two cameras, positioned such that their axes are close to perpendicular (Hamilton & Luttgens 2002); however, depending on the nature and scope of the movement studied, any numbers of cameras can be utilized. Since all kinematic calculations are based on position and time, it is essential that all cameras frame rates are carefully synchronized (Nigg & Herzog 1999). Synchronization can be accomplished somewhat formally using a "gen-lock" system that connects all cameras and locks their operating systems together (Hamilton & Luttgens 2002). Less formal methods can also be used to create a visual event in the video log that signals the start of each trial (e.g. dropping a marker, a flashing light, simultaneous electric signal, etc). In order to ensure accurate results, it is also essential to calibrate the measurement area in all three dimensions. Typically, this involves the use of a cube or multi-armed device with reflective markers placed at known geometric dimensions (Hamilton & Luttgens 2002). These geometric locations are later used to facilitate the transformation of multiple two dimensional planar values into three dimensional coordinate space (see 2.2.1).

Once collected, the researcher can import the data to a personal computer and begin chronophotographic (frame-by-frame) analysis. This process involves the digitization, which is the activation of a hand-held pen, cursor, or mouse over the image of the participant's joint centers or other positions of interest (Hall 1999). The position coordinates (i.e. digits) of each point are then stored in a computer data file. From this position data, other kinematic variables of interest (e.g. velocity, acceleration, joint angles, etc.) can be calculated and reported.

Each camera in the three-dimensional camera set-up can only record movements in two dimensions (Hamilton & Luttgens 2002). Therefore, each set of two dimensional data must be mathematically combined to create a three-dimensional representation of movements. This process will be described at length in the forthcoming section.

2.2.1 Three Dimensional Recording Techniques

Susanka and Diblik (1969) presented one of the first attempts at retrieving three-dimensional object coordinates from multiple two-dimensional camera views. This vector approach successfully obtained these coordinates and reduced perspective distortion. Later, Miller and colleagues (1980) developed a conceptually different surveying method to eliminate perspective error. However, both approaches required knowledge of relative camera positions and did not account for camera lens, film, or digitizer error. Also, in certain situations, their equations did not possess a direct algebraic solution; thus, requiring the researcher to make an approximation.

As such, researchers required a more generalized approach to three-dimensional filming, which would eliminate tedious camera set-ups, perspective errors, and account for image deformations caused by cameras, film, and data reduction. Abdel-Aziz and Karara (1971) attempted to achieve this by developing a series of equations known as Direct Linear Transform (DLT). DLT involves a linear transformation from image coordinates to object-space coordinates and is based on a series of equations that require colinearity; that is, the object point, the perspective center, and the image point must be situated along the same line (Figure 6). These equations are as follows (Equation 1 & Equation 2):

Equation 1 - Direct linear transformation equation for x-coordinate of a marker *i* on the film as measured with camera *j* (adapted from Abdel-Aziz & Karara, 1971)

$$x_{ij} = \frac{a_{1j}x_i + a_{2j}y_i + a_{3j}z_i + a_{4j}}{a_{9j}x_i + a_{10j}y_i + a_{11j}z_i + 1}$$

Equation 2 - Direct linear transformation equation for y-coordinate of a marker *i* on the film as measured with camera *j* (adapted from Abdel-Aziz & Karara, 1971)

$$y_{ij} = \frac{a_{5j}x_i + a_{6j}y_i + a_{7j}z_i + a_{8j}}{a_{9j}x_i + a_{10j}y_i + a_{11j}z_i + 1}$$

where for a given marker *i* :

x_{ij} = *x coordinate for marker i on the film measured with camera j*

y_{ij} = *y coordinate for marker i on the film measured with camera j*

x_i = *x coordinate for marker i in three dimensional space*

y_i = *y coordinate for marker i in three dimensional space*

z_i = *z coordinate for marker i in three dimensional space*

a_{kj} = *coefficient k in the transformation formulas for marker i*

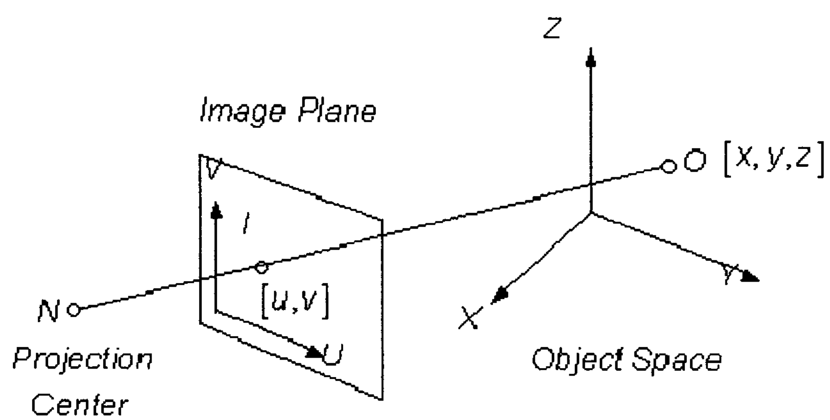

Figure 6 –The colinearity condition of the DLT method. The object-space reference frame (the XYZ-system) and image-plane reference frame (the UV-system). The optical system of the camera/projector maps point O in the object space to image I in the image plane. [x, y, z] is the object-space coordinates of point *O* while [*u, v*] is the image-plane coordinates of the image point *I*. Thus, points I, N, & O are collinear (adapted from http://www.kwon3d.com).

The simplest form of the DLT model (11 parameter) was tested and compared to a conventional model (9 parameters) using artificial data and the authors concluded it was at least as accurate as conventional, explicit models; however, it out-performed conventional models in that it did not require any approximations, it was easier to program, and required less total computer processing time. Following this validation, several authors began to develop software solutions that could accommodate 11, 12, 14, or 16 parameter DLT models (Marzan 1976; Marzan 1975).

Later work by Van Gheluwe (1973) also attempted to provide a solution similar to the DLT model. This method did not require camera measurements in the field, but did demand the focal length of each camera and the intersection of optical axes at the origin of the object reference frame such that a computer could calculate the classical orthogonal transformations required to output the three-dimensional coordinates. While this was an improvement on the work of Susanka and Diblik (1969) and Miller and colleagues (1980), it was unable to match the generality that DLT solutions provided.

Walton (1981) re-developed the DLT equations and created corresponding software that attempted to allow the experimenter to use the equations without understanding their underlying theory. The author incorporated some of the work of Marzan (1976), but also added features to make the software easier to use and interpret. Walton's (1981) approach also incorporated corrections for film deformations, camera lens and digitizer distortion. The software was robust enough to allow a maximum of thirty control points, twenty-five object points per frame, and up to nine cameras and included several numeric checks; such as: camera location and the focal length of each camera.

Advances in portable video technology raised the question of its ability to precisely record three-dimensional objects. Kennedy and colleagues (1989) made an initial comparison between film and video techniques for three-dimensional DLT predictions. Despite obtaining significant differences ($p<0.05$), the authors concluded that "...from a practical standpoint the video error was only 0.29% of the calibrated field compared to 0.24% for film" and that the "...video techniques are comparable in accuracy to 16 mm filming methods" for movements where 60 Hz was an adequate sampling rate. The restriction on sampling rate suggests that video be used for static situations or slow activities.

As the DLT method gained popularity, several researchers attempted to quantify its precise limitations through procedural refinements and error analysis. For instance, unpublished work by Putnam (1979) and Neal (1983) have demonstrated that neither camera position nor orientation is a critical factor. Reconstruction errors were reported to be less than 5 mm, and could be substantially improved with the inclusion of additional control points; such that, it was generally recommended to use as many control points as possible and ensure they were well distributed throughout the object space (Putnum 1979; Shapiro 1978). However, Wood and Marshall (1986) attempted to quantify the expected loss in precision if these guidelines were not followed; more specifically, to quantify expected extrapolation errors in different camera set-ups. The authors concluded that significant inaccuracies exist in three-dimensional reconstructions it the target point lays outside the calibrated area. In fact, in a case where compromises must be made using fewer control points well distributed throughout the object space produces significantly more accurate result than extrapolating. Also, based on the calculated reconstruction errors a camera set-up with a distance:base ratio of 1:2 will produce better results than a 1:1 set-up.

Later, Chen and colleagues (1994) also investigated the characteristics of errors associated with the variation in the number and configuration of control points used for calibration in the standard DLT. Similar to previous studies, the authors found that overall accuracy was improved as the number of control points increased from eight to twenty-four and that accuracy improved when control points were evenly distributed throughout the object space (Putnum 1979; Shapiro 1978; Wood & Marshall 1986). However, beyond a certain point, the inclusion of additional control points does not improve calibration accuracy significantly (Figure 7) because as the influence of random error is suppressed, the major component of total error are the systematic errors associated with set-up and lens distortions. Based on the results of this study, the authors recommend sixteen to twenty control points, which is similar to the twelve to twenty control points suggested by Shapiro (1978).

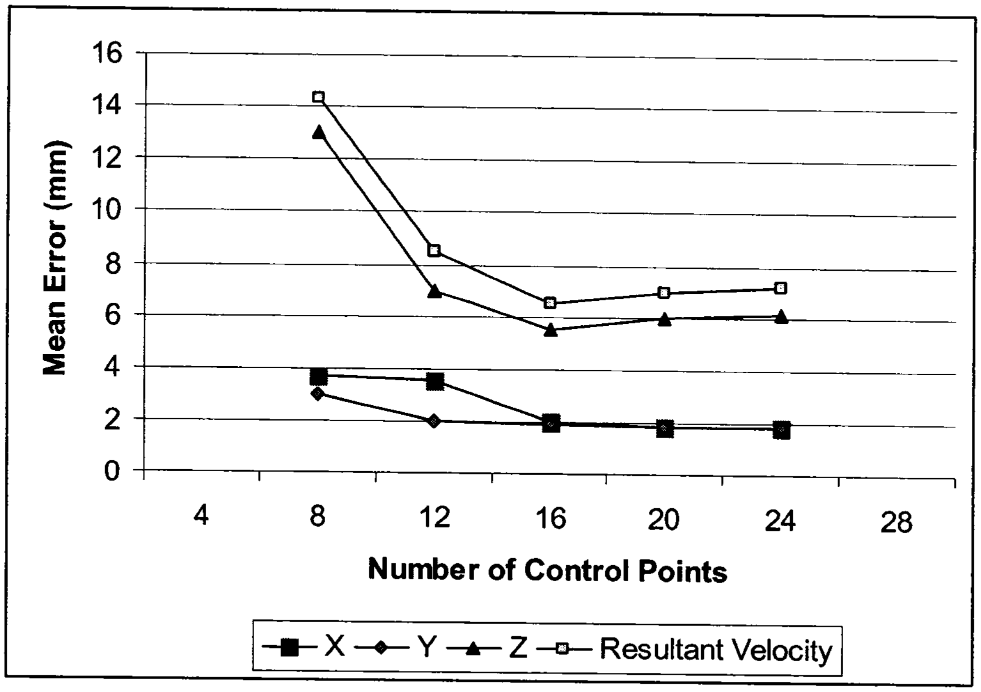

Figure 7 - Relationship between number of control points and the mean absolute coordinate errors (Adapted from Chen et al, 1994)

Chen and colleagues (1994) outline two approaches for correcting non-linear systematic errors of the standard DLT: (1) employing more parameters to reflect the nonlinearity in the standard method, and (2) use the standard DLT and then add a non-linear modification. The first approach was used by Hatze (1988); however, it required a large number of calibration points (thirty or more). Most authors use the second approach (e.g. (Marzan 1975; Miller et al. 1980). Chen at al (1994) used a quadratic function to modify the standard DLT, reducing errors by 20 to 40 %.

Since the DLT method can not extrapolate data points outside the calibrated area, it often requires large, cumbersome calibration frames that can be subject to stress deformation. As such, Dapena and colleagues (1982) proposed a method of three-dimensional reconstruction that involved a simple filming procedure, which allows portability and the deduction of coordinates in a large object volume. The method allows the calculation of the internal and external parameters of each camera; the former from measurements of the projected images of two calibrated crosses, and the latter from the projected images of points in a control object of an unknown shape (with at least one known length). The combination of internal and external camera parameters and measurements taken from images of a point in the projected films of each camera allow the researcher to calculate the three-dimensional coordinates of the point.

The chief advantage of the solution proposed by Dapena and colleagues (1982) is that a series of unconnected components can be placed as far apart as necessary to create a control "object" with a large volume but and unknown exact shape. Thus, allowing the calibration of a sufficiently large volume without the stress deformation and transportation problems associated with traditional, large calibration frames used with the DLT method. The method has also proven successful for intermediate and small object spaces. The authors report the overall accuracy of this approach to have root mean square values of 15, 13, and 6 millimetres in the X-, Y-, and Z-directions respectively, for an object volume of five-by-five-by-one and a half metres. Relative to length, the errors are 0.5, 0.7, and 0.5 %. While a portion of this error is random, most of it is systematic, the result of unmodelled lens/film distortion, digitizing errors, imperfect estimation of the projection of the principal point.

In an attempt to improve the precision of the DLT, Hatze (1988) presented a modified DLT (MDLT) method for both a linear and non-linear calibration. Both algorithms demonstrated an impressive overall accuracy and significant improvement over the traditional DLT. The linear MDLT achieve improvement by satisfying certain orthogonality conditions in the form of a non-linear constraint; thus effectively eliminating a redundant DLT parameter. While the improvement and reliability of the non-linear MDLT is a result of the elimination of implicit variables from one side of the approximating relation and the corresponding reformulation of the objective function to be minimized. Overall, the linear and non-linear MDLT algorithms permit reconstructions with an average accuracy of 0.041% (0.833mm) and 0.035% (0.733 mm) respectively. As such, the authors suggest that the non-linear MDLT should only be used if a large number (≥ 30) control points can be evenly distributed throughout the object space; while the linear MDLT should be used with at least fifteen control points evenly distributed. Finally, the authors submit that while in general the linear MDLT approach is less sensitive to modifications in control point configuration and is "...computationally less expensive..." than the non-linear MDLT, extremely accurate reconstructions warrant the application of the non-linear MDLT.

Gazzani (1993b) also attempted to overcome the drawbacks of the DLT approach by returning to the direct solution of the colinearity equations and including various refinements and expedients to improve reconstruction accuracy. The solution proposed was termed the Colinearity Equation Solution by Numerical Optimization (CESNO) and demonstrated promising extrapolation properties when tested by computer simulation. As such, Gazzani (1993a) compared the performance of the CESNO algorithm to both the DLT and MDLT; the results provide inclusive criteria for selecting the appropriate algorithm for accurate reconstruction. When good reconstruction accuracy in extrapolation is required, the choice of algorithm depends highly on lens distortion error; for instance: (1) if principal camera differences differ dramatically and lens distortion exceeds 1% or if lens distortion cannot be accurately the CESNO algorithm is preferred; (2) if lens distortion does not exceed 0.6%, then the eleven parameter DLT is acceptable; and (3) if lens distortion exceeds 0.6% the nonlinear CESNO tended to perform best. The choice of algorithm can also be determined by the number of calibration points. That is, the number of calibration points can be lowered to twelve with the linear DLT or CESNO, the non-linear CESNO provided good accuracy with twelve and the non-linear DLT require twelve to sixteen points. However, the sensitivity of reconstruction accuracy to single, large errors in the estimates of the positions of the control target points has yet to be investigated.

Hinrichs and McLean (1995) also proposed a method that would allow large control volumes to be established without the need to build oversized and cumbersome calibration frames. The authors discuss the merits of non-linear transformation methods (NLT), which involves the use of a single calibration pole with at least two marks denoting a known length. The pole is carried from place to place within the object space to define effectively "build" any size calibration frame necessary. The pole can contain additional markers or be moved to additional locations to increase the number of control points.

The authors compared the accuracy of the NLT to that of the DLT with and without extrapolation; they demonstrated that the NLT is comparable to the DLT in terms of accuracy when only sixteen to twenty control points are used for the DLT (as per Chen et al. 1994). The DLT was remarkably accurate when extrapolations were limited to 50% or less; however, if the extrapolation of 100% or more is required, the NLT is far more accurate. As such, the authors conclude that the NLT is a suitable replacement for the DLT when extrapolation of 100% or more is required, especially as it lends itself well to field work.

CHAPTER 3 - METHODS

3.1 Test Sticks

Six new carbon-fibre, composite hockey sticks, from three industry-leading manufacturers, each with unique blade construction features, were subjected to the testing protocol (described in detail in section 3.4). The make, model, and individual blade parameters are listed in Table 5.

Table 5 - Blade construction properties for each test stick.

Model	Abbreviation	Structure Type	Blade Weight	Materials	Lie Angle	Curve
CCM Vector 120	CCM	Sandwich Structure	Medium-Heavy	Fibreglass, Carbon, ABS Plastic	6	Heel
Bauer Vapor XX	VXX	Full Wrap RTM Blade	Medium	100 % Carbon, Low Density Foam	6	Mid
Easton Stealth	EAST	Full Wrap Prepreg Blade	Light	100 % Carbon, Low Density Foam	6	Mid-Heel
Easton Si-Core	SIC	Full Wrap Prepreg Blade With Silicon inserts	Medium	100 % Carbon, Low Density Foam, Silicon Inserts	6	Mid-Heel
Bauer Vapor XXX	VXXX	Full Wrap Prepreg Blade	Light	100% Carbon, High Density Foam	6	Mid
Bauer Vapor I CTC	CTC	Full Wrap Prepreg Blade	Medium - Heavy	80% Fibreglass, 20% Carbon	6	Mid

Each test stick was fitted with a series of reflective markers on the back of the blade and lower shaft, which were glued to stick and blade surface. Each blade and lower shaft were then wrapped with two layers of transparent, heat-shrinkable, plastic wrap and covered with black hockey tape, so as to reduce excess glare and assure all the markers remained fixed during impact. For reference, the blade markers were numbered according to their spatial location with marker 1-1 being the top row in the column closest to the heel of the blade, while the shaft markers were numbered S1 and S2, with S1 located on the top edge of the shaft (Figure 8). The front face of the blade (which contacts the puck) was divided into 6 vertical contact zones from the blade's heel to toe. The locations of these zones were determined with respect to marker locations (Figure 9).

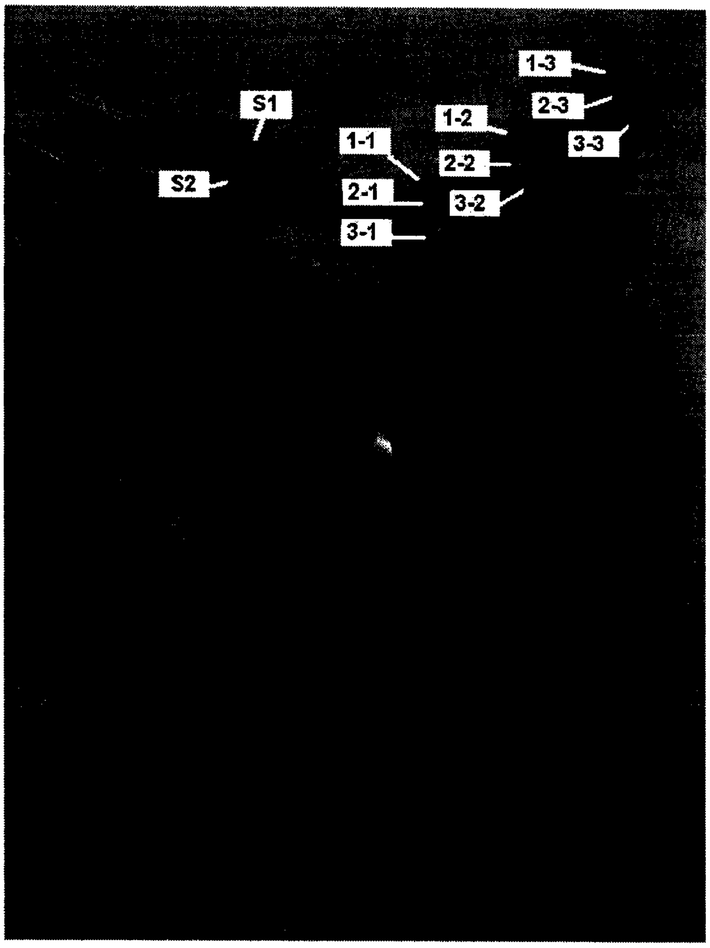

Figure 8 - Sample of test sticks, with markers (as labelled).

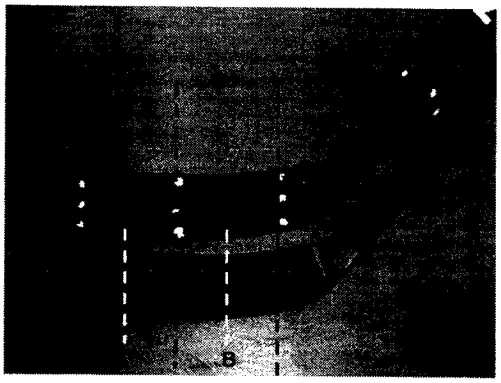

Figure 9 – Example of blade contact zones defined with respect reflective markers, axes A & B are located halfway between columns of markers.

3.2 Subjects

The 15 male subjects recruited for this study were divided into two groups, based on skill level. Elite subjects (i.e. ELITE) were collegiate hockey players from the McGill varsity ice hockey team, while recreational players (i.e. REC) were university students who played ice hockey less than three times per week. Mean height, mass, and shot handedness of each group of subjects are presented in Table 6. All participants were healthy at the time of testing, and showed no signs of physical injury that might have prevented them from performing the research task.

At the time of testing, all participants read and signed an informed consent form (Appendix A) in accordance with the Tri-Council Policy Statement *Ethical Conduct for Research Involving Humans* and University policy. The Ethics Committee of the Faculty of Education, McGill University, approved the study (Appendix B).

Table 6 - Subject height (cm), mass (kg), and shot handedness for the ELITE and REC groups.

ELITE	Height (cm)	Weight (kg)	Shot
ES1	188.0	95.3	Right
ES2	182.9	86.2	Left
ES3	177.8	95.3	Left
ES4	177.8	91.6	Left
ES5	175.0	79.8	Right
ES6	170.2	86.2	Left
ES7	175.3	74.8	Right
ES8	198.1	97.5	Left
Mean	180.6	88.3	
SD	8.9	8.1	
REC			
RS1	165.1	70.3	Left
RS2	180.3	84.8	Left
RS3	172.7	104.3	Right
RS4	185.4	79.4	Right
RS5	180.3	76.2	Right
RS6	167.6	64.9	Left
RS7	177.8	46.7	Right
Mean	175.6	75.2	
SD	7.4	17.8	

3.3 Testing Apparatus

Multiple technologies were used to investigate the dynamic characteristics of each stick during a stationary slap shot. Each of these technologies is discussed in greater detail in sections 3.3.1, 3.3.2, and 3.3.3.

3.3.1 High Speed Video Systems

Two high-speed video cameras (1000 Hz) were used to record the movements of the blade and lower shaft. As demonstrated in Figure 10, the cameras (PCI 100 HSC Motionscope, Redlake Imaging Inc., USA; & EKTAPRO, Kodak Inc., USA) were placed on opposite sides of the subject, approximately 4.7 m from the puck and 0.6 m above the puck. The angle between the cameras was 65°, for optimal post-three-dimensional reconstruction (Nigg & Herzog 1999). A specially constructed calibration frame, fitted with 26 hanging, reflective markers was used to calibrate the area of interest. The frame was 40.0 cm wide, 101.5 long, and 35.0 cm high (Figure 11). Both cameras were linked to a single trigger channel, which allowed simultaneous and synchronous recording.

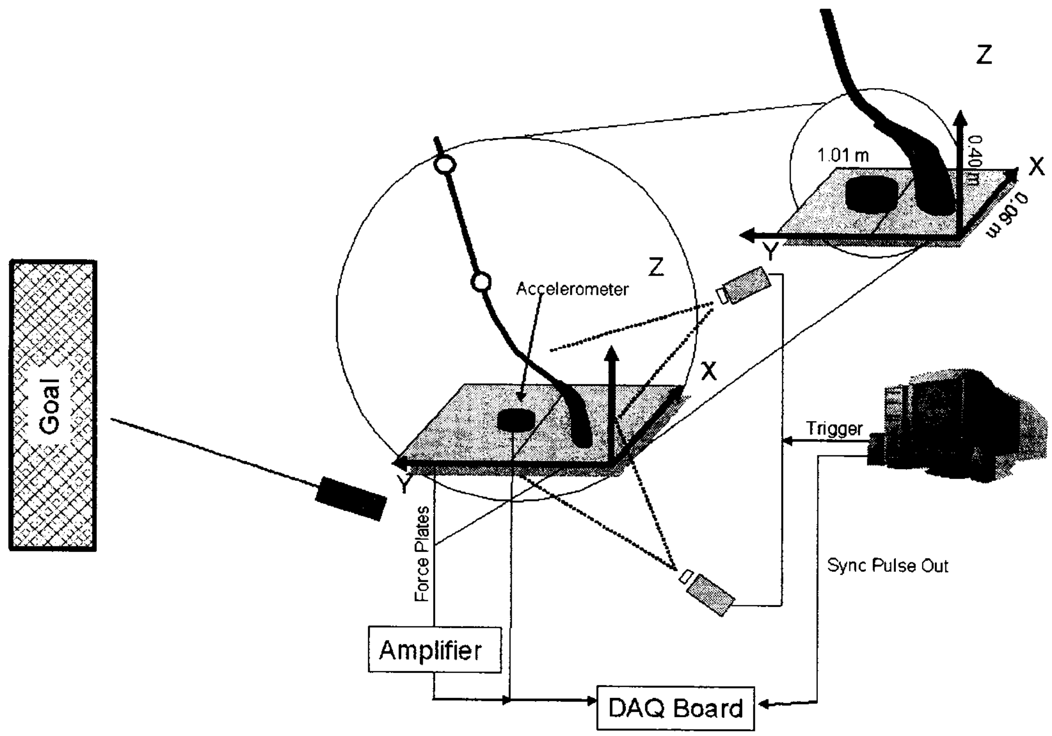

Figure 10 - Set-up of the experiment.

Spherical reflective markers, 6 mm in diameter, were placed along the blade and lower shaft of the stick as demonstrated in Figure 8. As blade kinematics have not been widely reported, the location of the markers and the collective axes they define were determined *a priori* by the investigator. Their locations were based on the major axes identified in Auto-Cad © (Auto Desk Inc, USA) sketches, provided by the manufacturer, and confirmed during pilot testing.

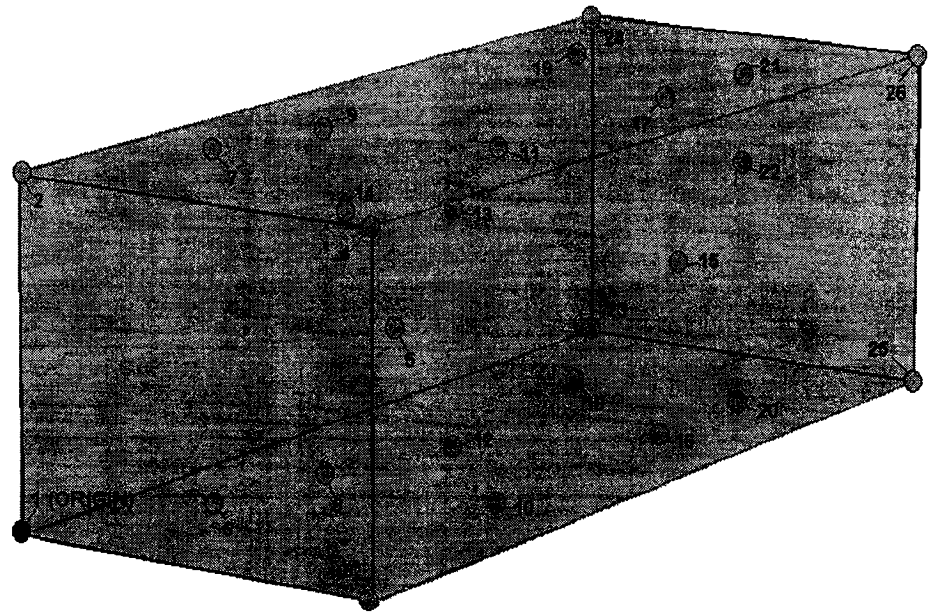

Figure 11 - Graphical representation of the calibration frame used to perform DLT

3.3.2 Accelerometer

A uniaxial accelerometer (ACH-01, Measurement Specialties Inc, NJ, USA) was used to identify initial puck-blade contact with respect to blade kinematic data. The accelerometer was mounted within a standard ice hockey puck, measuring 7.62 cm in diameter and 2.54 cm in thickness, and weighing 0.170 kg. The center of the puck was drilled out to accommodate the sensor and a thin metal cover was attached, the resulting puck weighed approximately 0.160 kg (Figure 12). The wire from the accelerometer was routed through a small trough in the edge of the puck and fed through the goal, to a PC data acquisition card (AT-MIO-16X PC DAQ Board, National Instruments Inc, USA). The resulting signals was recorded at 10 kHz using LabView 6.1© software (National Instruments Corp., USA).

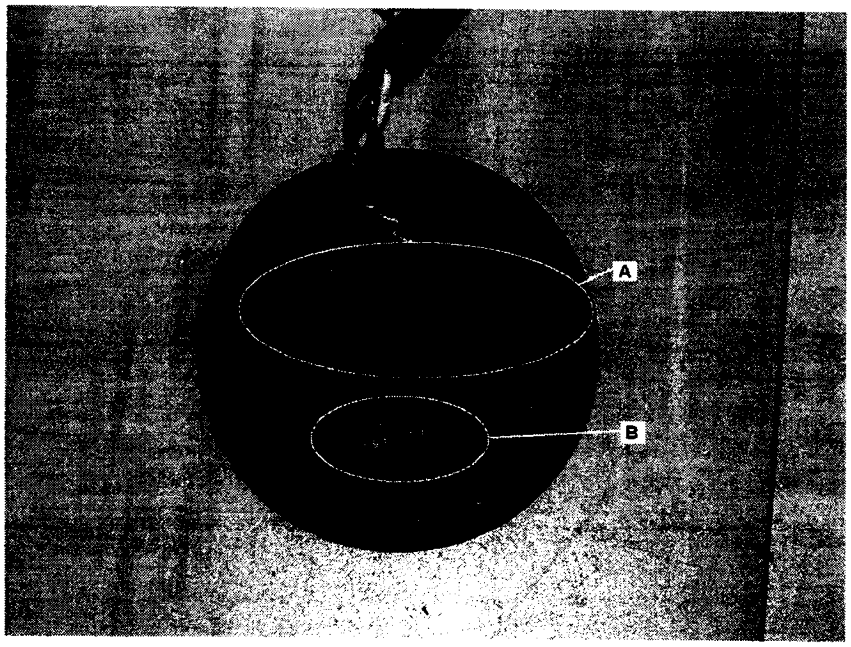

Figure 12 - The accelerometer set-up used, where A represents the drilled out area of the puck and B the accelerometer.

3.3.3 Force Plates

Two uniaxial force plates (6400 series, Pennsylvania Scale Company, USA) were used to measure the vertical GRF magnitude of blade-to-surface contact and to identify the blade-to-surface contact with respect to blade kinematics. Each device measured 18 x 24 inches and was located within the testing platform beneath the puck (Figure 13). Each force plate was connected to an individual power supply, a common amplifier and then to above-mentioned PC data acquisition card. The trigger output channel of the high-speed camera system was also connected to this DAQ card; thus, synchronizing the high-speed video, accelerometer and force plate data (see Figure 10 for full experimental set-up).

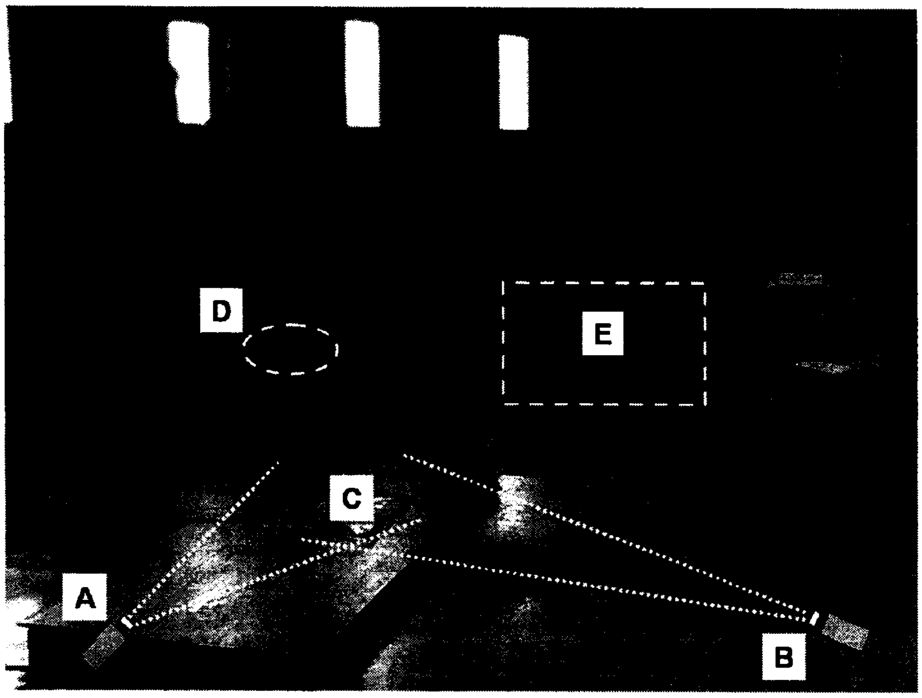

Figure 13 – Testing platform, highlighting the locations of A) High speed camera A, B) High speed camera B, C) Force plates, D) Radar gun, and E) Target Net.

3.4 Testing Protocol

3.4.1 Dynamic Blade Tests

Subjects performed this portion of testing on a wooden platform, 46 cm high, 240 cm wide, and 720 cm long. The shooting surface was covered with 1.0 mm thick, polyethylene sheets and sprayed with a silicon spray to simulate low friction ice surfaces, as pictured in Figure 13 (Pearsall et al. 1999; Wu et al. 2003). During each slap shot, all participants wore a standardized pair of Bauer Vapor XXX Pro gloves (Bauer Nike Hockey, Inc., NH, USA). Each subject took 5 practice shots, with a standard hockey puck, to acclimatize themselves to the testing environment. The velocity of these practice shots was recorded from the radar gun (SR3600, Sports Radar Ltd., USA) placed beside the testing platform, opposite the subject (Figure 13).

Subjects then took 3 shots with each of the 6 test sticks using the instrumented hockey puck, described earlier. Each trial consisted of a stationary slap shot into a designated target (located ~4.4 m in front of them) and involved the simultaneous recording of high-speed video cameras, the accelerometer, force plates and radar gun. Successful completion of a trial was determined by verbal confirmation from the participant approving the slap shot, and hitting the target (approximately 0.85 m wide X 1.13 m high and 4.4 m away) with the puck.

Prior to each trial, the edge of the instrumented puck was covered with coloured chalk, such that upon contact with the blade, the chalk illustrated the exact point of contact and the path of the puck across the blade (Figure 14). After each trial the contact zone where the puck first contacted the blade was recorded and the blade was wiped clean of all chalk residue for the subsequent trial (Simard et al. 2004).

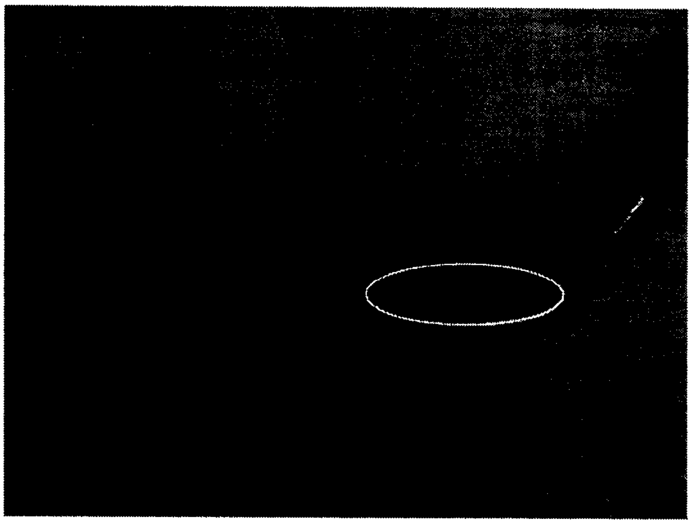

Figure 14 - Example of the chalk markings left on a blade after a trial. The encircled portion outlines the path of the puck from heel to toe, while the arrow indicates the initial contact point in zone 6.

3.5 Data Analysis

Data from each measurement device were treated separately and combined in order to provide detailed temporal analysis of three-dimensional blade position and deformation during a stationary slap shot. The complete data analysis process is outlined in Figure 15.

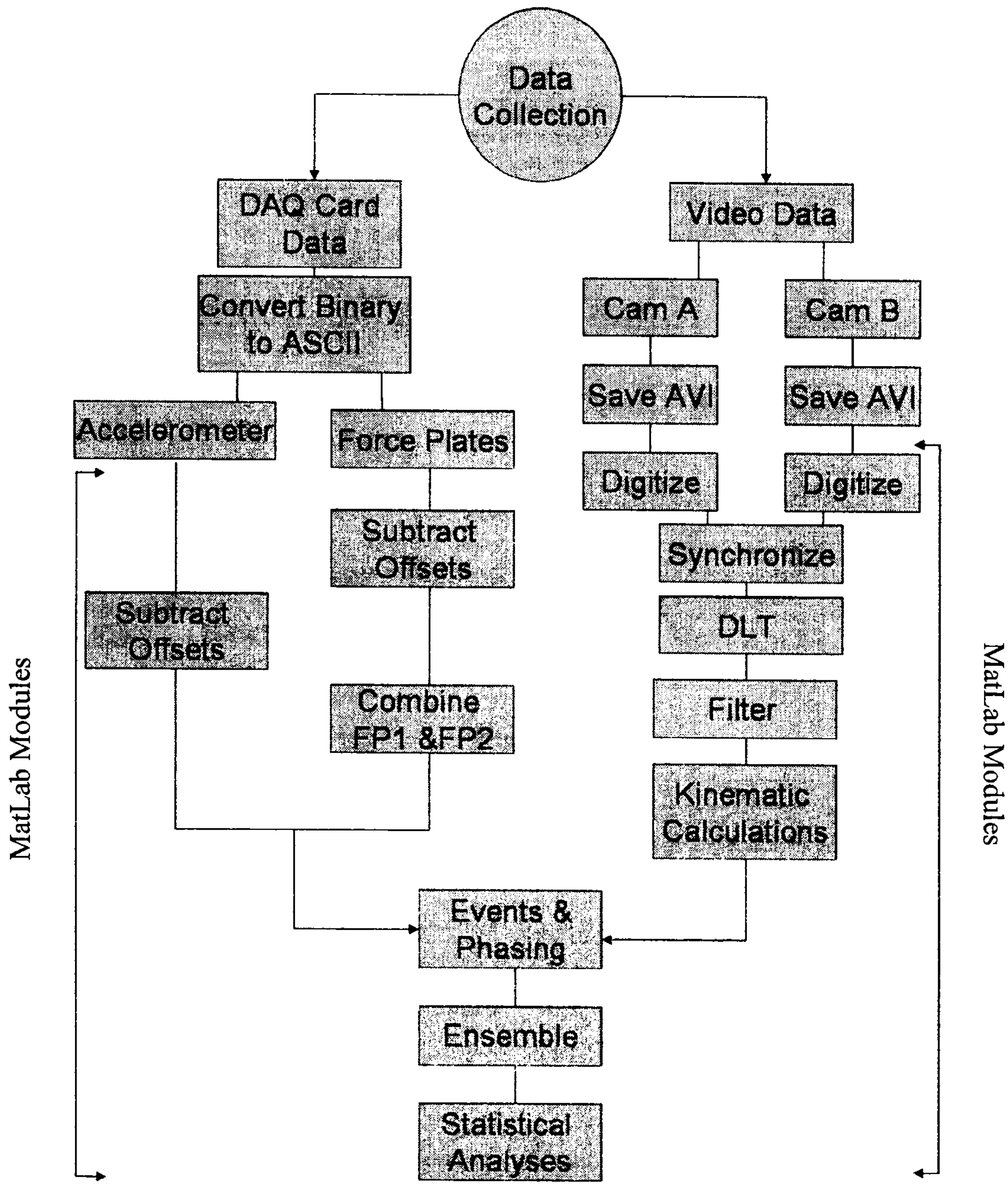

Figure 15 - Data analysis flow-chart, process within the brackets are performed using MatLab modules, as indicated.

Following testing, the high-speed video data from each trial and its corresponding calibration file were saved in AVI format. The spatial location of each marker was recorded by digitizing each file using MatLab® (version 6.0.0.88 release 12.0) (MathWorks Inc., Natick, MA, USA) modules. Trial video data were synchronized at the instant of initial blade-to-ground contact. Each trial's video data and the corresponding calibration files were then combined in a DLT reconstruction (Equation 1 and Equation 2), in order to obtain the three-dimensional spatial coordinates of each stick marker during each slap shot. The resulting data were filtered with a 4^{th} order Butterworth with a cut-off frequency of 75 Hz.

When reconstructed, the markers formed a series of linked segments (e.g. Figure 16). These data were used in various combinations to calculate linear displacement, velocity, and acceleration; local flexion angles; and a series of gross blade angles measured with respect to various global planes, in order to quantify the response of the ice hockey stick blade to the stationary slap shot.

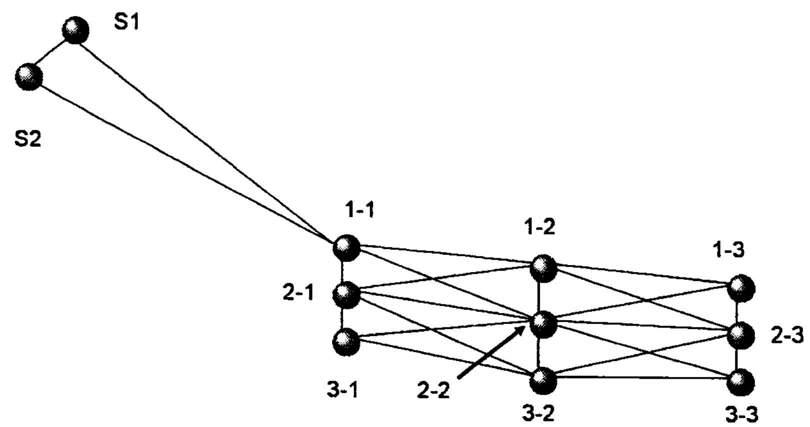

Figure 16 - Example of segments formed by digitized markers.

3.5.1 Temporal Events

Data from the force plates and accelerometer were synchronized with the kinematic data by aligning the trigger event signal in both the video and DAQ card data, such that the exact instances of key temporal events and phases could be determined. Events were formally defined using both video (i.e. toe-ground contact (TC), heel-ground contact (HC), and stick off ground (S-OFF)) and accelerometer (i.e. stick-puck contact (PC)) data. The event of the puck leaving the blade could not be precisely determined due to limitations of the accelerometer used in the current study. In identifying the event of initial blade-ground contact, video data were compared with force plate data to confirm its accuracy. These events were used to define phases of interest, which included: blade-ground contact (Δt_1), stick loading (Δt_2), and toe-to-heel contact (Δt_3), as demonstrated in Figure 17.

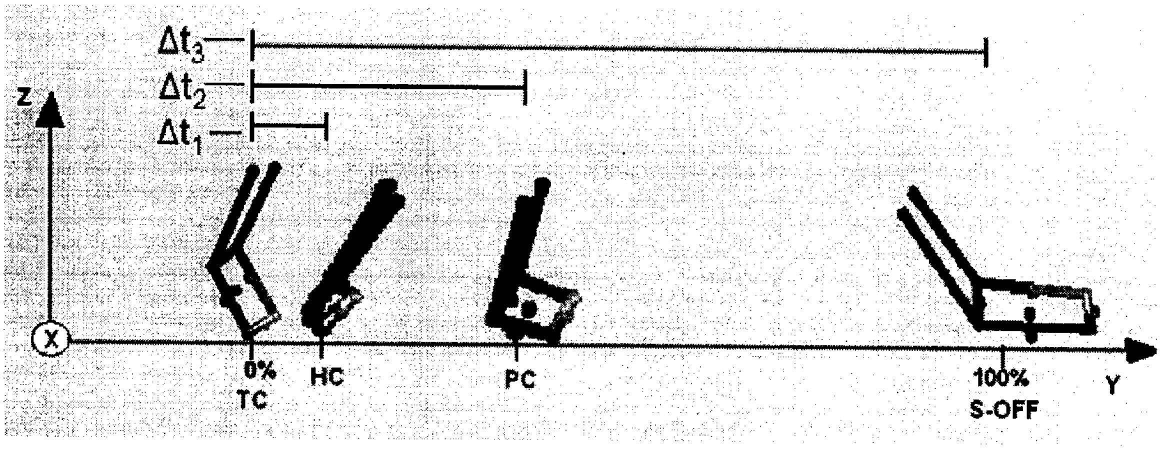

Figure 17 - Visual representation of temporal events TC, HC, PC, & S-OFF, and the corresponding phases they define (i.e. Δt_1, Δt_2, and Δt_3).

3.5.2 Angular 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, face angle, the angle between a segment along the length of the blade (i.e. from heel to toe) with respect to the frontal (XZ) plane was calculated (Figure 18).

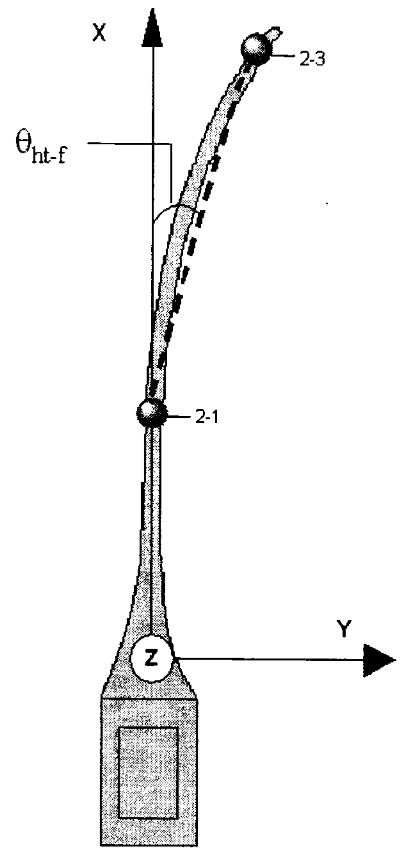

Figure 18 - Angle of a segment (from marker 2-1 to 2-3) with respect to the global frontal (XZ) plane, also referred to as face angle.

Second, tilt, the angle of the same heel-to-toe segment with respect to the global transverse plane, was also calculated (Figure 19). Finally, loft, the angle of a segment defined across the width of the blade (from 1-2 to 3-2) with respect to the global transverse plane, was measured (Figure 20)

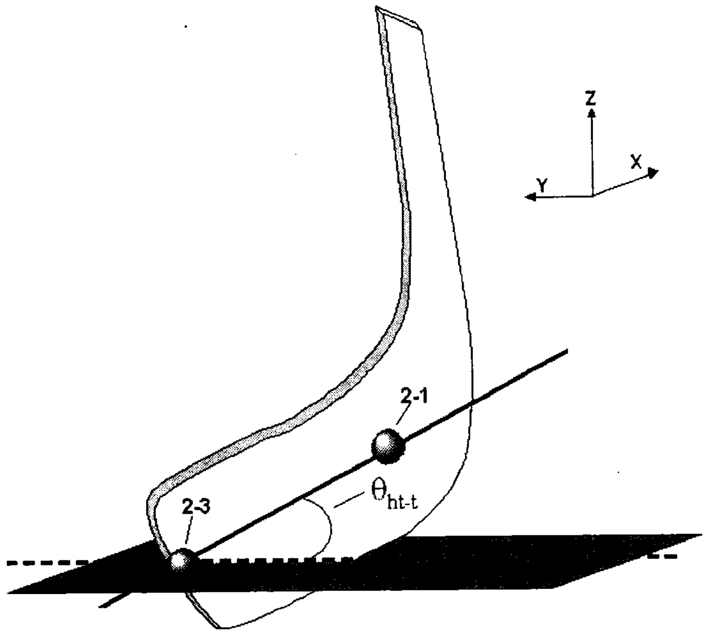

Figure 19 - An example of the angle (tilt) measured between a segment across the length of the blade (from 2-1 to 2-3) and the global frontal (XZ) plane.

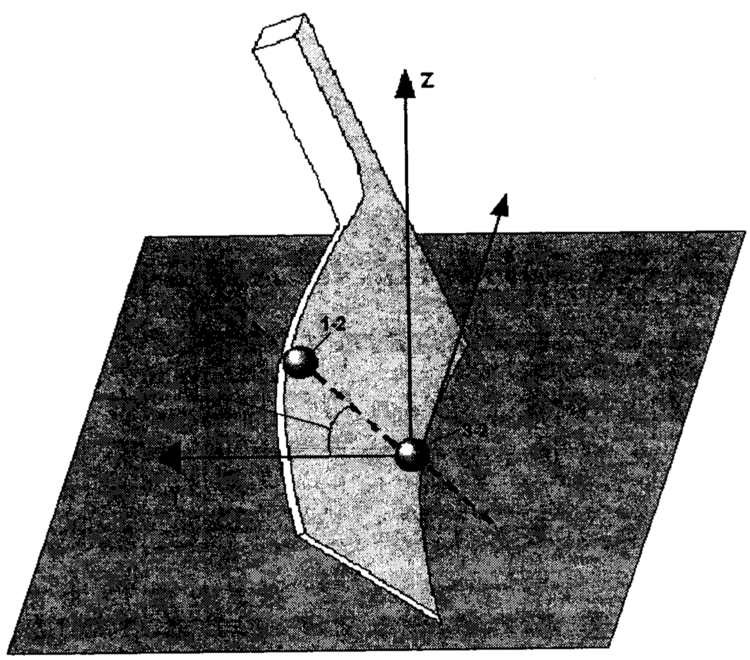

Figure 20 - An example of the angle (loft) measured between a segment across the width of the blade (from 1-2 to 3-2) and the global transverse (XY) plane.

in each simulated camera view, digitized and reconstructed. The resulting data was then compared to the original trial data to ensure that the three-dimensional transformation was accurate. Accuracy (i.e. the ability of the software to track the spatio-temporal patterns of the blade's movement path) was determined by calculating the Pearson product moment correlation co-efficient between the two data outputs, where highly correlated results ($r > 0.9$) were deemed accurate. Resolution was established by calculating the difference in root-mean-square (RMS) value of each data set using Microsoft® Excel 2002 (Microsoft Corporation, Redmond, WA, USA).

Intra-reliability of the author's digitizing was also assessed by comparing two data outputs of the same trial. The X and Y coordinates were examined separately for one marker (2-2) and both Pearson product moment correlation coefficients and RMS values were calculated (as described above) to determine accuracy and resolution.

The validity of the study was established by comparing the results with those from other investigators of similar variables (e.g. puck velocity). Experimental values were considered valid if they were of a similar magnitude to previously recorded data.

CHAPTER 4 - RESULTS

The forthcoming sections describe the data obtained through the aforementioned dynamic testing protocol. They include a detailed description of each significant DV from the dynamic protocol as recorded from groups of ELITE and REC hockey players (n=8 and n=7, respectively), using a variety of composite hockey sticks (n=6) (additional data can be found in Appendix C). Dynamic data are discussed in sequence with reference to key events and phases. The chapter concludes with a discussion of measurement uncertainty, reliability, and validity.

4.1 Dynamic Results

The following sections describe in detail the results of the previously-described dynamic testing protocol. Since no significant differences (NSD) were found between stick models on any variables, the results have been collapsed such that only skill differences are presented here (See Appendix C, for full statistical summary). Figure 21 illustrates a frame-by-frame overtrace of a segment along the length of the blade (from marker 2-1 to marker 2-3) during a typical trial. The events of TC and HC are marked to help illustrate the "rocker phenomenon" which will be discussed at length in Section 5.4.

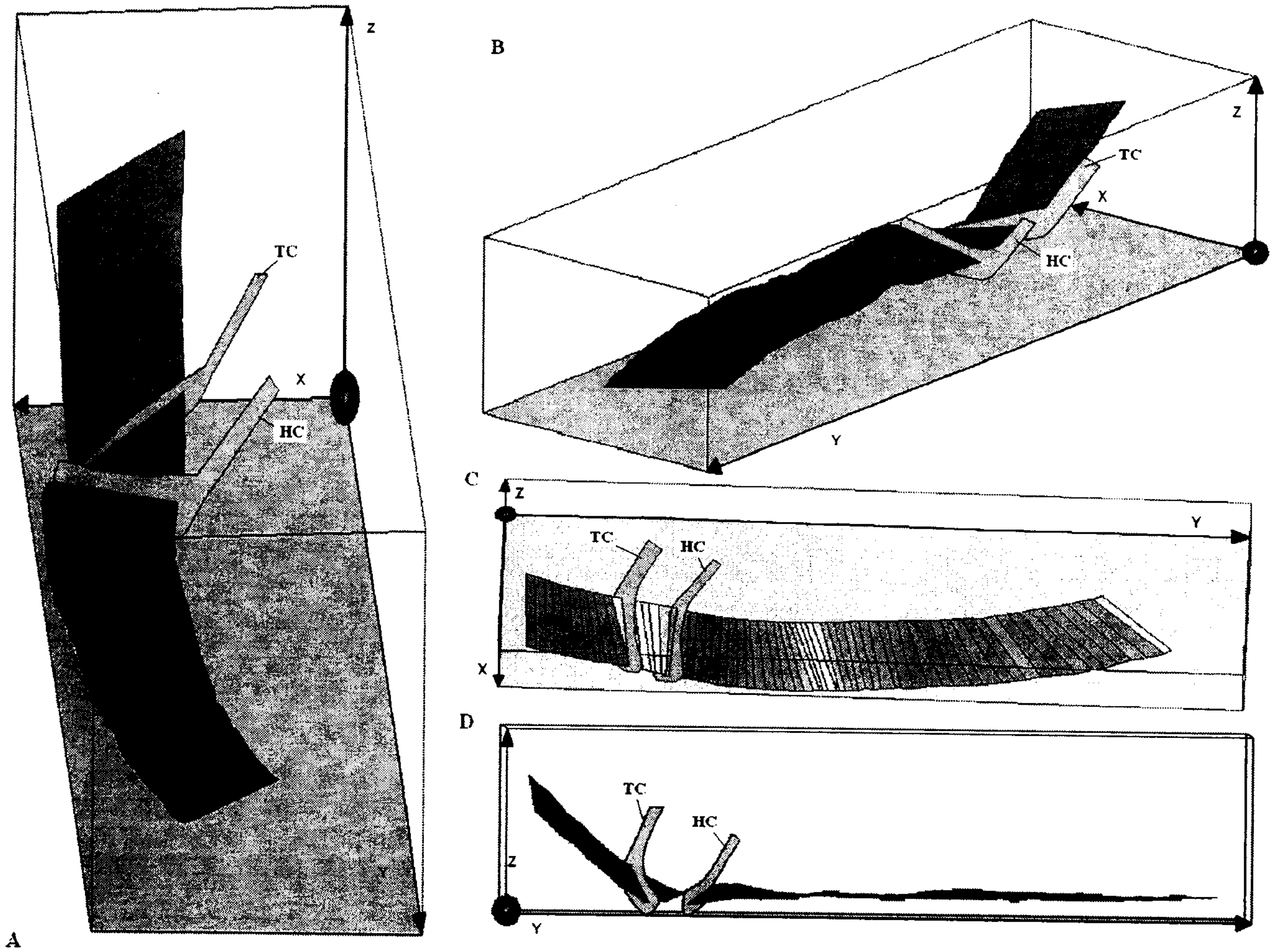

Figure 21 - Over trace of the three-dimensional movement path of the blade during a typical trial from: A) frontal oblique view, B) sagittal oblique view, C) above view, and D) sagittal view. The events of toe and heel contact are marked to help further illustrate the rocker phenomenon.

In the upcoming sections each phase will be briefly described and the results of each variable summarized with respect to the previously-described global axes and temporal events.

4.1.1 Event Data

The forthcoming sections summarize the findings of each variable as measured during each of the aforementioned key temporal events. Data were separated into linear and angular categories and, in the case of the linear variables, were further subdivided by the area of the stick being measured.

4.1.1.1 Linear Measures

Measures of linear displacement refer specifically to one component of a marker's displacement in a particular direction over a predetermined period of time (Figure 22). For instance, 3-3z refers to the vertical displacement (in the Z direction) of marker 3-3 throughout the shot (Figure 23).

Several markers were selected for this analysis, based on their ability to approximate the position of key areas of the hockey stick. These markers include: S1 (indicating gross shaft position), 2-2 (indicating gross blade position), 3-1 (indicating heel position), and 3-3 (indicating toe position). In addition to displacement measures, the linear velocity and acceleration were also calculated in the sagittal plane by differentiating the Y data for each of the aforementioned markers.

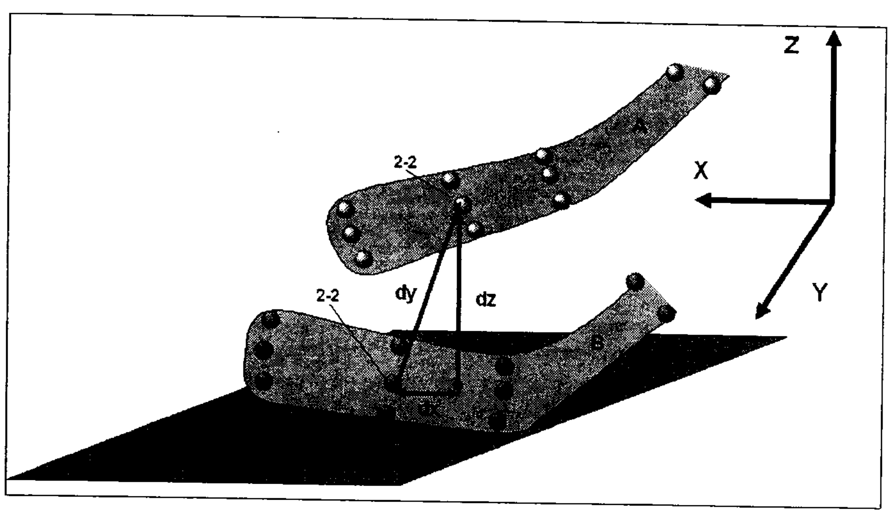

Figure 22 - Example of X, Y, and Z components of displacement for marker 2-2 from position A to position B.

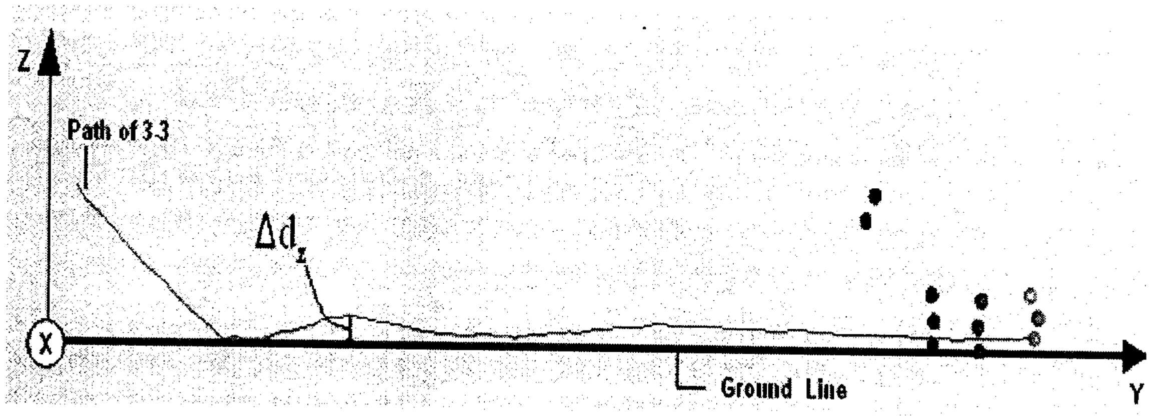

Figure 23 - An example of an overtrace of the path of marker 3-3 as viewed in the sagittal (YZ) plane, with an example of Δd_z highlighted.

Pearson correlation coefficients for the X, Y, and Z components of blade and shaft displacement are presented in Table 7. Y and Z components of shaft and blade displacement demonstrated a significant ($p< 0.01$) positive correlation, while X components demonstrated a significant ($p< 0.01$) negative correlation.

Table 7 – Pearson correlation coefficients between blade and shaft linear displacements in the X, Y and Z directions, respectively. Statistical significance is denoted by ** ($p< 0.01$).

Markers	Pearson Correlation
S1x & 2-2x	**-1.00
S1y & 2-2y	**1.00
S1z & 2-2z	**0.66

4.1.1.1.1 Blade Displacement

The mean overall displacement of the blade in the X, Y and Z directions throughout the shot is represented in Figure 24, the differences between the maximum and minimum values of each displacement graph were also calculated to represent the overall range of displacement in each direction. The only significant differences between skill groups occurred in the minimum X blade displacement ($p< 0.01$) (Figure 24 A) and the overall range of Y blade displacement ($p< 0.05$) (Figure 24 B).

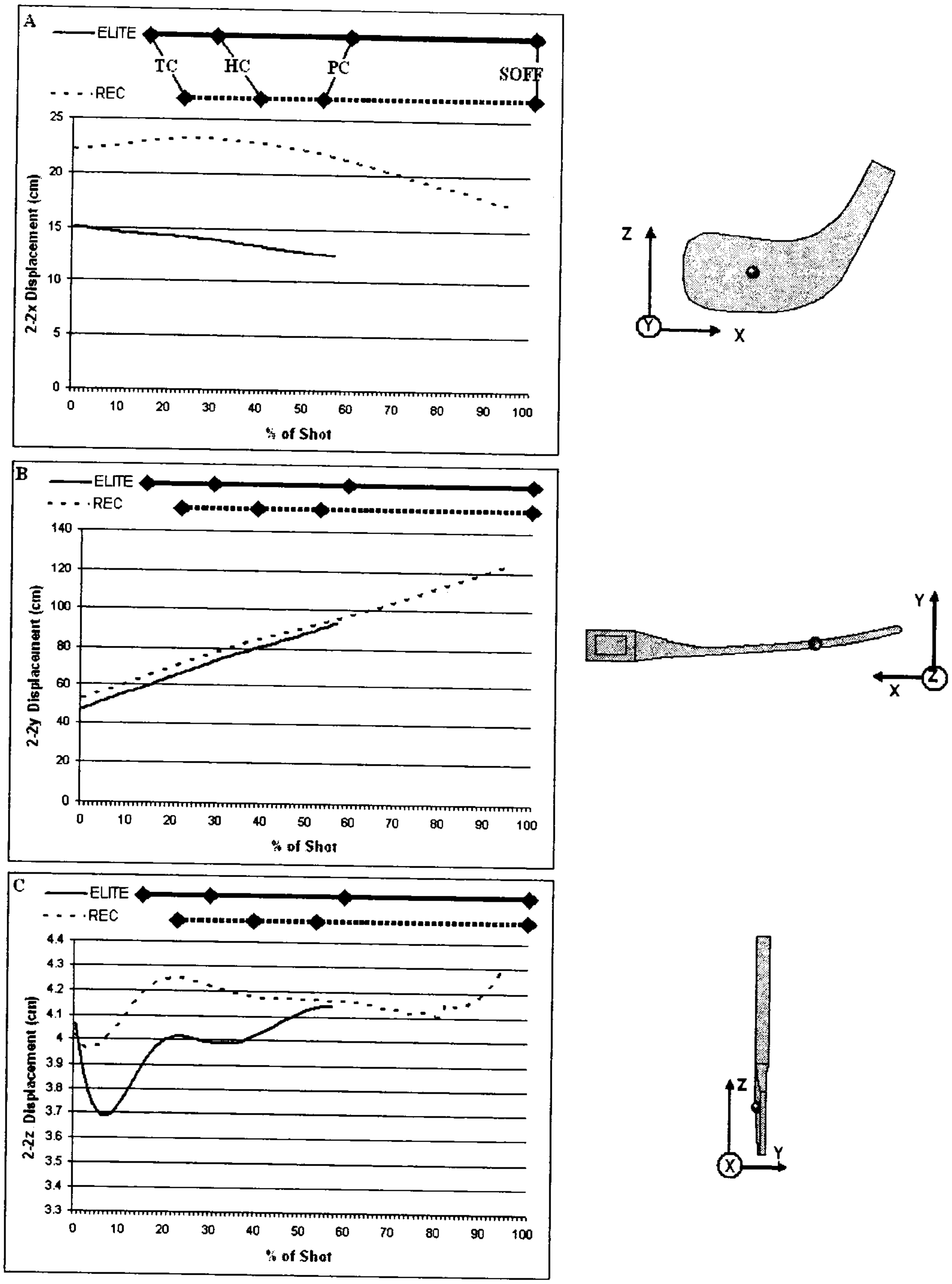

Figure 24 – Mean displacement (cm) of marker 2-2 in the X, Y, and Z components over time for each skill group are shown in the graphs A, B, and C, respectively. Events of TC, HC, PC, and S-OFF are indicated for each group.

Table 8 represents mean blade displacement, while Figure 25 (A, B, and C) illustrates the mean change in blade displacement during each phase of the slap shot in the X, Y, and Z directions, respectively. At the instant of TC, there were NSD in the position of the blade between the ELITE and REC groups in the Y and Z directions (Table 8). However, the REC group demonstrated significantly ($p < 0.01$) greater displacement away from the origin in the X direction than the ELITE group (Table 8). As the blade shifted from TC to HC the ELITE group demonstrated a significantly greater change in displacement (i.e. $\Delta d1$) in the X, Y, and Z directions (Figure 25 A, B, and C, respectively). The ELITE group produced significantly ($p < 0.01$) greater $\Delta d1$ in both X and Y blade displacements than the REC group; however, the ELITE group produced significantly greater $\Delta d1$ Z blade displacement than the REC group.

At HC and PC, again there are NSD between skill groups in the Y and Z blade displacements; however, X blade displacement is significantly ($p < 0.01$) greater for ELITE shooters (Table 8). During Δt_2, the ELITE group again demonstrated a consistent and significantly greater ($p < 0.05$) change in displacement (i.e. $\Delta d2$) of the blade in all directions (Figure 25 A, B and C, for X, Y, and Z, respectively). The ELITE group demonstrated less change in blade displacement in the X and Z directions than the REC group, but significantly greater change in Y blade displacement.

Finally, at S-OFF displacements in both the X and Y are significantly ($p < 0.01$) different between each skill group (Table 8); yet, there were NSD in X or Z blade displacement between skill groups during Δt_3 (Figure 25 A and C, respectively). However, Y blade displacement was significantly greater ($p<0.01$) in the ELITE group during this phase than in the REC group (Figure 25 B).

Table 8 - Mean component of displacement (cm) of marker 2-2 at each event. Statistical significance is denoted by ** ($p < 0.01$).

Displacement (cm)		TC		HC		PC		S-OFF	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
2-2x	ELITE	**15.1	10.8	**14.9	10.7	**13.9	10.4	**14.1	6.6
	REC	22.2	12.5	22.7	13.1	23.5	13.5	16.6	9.5
2-2y	ELITE	46.8	18.4	58.7	19.1	73.8	15.1	**140.6	20.8
	REC	52.6	13.4	59.8	15.2	75.1	15.9	126.4	17.4
2-2z	ELITE	4.1	1.6	3.7	1.6	4.0	1.5	5.4	3.7
	REC	4.0	1.4	4.0	1.6	4.3	1.7	4.7	2.2

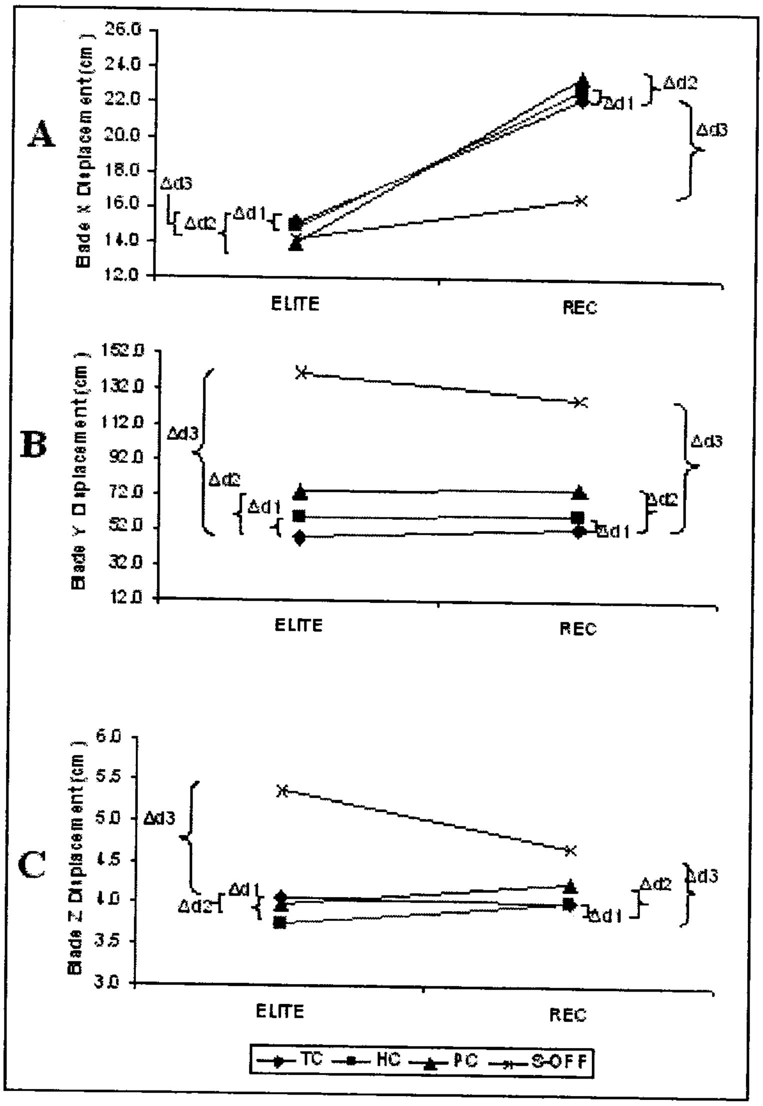

Figure 25 - Mean X, Y, and Z blade displacement (cm) at each event for each skill group and the total mean change (Δd1, Δd2, and Δd3) between events are presented in A, B, and C, respectively.

Blade displacement investigated further by examining the vertical displacement of the heel and toe markers (i.e. 3-1 and 3-3, respectively). The mean overall Z displacements of these markers are presented in Figure 26. Maximum and minimum values of each marker and the overall range of displacement were also calculated; however, only the minimum Z displacement of the heel of the blade was significantly different between skill groups ($p < 0.01$) (see Appendix D for full statistical summary).

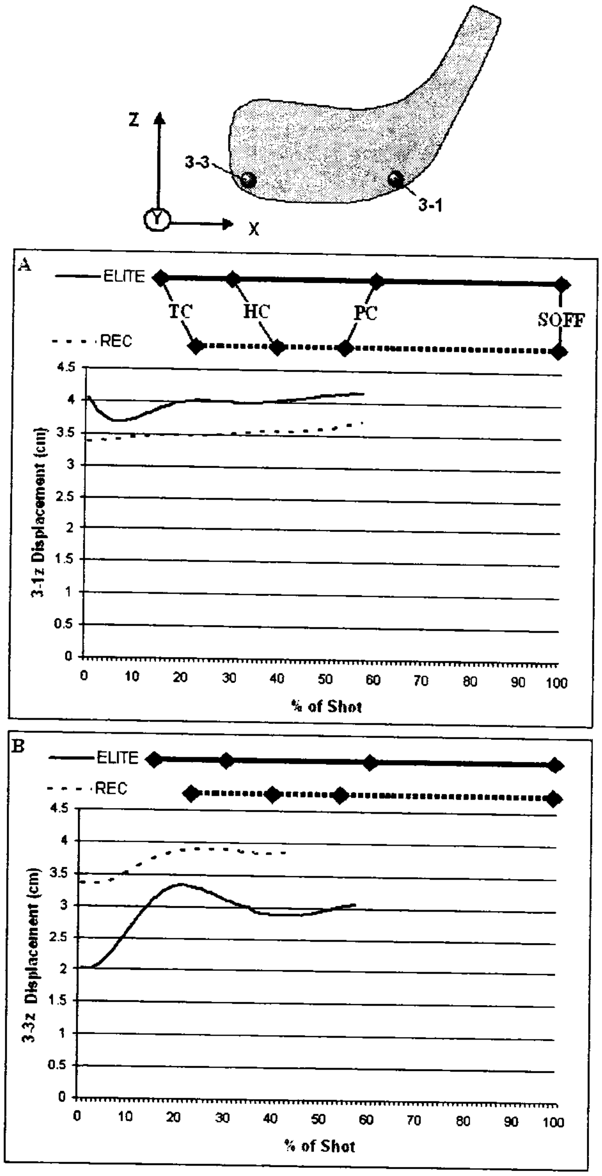

Figure 26 -Mean displacement (cm) of markers 3-1 and 3-3 in the Z components over time for each skill group are shown in graphs A and B, respectively. Events of TC, HC, PC, and S-OFF are indicated for each group.

There were NSD between skill groups in either heel or toe vertical displacement during either of the events investigated (Table 9). However, total mean changes in vertical heel displacement during Δt1 and Δt2 were significantly different ($p < 0.01$) between groups and total change in vertical toe displacement was significantly less in the ELITE group during Δt1 (Table 10).

Table 9 - Mean Z displacement (cm) of markers 3-1 and 3-3 at each event.

Displacement (cm)	3-1z		3-3z	
	ELITE	REC	ELITE	REC
TC	3.4	3.4	2.0	3.4
HC	2.2	3.5	2.7	3.4
PC	2.1	3.5	2.9	3.9
S-OFF	4.5	4.9	4.7	4.8

Table 10 - Mean change in Z displacement (cm) for 3-1 and 3-3 during each phase. Significance is denoted by ** ($p < 0.01$).

Displacement (cm)	Δt1		Δt2		Δt3	
	ELITE	REC	ELITE	REC	ELITE	REC
3-1z	**-1.3	0.1	**-1.3	0.1	1.1	1.5
3-3z	**0.7	0.0	0.9	0.5	2.7	1.5

4.1.1.1.2 Blade Velocity

The mean overall velocities of the blade in the X, Y and Z directions are presented in Figure 27 A, B, and C, respectively. Throughout the shot, the mean maximum and minimum values of shot, and the overall range of velocity were also calculated. The only significant differences between skill groups occurred in the maximum Y and Z blade velocities ($p < 0.01$) and the minimum Z blade velocity ($p < 0.01$) (see Appendix D for full statistical summary).

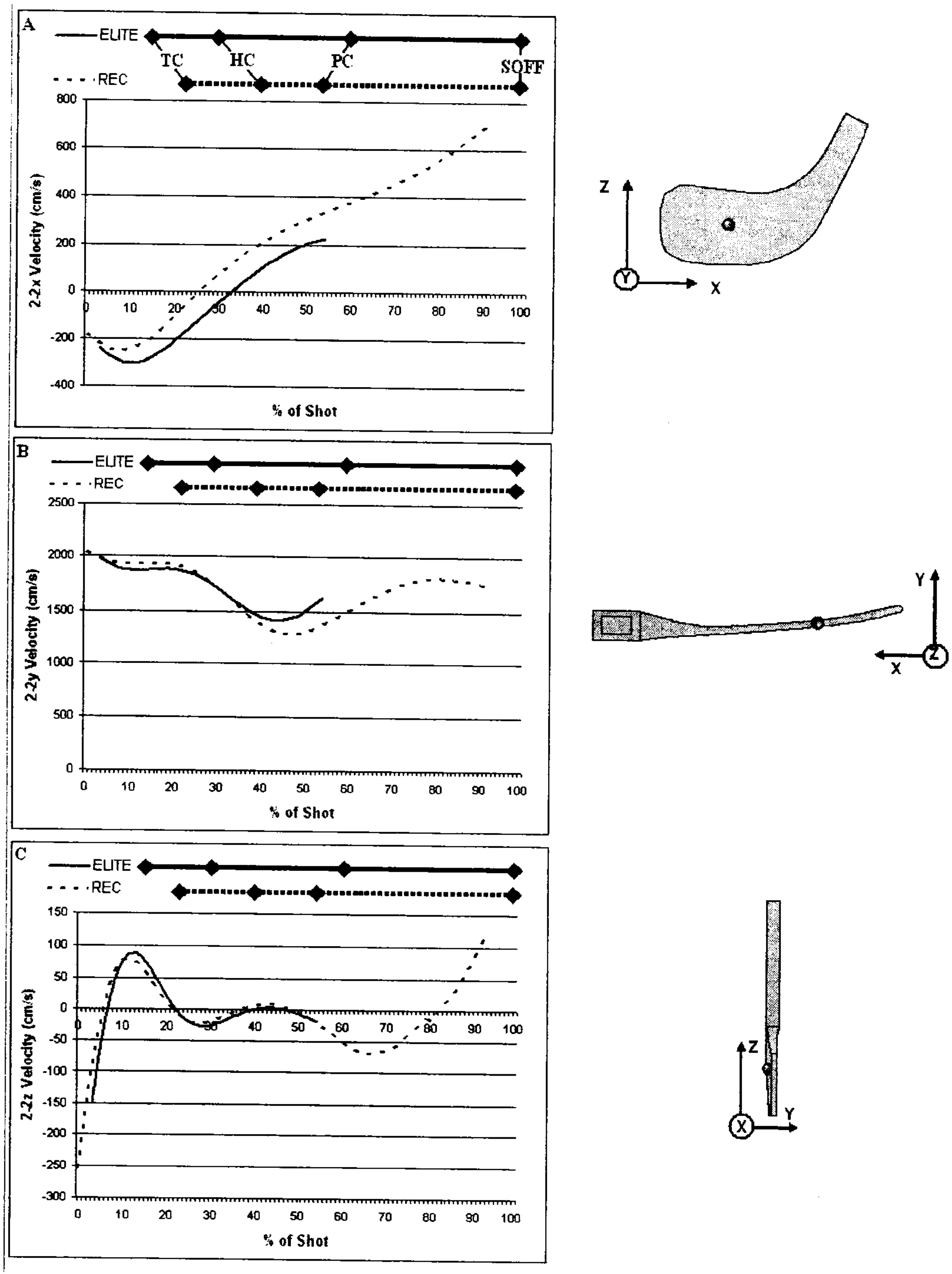

Figure 27 - Mean velocities (cm/s) of marker 2-2 in the X, Y, and Z components over time for each skill group are shown in graphs A, B and C, respectively. Events of TC, HC, PC, and S-OFF are indicated for each group.

Table 11 represents mean blade velocities at each event, while Figure 28 (A, B, and C) illustrates the mean change in blade velocity during each phase of the slap shot in the X, Y, and Z directions, respectively. At TC, only Z velocity demonstrates significant ($p < 0.01$)

difference between the skill groups, with the ELITE group achieving a downward velocity of 352.20 cm/s compared to only 246.57 cm/s in the REC group (Table 11,). At HC, velocities in both the Y and Z show significant differences. The resulting changes in velocity during Δt_1 were significant for X, Y, and Z components, with the ELITE group demonstrating greater magnitudes of $\Delta v1$ in all directions (Figure 28 A, B, and C, respectively).

While there were NSD between skill groups in any blade velocity component at PC; the total change ($\Delta v2$) in Z velocity was significantly greater in the ELITE group (Figure 28C). Finally, at S-OFF each component of blade velocity showed significant differences between skill groups (Table 11). With regard to total mean change in velocity during Δt_3 (i.e. $\Delta v3$), NSD existed in Z blade velocity; however, significant differences ($p < 0.01$) existed in both X and Y blade velocity (Figure 28 A, B, and C, for X, Y and Z, respectively).

Table 11 - Mean component of velocity (cm/s) of marker 2-2 at each event. Statistical significance is denoted by ** (p< 0.01) and * (p< 0.05).

Velocity (cm/s)		TC		HC		PC		S-OFF	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
2-2x	ELITE	-189.5	212.0	-295.1	226.8	-55.5	144.6	*972.4	379.1
	REC	-183.8	200.2	-201.1	185.5	-13.0	147.6	766.6	277.9
2-2y	ELITE	2073.4	166.1	*1881.5	176.7	1767.5	199.9	**2751.0	431.0
	REC	2042.7	258.2	1987.8	242.8	1831.0	330.9	1513.6	627.2
2-2z	ELITE	**-352.2	144.9	**86.1	75.8	19.0	58.8	**136.4	232.0
	REC	-246.6	94.5	-20.5	116.3	7.2	64.5	302.9	146.1

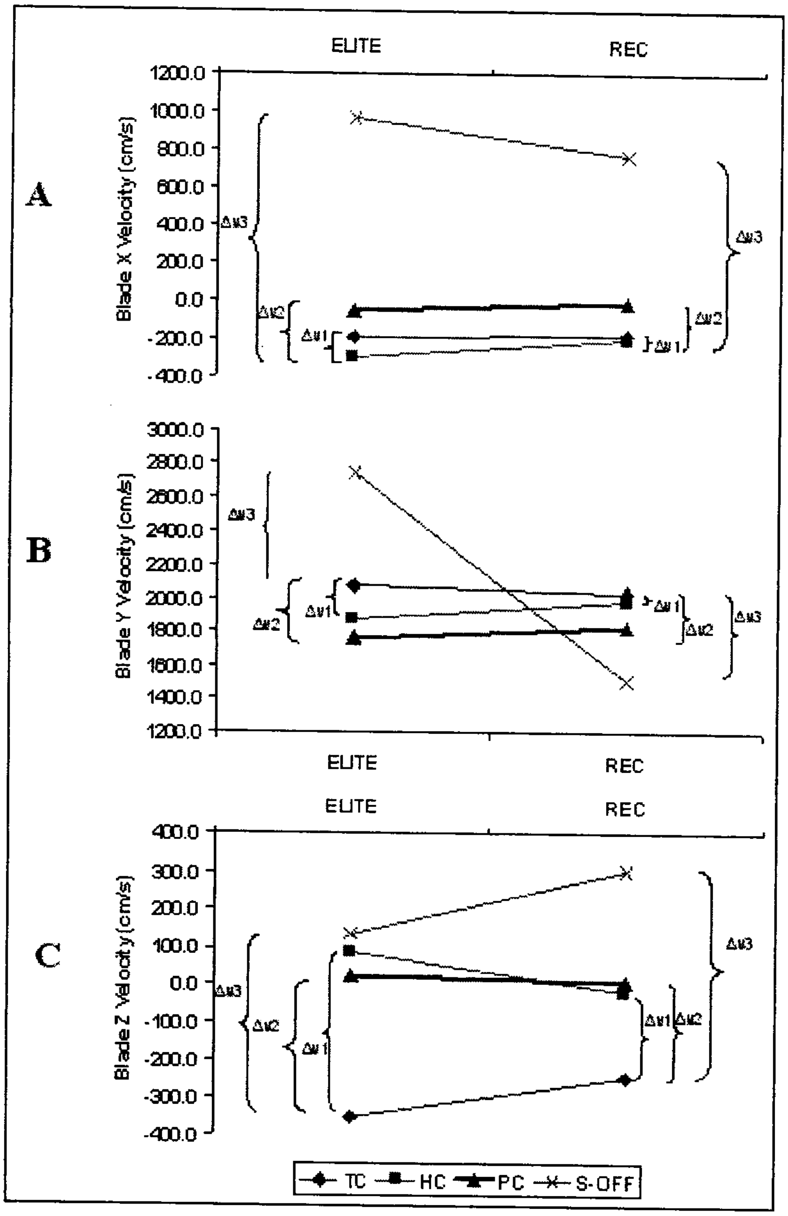

Figure 28 - Mean X, Y, and Z blade velocity (cm/s) at each event for each skill group and the total mean change (Δv1, Δv2, and Δv3) between events are presented in A, B, and C, respectively.

4.1.1.1.3 Shaft

Shaft and blade kinematics were highly correlated in the Y and Z directions (Table 7), such that shaft displacement and velocity trends closely mirror those previously described for the blade. As such, only shaft X data is presented in here (Y and Z data are presented in Appendix D for further information). The mean overall displacement and velocity of the shaft in the X direction throughout the shot are presented in Figure 29 A and B, respectively. Maximum and minimum values and the overall range of displacement were also calculated, with the lone significant difference between skill groups occurring in minimum X ($p<0.01$) displacement (see Appendix D for full statistical summary).

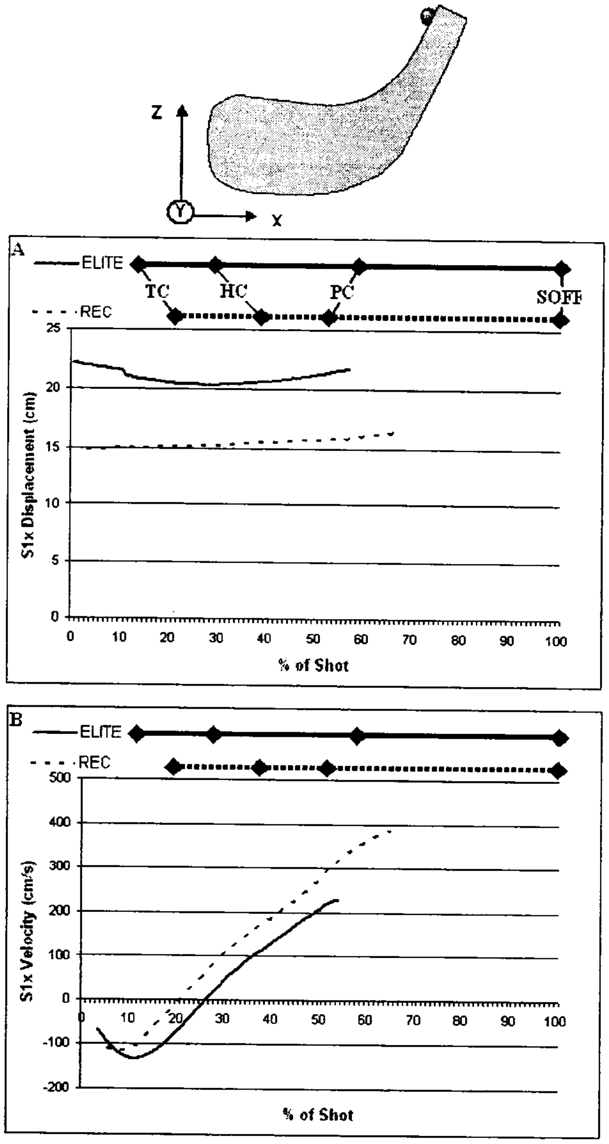

Figure 29 - Mean displacements (cm) and velocity of marker S1 in the X direction over time for each skill group are presented in graphs A, and B, respectively. Events of TC, HC, PC, and S-OFF are indicated for each group.

Table 12 represents mean shaft X displacement at each event, while Figure 30 illustrates the mean change in blade X displacement during each phase of the slap shot. At TC, the ELITE group positioned the shaft further away from the origin in the X direction (Table 12). The magnitudes of overall change in displacement S1 from TC to HC (i.e. Δd1) varied significantly ($p< 0.01$) between groups (Figure 30).

At PC, there were NSD in shaft displacement between skill groups; however, the mean total change during Δt_2 (i.e. Δd2) varied significantly ($p < 0.01$) between groups (Figure 30). The ELITE group consistently produced a significantly greater change in X shaft displacement.

Finally, at S-OFF significant differences were observed in X shaft displacement ($p < 0.05$). There were NSD in change in X shaft displacement between skill groups during any of the three phases (i.e. Δd1, Δd2, and Δd3) (Figure 30).

Table 12 - Mean X displacement (cm) of marker S1 at each event. Statistical significance is denoted by * (p< 0.05).

EVENT	ELITE		REC	
	Mean	SD	Mean	SD
TC	*22.2	13.2	15.4	12.7
HC	*21.1	12.8	15.2	12.3
PC	20.1	11.6	15.1	11.9
SOFF	*30.3	13.5	21.4	15.8

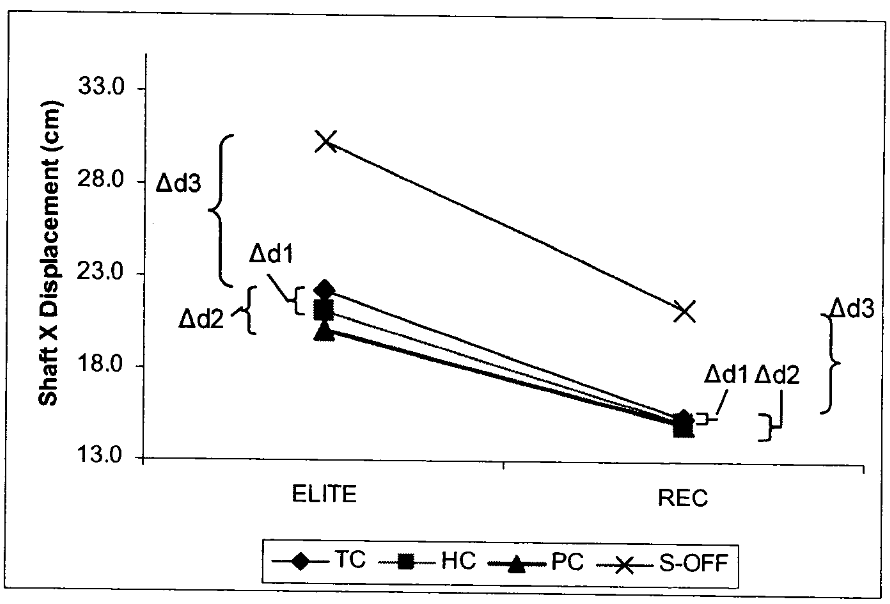

Figure 30 - Mean X shaft displacement at each event for each skill group and the total mean change (Δd1, Δd2, Δd3) between events.

Table 13 represents mean shaft X velocity at each event, while Figure 31 illustrates the mean change in blade X velocity during each phase of the slap shot. At TC, the REC group demonstrated a significantly greater shaft velocity than the ELITE group ($p<0.05$); however, there were NSD between skill groups at either of the remaining events (Table 13). Overall during Δt_1, the ELITE group experienced significantly higher ($p< 0.01$) mean total change in shaft velocity than the REC group; while there were NSD between groups during either of the remaining phases (Figure 31).

Table 13 Mean X components of shaft velocity (cm/s) at each event. Statistical significance is denoted by * (p< 0.05).

EVENT	ELITE		REC	
	Mean	SD	Mean	SD
TC	*-29.2	187.7	-45.6	292
HC	-121.9	198.8	-62.4	190.1
PC	20.3	140.4	51.2	133.9
SOFF	654.3	292.4	575.8	221.3

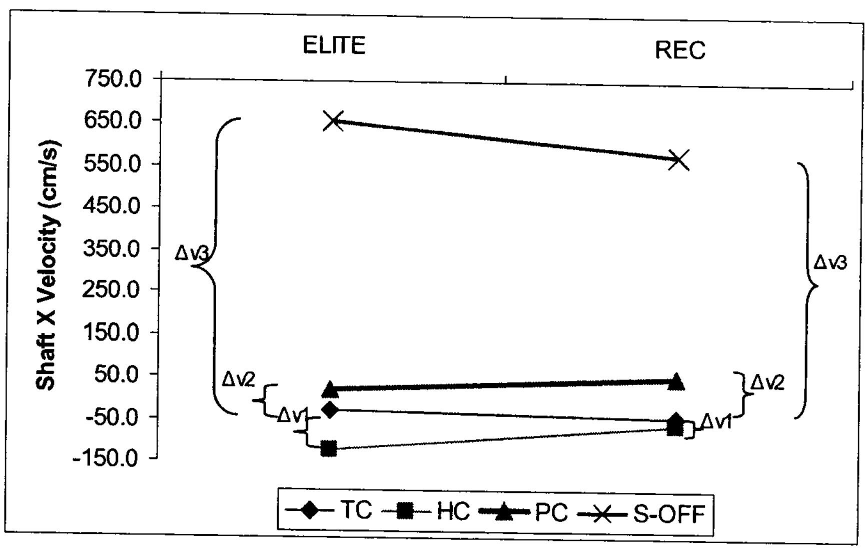

Figure 31 - Mean X shaft velocity (cm/s) at each event for each skill group and the total mean change (Δv1, Δv2, and Δv3) between events.

4.1.1.2 Angular Measures

Mean overall global angles (i.e. face, tilt, and loft angles) of the blade throughout the slap shot are presented in Figure 32. Maximum and minimum values and the overall range of the angles were also calculated and demonstrated significant differences between skill groups occurred in maximum tilt angle ($p< 0.01$), minimum loft and tilt angles ($p< 0.01$) and the overall range of face ($p<0.05$), loft , and tilt angles ($p< 0.01$).

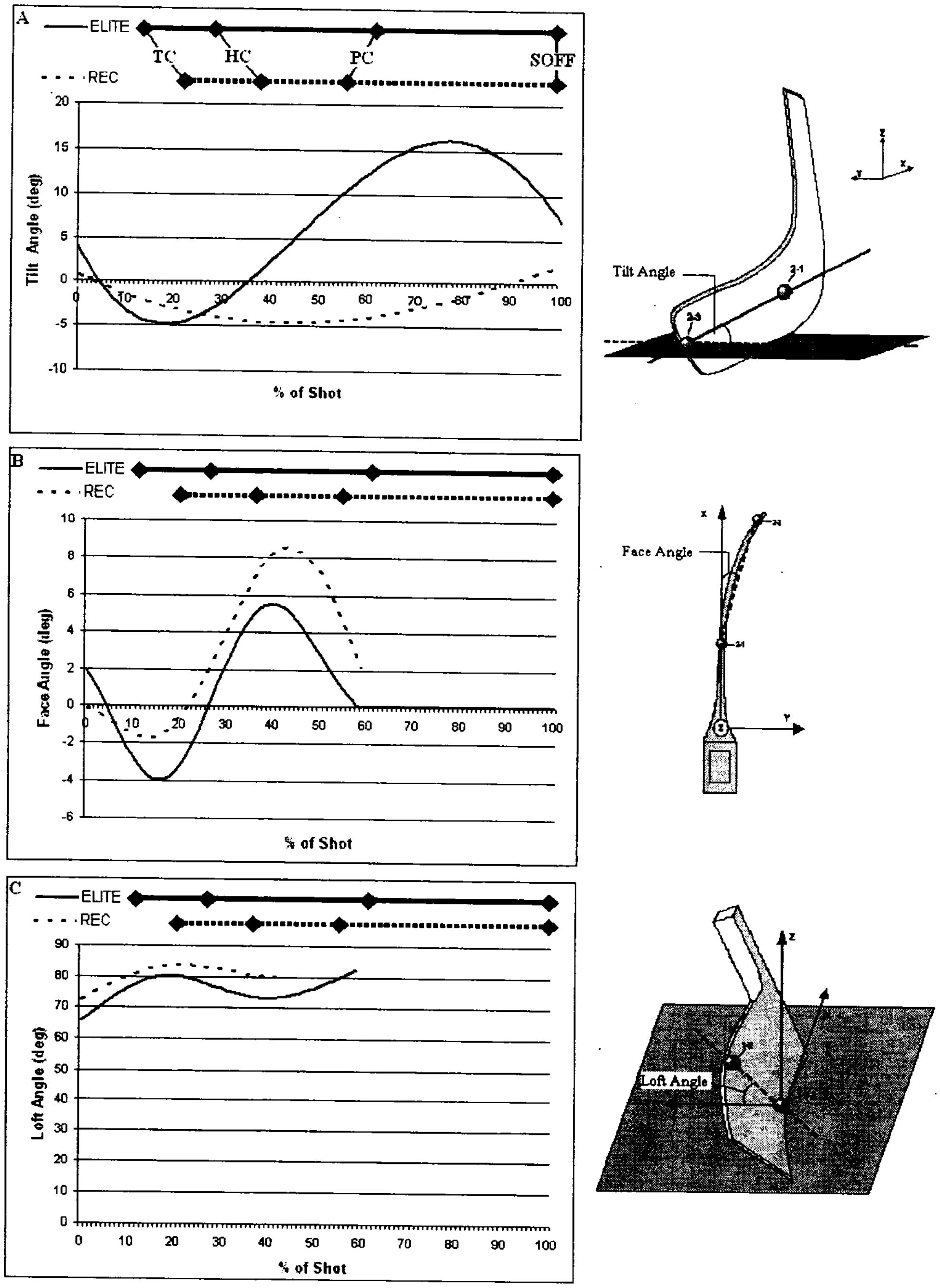

Figure 32 - Mean tilt, face, and loft angles (deg) of the blade over time for each skill group are presented in graphs A, B, and C, respectively. Events of TC, HC, PC, and S-OFF are indicated for each group.

Table 14 presents the mean global tilt, face and loft angles at each event,while Figure 33 (A, B, and C) demonstrates the mean change of each global angle during each phase of the slap shot, in the X, Y, and Z directions, respectively. Significant differences occurred between groups ($p< 0.01$) in tilt at TC, PC, and S-OFF (Table 14), and the overall change in tilt was significantly different during each of the three phases ($p < 0.01$ and $p < 0.05$) (Figure 33 A). However, there were NSD between groups in face angle at any of the four events (Table 14); yet, $\Delta\theta 1$ and $\Delta\theta 3$ of face angle were significantly greater ($p < 0.01$) in the ELITE group (Figure 33 B). The REC group demonstrated a significantly greater ($p < 0.01$) loft angle than the ELITE group at the TC and PC events (Table 14), but only $\Delta\theta 1$ in loft was significantly different ($p < 0.01$) between groups (Figure 33 C).

Table 14 - Mean global angle (deg) at each key event. Statistical significance is denoted by ** ($p < 0.01$).

Angle (deg)		TC		HC		PC		S-OFF	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
TILT ANGLE	ELITE	**5	4	-3	3	**-3	3	**5	5
	REC	1	3	-3	3	-5	3	2	4
FACE ANGLE	ELITE	2	8	-4	8	3	6	**18	13
	REC	0	9	-2	10	2	9	-2	10
LOFT ANGLE	ELITE	**66	6	79	7	**76	6	108	10
	REC	72	10	78	9	83	10	110	11

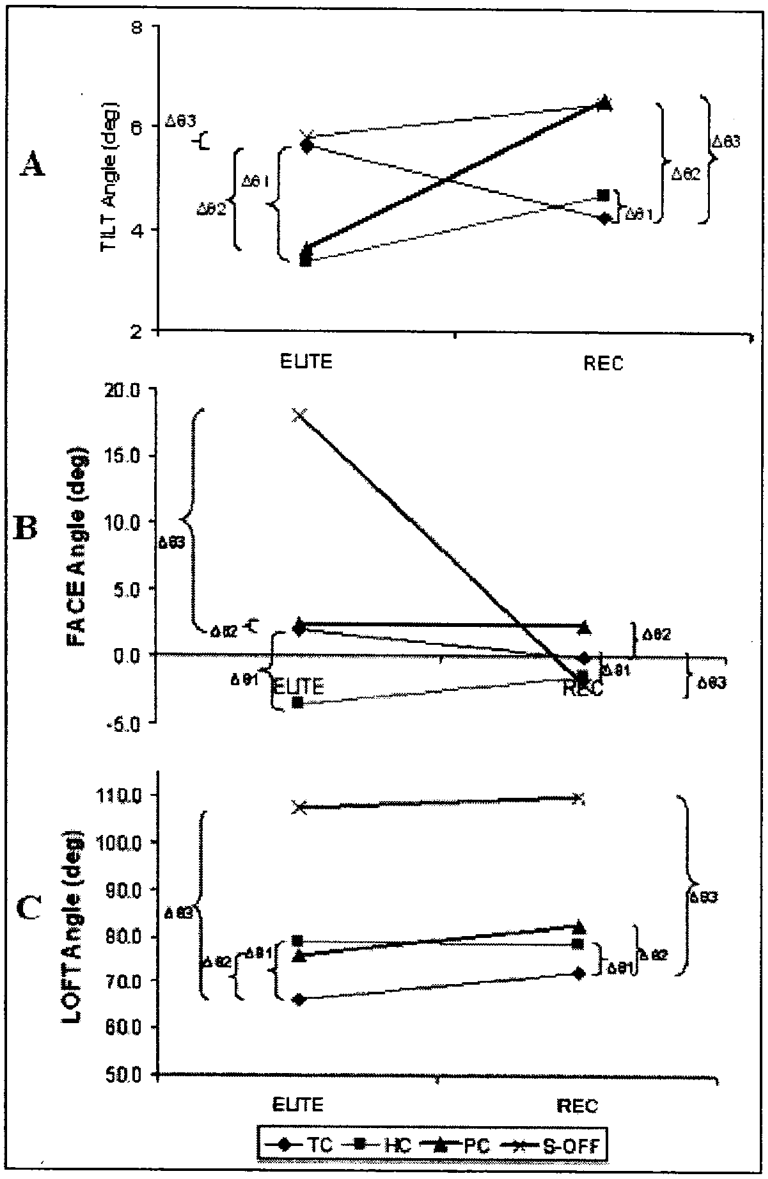

Figure 33 - Mean tilt angle (deg) at each event for each skill group and the total mean change (Δθ1, Δθ2, Δθ3) between events.

4.1.2 Temporal Phase Data

The slap shot was divided into three phases that included: 1) toe-to-heel contact; 2) stick loading; and 3) blade-ground contact (Figure 17). The backswing and follow-through phases previously described in the literature are ignored here as they are less likely to contribute to blade deformation. As such, all data is time-normalized so that TC and S-OFF represent 0% and 100% of the slap shot, respectively.

Figure 34 demonstrates the significant differences in the duration of each phase (in terms of absolute time in seconds and percentage of total shot, respectively). Toe-to-heel (Δt_1) contact was defined as the period of time from TC to HC. The duration of this phase was significantly different between groups in absolute time and percentage of shot ($p < 0.05$ and $p < 0.01$, respectively). This phase lasted 0.006 s or 13% of the shot in the ELITE group and 0.009 s or 21% of shot for the REC group.

Blade-puck contact (Δt_2) was defined as the period of time from TC to PC. The duration of this phase was significantly different between skill groups in absolute time and percentage of the shot ($p < 0.05$ and $p < 0.01$, respectively). Elite subjects averaged a Δt_2 of 0.014 s or 29% of each shot; whereas, the REC group's Δt_2 was 0.0017 s or 39% of each shot.

Blade-ground contact (i.e. Δt_3) was defined as the period of time from TC to S-OFF. This final phase of the slap shot was significantly longer in absolute and percentage of shot ($p < 0.01$ and $p < 0.05$, respectively) for the ELITE group. The ELITE group's duration was 0.027 s or 58% of shot; whereas, the REC group's duration of Δt_3 was 0.024 s or 53% of shot.

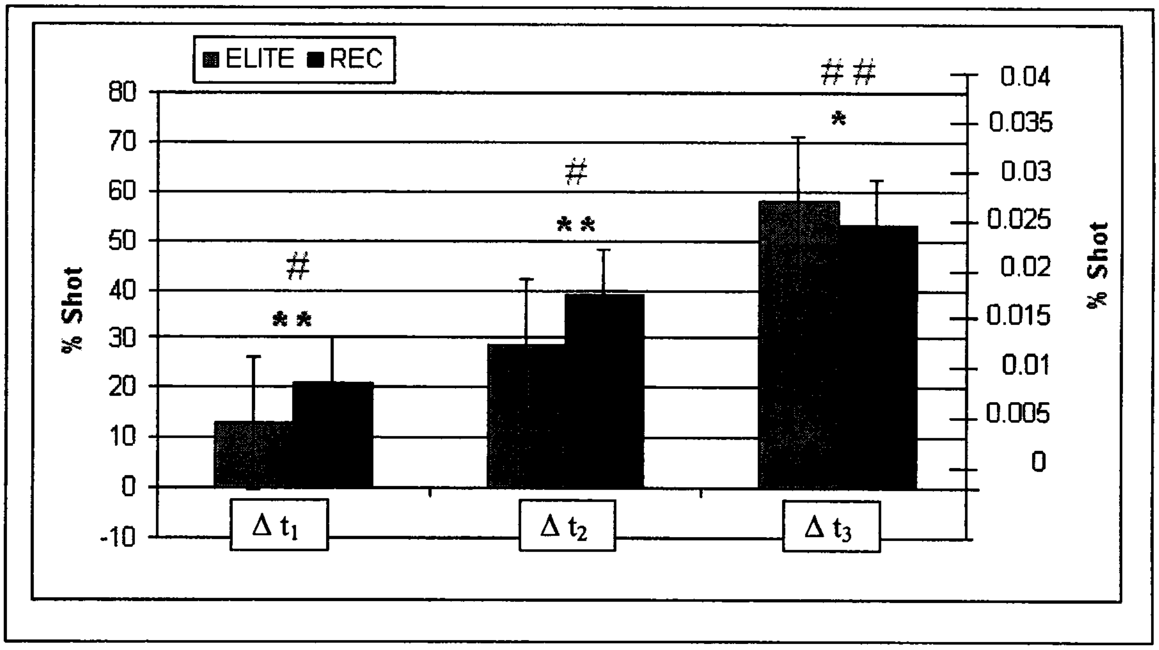

Figure 34 – Mean duration of each phase (in sec and percentage of total shot) of each phase for the each skill group. Statistical significance is denoted by * ($p<0.05$) and ** ($p<0.01$) for percent of shot and # ($p<0.05$) and # # ($p<0.01$) for absolute time in seconds.

4.1.3 Shot Velocity & Puck Contact Location

During the dynamic testing protocol, significant differences ($p< 0.01$) in puck velocity were found between skill groups (Table 15). However, since the instrumented puck used during the test shots was attached to a 6 m wire, the velocities of the test shots were less than practice shot velocities (taken with a standard puck). In fact, the instrumented puck decreased overall mean puck velocity approximately 30% during test trials (Table 15). However, there was no significant differences (NSD) ($p = 0.74$) between mean puck velocity and stick model (Table 16).

Table 15 - Mean puck velocity (km/h) and standard deviation (SD) for each skill group (ELITE & REC) in both practice and test trials. Mean percent difference between groups in practice and test shots is also presented. Statistical significance is denoted by ** ($p< 0.01$).

Skill Level	Mean Test Velocity (km/h)**	SD	Mean Practice Velocity (km/h)	SD	Mean % Difference
ELITE	73.7	13.6	109.4	9.0	32
REC	66.9	14.9	88.5	6.6	25
			Overall Mean		29

Table 16 - Mean puck velocity (km/h) and SD for each test stick model.

Stick Model	Mean (km/h)	SD
CCM	72.0	17.0
CTC	67.4	16.2
SIC	68.8	13.8
STE	70.4	12.7
VXX	72.2	18.2
VXXX	70.7	16.5

NSD were found between the location of initial puck contact and either skill level or stick model ($p = 0.3$ to 1.00), with subjects tending to contact the puck within zone 5 (Table 17). A complete list of probabilities for each variable is located in Appendix C.

Table 17 - Mean location of initial puck contact (by zone) and SD for each skill level and stick model.

Variable		Mean	SD
Skill Level	ELITE	5.3	1.1
	REC	5.2	0.7
		Mean	**SD**
Stick Model	CCM	5.2	1.0
	CTC	5.1	0.8
	SIC	5.2	0.9
	STE	5.4	0.9
	VXX	5.4	1.1
	VXXX	5.2	0.8

4.2 Measurement Certainty & Reliability Data

The distances between 1-1 and 1-3 ranged from 19.60 and 20.50 cm for each stick model. The mean calculated distance (of three trials) after the data were reconstructed ranged from 18.87 to 20.40 cm for each stick model, with an overall mean difference in measured versus calculated distance of -0.23 cm (Table 18).

Table 18 - Mean distance (cm) from 1-1 to 1-3 as calculated from three-dimensional calculations and as measured prior to experiments and the difference between each measure.

	Mean Calculated Distance (cm)	Measured Distance (cm)	Difference (cm)
CCM	20.4	20.3	0.1
CTC	19.3	20.1	-0.8
SIC	19.8	19.7	0.1
STE	18.9	19.6	-0.7
VXX	20.4	20.5	-0.1
VXXX	20.0	20.0	0.0
		Mean Difference	-0.2

Data from a manually digitized trial and a simulation of the same trial were compared to determine the measurement uncertainty associated with the data processing modules developed for this study. RMS values for the displacement data of a selected marker in each trial revealed minimal differences in each direction, not exceeding 0.30 cm (Table 19). Similarly, the data was highly correlated for the X, Y and Z coordinates – r = 0.89, r = 1.00, and r = 0.98, respectively.

Table 19 - RMS values (cm) and Pearson correlation coefficients for each axis of a manually digitized trial (X, Y, Z) and a simulated trial (X_s, Y_s, Z_s).

	RMS (cm)	Difference (cm)	R^2
X	2.6	0.2	0.89
X_s	2.4		
Y	76.5	-0.1	1.00
Y_s	76.6		
Z	5.3	0.3	0.98
Z_s	5.0		

The intra-reliability of the author's digitizing was assessed by comparing differences in RMS and the Pearson product moment correlation between selected markers on two digitizing attempts of the same trial. The differences in RMS values were greater in the X direction than in the Z (Table 20). The correlation between the data sets was relatively high in both X and Z directions (r = 0.90 and r = 0.91, respectively). Examples of the data sets for each digitizing attempts are located in Appendix C.

Table 20 - RMS values (cm) and Pearson correlation coefficients for the displacement data of a selected marker in the X and Z directions in two digitizing attempts of the same trial

	RMS (cm)	Difference (cm)	R^2
X1	135.8	1.0	0.90
X2	134.8		
Z1	83.1	-0.4	0.91
Z2	83.5		

CHAPTER 5 – DISCUSSION

The primary purpose of this study was to quantify the movement and orientation of the lower shaft and blade portion of the hockey stick during a stationary slap shot, with particular attention paid to the effects of blade construction and player skill. Despite substantial differences in blade construction and material properties (Table 5), there were no apparent trends toward significant differences between stick/blade models in the majority of dynamic DV were observed (Appendix C). These findings are consistent with those of Pearsall et al (1999) where no differences in shot velocity were attributed to shaft stiffness properties. Pearsall and colleagues (1999) did find significant ($p < 0.05$) differences in peak shaft deflection and time to peak shaft deflection; however, previous studies suggest that these differences may also be attributed to various factors (e.g. skill level, stature, strength, technique) (Pan et al. 1998; Roy & Doré 1979). Similarly, Wu and colleagues (2003) concluded that subject technique parameters are likely more influential over slap shot performance than stick parameters. As such, it appears that differences in blade construction parameters (as currently available on in the market) do not play a significant role in the overall response of the blade to the stationary slap shot.

5.1 Shot Velocity

Slap shot performance is primarily classified on the basis of puck velocity. In this study, mean puck velocity during test trials was measured with a radar gun to be 73.7 km/h and 66.9 km/h for the ELITE and REC groups, respectively (Table 15). These values are substantially lower than those previously reported for similar skill groups performing the stationary slap shot (Table 2), which ranged from 80 to 121 km/h. However, the additional weight of the wire in combination with the effective tethering of the test puck served to dramatically reduce puck velocity. In fact, the mean practice puck velocity (measured with normal pucks during the subject's warm-up) was 109.4 and 88.5 km/h for the ELITE and REC groups, respectively (Table 15). These mean practice puck velocities are within the range of previously reported data (Doré & Roy 1976; Furlong 1968; Pearsall et al. 1999;

Roy & Doré 1976; Roy et al. 1974; Simm & Chau 1978; Villaseñor-Herrera 2004; Wu et al. 2003).

Literature suggests that in highly skilled players utilize a variety of techniques to achieve their higher slap shot velocities. Primarily, ELITE shooters are thought to better utilize the loading phase of the slap shot, causing: increased shaft deflection; a longer period of stick-ground contact; and higher vertical ground reaction forces; which combine to generate higher stick elastic (i.e. bend) energy, thus, imparting a greater impulse on the puck (Doré & Roy 1976; Pearsall et al. 1999; Roy & Doré 1976; Villaseñor-Herrera 2004). Woo (2004) also attributed ELITE shooters increased shot velocity to increased translational acceleration of the stick; as compared to REC shooters who utilized more rotational acceleration (Table 3).

The previously cited works have made great strides in defining the overall role of the hockey stick shaft, including the effects of various shaft properties (e.g. stiffness and construction materials) (Hoerner 1989; Marino 1998; Marino & VanNeck 1998; Pearsall et al. 1999; Roy & Delisle 1984; Roy & Doré 1973; Roy & Doré 1975; Roy & Doré 1979; Simard et al. 2004; Villaseñor-Herrera 2004; Wu et al. 2003). Similarly, many authors have provided descriptions of whole body kinematics during the stationary slap shot using both two- and three-dimensional methods (Hayes 1965; Meng & Zhao 2000; Polano 2003; Roy & Doré 1976; Woo 2004). However, the role and response of the blade during the slap shot, particularly during impact events remains largely unknown.

To date, only two authors have specifically examined blade function; Nazar (1971) conducted a preliminary investigation into the role of curved blades on the velocity and accuracy of the slap shot, and Simard and colleagues (2004) examined both static and dynamic characteristics of composite hockey sticks. As such, many of the characteristics of blade construction and design are based primarily on speculation and supposition, and therefore could benefit greatly from further investigation. The current study is the most detailed report to date, providing substantive information about blade-to-ground and blade-to-puck kinematics. Granted, the amount of data presented is overwhelming on initial review and the functional relevance may not be readily apparent. Hence, the following passages will attempt to describe how each kinematic parameter relates to the overall skill execution.

5.2 *Linear Kinematics*

The results of this study confirm observations by Polano (2003) that initial blade-to-ice contact typically occurs between the toe portion of the blade and the ice, as opposed to the entire bottom edge of the blade. In this study, all trials demonstrated initial contact made by the toe, which was then followed by heel portion of the blade. As such, the first phase of the slap shot was defined as: toe-to-heel contact or the period of time from TC to HC.

With regards to puck positions, since subjects were free to position themselves anywhere on the testing platform, the horizontal distance between their feet and the puck varied substantially. As such, the resulting magnitude of X component shaft and blade displacement (Table 8 and Table 12, respectively) also varied considerably; consequently, shaft and blade X velocity (Table 11 and Table 13, respectively) and displacement calculations were also subject to substantial variation within and between skill groups. Therefore, significant differences between groups on X component linear variables may be a greater function of the individual player's preference on the horizontal distance between his feet and the puck than actual shot mechanics. In future, the standardization of this distance may help reduce this variation and further clarify the role of X component movement in a successful stationary slap shot.

Initiation of the downswing (from the top of backswing) causes a linear increase in stick displacement away from the origin in the Y direction (i.e. towards the target), resulting in an increase in linear velocity of the stick (Cotton 1966; Falconer 1994; Hoerner 1989; Polano 2003; Woo 2004). Shaft and blade Y displacements were highly correlated (Table 7). Thus, indicating that in this direction the shaft and blade tend to act as one unit, and any movements between the two structures (i.e. in the hosel) are beyond the scope of the current measurement system's resolution. As such, for clarity the shaft and blade Y kinematics will be referred to as a single unit hereafter.

As the stick approaches TC, Y velocity began to decrease as the loading of the stick (i.e. shaft deflection) process was begun. The mean Y velocities 2073.5 cm/s (20.74 m/s) and 2042.7 cm/s (20.43 m/s) for the ELITE and REC groups, respectively (Table 11), are similar to the 20 m/s reported by Roy and colleagues (1974) but substantially less than those reported by Polano (2003), where values ranged from 27.5 to 30.9 m/s, with a mean of 29.7 m/s. However, Polano's (2003) calculations were based on data from the three highest velocity slap shots performed by only three subjects .

The decrease in Y velocity continued through HC, where the velocity tended to stabilize and remain constant; thus, following Polano's (2003) observation that the toe's initial contact with the ground results in a dramatic decrease in velocity. This trend varied between skill groups, with the ELITE group demonstrating a significantly greater decrease in Y velocity during Δt_1 (Figure 28 B). The values obtained in the present study are substantially larger than the mean of 13.7 m/s reported by Polano (2003); however, these data represent the minimum toe velocity as opposed to the HC event.

The Y component of velocity remained constant until immediately prior to the PC event where upon the velocity decreased to its minimum value (i.e. 46.8 and 52.4 cm/s for ELITE and REC groups, respectively) at ~45% of the shot duration (Table 11). The resulting total decrease in Y blade velocity from TC through PC likely corresponded to the initial shaft deflection, which in skilled shooters typically began at the instant of blade-ground contact; whereas, in unskilled shooters deflection began much later, as much as halfway through blade-ground contact (Villaseñor-Herrera 2004).

Y velocities at PC were 1767.5 and 1831.0 cm/s (17.3 and 18.3 m/s) for the ELITE and REC groups, respectively. These values were substantially less than the 29.1 and 26.5 m/s obtained by Woo (2004) for ELITE and REC shooters, respectively; however, these values represent an overall resultant blade velocity as data were not examined in terms of its respective components. From its minimum value, Y blade velocity increased steadily; the REC group's velocity tended to peak at ~80% of the shot, whereas ELITE shooters were able to peak closer to S-OFF at substantially larger velocities (Figure 24).

The Z components of linear kinematic measures of the shaft and blade were also significantly correlated (Table 7) and as such, shaft and blade measures will again be discussed primarily as a single unit and referred to as the stick for simplicity. The downswing phase is aptly named as during this phase (from the top of backswing to TC) the stick experiences a significant downward shift in displacement (Woo 2004). Immediately prior to HC the blade portion of the stick experienced a slight upward displacement, which continued through PC; meanwhile the shaft continued its downward shift in displacement through HC, reaching its minimum immediately prior to PC (Figure 24).

This appears to indicate a "rocker" phenomenon within the blade, such that its forward momentum was maintained as the stick pivoted about the toe at TC and then "rocked" upward (i.e. as heel makes contact with the ground the toe portion of the blade moved vertically upward) (Figure 35). During this phenomenon, the shaft maintained its downward displacement as it was deflected to store elastic energy that would later be transferred to the puck (Villaseñor-Herrera 2004). The rocker phenomenon will be discussed at greater length with respect to the global orientation of the blade in section 5.3.2. From PC to S-OFF the blade position remained constant at ~4.2 cm, while the shaft continued to increase its upward displacement.

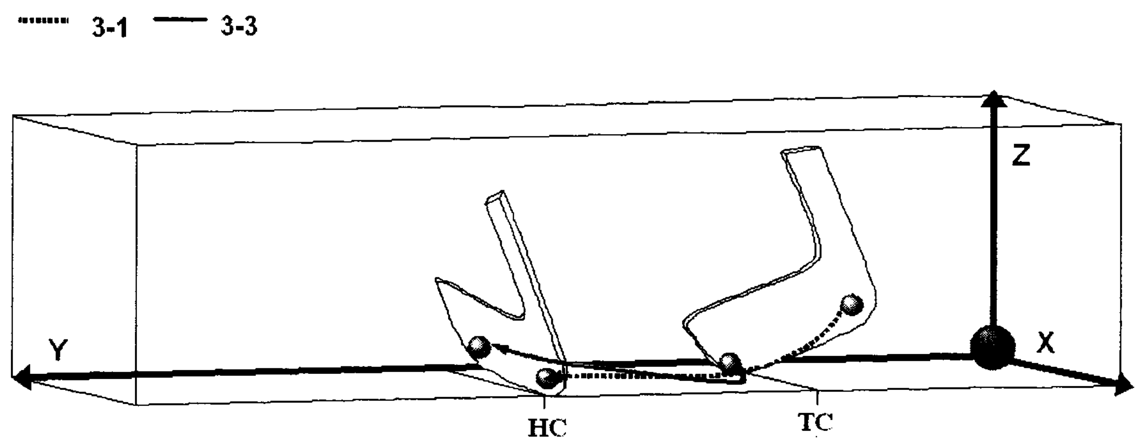

Figure 35 - Rocker phenomenon. TC and HC are marked, the origin is indicated by a sphere, and paths of toe marker (3-3) and heel marker (3-1) are indicated by solid and dashed lines, respectively.

During Δt_1, the stick experienced a linear increase in Z velocity, that for the blade portion peaked near HC and for the shaft peaked just after PC (at ~35% of shot) (Figure 27 C and Figure 28 C). From HC to S-OFF blade Z velocity remained relatively constant with a trend towards increasing immediately prior to S-OFF. Similarly, after peaking the shaft Z velocity remained constant post-PC; however, it tended to decrease at S-OFF.

The increase in stick Z velocity during Δt_1 was also accompanied by acceleration of the stick. As was the case with velocity, blade acceleration occurred from TC through HC (to ~12% of shot), while shaft acceleration persisted until well after PC (to ~ 40% of shot). From PC, the blade fluctuated from acceleration to deceleration, ultimately experiencing a positive acceleration at the S-OFF event. Similarly, the shaft experienced a brief period of deceleration post-PC, but ultimately demonstrated a positive acceleration at S-OFF. Unexpectedly, the REC group tended to demonstrate a greater final acceleration at the S-OFF event than the ELITE group.

Shaft and blade X displacement data demonstrated a significant negative correlation (Table 7), that initially appears counterintuitive given the single unit assumption. Mean displacement time graphs for these data appear to suggest that from TC to S-OFF the blade shifted away from the base of support (i.e. towards the origin), while the shaft shifted closer to the base of support. Thus, indicating that while the stick was in contact with the ground, the blade slid onto its heel (i.e. away form the player's base of support), effectively increasing the stick's lie angle, which my be an underlying function of the rocker effect (Figure 36). Overall, stick X velocity tended to decrease during Δt_1 and then increase steadily from HC through S-OFF. Similarly, the stick tended to decelerate in the X direction during Δt_1 and then increase linearly throughout the remainder of the shot.

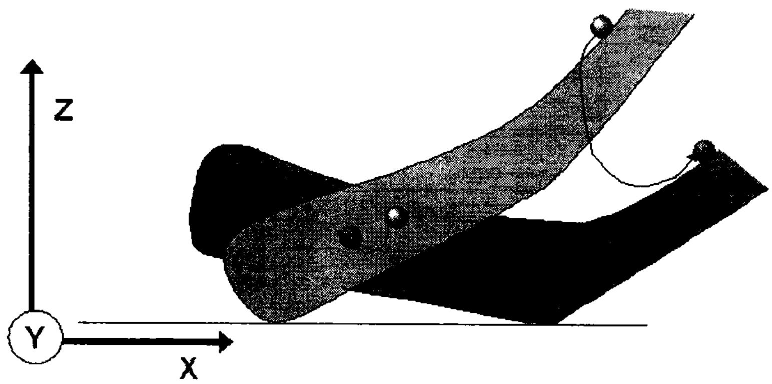

Figure 36 - Example shift in blade (2-2) and shaft (S1) X displacement from TC to HC, as a function of the "rocker" phenomenon.

5.3 Temporal Phases

Proper timing and sequencing of movements has long been recognized as an essential component in successful striking tasks (Caljouw et al., in press; Hamilton & Luttgens 2002). Yet, the overall joint sequencing patterns and the exact timing parameters between the stick and puck within the ice hockey slap shot have remained largely unstudied until recently. Woo (2004) provided a preliminary investigation into the sequencing of joint movements during a stationary slap shot, and was able to quantify an apparent proximal-to-distal joint sequence that had previously only been alluded to in qualitative descriptions (Emmert 1984; Falconer 1994; Hayes 1965). Similarly, recent investigations have begun to examine timing parameters between the stick and puck; these include: time to peak force (Pearsall et al. 1999), time from initial ground contact to puck contact (Polano 2003), and duration of puck-blade contact (Polano 2003; Villaseñor-Herrera 2004). However, the present study is the first attempt to provide a detailed temporal analysis of all of the impact events associated with the blade during the stationary slap shot.

Significant differences between skill groups in the duration of each of the three phases of the slap shot were apparent in terms of both absolute time (i.e. in seconds) and percentage time of total shot (Figure 34). The ELITE group's greater blade velocities accounted for significantly shorter Δt_1 than the REC group in all directions (Figure 27 A, B, and C).

The same pattern held true for Δt_2, where the ELITE group reached PC in only 0.014 s (29 % of shot) as compared to the REC group which took 0.017s (39% of shot) to reach the same event (Figure 34). These values are comparable to those reported by Polano (2003) who reported a mean of three skilled shooters of 19 ms (or 0.019 s) for the same phase of a stationary slap shot performed on ice.

The final phase, Δt_3, was significantly longer in the ELITE group (e.g. 0.027 s or 58% of shot) than in the REC group (e.g. 0.024 s or 53% of shot) (Figure 34). Doré and Roy (1976) reported a longer duration of stick-ground contact (40 ms or 0.040 s) during a slap shot; however, this study may have been somewhat limited by its use of two-dimensional kinematic data to identify some temporal events.

While the introduction of signal drift in the accelerometer data prevented the accurate identification of the exact moment the puck left the blade, other authors have reported this data. Polano (2003) reports a total puck-blade contact time of 35 ms in skilled shooters; however, Villaseñor-Herrera (2004) measured the same value with a larger number of subjects and a higher sampling frequency and obtained substantially longer contact time of 44 ms in skilled shooters.

5.4 Global Angles

There are three primary factors that influence the final direction of the puck once as it leaves the blade, they are: 1) the direction of the blade prior to, during, and immediately following impact; 2) the orientation of the blade relative to this direction; and 3) frictional interactions between the surface of the blade and puck during impact (adapted from

Williams & Sih 2002). Thus far, the linear kinematics has described the direction of both the blade and shaft in great detail from initial TC to S-OFF; while frictional interactions were beyond the scope of the present study and will not be discussed. The third and final factor, blade orientation, will be addressed in the forthcoming section. Global blade orientation will be expressed through a series of angle (described previously in Section 3.5.2).

5.4.1 Loft Angle

The loft angle was measured between a segment from markers 1-2 and 3-2 and the global transverse plane, where an increasing angle (i.e. 1-2 moves away from the puck) is termed "opening" of the blade and a decreasing angle is termed "closing" of the blade (Figure 37, A & B, respectively). At TC, the ELITE group maintained a significantly more closed blade position than the REC group (Table 14 and Figure 32 C).

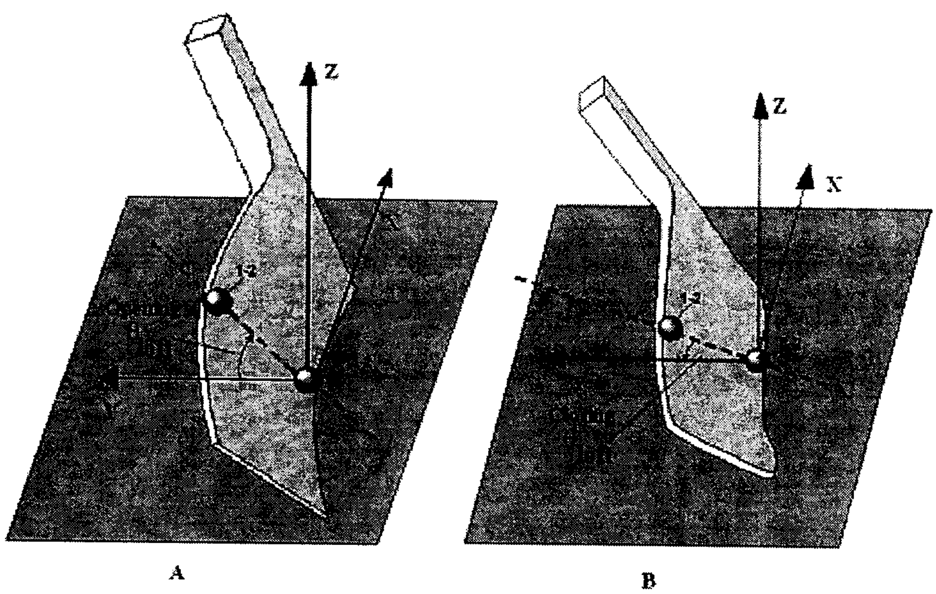

Figure 37 – Opening loft angle (A) and closing loft angle (B).

From TC through HC the blade opens until it reaches its maximum loft approximately midway between HC and PC. This trend was consistent between groups; however, the ELITE group utilized a greater range of loft (13°) that the REC group (6°), which suggests an increased rolling of the wrists (i.e. combination of flexion/extension and pronation/supination) to open the face of the blade. This coincides with early, and primarily qualitative, descriptions of the slap shot that highlight the importance of the wrist snap, where as the stick moves from backswing to downswing the top wrist shifts from supination to extension and the lower wrist shifts from pronation to flexion (Alexander et al. 1964; Alexander et al. 1963; Emmert 1984; Hayes 1965). The wrist snap is thought to help increase puck acceleration by maintaining blade-puck contact, and allowing the frictional force between that develops between the blade and the puck to accelerate the puck into rotation (Falconer 1994; Therrian & Bourassa 1982).

From its maximum loft, both groups began to close the blade as it approached PC; however, at PC the ELITE group displayed a significantly smaller angle than the REC group. This seems to suggest that the ELITE group was able to accomplish a much greater wrist snap than the REC group (Figure 32 C). Once the wrist snap was completed, the blade began to open again. This opening continued through to S-OFF as the puck rolled along the length of the blade (Simard et al. 2004).

5.4.2 Face Angle

The face angle was measured between a segment from markers 2-1 and 2-3 and the global frontal plane, such that when the blade is ahead of the shaft (i.e. is in front of the projected global frontal plane) the angle is positive and when the blade is positioned behind the shaft (i.e. behind the projected global frontal plane) the angle is negative (Figure 38, A and B, respectively). At TC, the ELITE group tended to display a slightly positive face angle, while the REC group positioned their blade closer to a neutral (i.e. blade and shaft in line along the projected global frontal plane) position (Figure 32 B).

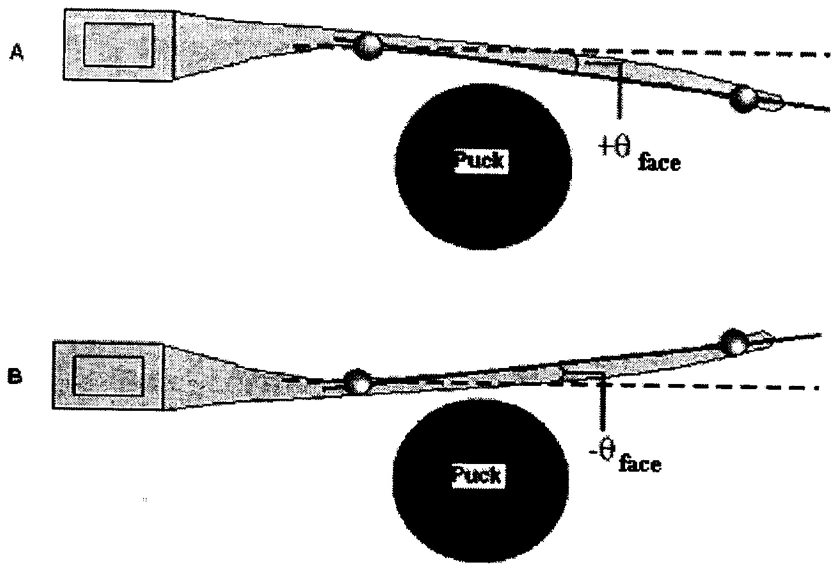

Figure 38 – Illustration of positive (+θ_{face}) and negative (-θ_{face}) face angles. The dotted line represents the global frontal plane.

Overall throughout the Δt_1 phase, both groups decreased face angles to -4° and -2° for the ELITE and REC groups, respectively. Both groups maintained this negative blade orientation through HC, reaching a minimum value at ~15% of shot. From this minimum, the blade shifted towards a positive orientation, reaching positive face angle at ~25% of shot, immediately prior to PC. The face angle continued to increase in the positive direction through PC until it reached its maximum value, near 40% of shot. The overall range of face angle was significantly greater in the REC group. This may be an indication of a greater overall X excursion in the REC group. However, since horizontal distance between the feet and the puck was not standardized between subjects there was too much variability between subjects to accurately discern this.

After, reaching its maximum face angle approached a neutral position, which eventually became increasingly positive through S-OFF as the stick began to enter follow-though. Initially, it was hypothesized that the amount of opening/closing of the blade would be a function of the individual blade construction properties; however, NSD were found between stick models in this investigation.

5.4.3 Tilt Angle

The most substantial differences in blade orientation between skill groups occurred in tilt. The tilt angle was defined as the angle between the segment from 2-1 to 2-3 as projected onto the global transverse plane, such that when the heel portion of the blade is higher than the toe the angle is positive and when the toe portion is higher than the heel , the angle is negative (Figure 39).

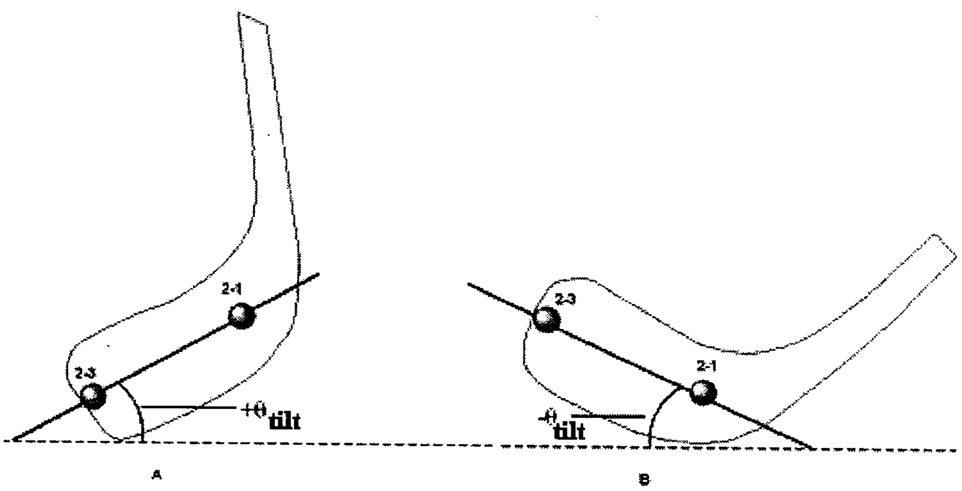

Figure 39 – Illustration of positive ($+\theta_{tilt}$) versus negative ($-\theta_{tilt}$) tilt angles. The dotted line represents the global transverse plane.

As earlier linear kinematic data and previous research suggests, the toe end of the blade tends to make contact with the ground first (Polano 2003); so, it was not surprising that at TC both groups displayed a positive tilt. However, the ELITE group tended to demonstrate a significantly greater tilt angle than the REC group. As the blade moved to HC, tilt became progressively more negative; thus, indicating that the heel portion of the blade was making ground contact. The combined shift from positive face and tilt angle at TC to negative face and tilt angle at HC seems to indicate that upon stick-ground contact the blade pivoted about the toe and translated forward (i.e. toward the target in the Y direction) as the heel shifted vertically downward to make ground contact. HC ultimately resulted in the toe portion of the blade shifting vertically upwards as the blade "rocked" about the heel (Figure 35 and Figure 36).

This phenomenon was further quantified through the vertical change in displacement of the heel and toe portions of the blade. During the initial Δt_{I} phase, the total change in vertical displacement of the heel portion of the blade was significantly greater in the ELITE group (Table 10). This apparent continued downward momentum in ELITE shooters may represent the beginning of a more efficient (i.e. longer) loading phase identified by other authors (Roy et al. 1974; Villaseñor-Herrera 2004), which is marked by increased translational components of acceleration of the stick (Woo 2004).

Following the rocker phase, blade orientation varied dramatically between skill groups. The ELITE group maintained an increasingly negative tilt through HC to it minimum value at ~ 20% of shot (i.e. midway between HC and PC), at which point the orientation shifted to become increasingly positive through PC and towards its maximum (~80% of shot). From its maximum tilt (i.e. 10°) the ELITE groups' values became increasingly less positive through S-OFF. However, the REC group maintained and an increasingly negative tilt through HC and PC to a minimum value at ~50% of shot, where the orientation shifted to a positive maximum value at S-OFF.

Overall the substantially greater range of tilt angle demonstrated by ELITE subjects (particularly during Δt_{I}), seems to be indicative of their ability to better utilize the rocker phase. However, the question of whether or not this effect can produce a superior shot remains a subject for further investigations.

5.5 *Overview of Blade Function*

In Figure 21, panels A through D shows an overtrace of the movement path of the blade during a typical trial from several different angles. Panels A and B appear to confirm earlier observations that the path of the stick from the top of the backswing to initial ground contact is primarily pendular in nature (Polano 2003; Woo 2004), similar to a golf swing (Mason et al. 1992; Neal 1983; Whittaker 1999). However, once the toe contacts the ground the blade's movement path shifts dramatically in all directions. The blade's sagittal

(YZ) plane movement becomes more linear (or translational) (Figure 21 C and D) (Woo 2004) and it shifts away from the base of support in the X direction (Figure 21 A). Thus, suggesting that the previously described rocker phase is an important transition phase between the primarily rotational acceleration of the stick in downswing and the primarily linear acceleration of the stick during loading (Woo 2004).

As such, it appears that the rocker phase is at least partially a function of the stick's geometry (particularly the lie angle). That is, with all other variables being equal, increasing the lie stick's lie angle should result in an earlier TC event and longer Δt_1, Δt_2, and Δt_3, thereby potentially increasing puck-blade contact time and consequently, puck velocity (Villaseñor-Herrera 2004). Conversely under the same conditions, decreasing the lie angle would theoretically result in a later TC event and shorter Δt_1, Δt_2, and Δt_3, phases; potentially decreasing puck-blade contact time and puck velocity. However, since lie angle was not a dependent variable in this study, these hypotheses remain a subject for future investigations.

Additionally, the exact purpose of loading the stick from toe to heel remains unknown. To date, this pattern has only been documented in one other study (Polano 2003) where lie angle was not reported. Since the lie angle was kept constant in the present study, it is impossible to determine if this pattern holds for other stick geometries. One might expect that as the lie angle decreased (i.e. approached 90°) the point of initial blade-ground contact would shift towards mid-blade, possibly eliminating rocker phase in extreme cases. Conversely, the TC event may also be an intentional technique employed by players to: help dampen vibration harmonics upon stick-ground contact (Irvine 2004; Merkel & Blough 1999; Roberts et al. 2005) or to improve shot accuracy by providing players with some proprioceptive feedback (Falconer 1994).

CHAPTER 6 - CONCLUSIONS

The current study has provided a comprehensive examination of the blade's three-dimensional response during the slap shot. Contrary to popular and industry opinion, the different construction parameters of blades currently on the market did not alter the blade's response (either positively or negatively) during the slap shot. The results were consistent with previous examination of shaft construction, demonstrating NSD in performance variables (Doré 1978; Marino 1998; Pearsall et al. 1999; Roy & Doré 1975; Roy & Doré 1979; Roy et al. 1974; Wu et al. 2003). However, these analyses identified a unique rocker phase within the execution of the slap shot, demonstrated by both elite and recreational groups. Within the rocker phase, elite shooters tended to alter timing parameters (i.e. phase length), magnitude of linear variables (i.e. displacement, velocity and acceleration), and the overall blade orientation that may correspond to higher puck velocity. As such, these findings provoke a series of additional research questions relevant to design engineers, as well as coaches and athletes.

Future studies should attempt to address the role and purpose of this phase to determine if it is merely a function of the geometric constraints (e.g. lie angle or blade curvature) of the stick or if it has performance enhancing characteristics. For instance, when combined with translational acceleration and blade torsion (Therrian & Bourassa 1982; Woo 2004), might the rocker phase be used to generate increased torque about the stick and ultimately increase the energy transferred to puck, increasing velocity (Villaseñor-Herrera 2004) and, if so, might changes in lie angle improve this energy transfer? Once a better understanding of the rocker phase's role, or lack thereof, in a successful slap shot is achieved, manufacturers and designers will be better equipped to develop products that maximize or minimize the phase as necessary.

The methodologies employed in the present study demonstrated several strengths in terms of instrumentation and consistency of results for the measurements presented. Measurement error was calculated to be ~ 0.2 cm; however, some experimental limitations did exist and should be noted. For instance, the polyethylene sheets that served as the shooting surface do not exactly mimic on-ice conditions or frictional coefficients; the puck used was both at room temperature and as such may have responded slightly differently than the frozen pucks used in game situations; the subjects only performed stationary slap shot, as opposed to the skating slap shots used in games; whole shaft kinematics were not examined; and subjects did not wear full hockey gear, only gloves.

As such, several methodological improvements could be made for future studies; including, utilizing a larger sample size and standardizing the horizontal distance from the feet to the puck in order to reduce between subject variability and improve statistical power. Also, improving the grounding the accelerometer circuit to reduce signal drift would provide a definitive definition of total puck-blade contact time and a description of the blade's role in accelerating the puck. The ability to employ a system with a similar resolution and a larger field of view, such as the VICON™, would allow a more thorough examination of the sticks motion pre- and post-ground contact. Also, employing such a system at a higher sampling frequency may also increase resolution enough to accurately record the torsional response of the lower shaft and blade.

Similarly, the use of a higher sensitivity, triaxial accelerometer within the puck would provide detailed puck acceleration profiles that could be used to determine the precise moment the puck leaves the blade, energy transfer, and impulse between the puck and blade. The recent inclusion of wireless technology in accelerometer design (e.g. http://www.techkor.com/industrial/accel.htm or http://www.microstrain.com/g-link.aspx) may also allow researchers to eliminate cumbersome cables in this type of investigation; thus, providing a more natural puck response and allowing researchers to address question of puck movement and accuracy within various hockey shots.

Additionally, the fundamental question of the role of blade construction in the execution of the slap shot could be more effectively analyzed using a greater variety of sticks. The present study limited itself to those commercially available, which must conform to strict NHL guideline in terms of dimensions, and material properties. Yet using comparing samples with extreme differences in stiffness properties, geometric dimension, lie angles, etc could provide more useful insight into the blades function in a slap shot.

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APPENDIX B – INFORMED CONSENT FORM

This is to state that I, , agree to participate in the research project entitled: **Three dimensional blade dynamics during shooting in ice hockey**.

And conducted by: Karen Lomond & Dr. David Pearsall of McGill University
(Names of the researcher or group, researcher's supervisor (if applicable) and institution)

1. ***Purpose*** – To examine the three dimensional bending and torsion properties in hockey stick blades of varying stiffness during a stationary ice hockey slap shot

2. ***Procedures*** – Your participation in this study is completely voluntary, and as such, you are free to discontinue your participation at any time, without negative consequences. Your name will not be recorded on any of the data obtained; only a number will identify you. The data collected will be stored safely and securely and will not be viewed by anyone other than the researcher without your specific consent. You will be asked to use three prototype carbon-fibre hockey sticks, each having different blade stiffness co-efficient and fitted with multiples reflective markers, to take 5 slap shots with an instrumented hockey puck. During each shot the blade and lower shaft of the stick will be filmed with 2 high-speed video cameras. Following this data collection all data will be downloaded onto a computer and analyzed by the researcher.

3. ***Conditions of Participation*** – Participants will be asked to report to the biomechanics lab with their hockey gloves at a scheduled testing time to be familiarized with the testing procedure and equipment. At this time they will have five minutes to warm-up. Following the warm-up, participants will be asked to take 5 slap shots the abovementioned instrumented hockey sticks and puck. Participants will be asked to take a minimum of thirty second breaks between each shot. The testing process will be scheduled at the participant's convenience wherever possible.

By signing below, you indicate the following:

- I understand the purpose of this study and know about the risks, benefits and inconveniences that this research project entails.
- I understand that I am free to withdraw at anytime from the study without any penalty or prejudice.
- I understand that this research will not affect my grades or evaluation of my work.
- I understand how confidentiality will be maintained during this research project.
- I understand the anticipated uses of data, especially with respect to publication, communication and dissemination of results.

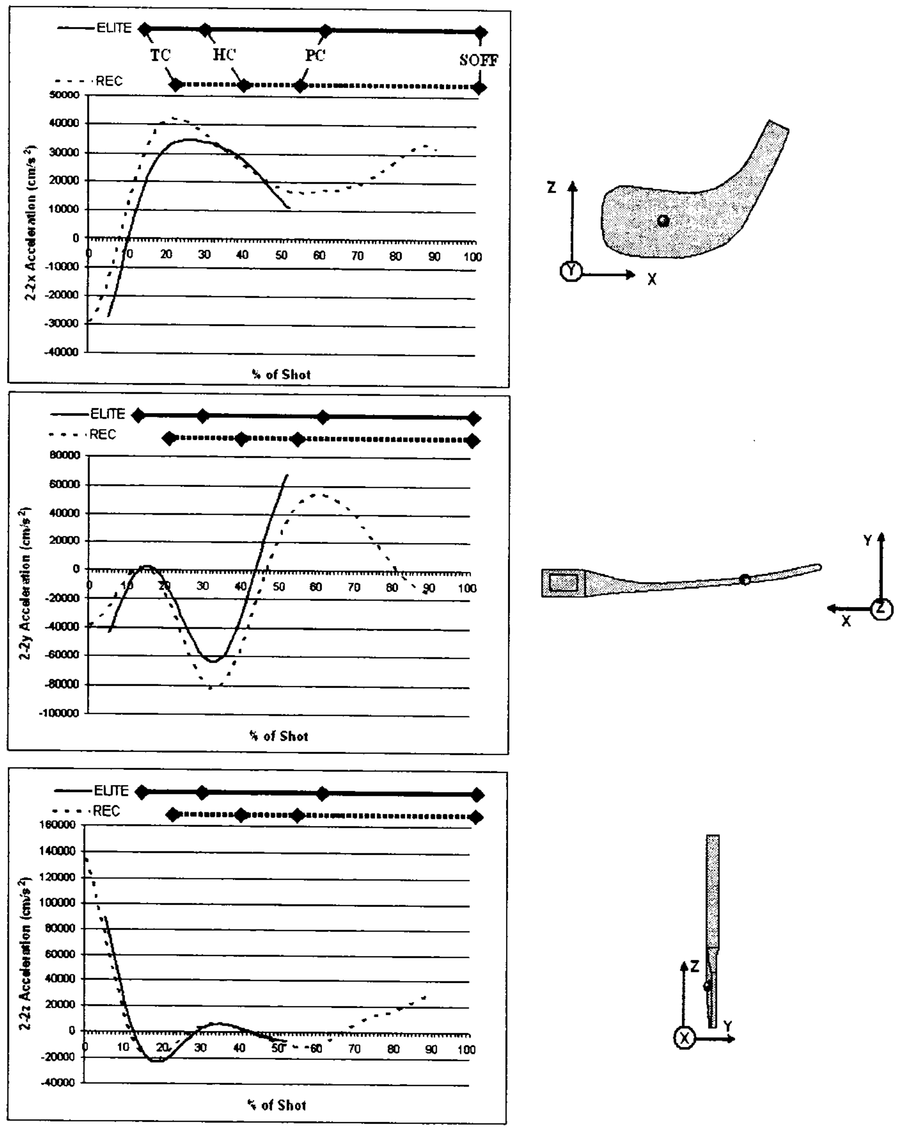
I have read the above and I understand all of the above conditions. I freely consent and voluntarily agree to participate in this study.

Name (please print) ______________________________

Signature ______________________________ Date ____________________

APPENDIX C – ADDITIONAL DATA

Blade Acceleration



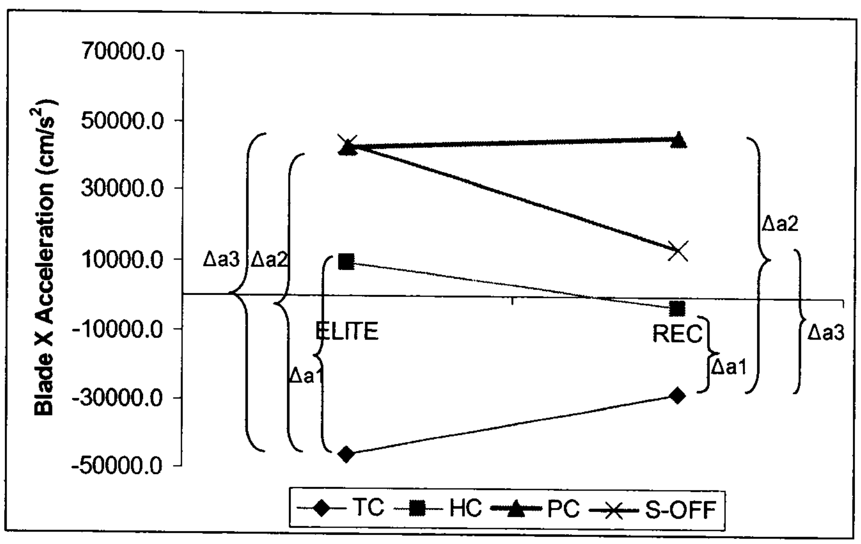
Mean acceleration (cm/s2) of marker 2-2 in the X, Y, and Z components over time for each skill group. Vertical line represents events of TC, HC, PC, and S-OFF; while the shaded regions represent the phases of toe-to-heel contact, blade-puck contact, and stick-ground contact. Minimum, maximum and range are marked as indicated. Statistical significance is denoted by * ($p < 0.05$) and ** ($p < 0.01$).

Mean component of acceleration (cm/s^2) of marker 2-2 at each event. Statistical significance is denoted by ** (p< 0.01) and * (p< 0.05).

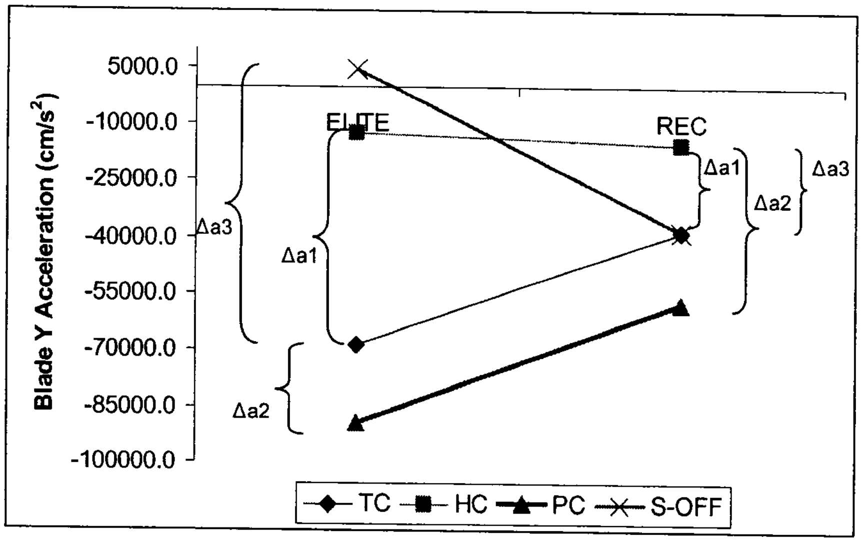
Acceleration (cm/s^2)		TC Mean	TC SD	HC Mean	HC SD	PC Mean	PC SD	S-OFF Mean	S-OFF SD
2-2x	ELITE	**-46266.9	19183.2	*9328.0	20556.6	42612.2	18400.9	**43794.6	19678.8
	REC	-28303.4	29744.0	-3310.8	32479.6	45767.3	20054.7	13489.8	28147.8
2-2y	ELITE	**-68467.5	29150.8	**-12379.2	36569.2	-89207.5	40632.1	**4504.3	57737.9
	REC	-38404.7	31208.0	-15387.6	32092.6	-57607.9	45239.1	-38356.6	52119.4
2-2z	ELITE	**158413.9	40861.0	**14417.1	28080.0	-2754.1	20534.1	35659.3	24442.7
	REC	132386.9	40106.5	59641.2	55642.4	-6317.7	18773.0	44920.3	28178.0

Mean change in blade acceleration (cm/s^2) during each phase. Significance is denoted by * (p< 0.05) and ** (p< 0.01).

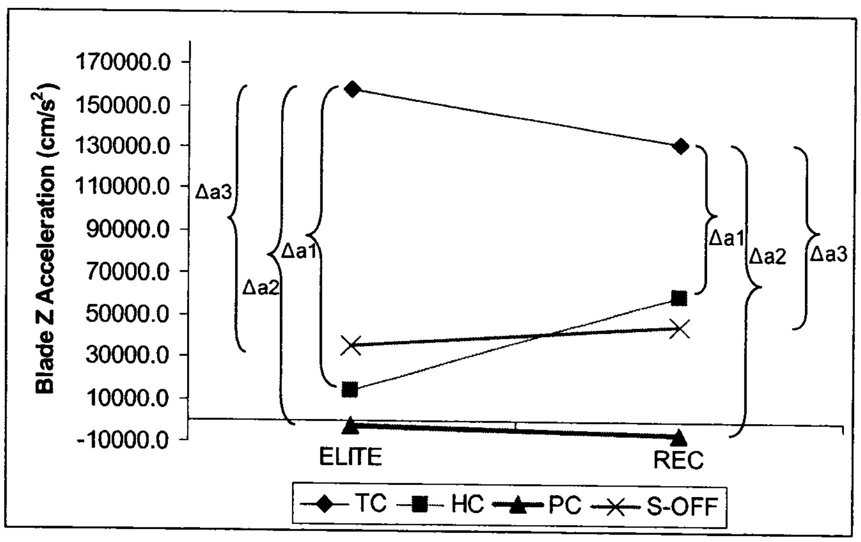
Acceleration (cm/s^2)	Δt1 ELITE	Δt1 REC	Δt2 ELITE	Δt2 REC	Δt3 ELITE	Δt3 REC
2-2x	**55594.9	24992.6	*88879.0	74070.7	**90061.5	41793.2
2-2y	**56088.4	23017.1	74070.7	-20740.0	**41793.2	72971.8
2-2z	**-143996.8	-72745.7	*-20740.0	-19203.2	**72971.8	48.1



Mean X blade acceleration (cm/s^2) at each event for each skill group and the total mean change (Δa1, Δa2, Δa3) between events.

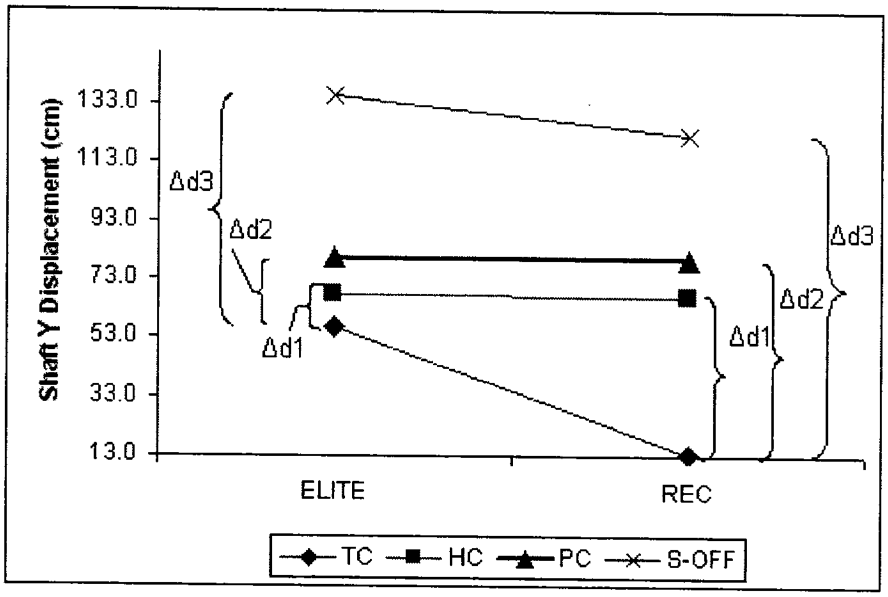


Mean Y blade acceleration (cm/s²) at each event for each skill group and the total mean change (Δa1, Δa2, Δa3) between events.

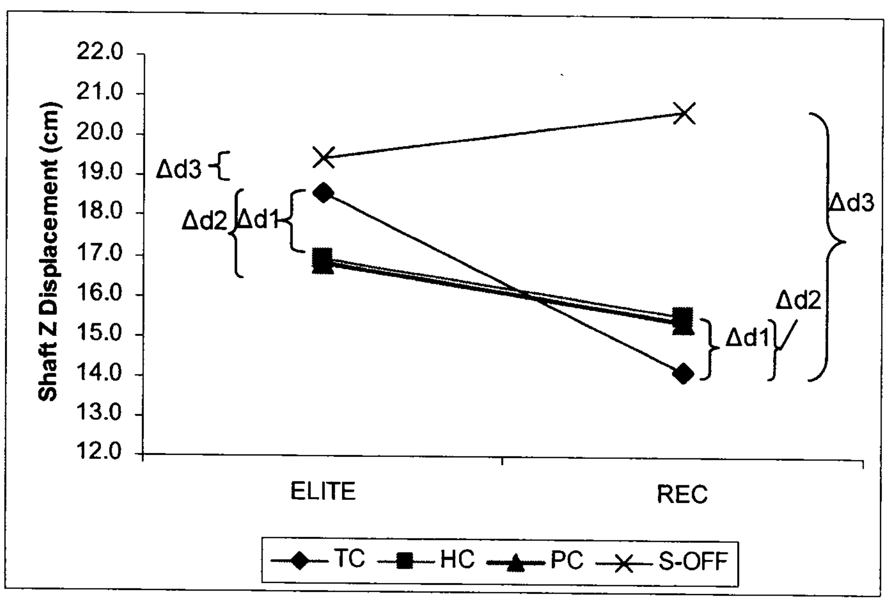


Mean Z blade acceleration (cm/s²) at each event for each skill group and the total mean change (Δa1, Δa2, Δa3) between events.

Shaft Y and Z Displacement

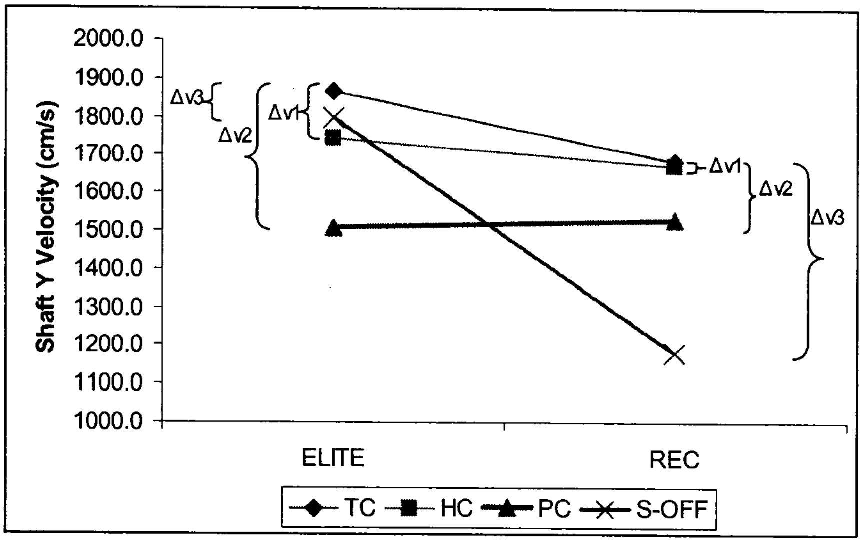


Mean Y shaft displacement at each event for each skill group and the total mean change (Δd1, Δd2, Δd3) between events.

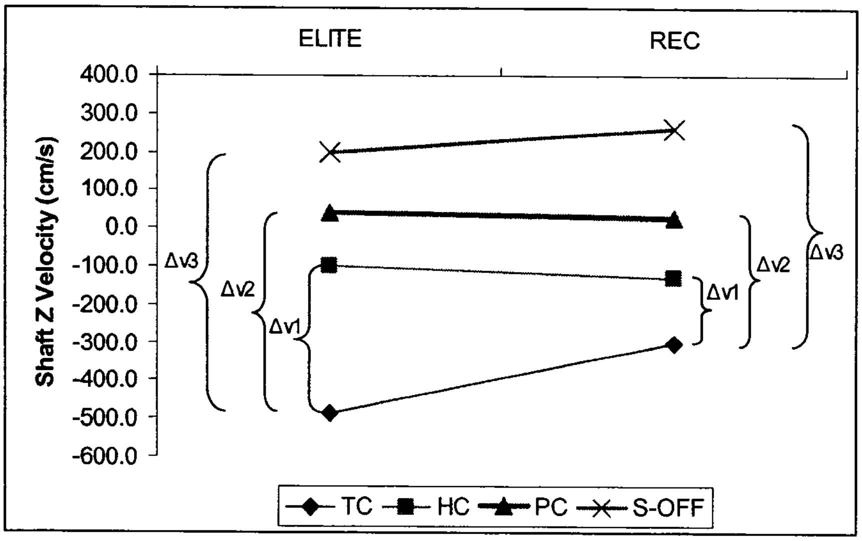


Mean Z shaft displacement at each event for each skill group and the total mean change (Δd1, Δd2, Δd3) between events.

Shaft Y and Z Velocity



Mean Y shaft velocity (cm/s) at each event for each skill group and the total mean change (Δv1, Δv2, and Δv3) between events.

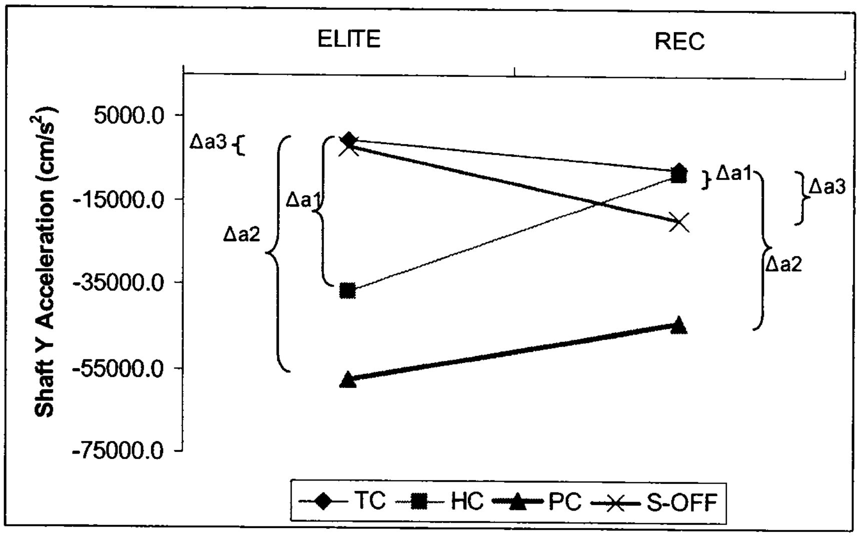


Mean Z shaft velocity (cm/s) at each event for each skill group and the total mean change (Δv1, Δv2, and Δv3) between events.

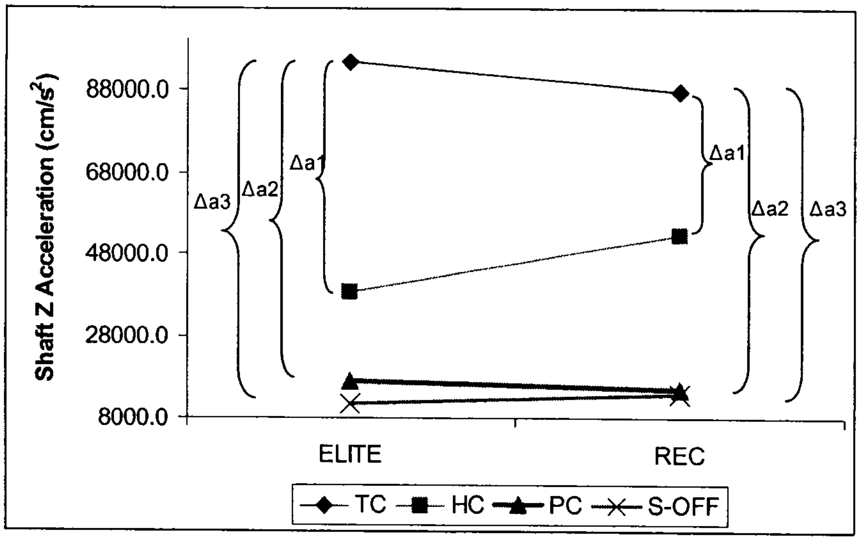
Mean and standard deviations of shaft Y and Z displacement (cm) and velocity (cm/s) at each temporal event (TC, HC, PC, adn S-OFF). Significant differences between skill groups are denoted by * (p<0.05) and ** (p<0.01).

			TC		HC		PC		S-OFF	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Displacement (cm)	S1y	ELITE	56.4	17.7	67.5	18.0	80.3	15.2	*135.8	18.2
		REC	13.9	10.4	67.0	15.9	79.9	16.7	122.4	18.4
	S1z	ELITE	*18.6	3.6	16.9	3.4	16.8	3.5	19.5	3.7
		REC	14.1	6.6	15.5	4.1	15.4	4.3	20.6	4.8
Velocity (cm/s)	S1y	ELITE	**1864.9	105.7	1743.9	109.6	1509.9	148.7	**1798.0	153.5
		REC	1684.8	255.7	1672.8	227.8	1529.4	253.7	1180.2	350.6
	S1z	ELITE	**-486.2	205.6	-100.6	73.9	39.5	68.6	*198.1	92.8
		REC	-300.3	105.7	-128.9	103.4	26.7	80.8	259.3	68.1

Shaft Acceleration



Mean Y shaft acceleration (cm/s^2) at each event for each skill group and the total mean change (Δa1, Δa2, Δa3) between events



Mean Z shaft acceleration (cm/s^2) at each event for each skill group and the total mean change (Δa1, Δa2, Δa3) between events.

APPENDIX D - SUMMARY OF STATISTICAL RESULTS

ANOVA Summary of all Effects			
	df 1	df 2	p-level
SKILL	2	83	0.0001
STICK	10	166	0.3808
SKILL*STICK	10	166	0.8327

Puck Contact Location:

Tukey HSD Test (PUCK CONTACT)		
Probabilities for Post Hoc Tests	ELITE	REC
Mean	5.26	5.23
ELITE		0.7378
REC	0.7378	

Unequal N HSD (PUCK CONTACT)						
Probabilities for Post Hoc Tests	CCM	CTC	SIC	STE	VXX	VXXX
Mean	5.19	5.08	5.22	5.42	5.40	5.19
CCM		0.9866	0.9999	0.7083	0.7839	1.000
CTC	0.9866		0.9581	0.3068	0.3788	0.9866
SIC	0.9999	0.9581		0.8175	0.8773	0.9999
EAST	0.7083	0.3068	0.8175		1.000	0.7083
VXX	0.7839	0.3788	0.8773	1.000		0.7839
VXXX	1.000	0.9866	0.9999	0.7083	0.7839	

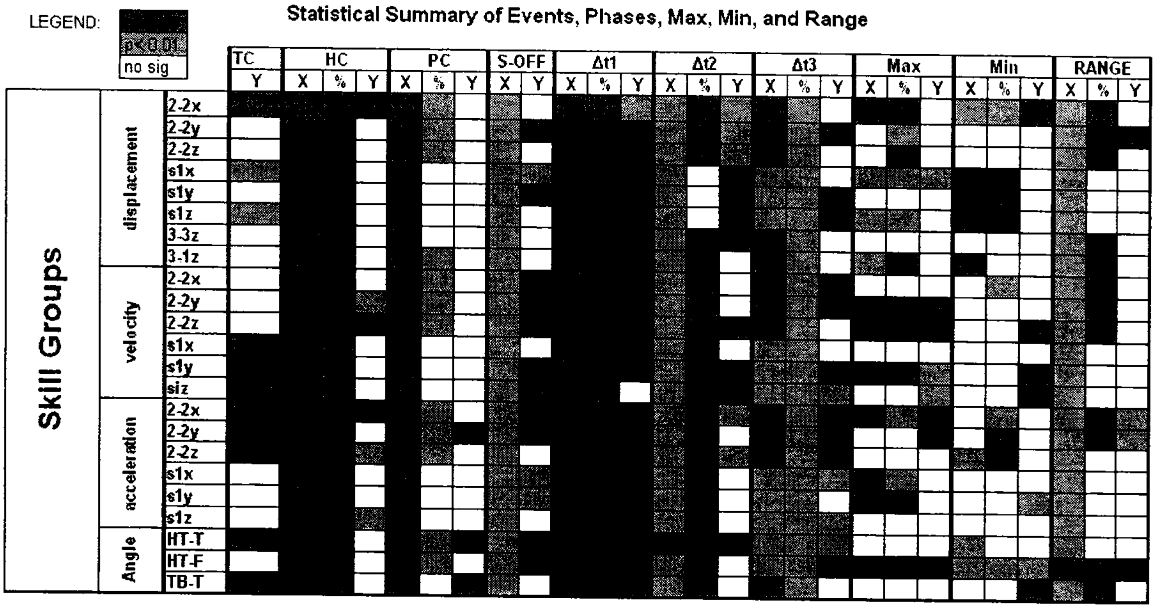
Puck Velocity:

Tukey HSD Test (VELOCITY)		
Probabilities for Post Hoc Tests	ELITE	REC
Mean	73.67	66.85
ELITE		0.00013
REC	0.00013	

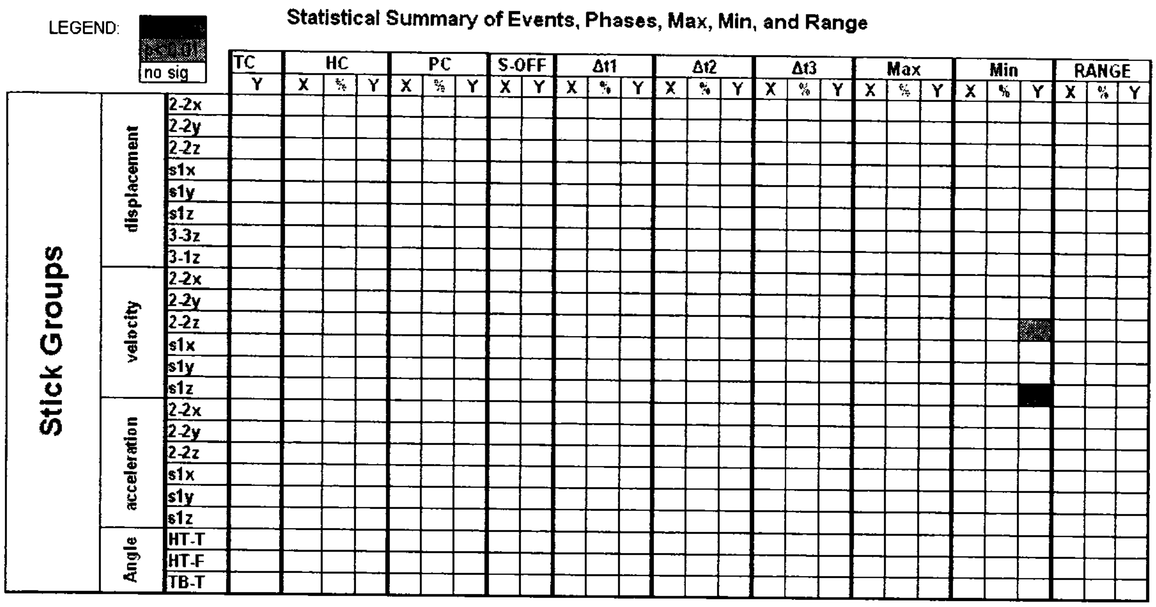
Tukey HSD test (VELOCITY)						
Probabilities for Post Hoc Tests	CCM	CTC	SIC	STE	VXX	VXXX
Mean	72.04	67.44	68.84	70.36	72.19	70.71
CCM		0.4806	0.8152	0.9865	1.000	0.9954
CTC	0.4806		0.9941	0.8659	0.4450	0.8011
SIC	0.8152	0.9941		0.9915	0.7854	0.9784
EAST	0.9865	0.8659	0.9915		0.9805	1.000
VXX	1.000	0.4450	0.7854	0.9805		0.9925
VXXX	0.9954	0.8011	0.9784	0.9999	0.9925	

Kinematic Data:

Statistical summary of skill effects for events, phases, max, min, and range.

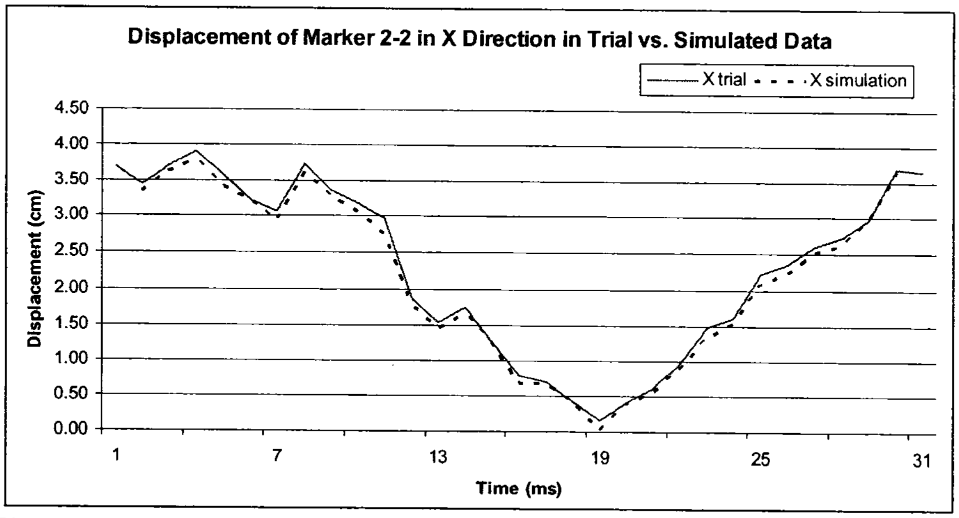


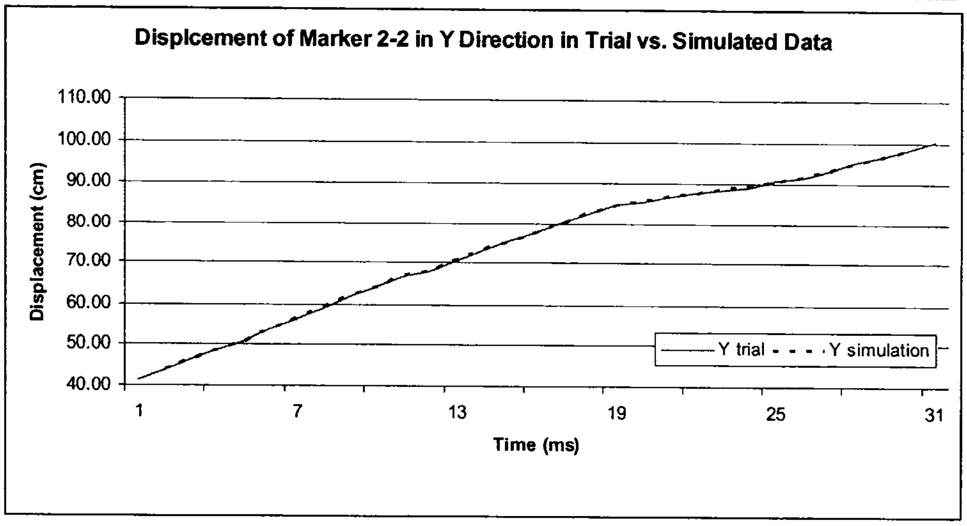
Statistical summary of stick effects for events, phases, max, min, and range.

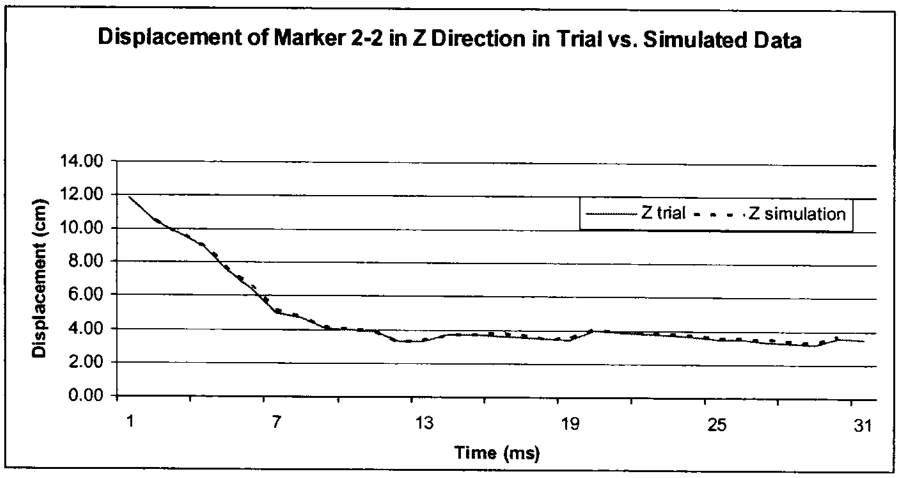


APPENDIX E – MEASUREMENT UNCERTAINTY & RELIABILITY DATA

Measurement Uncertainty







Intra-reliability