The Performance of the Ice Hockey Slap and Wrist Shots: The Effects of Stick Construction and Player Skill

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Definitions

1 RM: 1 repetition of maximum muscle exertion on a specific weight load.

Attacking angle: The angle between major axis of the stick and ground during the impact with the puck.

Backswing: The stick is raised backward from behind the puck to the highest point over the shoulders.

Bending angle: Stick shaft deformation in the minor axis during the impact with the puck.

Deflection: The distance of stick shaft deformation in the minor axis during the impact with the puck.

Downswing: The stick is swung forward from the highest point over the shoulders to the impact with the ground.

Follow through: The phase when the stick is off the ground and continuously decelerates forward until the end of swing movement.

Impact: The instant contact point between the blade and the puck.

Loading: The maximum bending and torsion occur on the shaft of the stick during the impact between the stick and the puck.

Peak velocity: The maximum velocity of the puck before it enters the net.

Pre-loading: The initial impact between the stick and the ground.

Release: The moment when the puck is propelled by the stick.

Shaft stiffness: Linear deformation of the shaft in the minor axis on the stick by the static three point bending test.

Slap shot: A type of shooting technique that is able to produce the maximum puck velocity in ice hockey.

Wrist shot: A type of shooting technique that is able to produce the maximum accuracy in ice hockey.

Abstract

This thesis was to examine the interaction of players' skill level, body strength, and various types of stick construction and stiffness on the performance of the hockey shots. Forty subjects were tested, and each subject performed the slap and wrist shots with different stick shaft constructions and stiffness. Shot mechanics were evaluated by simultaneously recording of ground reaction forces, stick movements and peak puck velocity. Data analyzed with a 4-way ANOVA for several dependent variables. The results indicated that: 1) the slap shot was faster than the wrist shot corresponding to greater vertical force, stick bending and hand placement; 2) the puck velocity was influenced by skill level and body strength not stick type; and, 3) the skilled players generated greater vertical force and stick bending by adjusting their hand positions. Further studies are needed to address the specific stick material and construction properties.

Résumé

Cette étude a pour but d'examiner l'interaction entre la maîtrise technique, la force physique des joueurs, le type de fabrication et la rigidité des bâtons sur la performance des lancers frappés et tirs du poignet au hockey sur glace. Quarante sujets masculins et féminins ont été testés. Outre les tests de force des membres supérieurs, chaque sujet a exécuté les lancers frappés et les tirs des poignets à l'aide de trois manches de bâton de fabrication et de rigidité différentes. Les mécaniques des lancers ont été évaluées en enregistrant simultanément les forces de réaction au sol à l'aide d'un piston de compression, le mouvement et la courbure du bâton en filmant à haute vitesse, et la vitesse de pointe de la rondelle à l'aide d'un vélocimètre de lancers. Les données ont été soumises à l'analyse de la variance (4-way ANOVA. Il ressort que : 1) le lancer frappé est beaucoup plus rapide que le tir des poignets, ce qui correspond à une force de charge verticale supérieure, à une courbure du bâton supérieure et à un écart entre les mains supérieur; 2) la vitesse de la rondelle est influencée par le degré de maîtrise technique et la force physique et non pas par le genre de bâton et 3) les joueurs et joueuses techniques sont capables de produire une plus grande force verticale et courbure du bâton en partie en ajustant la position des mains sur le bâton. Il faudrait effectuer d'autres études pour examiner l'influence particulière de la maîtrise technique et de la force physique sur les techniques de ces lancers et par rapport aux matériaux et aux caractéristiques de fabrication du bâton.

Chapter 1: Introduction

1.1 Nature and Scope of the Problem

Over the decades, sport awareness and popularity have increased both in the local and international levels. Today, many young athletes or players pursue professional sports to make millions of dollars in salary. Therefore, the goal has become extremely competitive and challenge; hence, athletes or players must seek every possible winning edge that they can obtain in various aspect such as in physiology, psychology, nutrition, facility and equipment. Equipment has been a vital part of the success because it has evolved greatly in the last several years. For example, in softball and baseball, players used to play with bats that were constructed with a single layer of aluminum. However in the last couple of years, several manufactures have designed bats with aluminum alloy material plus a Z-core inside the bat to increase the "springing" effect which allows the ball to travel further. Recently, some manufactures have improved the bat's durability performance by increasing up to two or four layers of wall in the bat. Moreover, in golf, golf players used to play with the stainless steel golf clubs; then later on the manufactures replaced them with graphite shaft for better performance. Today most of golf clubs are made of titanium-head because it can greatly reduce the stress and vibration at the impact. In result, a golf ball can travel further and with more accuracy. Inevitably, ice hockey equipment has changed to enhance the performance as well, and ice hockey sticks are no exceptions. Initially, hockey sticks were made of wood, but in order to increase their durability, the manufactures had designed sticks with aluminum material.

Currently, certain manufactures have designed sticks with composite material to improvement shot velocity in performance. However, the dynamic stick shaft responses during the impact of the shot are still unclear; therefore, more researches are needed to address in this area.

1.2 Significance of the Study

In ice hockey, coaches and players constantly try to find a way to improve their performance, and this can be seen from the local community hockey leagues up to Olympics, world championships and professional leagues. The expectations of the newer hockey equipment have increased enormously. The manufactures have used modern technology to design the highest quality equipment to help the coaches and players for performance improvement, and hockey sticks are no exceptions. In the game of ice hockey, the hockey stick is a vital piece of equipment because it is used for shooting, passing, and stick handling in playing the game. Two common shooting techniques of interest in this study are the slap and wrist shots. A slap shot is commonly used by both offensive and defensive players to generate maximum puck velocity upwards of 30m/s (Pearsall et al, 1999). A wrist shot involves less swing than the slap shot and is used for higher accuracy, and the stick is swung forward in snapping or pushing action to propel the puck upwards of 20 m/s. The slap shot is a more powerful type of shot, but the wrist shot produces better shooting accuracy. The coaches and players are in search for the sticks that can allow them to produce the fastest shot with best accuracy. Hence, many manufactures seek to design the optimal sticks for the demands of the market. Several factors are commonly thought to influence the outcome of the shots such as the skill level, body strength, stick material type and ice surface condition. More precisely, some of the mechanical factors identified as important in shooting specifically include: (1) the velocity of the lower (distal) end of the shaft prior to contact with the ice, (2) pre-loading of the stick, (3) elastic stiffness characteristics of the stick, and (4) contact time with the puck (Doré & Roy, 1976; Hoerner, 1989, Mario, 1998). However, the direct relationship between mechanical properties of the stick and shot performance has not been identified conclusively. This is an important issue to coaches and athletes alike. Recently to address this matter, Pearsall et al (1999) conducted a biomechanics analysis of the slap shots, which performed by six highly skilled players using different sticks. Surprising the stick stiffness properties had minimal effect on shot velocity for six highly skilled players. However, given the small homogeneous sample, it is not possible to generalize to all player levels or all forms of stick shots. Hence, the purpose of this study was to investigate further the performance of the slap and wrist shots as affected by different stick types across different skill levels and body strengths of the players.

1.3 Objectives of the Study

The focus of this study was to evaluate the effects of stick construction and player skill level to the slap and wrist shots velocity. The short-term goal is to have a complete understanding of how stick characteristics in different skill levels can influence the slap and wrist shots performance. The long-term goal is to develop a protocol so that other researchers, in the future, can examine different stick constructions and responses in stick overall and segment bending and torsion. Hence, the designers and engineers of the manufacture companies will be able to design better sticks for the players.

Chapter 2: Review of Literature

2.1 Brief History of Ice Hockey

Ice hockey is one of the most action-packed winter sports. In the language of French, the term for a Shepherd's stick is known as the word "hockey", which is said to be an Anglicization of "hoquet." It simply resembles the stick with which hockey is played. The origin of ice hockey and the date have been the subjects of debate. The governing officials held a contest for the community that could best produce the evidence that it was the game's birthplace. City of Montreal, Kingston, and Halifax made the strongest bids, and at the end it was awarded to Kingston, Ontario, Canada. The first game of ice hockey was played by a group of British soldiers in Kingston, Ontario and Halifax, N.S. in 1855. The idea of ice hockey can be traced to field hockey, shinny, hurley, bandy and lacrosse. The first game of ice hockey with rules was played in Montreal by teams of McGill University students in 1875. In 1917, the National Hockey League association (NHL) was formed in Montreal from an earlier professional league. The original NHL teams were: Montreal Canadians, Montreal Wanderers, Ottawa Senators and Toronto Arenas (Pearsall et al, 2000; Menke, 1976; World Book Encyclopedia, 1995).

2.2 Evolution of Hockey Sticks

In the last few decades, ice hockey equipment has evolved substantially, including the ice hockey sticks (Pearsall & Turcotte, 2000). An ice hockey stick is a fundamental implement for playing the game. Originally, the hockey sticks were made entirely from a single piece of wood. Starting in 1950's, manufactures began to construct modular shaft and blade components separately and later joined them to form a stick. In the late 1960s, the curvature of the blade was introduced. This allowed the players to have better maneuverability of the puck during forehand stick handling and directional control during the shot. In particular, this lead to the practical use of the slap shot since both accuracy and velocity were seen (Nazar, 1971). In the 1970s, the trend was to reduce the use the amount of wood in the stick by substituting different materials such as fiberglass and plastic, in part to decrease the weight of the stick. During 1980s, to increase the durability of the stick, several manufactures inserted plastic blade bottoms in material to increase the lifetime of the stick (Roy & Delisle, 1984). Recently with advance technology, new sticks have seen constructed with aluminum, carbon fiber or composite materials (Marino, 1998). Currently, official rulebooks stipulate the dimension of the shaft and blade; however, they do not restrict the material composition of sticks (Hoerner, 1989; Pearsall et al, 1999).

2.3 Shots in Ice Hockey

Hockey players use the stick for passing, stick handling and shooting. There are several types of shot: slap, wrist, snap, sweep, backhand, flick and lob shots (Pearsall & Turcotte, 2000). The slap and wrist shots are the most common and important shots in playing the game. The slap shot allows the player to generate the maximum puck velocity where the wrist shot enables the player to produce the best accuracy (Hoerner, 1989). In ice hockey, the ability to shoot the puck with optimal velocity and precision is a decisive factor in the overall performance of a player (Lariviere and Lavallee, 1972).

The slap shot is executed by grasping the stick with both hands approximately 0.40 to 0.60 m apart. The stick is initially raised backwards then swung forwards with maximum effort to impact the puck upwards of 30 m/s or 110 kph. The puck is propelled by the blade of the stick. This movement may be described in six phases: backswing, downswing, pre-loading, loading, release and follow through, Figure 1 (Pearsall et al, 2001). As for the wrist shot, the stick is grasped with both hands approximately 0.15 to 0.30 m apart. Initially the stick blade begins in contact with the puck then the stick is swung forward in snapping or pushing action to propel the puck upwards of 20 m/s or 70 kph. This movement may be broken into four or five phases: draw back (optional), blade positioning, loading, pushing, and follow through, Figure 2. The slap shot is a more powerful type of shot, but the wrist shot produces better shooting accuracy.

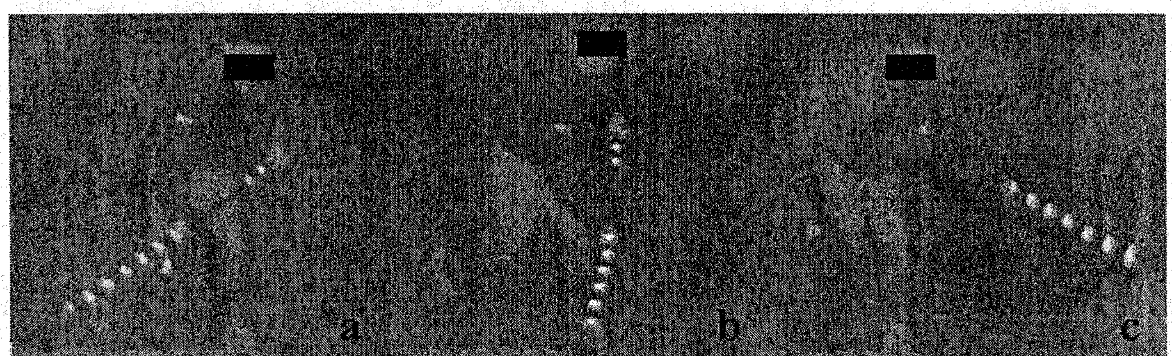

Figure 1. The phases of the slap shot include the backswing; (a) downswing; (b) pre-loading; loading; (c) release and follow through.

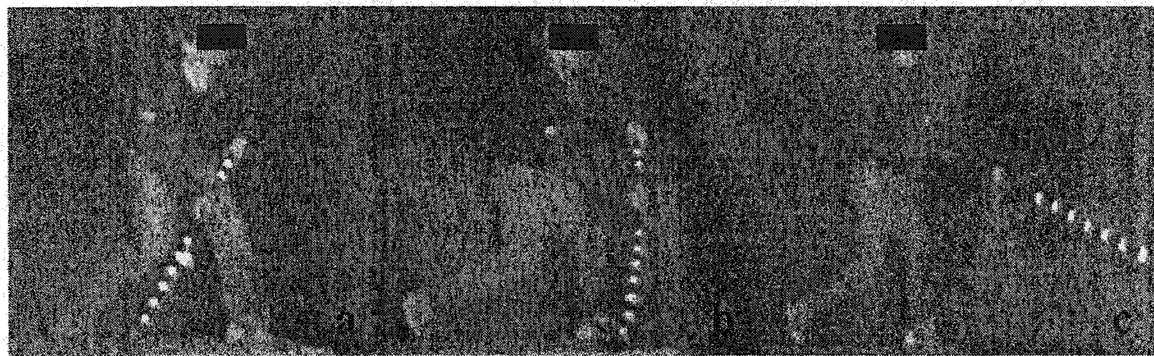

Figure 2. The phases of the wrist shot include the (a) blade positioning; loading; (b) pushing and (c) follow through.

Over the years, some studies have examined the various types of shot while others have evaluated different materials and properties to the performance. In terms of various types of shot, most studies have analyzed the slap shot because it is the most powerful shot. Hayes (1964) analyzed the specific mechanics of the shot, and Wells and Luttgens (1976) found that the performance of a slap shot requires the contribution from different body parts: 25% trunk, 40 to 45% shoulders, and 30 to 35% elbow and wrist movements. In 1984, Emmert developed a strength and conditioning program targeting specific muscles involving in the different phases of the slap shot. During the backswing phase, the main muscles that are involved in the action are the pectoralis major, deltoid and biceps brachii. In the downswing phase, the muscles are the pectoralis major, anterior deltoid, and external and internal obliques. At the impact and follow through phases, the teres major, latissimus dorsi and oblique muscles contribute from the trunk region while the triceps and anterior deltoid muscles support from the shoulder region (Emmert, 1984). From the above, it clearly demonstrates that the upper body strength has significant influence on the outcome of the shot.

Several studies have compared various types of shot. Alexander et al (1963) proposed the first study to compare the ice hockey wrist and slap shots with respect to speed and accuracy. The results showed the slap shot (30.8 to 35.3 m/s) was faster than the wrist shot (26.6 to 32.6 m/s), particular the skating slap shot executed by the professional players with the velocity of 38.2 m/s. The standing slap shot was the least accurate while the skating wrist shot was the most accurate. In 1975, Naud also reported similar findings with two professional hockey players. He examined three types of shot: slap, snap and wrist shots. He found the slap shot was the fastest and the wrist shot was the slowest of all. In order to understand the mechanics of the shot better, Naud (1975) used a cinematographic instrument to analyze the contact and release points in the slap, snap and wrist shots. The blade of the ice hockey stick was divided equally into ten parts with center point as zero, heel point as minus five and toe point as plus five. Each part was known as a unit of 0.0254 m. A Locam 16mm camera was set to 200 FPS with exposure time of 1/1200 second, and it was placed approximately 0.45 m in front of shooting area behind a 0.12 x 0.12 m piece of Plexiglas to obtain the contact and release points. The results showed the average length of travel of the puck of the blade for the wrist shot was 0.216 m while the slap and snap shots averaged 0.152 m.

2.4 Mechanics of Implement in Sport

An implement of a hockey stick has several important properties that are similar to a baseball bat, tennis racquet or golf club, which affects its performance. First, there is a location on the stick identified as the "sweet" spot, which can cause the maximum transfer of energy when it is struck by the object. This spot is also called the center of oscillation or center of percussion (Cherellia, 1975; Connolly & Christian, 1980). The sweet spot has three major features: 1) it produces the maximum speed or power when the object is struck; 2) the spot is minimum vibration, and 3) it causes the least amount of shock to your hands and arms (Georgia sports medicine tech & performance newsletter, 1999).

For example in golf, the manufactures have tried to enlarge the sweet spot so that better performance can be produced. In 1954, a mechanical engineer named Karsten Solheim developed a heel-and-toe weighting golf club. The club was constructed with its weight concentrated on the heel and toe while leaving empty at the center. In result, when the club struck the ball, it would produce a "ping" sound. This involved moving weight from the center of a club, directly behind the hitting area out to its edges. Hence, the sweet spot was effectively enlarged and reduced twist on mis-hits because "a higher moment of inertia or resistance to twisting reduces gear effect, so that the ball travels straighter and thus farther" (Braham, 1992). The sweet spot of the hockey stick is presumably at the blade area; however, so far no studies have examined on this specific issue.

Another important property of the stick is its elasticity. All real "rigid" bodies or objects are to some extend elastic. The form of the bodies can be changed slightly by pulling, pushing, twisting or compressing them (Rosnick et al, 1992; Halliday et al, 1993). In tennis, Su (1997) conducted a study for selecting an optimal tennis racket. The author carried out two tests: material test in a laboratory and subject test on a tennis court. The purpose of the material test was to examine the effects of the impact phenomenon. The impact was created by projecting the tennis balls at approximately 20 m/s vertically to strike the tennis rackets that were fixed in a C-clamp. In the meantime, NAC high-speed camera was filmed at 1000 frames/s and digitized using Peak Performed System to obtain the coefficient of restitution (COR). In the subject test, three highly skilled tennis players performed with rackets of various stiffness and string tension combinations randomly. Control and speed of the serve were the two key factors being evaluated. The results showed the higher stiffness of racket would acquire higher coefficient of restitution (COR). Also, the higher stiffness and string tension rackets demonstrated better performance in control and serving than lower stiffness and string tension rackets.

In the field of golf, Mather & Jowett (1998) discussed the theory of stiffening effects. The authors proposed that when a golf club is swung to strike a golf ball, a significant amount of the centrifugal force is generated before the impact occurs, which stiffens the shaft of the golf club and changes its elastic characteristics. Two experimental methods were used in this study. The first test was whirling the shaft at different speeds to generate the centrifugal force; the second test was done by a professional golfer swinging the shaft. They concluded in a whirl rig the kick point moved towards the butt of the golf club while the general shape of the shafts remained different. In an actual golf swing, "the centrifugal force/acceleration acting on the club created shaft deflection patterns which were controlled and dominated by the mass and position of the center of gravity of the head" (Mather & Jowett, 1998).

In ice hockey, some studies have examined the properties of the hockey sticks. In 1994, Dr. Lessard and his students in Department of Mechanical Engineering of McGill University used various materials of hockey sticks including wood, aluminum and carbon fiber to test their linear deformation (static bending stiffness) and torsional deformation (torsional stiffness). Three-point bending test was performed to test the stiffness, and cantilever was used to exam the torsion of the sticks. Both aluminum and carbon fiber sticks were found to be stiffer than wood in bending and in torsion. In general, "the aluminum shafts demonstrated poor damping properties while the carbon fiber shafts better resembled wood" (Lessard et al, 1994).

Marino (1998) further investigated the performance characteristics of composite, wood and aluminum hockey sticks. In the study, a large sample of sticks was evaluated: wood (N = 40), aluminum (N = 32) and composite (N = 55). Several important stick characteristics were tested: weight, center of mass, flex strength, torsional resistance and break force. Aluminum sticks were the strongest while the composite sticks were found to be the lightest of all. Unfortunately, aluminum sticks would produce significant amount of vibration during the impact, so the players would have a difficult time to feel the puck. In terms of technology, composite manufacturing is more advanced and has better precision level than wood technology; hence, the composite sticks serve as a better choice. Moreover, since most breakage of sticks occurred at the blade area, composite sticks could allow the players to replace the blade and to enhance the attractiveness at the same time.

2.5 Influence of Stick Material Properties on Shot Performance

Another aspect of shot performance is to evaluate the stick material properties. Back in 1973, Roy and Dore examined the kinematics of the slap shot with different age groups. Three different age groups of boys were tested: 11 to 12, 15 to 16, and 17 years old and over. The shot velocity was measured with a digital time counter that was triggered by a magnetic cell inserted in the ice. As soon as the puck struck on the target, the counter would stop by a microphone sensitive to the noise. In addition, each individual also performed the anthropometrics measures: height, weight, and trunk and upper segment lengths. They concluded younger players have disadvantages in morphological and strength attributes. Therefore, it is more difficult for them to use the same size and weight of the hockey sticks as the older players; hence, they suggested the younger players should use a more flexible hockey stick for better performance in shot velocity.

Dore and Roy (1976) measured the variation in forces with time as applied on a hockey stick with the wrist, sweep and slap shots by using strain gauges. In their results, they found "some difference exists in the shape of the force-time diagrams between different types of shot performed by the same player." In the sweep, wrist and slap shots in the maximum value of the G'5 force (one of the forces at the lower hand) was nearly constant at around 10 kg, but in the slap shot while stationary, the G'5 force was somewhat lower. Since stationary slap shot usually has higher velocity than other types of shot, this suggested the significant effect of the impact between stick's blade with the ground during the slap shot. In addition, Roy and Dore (1979) subsequently conducted an experiment on several peewee hockey players with the use of strain gages fixed to the hockey sticks. The experiment determined the speed of shooting was directly related to the acceleration imparted to the stick, and it was demonstrated that in order to produce a certain puck velocity, the more flexible stick required a smaller force than the rigid one. Hence, the study proposed that smaller and weaker players are more suitable to the use of a flexible stick in speed and accuracy. In 1982, Therrien and Bourassa (1982) used a Hycam high speed camera with a Kodak 4X reversal film 7277 under 5000 watts of light intensity to understand the static and dynamic of the ice hockey sticks. An ice hockey stick was clamped along a central part of the handle as the hand placements of a hockey player. The blade shooting motion was photographed at the rate of 2000 frames/s against a grating at the moment of impact, so that the kinematics of the motion was quantitatively evaluated. From the observations, they suggested the blade bending and torsional rigidity are crucial factors in affecting the control and precision of the shot.

In addition, Roy and Delisle (1984) evaluated the geometrical and dynamic characteristics of the hockey sticks in terms of longevity and durability. Forty-five midget AA players were selected and each player was given randomly two sample sticks. The players had to use those sticks in practices and in game situations for the evaluation in longevity of the sticks. Also, fifteen adult players were given four sample sticks and had to execute as many slap shots as they could until the stick broke for testing of durability of the sticks. The authors concluded that there was a high level of variability in longevity and durability of the sticks, and width and thickness of the handle, the rupture coefficient, and the module of rigidity of the handle were significant factors to the longevity of the stick.

In 1991, Marino and VanNeck from University of Windsor compared the static and dynamic characteristics of aluminum versus wooden hockey sticks. The experiment used 72 wooden and 10 aluminum hockey sticks. Ten highly skilled hockey players were assigned both the wooden and aluminum sticks and performed five slap shots with each type of sticks. The wooden and aluminum sticks produced an average slap shot velocity of 29.1 ± 2.9 m/s and 29.8 ± 3.2 m/s, respectively. They observed that aluminum hockey sticks were lighter than wooden sticks, and there was no significant difference in the coefficient of rigidity between them. Also, aluminum hockey sticks had a higher tolerance level of shear force than wooden sticks at all locations tested. Finally, the authors concluded that aluminum hockey sticks provide a slightly lighter and stronger alternative to wooden sticks, but no significant advantages in performance of shot velocity and safety risk.

Pearsall et al (1999) had examined on the influence of stick stiffness on the performance of ice hockey slap shots. In their experiment, they had used six elite hockey players as the subjects (five varsity and one professional players). There were four different stiffness types of hockey sticks (13 kN/m, 16 kN/m, 17 kN/m and 19 kN/m). Each subject "took six slap shots with the four stick types in random order" (Pearsall et al, 1999). A 30 seconds rest interval was given between each trial of one type of stick and a 3-min rest interval was given between sticks of different stiffness. Three variables were measured and analyzed in the data collection: puck velocity, reaction forces and stick deformation. Minimal differences in the puck velocity were measured by a radar gun. They found, on average, the sticks with a stiffness of 13 kN/m, 16 kN/m, 17 kN/m and 19 kN/m had the puck velocity of 30.1 m/s, 29.7 m/s, 29.4 m/s and 29.5 m/s, respectively. In addition, from the ground reaction force measured by a force plate, the results showed that the stick with the stiffness of 17 kN/m had the highest peak vertical force and the stick with the stiffness of 13 kN/m had the lowest peak vertical force. Also, there was no difference in peak forward-backward force among the four types of stick. Moreover, in terms of stick deformation which was measured and recorded by a high speed camera, the results indicated that the sticks with the stiffness of 13 kN/m had the highest peak deflection and greatest time to reach the peak deflection than any other types of sticks. Noteworthy, the variability across the subjects was greater than stick types, and due to small homogenous sample size, it was not possible to generalize all skill levels.

To address some of the issues raised, Pearsall et al (2001) subsequently measured the interaction of players' skill level, body strength, and sticks of various construction and stiffness on the performance of the slap shot in ice hockey. Twenty males players were tested, ten of each group were considered skilled and ten unskilled. Each subject performed three slap shots with three sticks shafts of different construction and stiffness. Shot mechanics were evaluated by simultaneously recording ground reaction forces from a force plate platform and stick kinematics from a high-speed video system (480 frames/second). A sports radar gun was used to record the peak puck velocity of each trial. The results indicated that 1) puck velocity was influenced by the skill level and body strength but not stick type, and that 2) variability in performance measures across subjects was greater than the variability across the stick stiffness.

In Appendix A, it summarizes all the previous studies done on shot velocity in both the slap and wrist shots while standing stationary and in skating motion. The range of the standing slap shot for elite players (varsity & professional players) is from 25.6 to 46.4 m/s, skating slap shot from 27.8 to 48.6 m/s, standing wrist shot from 19.5 to 36.7 m/s, and skating wrist shot from 25.0 to 45.3 m/s.

Chapter 3: Purpose of the Study

The purpose of this study was to examine the influence of various types of hockey stick characteristics and the player skill levels to the slap and wrist shots velocity.

3.1 Hypotheses

It was hypothesized that:

1. There would be a significant difference between sticks of different stiffness and peak puck velocity.
2. Skilled players would have higher shot velocity than unskilled players in both the slap and wrist shots.
3. The players with stronger upper body strength would have faster shot velocity in the slap and wrist shots.
4. The bending and attacking angles of stick would have a high correlation to peak puck velocity.
5. The hand placements on the stick would have a significant influence to peak puck velocity in both the slap and wrist shots.
6. Male players would have greater shot velocity then females in the slap and wrist shots.
7. The slap shots would have a great peak velocity than the wrist shots in all skill levels.

3.2 Limitations

1. The experiment was conducted in room temperature (22° to 24°c) instead of ice rink temperature.
2. The subjects performed the tasks on a polyethylene sheet (artificial ice surface) instead of the actual ice surface.
3. The subjects did not wear the full gear (shoulder pads, helmet, elbow pads, shin pads, etc).
4. In terms of physiological and psychological responses, the experiment was not performed under a real game situation.

5. All the shots were performing in stationary.

6. A sport radar gun was used to detect only the peak puck velocity at the net.

7. The target(net) was only 3 m away.

8. One maximum repetition of bench press and hand grip strength tests may not be sufficient to measure all players' upper body strength.

3.3 Delimitations

1. Each subject had as many warm up shots as he/she needed until he/she felt comfortable with the sticks and the environment; however, this usage of sticks may or may not result in unknown alternation in stick properties.

3. Only the slap and wrist shot were tested; hence, it was not possible to generalize the effect of the sticks to all other types of shot.

4. Peak puck velocity was used as the only performance criteria.

3.4 Independent (IV) and Dependent (DV) Variables

IV: gender (2), stick types (3), shots (2) and trials (3).

DV: peak velocity, bending and attacking angles, vertical force, linear shaft deflection, 1 RM of bench press, grip strength, height and mass of players, and hand position in relation to stick length.

Chapter 4: Methods and Procedures

4.1 Hockey Sticks

Bauer-Nike Hockey Inc. provided three different shaft constructions of hockey sticks with left- and right- handed blades, and they were carbon composite, medium and stiff wood materials. The Bauer 300 (P66) blades of 0.0125 m curvature depth with mass of 0.0025 kg were used for all sticks. The shafts were similar in length (0.140 m) and mass (0.320 kg). Each stick was coded so that the subjects and testers were unaware of the shaft characteristics during testing. Each stick was examined by a static three-point bending test to determine its' shaft stiffness in the major axis. The shaft construction in the minor axis was similar in all sticks, Figure3. The stick shafts were subjected to three point bending tests with 0.05 m linear deformation to measure shaft stiffness of the medium (13.0 ± kN/m), stiff wood (16.6 ± kN/m) and carbon composite (17.9 ± kN/m).

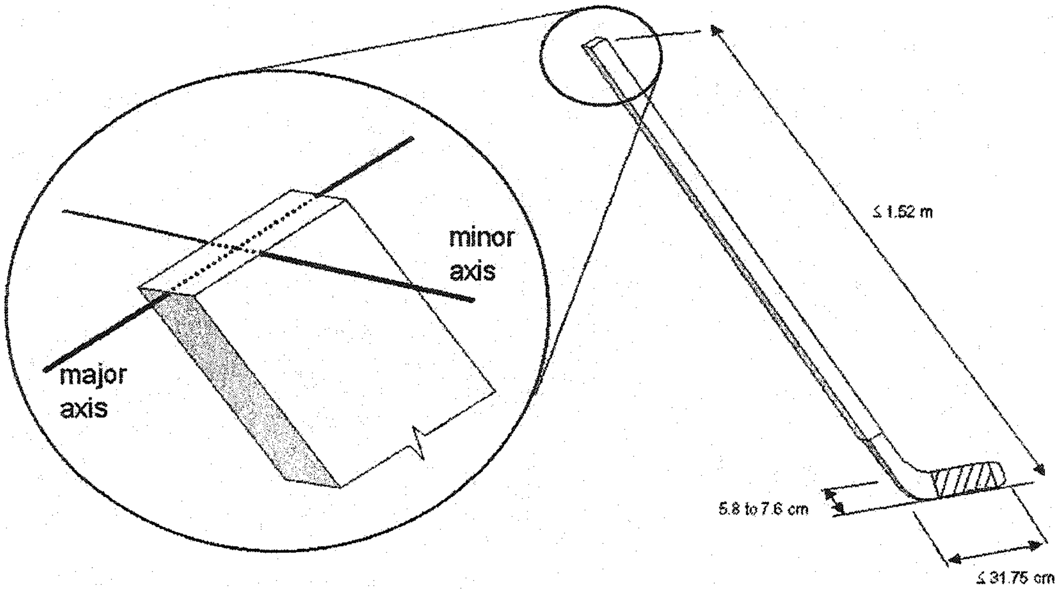

Figure 3. Major and minor axes of the hockey stick shaft (Pearsall et al, 1999).

The three-point bending test is a quasi-static method to measure the shaft stiffness by using a linear deformation technique. The three-point bend involves supporting the stick shaft at two roller points with 1.05 m apart, and then applying a known weight (force) at the center of the shaft to result in a constant 0.05 m deflection. The test was terminated before the stick shafts were permanently damaged, and no damage to sticks which typically could defect up to 0.10 to 0.12 m before fractures. The purpose of the test was to identify the modules of elasticity for bending around the major axis. When a sufficient load is applied to the shaft, the stick bends which is known as the coefficient of elasticity. The elastic component is when a range of load/force is removed after applying to the shaft, and the shaft can still regain its original form. The plastic component is when a range of load/force is removed after applying to the shaft of the stick, and the shaft remains permanently deformed. The failure point represents the force required to break the shaft, and the amount of force is known as maximum breaking load (Rothsching, 1997). In this study, the test was only performed within the elastic component functional range (A), Figure 4.

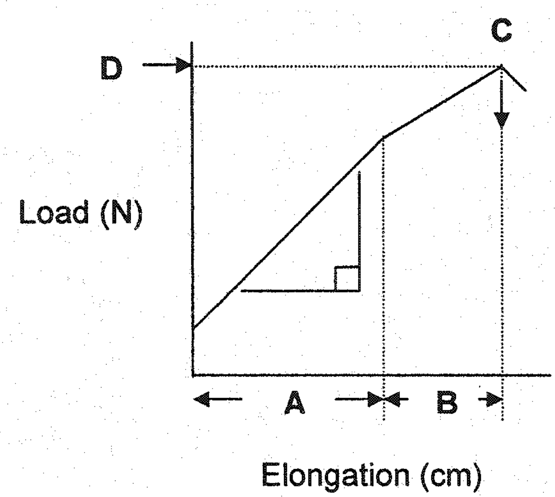

Figure 4. Characteristics of the shaft: (A) elastic component, (B) plastic component, (C) failure point and (D) maximum breaking load (Rothsching, 1997).

4.2 Subjects

Forty subjects (20 males and 20 females) completed the consent form and volunteered to participate in both shooting and general strength tests of this study. Within each gender group, ten interuniversity or college level ice hockey players were classified as the skilled group; the remaining ten subjects with recreational experience in ice hockey were grouped as unskilled. Subjects were further selected to provide an equal distribution of right- and left-hand shooters, as well as to represent a range of body sizes and strengths. The players selected were 17 to 26 years of age (Table 1).

Table 1. General subject characteristics of sub groups

GENDER\LEVEL	SKILLED	SD	UNSKILLED	SD
FEMALE				
AGE (yrs)	19.1	1.7	23.0	4.7
HEIGHT (m)	1.66	0.06	1.63	0.07
MASS (kg)	66.5	6.5	58.8	7.9
BENCH (kg)	43.7	5.1	37.8	6.7
GRIPR (kg)	40.3	3.5	33.5	3.9
MALE				
AGE (yrs)	22.8	1.6	25.4	7.3
HEIGHT (m)	1.78	0.08	1.72	0.09
MASS (kg)	83.0	5.8	77.3	6.6
BENCH (kg)	93.0	22.1	82.0	26.7
GRIPR (kg)	59.0	11.6	57.5	9.1

The subjects wore ice hockey skates and stood on a 3 m square piece of 0.004 m thick polyethylene (artificial ice) to execute the slap and wrist shots. Subjects performed a minimum of three practice trials with each stick until they felt comfortable with the sticks and the environment. Each subject took three slap and three wrist shots with the three stick types in random order. A minimum of 30 s occurred between each trial of one stick type and a 3-min rest period between sticks of different stiffness. A shot was considered a good trial if: (1) the puck went into the target area (0.60 x 0.60 m) approximately 3 m from shot to goal, (2) the stick made initial contact with the force platform, and (3) the subject was satisfied that the trial was a maximal effort.

4.3 Force Platform

Similar test conditions were used as in the prior study (Pearsall et al., 1999). A model OR 6-5 Biomechanics Platform (0.51 x 0.47 m) from Advanced Mechanical Technology Inc. was used to record the reaction forces occurring between the stick and surface during the shot. The puck was positioned to the front edge of the force platform to ensure that the stick struck the platform during the pre-loading phase of the slap shot. In the previous thesis study done by Rothsching (1997), he had shown that the least friction condition was observed with the metal platform and WD-40 lubricating fluid. Hence, lubricating fluid (WD-40™) was applied to the force platform to reduce the coefficient of friction between the force platform surface and the stick blade ($\mu_{static} \approx 0.5$).

4.4 High Speed DAQ Board

A high speed National Instruments data acquisition card with sixteen channels (Model AT-MIO 16X) was used to collect the data at 1000 Hz for 2 seconds in conjunction with the use of Labview 4.1 version on a Pentium PC. Force-time profiles were recorded in the X (transverse), Y (front-back) and Z (vertical) directions.

4.5 High Speed Video System

A high-speed video (480 Hz) system was used to record the kinematics of the stick. The camera was positioned 3.3 m laterally to the puck and 1.83 m vertically above the puck. The camera was oriented 20° below horizontal and approximately perpendicular to the stick's plane of motion determined from pre-trials. Reflective markers were placed on the shaft at 0.10 m intervals along the top 0.30 m and lower 0.60 m of the shaft. Markers were also placed on the back of the gloves over the left and right thumbs. The marker locations were digitized using the Ariel Performance Analysis System™ (Ariel Dynamics, San Diego, CA). Markers could be located to within 0.003 m per pixel (picture element) from the video recording of an 1.5 m by 1.5 m field of view. Peak deflection (d), peak bending angle (θ), attacking angle (β), and hand placement along the stick were the dependant stick variables obtained from this analysis (Figure 5). Peak deflection of simple bending observed in the camera's plane of view was calculated as the intercept angle (θ) between projection lines from the upper and lower stick segments. The attacking angle (β) between the lower stick and ground surface was also calculated. The upper and lower stick segments were located between the top two and lowest two markers on the stick, respectively.

4.6 Sports Radar Gun

A Sports Radar Gun (Model SR 3300) was used to record the peak velocity of the puck for each trial. The radar gun uses the principle of Doppler radar, and the gun sends out a signal that bounces off the puck and sends the signal back to the radar gun. The radar gun was located behind the target area of the hockey net. Peak velocity could be recorded between 1 to 65 $\pm$ 0.3 m/s. Only shots into the target area were recorded as official trials. Using a metal stick to make impact with any metal material to produce the resonant wave of 55 MPH (24.6 m/s) ensured the calibration of the spots radar gun.

4.7 Bench Press and Hand Dynamometer

Following the shooting test, the players also performed a general strength test consisting of 1RM bench press and a grip strength test. Subjects warmed up with a low resistance. After successful completion of one repetition, the weight was increased with a minimum of 2.2 kg increment and the subject attempted the new weight after a brief rest. Each subject was given three chances to lift a maximal weight. Subsequently, all subjects performed a maximal grip test with a grip dynamometer. Each subject performed two grip tests with each hand, and the highest score for each hand was recorded. These tests were used as the measurement of players' overall upper body strength level. The set up of the experiment is illustrated in Figure 5. All the data were analyzed by Excel and Statistica software programs.

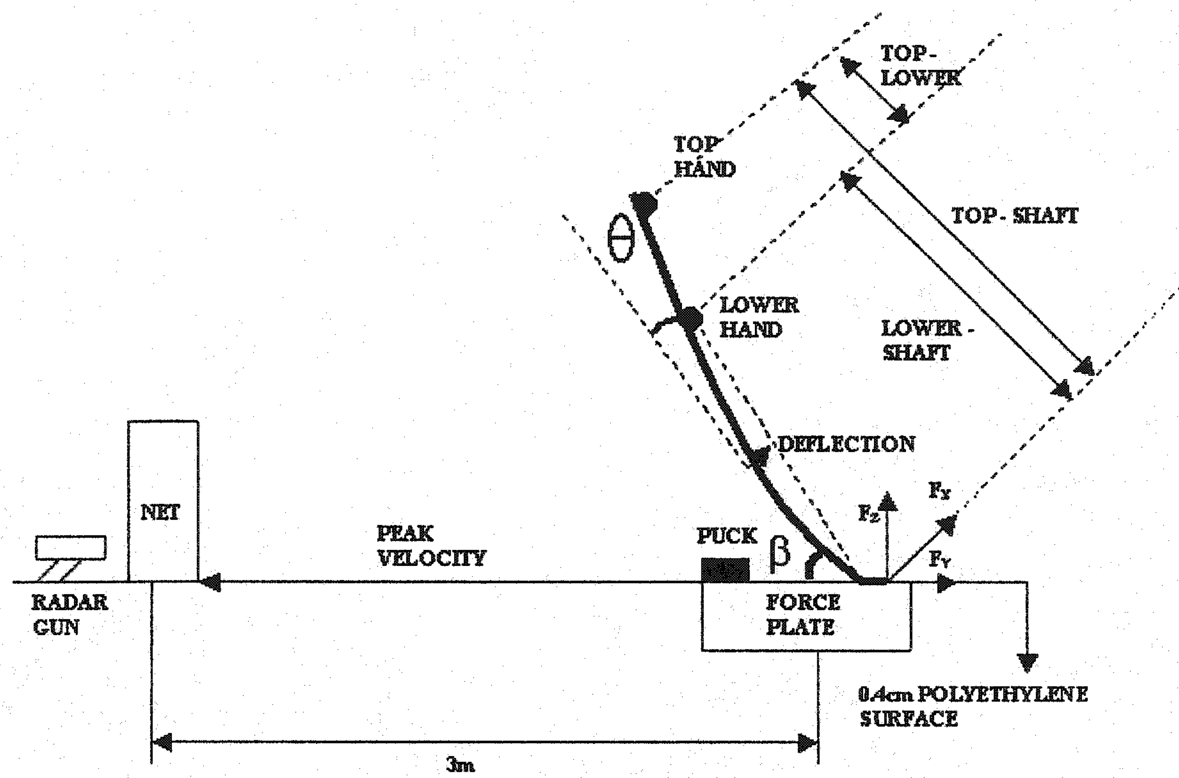

Figure 5. Set up of the experiment: ground reaction forces (F_x, F_y and F_z), stick bending angle = θ and stick attacking angle = β.

Chapter 5: Experiment Design and Statistical Analysis

The experimental design involved the subjects (S = 10) and the following independent variables: Gender (G = 2), Skill (Sk = 2), Shot type (Sh = 2), and Stiffness (St = 3), with repeated trials (T = 3). The data were analyzed statistically using a repeated measure analysis of variance (ANOVA) for each dependant variable (Frank & Althoen, 1994). The dependent variables included puck velocity, peak Z (vertical) force, peak deflection, peak bending angle (θ), stick to ground angle (β), hand placement on the stick. The ANOVA is described as $S_{10}(G_2 \times Sk_2) \times Sh_2(St_3 \times T_3)$. In addition, the relationship between strength test independent variables for Bench (B = 1) and (Gr = 2) were compared to the above. All the data were measured and analyzed by Excel and Statistica software programs. Statistical significance was declared if $P < 0.05$ with t-test, interclass correlation, and Pearson Product correlation (Table 2). Also, the post-hoc analysis was performed using Bonferroni procedure.

Table 2. Experimental design

Gender	Skill Levels (Subjects)	Stick Types						Mean	SD	CV	t-test	ICC	P. r
		Composite		Medium		Stiff							
		Shot Types		Shot Types		Shot Types							
		Slap	Wrist	Slap	Wrist	Slap	Wrist						
Females	Skilled 1 2 . . 10	1.2.3	1.2.3	1.2.3	1.2.3	1.2.3	1.2.3						
	Unskilled 1 2 . . 10												
Males	Skilled 1 2 . . 10												
	Unskilled 1 2 . . 10												
Mean													
SD													
CV													
t-test													
ICC													
P. r													

Chapter 6: Results

6.1 Slap Shot versus Wrist Shot

In this experiment, all players executed both the slap and wrist shots. On average, the slap shot produced greater peak velocity than the wrist shot, 21.2 ± 6.8 m/s and 14.5 ± 4.4 m/s respectively (Table 3). In general the slap shot had a peak vertical impact force of 97.6 ± 63.6 N, corresponding to an average shaft bending of 12.7° or 0.038 m. As for the wrist shot, the average peak vertical force was only 44.2 ± 30.0 N during the impact, corresponding to a peak bending of 10.8° and linear shaft deflection of 0.032 m. Similar attacking angles (β) were seen in both the slap and wrist shots: 54.9° and 53.0°, respectively. Significant differences between the slap and wrist shots were observed with respect to hand placements.

Table 3. Comparison of shot and stick mechanical measures for the slap and wrist shots

VARIABLES\SHOTS	SLAP MEAN	SD	WRIST MEAN	SD	P
VELOCITY (m/s)	21.2	6.8	14.5	4.4	0.00
VERTICAL FORCE (N)	97.6	63.6	44.2	30.0	0.00
STICK BENDING (degrees)	12.7	5.5	10.8	5.6	0.03
ATTACKING ANGLE (degrees)	54.9	16.1	53.0	31.2	0.63
LOWER HAND – SHAFT (m)	0.593	0.093	0.626	0.039	0.07
TOP HAND - SHAFT (m)	1.193	0.100	0.959	0.049	0.00
TOP HAND - LOWER HAND (m)	0.602	0.125	0.337	0.058	0.00
SHAFT DEFLECTION (m)	0.038	0.016	0.032	0.017	0.03

Statistically significant different at $p < 0.05$, ANOVA 1W

In general, during the slap shot, players would grasp their lower hand down the shaft from the shaft blade end (0.593 ± 0.093 m) than for the wrist shot (0.626 ± 0.039 m). In contrast, the upper hand would be placed closer to the top (butt) of the stick (1.193 ± 0.100 m) for the slap than the wrist shot (0.959 ± 0.049 m). As a result, the distance between the upper and the lower hands was greater in slap (0.602 ± 0.125 m) than the wrist (0.337 ± 0.058 m) shot. No significant difference was found in the attacking angle (the angle between the stick and the floor) in both slap and wrist shots.

6.2 Stick Models, Genders and Skill Levels

With regards to various stick models both in the slap and wrist shots, several variables were analyzed including velocity, vertical force, stick bending and attacking angles, hand placements and shaft deflection. Both in the slap and wrist shots, no significant differences were observed in all the variables (Tables 4 & 5). The results may suggest that the stick characteristics were quite similar among all three different stick types; hence, no significant difference in velocity could be observed.

Table 4. Comparison of stick mechanical measures for stick types in the slap shot

SLAP SHOT *VARIABLES\STICK TYPES*	COMPOSITE MEAN	SD	MEDIUM MEAN	SD	STIFF MEAN	SD	P
VELOCITY (m/s)	21.08	7.27	21.30	6.33	21.31	6.77	0.99
VERTICAL FORCE (N)	100.99	69.07	93.19	57.72	98.91	65.25	0.85
STICK BENDING (degrees)	11.42	4.65	14.32	6.36	12.13	4.95	0.11
ATTACKING ANGLE (degrees)	54.82	17.28	54.14	16.79	55.77	14.22	0.93
LOWER HAND - SHAFT (m)	0.60	0.09	0.60	0.10	0.58	0.10	0.96
TOP HAND - SHAFT (m)	1.20	0.11	1.20	0.11	1.17	0.09	0.78
TOP HAND – LOWER HAND (m)	0.60	0.14	0.61	0.13	0.59	0.11	0.94
SHAFT DEFLECTION (m)	0.03	0.01	0.04	0.02	0.04	0.01	0.11

Statistically significant different at $p < 0.05$, ANOVA 1W

Table 5. Comparison of stick mechanical measures for stick types in the wrist shot

WRIST SHOT *VARIABLES\STICK TYPES*	COMPOSITE MEAN	SD	MEDIUM MEAN	SD	STIFF MEAN	SD	P
VELOCITY (m/s)	14.73	4.49	14.65	4.43	14.06	4.28	0.80
VERTICAL FORCE (N)	44.46	26.03	43.61	28.92	44.75	36.47	0.98
STICK BENDING (degrees)	10.40	5.62	12.39	6.06	9.43	4.80	0.12
ATTACKING ANGLE (degrees)	50.60	31.56	50.52	32.18	58.93	29.84	0.52
LOWER HAND - SHAFT (m)	0.62	0.04	0.63	0.03	0.63	0.06	0.92
TOP HAND - SHAFT (m)	0.95	0.07	0.96	0.04	0.97	0.03	0.70
TOP HAND – LOWER HAND (m)	0.33	0.07	0.33	0.05	0.35	0.06	0.88
SHAFT DEFLECTION (m)	0.03	0.02	0.04	0.02	0.03	0.01	0.12

Statistically significant different at $p < 0.05$, ANOVA 1W

Further ANOVA 4W analysis was conducted in each sub-group of genders and skill levels, and no significances were found for all the variables across the stick types both in the slap and wrist shots (Appendix B-E).

Significant differences in peak velocity were observed between males and females, and skilled and unskilled sub-groups in both the wrist and slap shots (Table 6 & Figure 6).

Table 6. Average peak shot velocity for each types of stick in each group

Male/Skilled				**Female/Skilled**			
Slap shot	**Velocity (m/s)**	**SD**	**CV**	**Slap shot**	**Velocity (m/s)**	**SD**	**CV**
Composite	30.6	2.6	8.5	***Composite***	18.4	2.8	15.2
Medium	29.2	2.6	8.9	***Medium***	18.7	2.8	15.0
Stiff	30.3	2.5	8.3	***Stiff***	19.2	2.1	10.9
Mean	30.0	2.6	8.6	***Mean***	18.8	2.6	13.7
Wrist shot				**Wrist shot**			
Composite	19.9	2.6	13.1	***Composite***	13.9	1.7	12.2
Medium	19.5	2.5	12.8	***Medium***	14.0	1.6	11.4
Stiff	19.6	3.1	15.8	***Stiff***	13.0	1.2	9.2
Mean	19.7	2.8	13.9	***Mean***	13.6	1.5	11.0
Male/Unskilled				**Female/Unskilled**			
Slap shot	**Velocity (m/s)**	**SD**	**CV**	**Slap shot**	**Velocity (m/s)**	**SD**	**CV**
Composite	23.0	3.8	16.5	***Composite***	12.4	1.9	15.3
Medium	23.3	3.6	15.5	***Medium***	14.0	2.4	17.1
Stiff	23.6	4.4	18.6	***Stiff***	13.4	1.7	12.7
Mean	23.3	3.9	16.9	***Mean***	13.3	2.0	15.1
Wrist shot				**Wrist shot**			
Composite	16.1	2.7	16.8	***Composite***	9.0	0.9	10.0
Medium	16.4	2.3	14.0	***Medium***	8.7	1.3	14.9
Stiff	15.5	2.4	15.5	***Stiff***	8.8	0.9	8.6
Mean	16.0	2.5	15.4	***Mean***	9.4	1.0	11.2

$p < 0.05$, ANOVA 4W analysis conducted

An observed covariate between the gender sub groups was body size and strength such that the male groups were stronger and taller in comparison to the female groups. Hence, body size and strength were presumed to be the primary factors in influencing the peak puck velocity, not gender per se. On average male skilled and unskilled groups performed the slap shots at 30.0 ± 2.6 m/s and 23.3 ± 3.9 m/s, respectively and wrist shot at 19.7 ± 2.8 m/s and 16.0 ± 2.5 m/s, respectively. Female skilled and unskilled groups performed the slap shot at 18.8 ± 2.6 m/s and 13.3 ± 2.1 m/s, respectively and wrist shot at 13.6 ± 1.5 m/s and 9.4 ± 1.1 m/s, respectively. In general, the slap shot was 1.2 to 1.4 times faster than the wrist shot.

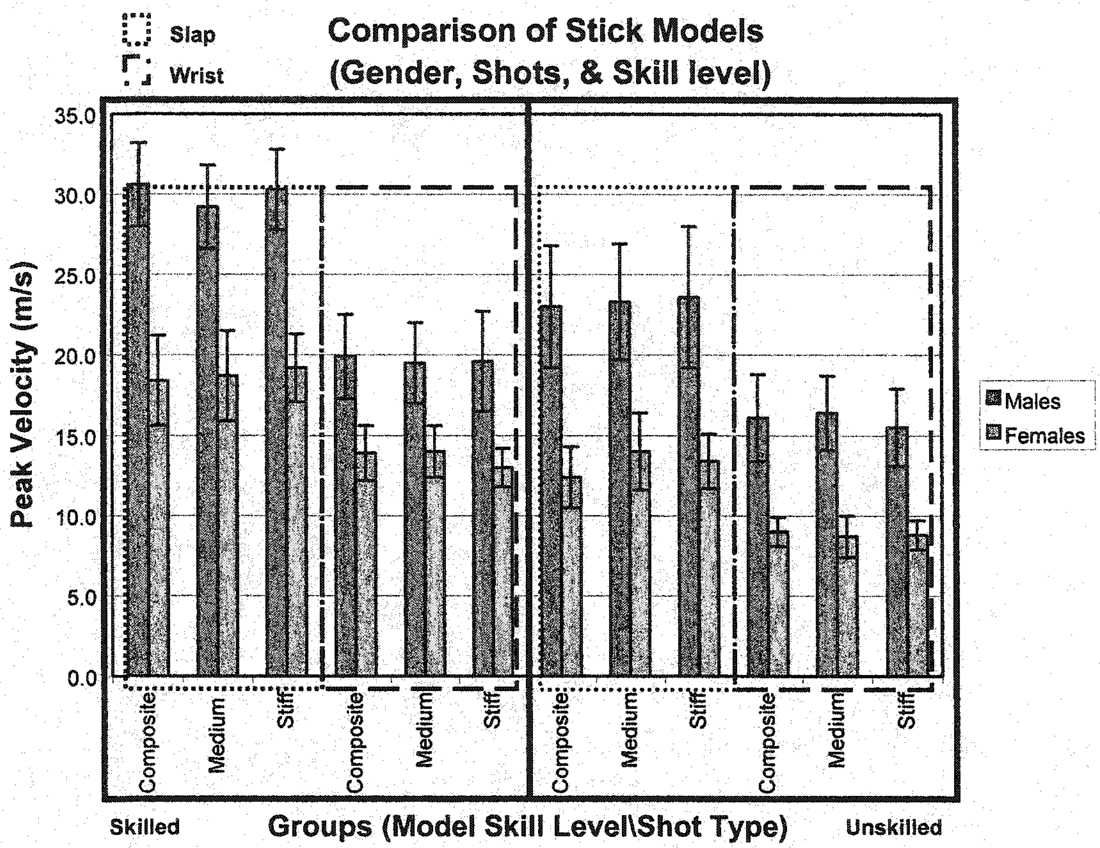

Figure 6. Comparison of stick models (composite, medium and stiff) in different skill level (skilled and unskilled), shot types (slap shot and wrist shot) and genders (males and females)

Other dependent variables that also showed the significant differences in males and females, skilled and unskilled sub-groups included vertical force, stick bending angle and shaft deflection in both the wrist and slap shots. Moreover, the interaction effects between genders and skill levels were seen in the stick bending angle and shaft deflection in the slap shot (Appendix F & G) while the vertical force, stick bending angle and shaft deflection were identified in the wrist shot (Appendix H – J).

Further compared analysis was done between skilled and unskilled players in the slap and wrist shots. In addition to greater puck velocity, skilled players were able to shoot the puck faster and generated more vertical force during the impact ($p < 0.05$). For the slap shot, skilled players produced an average of 123.1 ± 68.0 N comparing to 72.6 ± 47.6 N by the unskilled players in the vertical force. For the wrist shot, skilled and unskilled players generated 51.3 ± 38.0 N and 37.4 ± 17.3 N, respectively. Corresponding to the greater vertical forces, the hockey sticks were bent to a greater extent during the slap shot. The stick shaft bent 15.3° and linearly deflected 0.045 ± 0.018 m for skilled players while it was only bent 10.5° and deflected 0.031 ± 0.011 m for unskilled players in the slap shot. In the wrist shot, the stick shaft also bent 12.8° with linear shaft deflection of 0.038 ± 0.017 m and bent 9.1° with deflection of 0.027 ± 0.014 m for the skilled and unskilled players, respectively. A major difference in shooting technique between the skilled and unskilled players in the slap shot was the lower hand placement. Skilled players would grasp further down to the shaft of the stick with their lower (bottom) hand (0.551 ± 0.077 m) than unskilled players (0.624 ± 0.094 m). In the wrist shot, the technique difference between skilled and unskilled players was observed with the top hand placement. The skilled players would place their top hand lower (0.939 ± 0.040 m) than unskilled players (0.975 ± 0.050 m) (Table 7 & Table 8). In addition, it was observed that minimal differences existed in strength (bench and grip) between the skilled and unskilled players ($p < 0.05$) and as well as the attacking angle.

Table 7. Comparison of stick mechanical measures and upper body strength for skill levels in the slap shot

VARIABLES\SLAP SHOT	SKILLED MEAN	SD	UNSKILLED MEAN	SD	P
VELOCITY (m/s)	24.3	6.2	18.3	5.9	**0.00**
BENCH PRESS (kg)	67.8	29.6	61.1	28.2	0.23
RIGHT GRIP (kg)	49.5	12.6	47.1	14.4	0.34
LEFT GRIP (kg)	47.9	14.3	43.3	13.6	0.08
VERTICAL FORCE (N)	123.1	68.0	72.6	47.6	**0.00**
STICK BENDING (degrees)	15.3	6.1	10.5	3.7	**0.00**
ATTACKING ANGLE (degrees)	54.0	14.7	55.5	17.3	0.67
LOWER HAND – SHAFT (m)	0.551	0.077	0.624	0.094	**0.02**
TOP HAND - SHAFT (m)	1.187	0.062	1.197	0.123	0.78
TOP HAND - LOWER HAND (m)	0.637	0.061	0.576	0.152	0.16
SHAFT DEFLECTION (m)	0.045	0.018	0.031	0.011	**0.00**

Statistically significant different at $p < 0.05$, ANOVA 1W

Table 8. Comparison of stick mechanical measures and upper body strength for skill levels in the wrist shot

VARIABLES\WRIST SHOT	SKILLED MEAN	SD	UNSKILLED MEAN	SD	P
VELOCITY (kph)	16.6	3.7	12.4	4.1	**0.00**
BENCH PRESS (kg)	67.8	29.6	61.1	28.2	0.23
RIGHT GRIP (kg)	49.5	12.6	47.1	14.4	0.34
LEFT GRIP (kg)	47.9	14.3	43.3	13.6	0.08
VERTICAL FORCE (N)	51.3	38.0	37.4	17.3	**0.01**
STICK BENDING (degrees)	12.8	5.9	9.1	4.8	**0.00**
ATTACKING ANGLE (degrees)	53.9	30.9	52.3	31.7	0.81
LOWER HAND - SHAFT (m)	0.624	0.031	0.627	0.046	0.81
TOP HAND - SHAFT (m)	0.939	0.040	0.975	0.050	**0.03**
TOP HAND - LOWER HAND (m)	0.320	0.057	0.350	0.057	0.15
SHAFT DEFLECTION (m)	0.038	0.017	0.027	0.014	**0.00**

Statistically significant different at $p < 0.05$, ANOVA 1W

6.3 Body Size and Strength

Within each sub-group, the peak puck velocity correlated most substantially to the subject characteristics in height, mass, bench press, and grip strength in both the slap and wrist shots (Table 9). Though, it is not possible to establish a causal relation between these variables and puck velocity, it does suggest the importance of size and strength.

Table 9. Correlation between various variables in slap and wrist shots with peak velocity

VAR\SHOTS	SLAP SHOT	WRIST SHOT
VELOCITY	1.00	1.00
HEIGHT	0.64*	0.56*
WEIGHT	0.88*	0.83*
BENCH	0.79*	0.75*
GRIPR	0.67*	0.66*
GRIPL	0.59*	0.61*
VERTICAL FORCE	0.91*	0.78*
BENDING ANGLE	0.80*	0.88*
ATTACKING ANGLE	-0.06	-0.39*
LOWER-SHAFT	-0.74*	0.09
TOP-SHAFT	0.12	-0.34
TOP-LOWER	0.61*	-0.34
DEFLECTION	0.80*	0.88*

In terms of stick properties, stick bending and deflection correlated highly to peak velocity (r = 0.80 to 0.90) in both the slap and wrist shots. In terms of technique, the slap shot was significantly correlated to lower hand placement and the top to lower hand distance. The top hand placement and attacking angle were not significant. For the wrist shot, the attacking angle was the only technique variable that was significantly correlated to peak velocity (r = 0.39). This information clearly indicated the importance and the differences in the slap and wrist shots shooting technique.

Chapter 7: Discussion and Conclusion

In this study, the skilled and unskilled players performed the slap shot with the range of 24.3 ± 6.2 m/s and 18.3 ± 5.9 m/s, respectively. The results were similar to the pervious studies (Alexander et al, 1963; Cotton, 1966; Chao et al, 1973; Roy & Dore, 1974 & 1976; Dore & Roy, 1976; Pearsall et al, 1999). For the wrist shot, the skilled and unskilled players performed at 16.6 ± 3.7 m/s and 12.4 ± 4.1 m/s. Only Roy (1974) had similar findings, but all other studies had reported higher velocity (Alexander et al, 1963; Cotton, 1966; Chao et al, 1973; Naud & Holt, 1975; Sim & Chao, 1978). The reason may be related to all previous studies using elite male players only; hence, the shots were significantly faster for them. Similar differences were observed when comparing the stick bending angle with other studies. For the slap shot, this study recorded 15.3° ± 6.1° and 10.5° ± 3.7° for the skilled and unskilled players, respectively. Previously, Pearsall et al (1999) found the stick bending angle was 17.9° to 20.4° with six varsity players, and Naud and Holt (1975) reported the angle was 20° and 26° with two professional players. Both studies had small homogeneous groups so it was not possible to generalize to all the populations. In the wrist shot, this study found the stick bending angle to be on average of 12.8° ± 5.9° and 9.1° ± 4.8° for the skilled and unskilled players, respectively. The only previous study reported angles of 13° and 15° with two professional players (Naud & Holt, 1975).

Not surprisingly, the slap shot produced greater puck velocity than the wrist shot. For the slap shot, the players tended to place their hands further apart on the stick than the wrist shot. This technique difference may, in part, allow greater vertical loading force and stick bending, resulting the faster shots. Other technique parameters need to be addressed to understand the interest of the player with the stick in future studies.

In addition, the results of this study suggested that the different stick stiffness properties did not significantly nor substantially affect puck velocity. Consequently, skilled and unskilled players could use any stick type and expect to produce the similar or same maximum velocity. The reason may due to differences in stick materials for three stick types (medium: 13.0 ± kN/m, stiff wood: 16.6 ± kN/m and carbon composite: 17.9 ± kN/m) maybe too small to detect any significant functional difference. With greater differences in stick stiffness between stick types, the influence of stick stiffness to maximum velocity may potentially be observed. When comparing stick models with the hand placement and attacking angle for the slap and wrist shots within the skilled and unskilled sub-group players, no significant technique difference was found. This indicates that the players did not change their hand placements or stick movement for the various stick models. It appears that the player's traits (i.e. skill, body, and strength) above were the critical factors in determining puck velocity in both the slap and wrist shots. This agrees with the previous study (Pearsall et al, 1999). Moreover, the vertical force, stick bending and deflection angles measures were observed to be significantly different between skilled and unskilled players, but no similar significant differences in bench press and right and left hand grip strengths were observed. Basically, the skilled and unskilled groups had similar physical strength characteristics, thus performance differences have to be attributed to technique difference. More specially, when skilled players were performing the slap or wrist shot, they struck the puck harder than unskilled players as observed by the greater vertical loading force at the impact presumably, resulting in greater stick shaft bending and deflection. Other technique differences include hand positions: the skilled players would place their bottom hand lower in the slap shot and the unskilled players would place their top hand higher in the wrist shot. As an extension of the above, the player's height, weight, bench press, and grip strength variables were positively correlated to the velocity. Therefore, it may well be that in order to have a faster slap or wrist shot, both shooting technique (i.e. skill) and body strength are critical factors.

Several experimental limitations should be noted. First of all, the experiment was done in a laboratory on an artificial ice surface as opposed to an actual ice surface at the rink. Also, the subjects performed the task in a stationary position rather than with prior motion. These factors in mimicking the actual performance playing and conditions should be evaluated. Secondly, more accommodation time for the subjects to the testing conditions with each different stick type should be examined. For instance, though significant differences between sticks in shot velocity were not observed within the short duration of testing period, potentially that stick performance differences may change when a player learns or adapts to the advantage of different stick properties. Thirdly, the fixed stick length may also affect performance versus the player's preferred length of the stick. Players tend to cut the stick to a preferred height such that during a wrist shot the top hand is at the top (butt) end of the stick. Hence, a survey of player's height to stick length ratio should be conducted as well as a comparison of shooting technique with their own stick to identify the effects of stick length on shooting technique in the future. Fourthly, in this study, the subjects ranged from 17 to 26 of age. Since it is not necessary possible to extend the same findings for the children and adolescents, further research is needed within these age categories. Fifthly, this study did not examine interaction with other stick properties. For example, different blade stiffness and curvatures may affect shot performance (i.e. accuracy in the wrist shot & velocity in the slap shot). For instance, Nazar (1971) reported a curved blade had better accuracy and velocity than straight blade hockey sticks. Lastly, this experiment was done on a 2D analysis in terms of technique. With more advanced technology and instrumentation, the 3D shooting technique can be analyzed. This way it will be possible to clearly identify the differences in shooting technique between the skilled and unskilled players.

Some questions still remain unanswered from this study. For example, in this experiment the criteria for the performance was based on peak velocity of the shot; however, other performance criteria such as accuracy of puck shot placement as well as passing, receiving, and stick handling should be examined with respect to stick design. Moreover, in addition to general stick stiffness about the major axis, the axial torsion stiffness and the inhomogeneity of stick stiffness are other design variables of interest. Also, different hand placement and grip strength on the stick may cause the stick to bend and twist differently during the impact because the different leverage effects of the stick. Therefore, more in depth studies are needed to address the importance of the physical characteristics and identify the specific motor technique of skilled shooting as well as the relation to stick properties.

Appendix A

Summary of the Slap and Wrist Shots Velocity

Table 10. Different types of the slap and wrist shots in various studies

Studies	Year	N	Age (Level)	Types	Shots/Sticks	Velocity (MPH)	KPH	MPS
Alexander	1963	11	Pro	Impact	Slap Stand	74.5	119.9	33.3
					Slap Skate	85.5	137.6	38.2
					Wrist Stand	63.1	101.5	28.2
					Wrist Skate	78.6	126.5	35.1
		7	Amateur	Impact	Slap Stand	72.3	116.4	32.3
					Slap Skate	79.0	127.1	35.3
					Wrist Stand	62.4	100.4	27.9
					Wrist Skate	70.5	113.5	31.5
		6	Amateur	Impact	Slap Stand	69.6	112.0	31.1
					Slap Skate	75.7	121.8	33.8
					Wrist Stand	58.7	94.5	26.2
					Wrist Skate	69.1	111.2	30.9
		6	University	Impact	Slap Stand	59.5	95.8	26.6
					Slap Skate	75.5	121.5	33.8
					Wrist Stand	54.3	87.4	24.3
					Wrist Skate	73.5	118.3	32.9
		30	All	Average	Slap Stand	69.0	111.0	30.8
					Slap Skate	79.0	127.1	35.3
					Wrist Stand	59.6	95.9	26.6
					Wrist Skate	72.9	117.3	32.6
Alexander	1964		Varsity	Impact	Slap Skate	75.2	121.0	33.6
					Wrist Skate	70.8	114.0	31.7
Cotton	1966		Adult		Slap Stand	55.9	90.0	25.0
					Slap Skate	62.1	100.0	27.8
					Wrist Stand	50.3	81.0	22.5
					Wrist Skate	55.9	90.0	25.0
					Sweep Stand	51.6	83.0	23.1
					Sweep Skate	55.9	90.0	25.0
Furlong	1968		Pro	Average	Slap Skate	108.7	175.0	48.6
					Wrist Skate	101.3	163.0	45.3
Chao	1973		Adult	Instant.	Slap Stand	68.4	110.0	30.6
					Slap Skate	82.0	132.0	36.7
					Wrist Stand	82.0	132.0	36.7
					Wrist Skate	88.9	143.0	39.7
Dore	1973				Slap Stand	60.2	96.8	26.9
					Slap Skate	64.9	104.4	29.0
Roy	1973	10	11 to 12		Slap	43.0	69.1	19.2
		10	15 to 16		Slap	58.4	94.0	26.1
		19	17 +		Slap	59.7	96.1	26.7

...continued

Table 10. Continued

Roy	1974		Jr.B	Average	Slap Stand	57.2	92.0	25.6
					Slap Skate	55.3	89.0	24.7
					Wrist Stand	39.8	64.0	17.8
					Wrist Skate	50.3	81.0	22.5
					Sweep Skate	52.8	85.0	23.6
					Backhand Skate	39.8	64.0	17.8
Naud	1975	2	Pro	Average	Slap Stand	83.0	133.6	37.1
					Wrist Stand	55.0	88.5	24.6
					Snap Stand	61.0	98.2	27.3
Dore	1976		Adult	Average	Slap Stand	60.3	97.0	26.9
					Slap Skate	64.6	104.0	28.9
Roy	1976		Pee-wee	Average	Slap Stand	42.9	69.0	19.2
			Adult		Slap Stand	59.7	96.0	26.7
Roy	1978		Pee-wee	Max.	Slap Stand	57.0	91.7	25.5
					Sweep Stand	52.0	83.7	23.2
Sim	1978		Adult	Average	Slap Stand	68.2	109.8	30.5
					Slap Skate	81.8	131.6	36.6
					Wrist Stand	81.8	131.6	36.6
					Wrist Skate	88.6	142.6	39.6
			Juvenile	Average	Wrist Skate	54.5	87.7	24.4
Marino	1991	10 (n = 72)	Skilled	Average	Slap Stand/Wood	65.1	104.8	29.1
		10 (n = 10)			Slap Stand/Aluminum	66.6	107.2	29.8
NHL	1996		Pro	Max.	Slap Stand	103.8	167.0	46.4
Pearsall	1999	6	University	Average	Slap Stand/Medium	67.2	108.2	30.1
					Slap Stand/Stiff	66.5	107.0	29.7
					Slap Stand/Extra	65.8	105.9	29.4
					Slap Stand/Pro stiff	66.1	106.3	29.5
Pearsall	2001	10 (Male)	University	Average	Slap Stand/Medium	68.5	110.2	30.6
					Slap Stand/Stiff	65.3	105.1	29.2
					Slap Stand/Composite	67.8	109.1	30.3
					Slap Stand/All	67.1	108.0	30.0
		10	Rec. to No exp.	Average	Slap Stand/Medium	51.5	82.8	23.0
					Slap Stand/Stiff	52.1	83.9	23.3
					Slap Stand/Composite	52.8	85.0	23.6
					Slap Stand/All	52.1	83.9	23.3
Wu	2001	10 (Male)	University	Average	Slap Stand/Composite	68.4	110.1	30.6
					Slap Stand/Medium	65.3	105.1	29.2
					Slap Stand/Stiff	67.7	109.0	30.3
					Slap Stand/All	67.1	108.0	30.0
					Wrist Stand/Composite	44.6	71.8	19.9
					Wrist Stand/Medium	43.7	70.3	19.5
					Wrist Stand/Stiff	43.9	70.6	19.6
					Wrist Stand/All	44.1	70.9	19.7
		10 (Male)	Rec. to No exp.	Average	Slap Stand/Composite	51.4	82.7	23.0

...continued

Table 10. Continued

					Slap Stand/Medium	52.1	83.8	23.3
					Slap Stand/Stiff	52.8	84.9	23.6
					Slap Stand/All	52.1	83.8	23.3
					Wrist Stand/Composite	36.0	57.9	16.1
					Wrist Stand/Medium	36.6	58.9	16.4
					Wrist Stand/Stiff	34.6	55.7	15.5
					Wrist Stand/All	35.7	57.5	16.0
		10 (Female)	University	Average	Slap Stand/Composite	41.1	66.1	18.4
					Slap Stand/Medium	41.9	67.4	18.7
					Slap Stand/Stiff	42.9	69.0	19.2
					Slap Stand/All	41.9	67.5	18.8
					Wrist Stand/Composite	31.1	50.1	13.9
					Wrist Stand/Medium	31.3	50.4	14.0
					Wrist Stand/Stiff	29.1	46.9	13.0
					Wrist Stand/All	30.5	49.1	13.6
		10 (Female)	Rec. to No exp.	Average	Slap Stand/Composite	27.7	44.6	12.4
					Slap Stand/Medium	31.3	50.4	14.0
					Slap Stand/Stiff	29.9	48.1	13.4
					Slap Stand/All	29.6	47.7	13.3
					Wrist Stand/Composite	20.1	32.4	9.0
					Wrist Stand/Medium	19.5	31.4	8.7
					Wrist Stand/Stiff	23.5	37.8	10.5
					Wrist Stand/All	21.0	33.8	9.4

Appendix B

Average Peak Vertical Force for Each Type of Sticks in Each Sub-group

Table 11. Average peak vertical force for each type of sticks in each sub-group

Male/Skilled				**Female/Skilled**			
Slap shot	**Vertical Force (N)**	**SD**	**CV**	**Slap shot**	**Vertical Force (N)**	**SD**	**CV**
Composite	169.8	52.9	31.1	***Composite***	87.1	67.9	77.9
Medium	147.9	47.2	31.9	***Medium***	84.9	58.7	69.2
Stiff	181.3	49.0	27.0	***Stiff***	75.3	53.7	71.3
Mean	166.3	49.7	30.0	***Mean***	82.4	60.1	72.8
Wrist shot				**Wrist shot**			
Composite	69.7	32.3	46.3	***Composite***	31.3	10.2	32.6
Medium	73.8	38.2	51.7	***Medium***	26.1	13.1	50.2
Stiff	93.0	44.2	47.5	***Stiff***	17.5	6.1	34.5
Mean	78.8	38.2	48.5	***Mean***	25.0	9.8	39.1
Male/Unskilled				**Female/Unskilled**			
Slap shot	**Vertical Force (N)**	**SD**	**CV**	**Slap shot**	**Vertical Force (N)**	**SD**	**CV**
Composite	108.4	57.0	52.6	***Composite***	38.6	13.5	35.0
Medium	100.1	45.1	45.1	***Medium***	39.9	10.9	27.3
Stiff	105.6	46.1	43.6	***Stiff***	43.6	14.5	33.1
Mean	104.7	49.4	47.1	***Mean***	40.7	12.9	31.8
Wrist shot				**Wrist shot**			
Composite	46.7	20.7	44.3	***Composite***	28.9	12.1	42.0
Medium	44.8	16.4	36.6	***Medium***	29.7	12.5	42.0
Stiff	48.5	15.5	32.0	***Stiff***	25.9	12.3	47.6
Mean	46.7	17.5	37.6	***Mean***	28.2	12.3	43.9

$p < 0.05$, ANOVA 4W analysis conducted

Appendix C

Average Peak Bending Angle for Each Type of Sticks in Each Sub-group

Table 12. Average peak bending angle for each type of sticks in each sub-group

Male/Skilled				Female/Skilled			
Slap shot	**Bending Angle (deg)**	**SD**	**CV**	**Slap shot**	**Bending Angle (deg)**	**SD**	**CV**
Composite	16.8	3.0	18.0	***Composite***	10.1	3.4	33.9
Medium	22.5	4.5	19.8	***Medium***	10.5	4.3	40.7
Stiff	17.5	5.7	32.6	***Stiff***	10.3	2.7	26.5
Mean	18.9	4.4	23.5	***Mean***	10.3	3.5	33.7
Wrist shot				**Wrist shot**			
Composite	15.6	4.5	28.9	***Composite***	8.2	2.2	27.1
Medium	21.0	3.5	16.7	***Medium***	8.4	2.0	23.1
Stiff	16.0	3.7	23.0	***Stiff***	6.7	1.7	24.5
Mean	17.5	3.9	22.9	***Mean***	7.8	1.9	24.9
Male/Unskilled				**Female/Unskilled**			
Slap shot	**Bending Angle (deg)**	**SD**	**CV**	**Slap shot**	**Bending Angle (deg)**	**SD**	**CV**
Composite	9.8	4.0	41.2	***Composite***	7.8	1.1	13.6
Medium	14.7	1.7	11.6	***Medium***	8.6	3.2	37.6
Stiff	12.4	2.8	22.6	***Stiff***	8.8	3.6	40.8
Mean	12.3	2.9	25.1	***Mean***	8.4	2.6	30.7
Wrist shot				**Wrist shot**			
Composite	11.4	5.4	47.7	***Composite***	4.1	1.9	44.9
Medium	13.0	3.0	23.0	***Medium***	6.6	4.5	68.2
Stiff	10.4	2.0	19.3	***Stiff***	5.6	3.1	54.1
Mean	11.6	3.5	30.0	***Mean***	5.5	3.1	55.7

$p < 0.05$, ANOVA 4W analysis conducted

Appendix D

Average Peak Attacking Angle for Each Type of Sticks in Each Sub-group

Table 13. Average peak attacking angle for each type of sticks in each sub-group

Male/Skilled				**Female/Skilled**			
Slap shot	**Attacking Angle (deg)**	**SD**	**CV**	**Slap shot**	**Attacking Angle (deg)**	**SD**	**CV**
Composite	50.5	14.0	27.7	***Composite***	56.6	16.4	29.0
Medium	52.0	14.4	27.8	***Medium***	59.1	18.7	31.6
Stiff	51.4	16.1	31.4	***Stiff***	56.2	13.0	23.1
Mean	51.3	14.8	28.9	***Mean***	57.3	16.0	27.9
Wrist shot				**Wrist shot**			
Composite	44.0	34.3	78.0	***Composite***	66.0	26.0	39.4
Medium	44.3	35.2	79.6	***Medium***	59.1	30.4	51.5
Stiff	43.1	31.0	71.9	***Stiff***	69.8	24.3	34.8
Mean	43.8	33.5	76.5	***Mean***	65.0	26.9	41.9
Male/Unskilled				**Female/Unskilled**			
Slap shot	**Attacking Angle (deg)**	**SD**	**CV**	**Slap shot**	**Attacking Angle (deg)**	**SD**	**CV**
Composite	53.5	22.5	42.1	***Composite***	58.7	17.3	29.4
Medium	50.5	18.9	37.5	***Medium***	56.7	16.6	29.3
Stiff	60.5	13.4	22.2	***Stiff***	55.1	16.3	29.5
Mean	54.8	18.3	33.9	***Mean***	56.8	16.7	29.4
Wrist shot				**Wrist shot**			
Composite	50.1	32.7	65.2	***Composite***	44.9	33.7	75.1
Medium	49.5	35.2	71.1	***Medium***	50.6	31.2	61.8
Stiff	67.3	28.5	42.3	***Stiff***	54.4	3.1	5.7
Mean	55.6	32.1	59.6	***Mean***	50.0	22.7	47.5

$p < 0.05$, ANOVA 4W analysis conducted

Appendix E

Average Peak Shaft Deflection for Each Type of Sticks in Each Sub-group

Table 14. Average peak shaft deflection for each type of sticks in each sub-group

Male/Skilled				**Female/Skilled**			
Slap shot	**Shaft Deflection (m)**	**SD**	**CV**	**Slap shot**	**Shaft Deflection (m)**	**SD**	**CV**
Composite	0.050	0.009	17.9	***Composite***	0.030	0.010	33.9
Medium	0.067	0.013	19.7	***Medium***	0.031	0.013	40.7
Stiff	0.052	0.017	32.6	***Stiff***	0.031	0.008	26.5
Mean	0.056	0.013	23.4	***Mean***	0.031	0.010	33.7
Wrist shot				**Wrist shot**			
Composite	0.046	0.012	26.9	***Composite***	0.024	0.006	26.6
Medium	0.060	0.010	17.4	***Medium***	0.025	0.006	23.2
Stiff	0.048	0.011	23.0	***Stiff***	0.020	0.005	24.5
Mean	0.051	0.011	22.4	***Mean***	0.023	0.006	24.8
Male/Unskilled				**Female/Unskilled**			
Slap shot	**Shaft Deflection (m)**	**SD**	**CV**	**Slap shot**	**Shaft Deflection (m)**	**SD**	**CV**
Composite	0.029	0.012	41.2	***Composite***	0.023	0.003	13.7
Medium	0.044	0.005	11.7	***Medium***	0.026	0.010	37.6
Stiff	0.037	0.008	22.6	***Stiff***	0.026	0.011	40.8
Mean	0.037	0.009	25.1	***Mean***	0.025	0.008	30.7
Wrist shot				**Wrist shot**			
Composite	0.034	0.016	47.7	***Composite***	0.012	0.006	44.9
Medium	0.039	0.009	23.0	***Medium***	0.020	0.013	68.1
Stiff	0.031	0.006	19.2	***Stiff***	0.017	0.009	54.2
Mean	0.035	0.010	30.0	***Mean***	0.016	0.009	55.7

$p < 0.05$, ANOVA 4W analysis conducted

Appendix F

Interaction Effects of Genders and Skill Levels in Stick Bending Angle of the Slap Shot

Table 15. Stick bending angle of the slap shot comparison between skilled and unskilled players in both genders

Skill Levels\Genders	Male	SD	Female	SD
Skilled (deg)	19.05	4.96	10.33	3.32
Unskilled (deg)	12.51	3.48	8.43	2.77

Slap shot: ANOVA 2 W; $p < 0.0064$

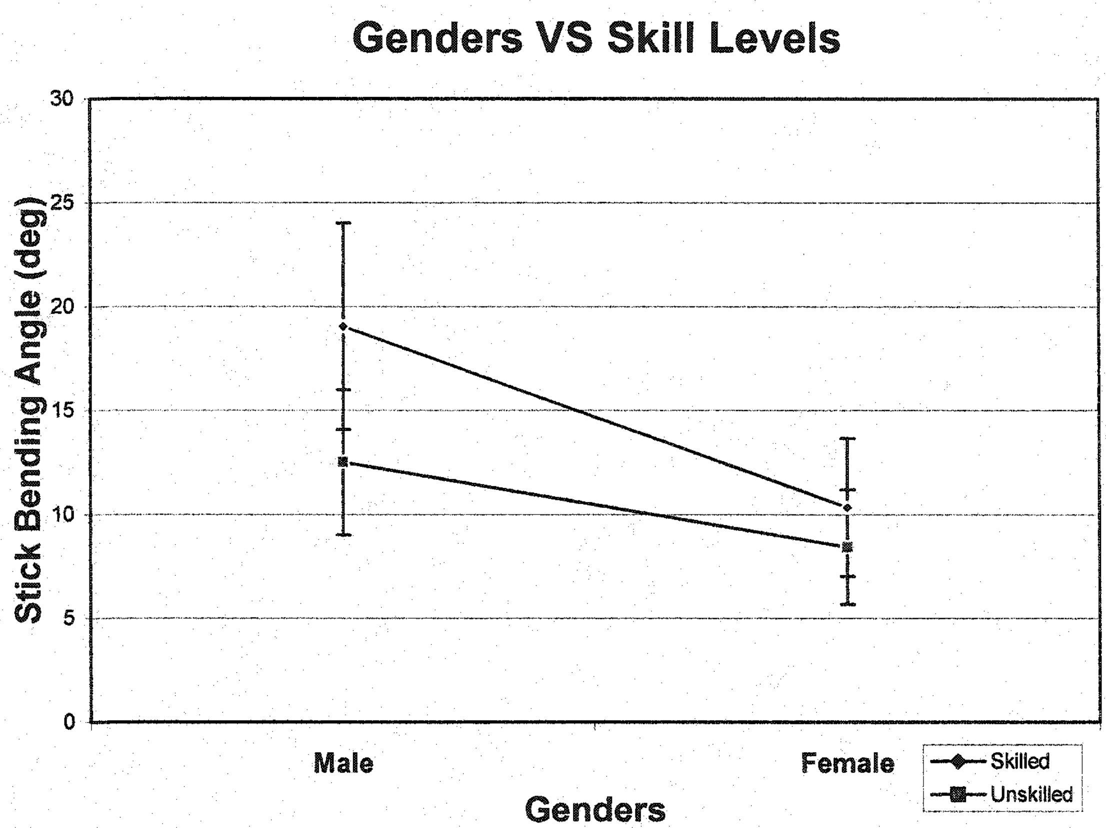

Figure 7. Slap shot: stick bending angle between genders (male and female) and skill levels (skilled and unskilled).

Appendix G

Interaction Effects of Genders and Skill Levels in Shaft Deflection of the Slap Shot

Table 16. Shaft deflection of the slap shot comparison between skilled and unskilled players in both genders

Skill Levels\Genders	Male	SD	Female	SD
Skilled (m)	0.057	0.015	0.031	0.010
Unskilled (m)	0.037	0.010	0.025	0.010

Slap shot: ANOVA 2 W; $p < 0.0065$

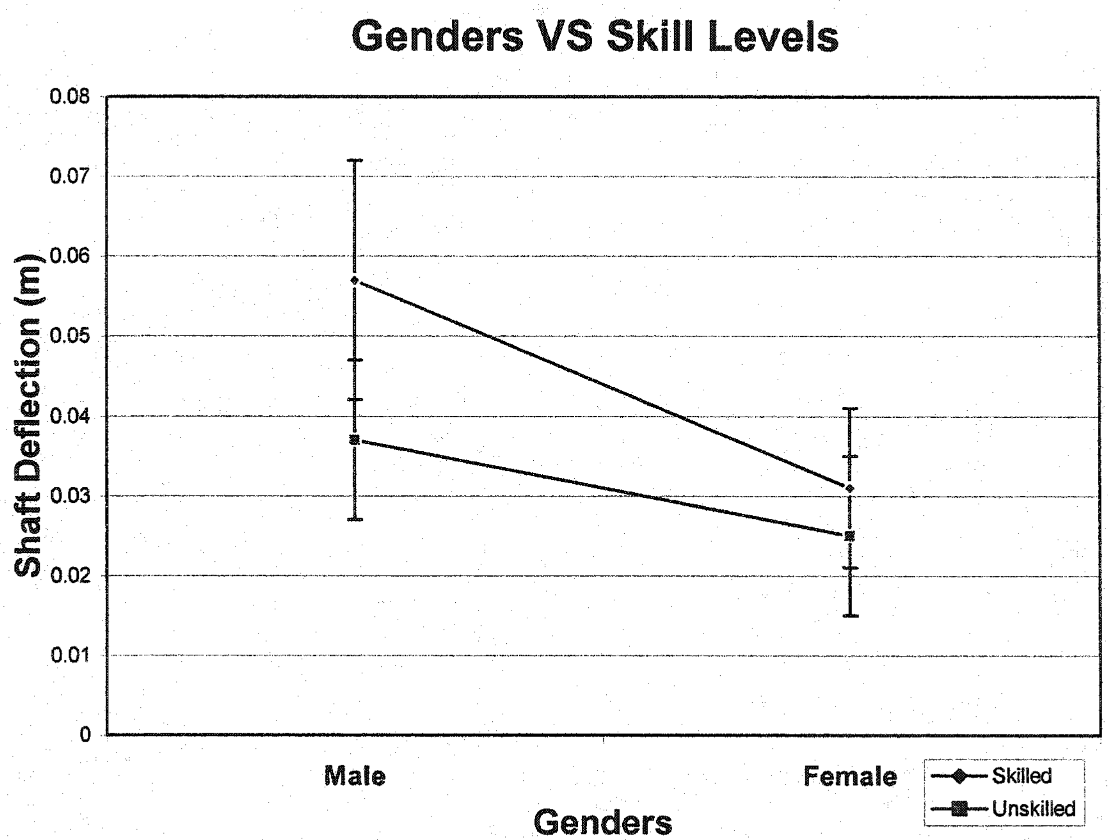

Figure 8. Slap shot: shaft deflection between genders (male and female) and skill levels (skilled and unskilled).

Appendix H

Interaction Effects of Genders and Skill Levels in Vertical Force of the Wrist Shot

Table 17. Vertical force of the wrist shot comparison between skilled and unskilled players in both genders

Skill Levels\Genders	Male	SD	Female	SD
Skilled (N)	77.25	37.54	25.31	11.52
Unskilled (N)	46.53	17.24	28.34	11.96

Wrist shot: ANOVA 2 W; $p < 0.0001$

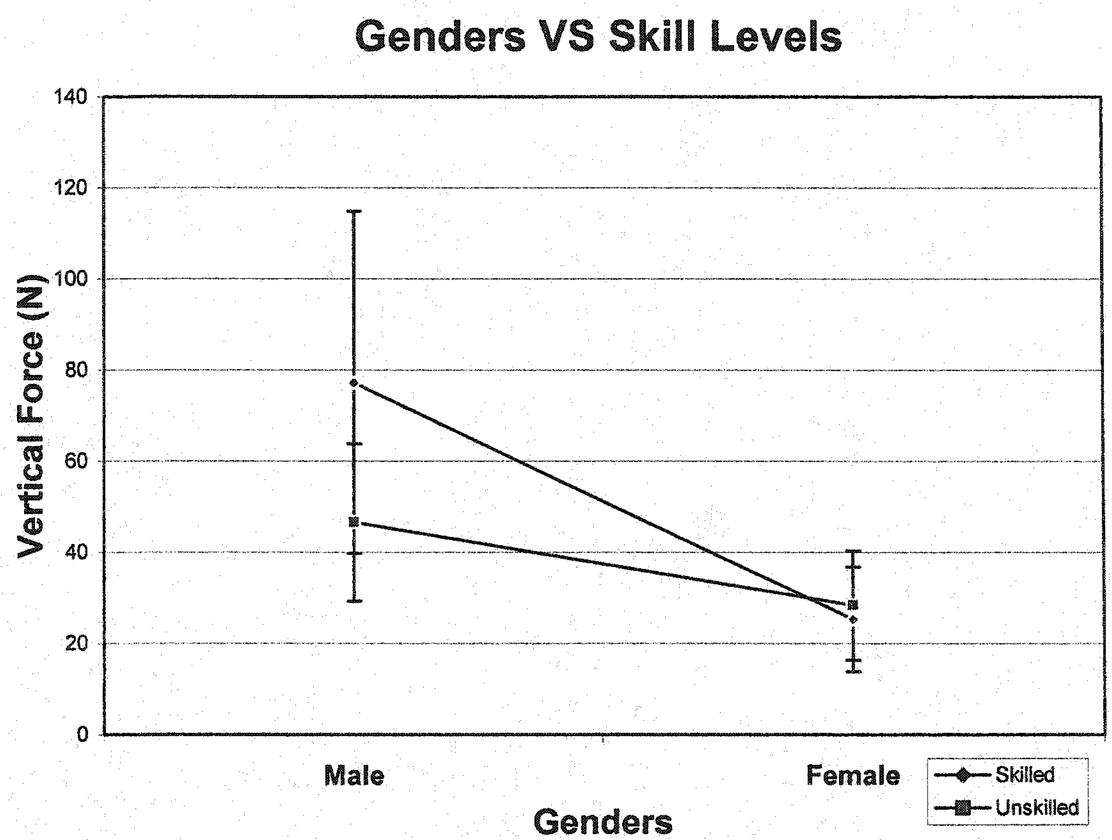

Figure 9. Wrist shot: vertical force between genders (male and female) and skill levels (skilled and unskilled).

Appendix I

Interaction Effects of Genders and Skill Levels in Stick Bending Angle of the Wrist Shot

Table 18. Stick bending angle of the wrist shot comparison between skilled and unskilled players in both genders

Skill Levels\Genders	Male	SD	Female	SD
Skilled (deg)	17.34	4.24	7.77	2.00
Unskilled (deg)	11.77	3.96	5.53	3.37

Wrist shot: ANOVA 2 W; p < 0.032

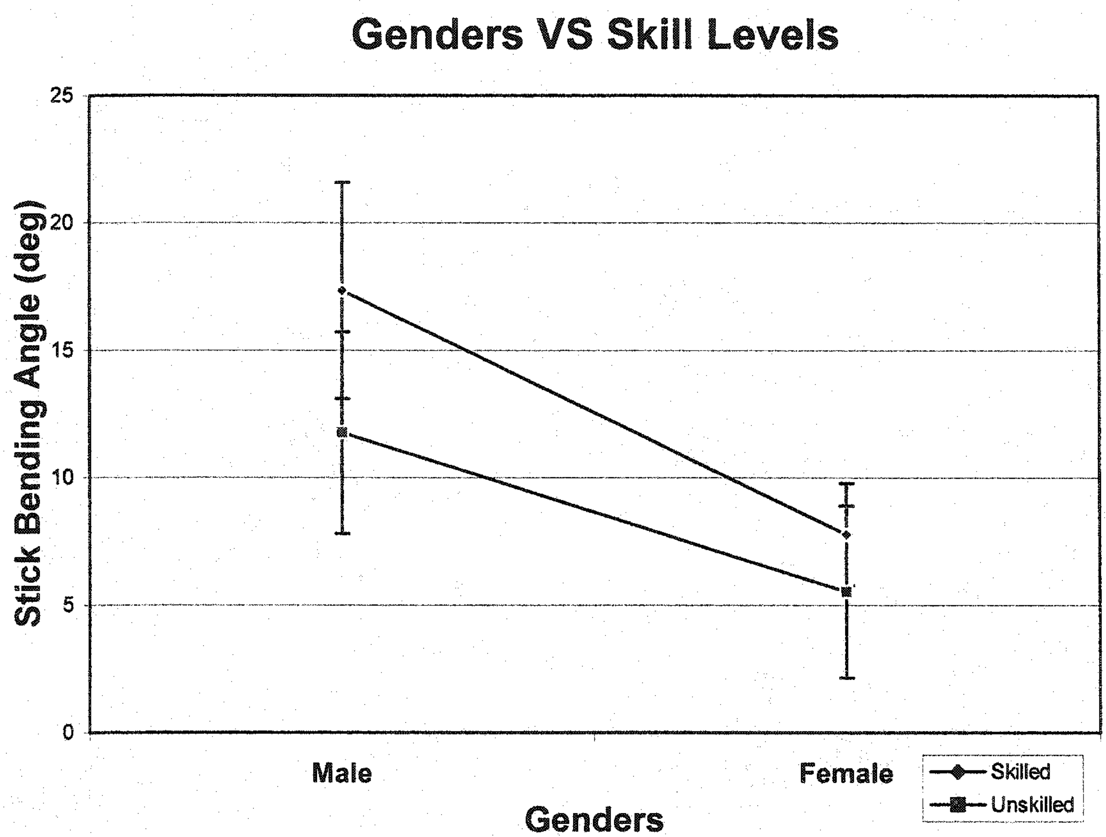

Figure 10. Wrist shot: stick bending angle between genders (male and female) and skill levels (skilled and unskilled).

Appendix J

Interaction Effects of Genders and Skill Levels in Shaft Deflection of the Wrist Shot

Table 19. Shaft deflection of the wrist shot comparison between skilled and unskilled players in both genders

Skill Levels\Genders	Male	SD	Female	SD
Skilled (m)	0.052	0.013	0.023	0.006
Unskilled (m)	0.035	0.012	0.017	0.010

Wrist shot: ANOVA 2 W; $p < 0.032$

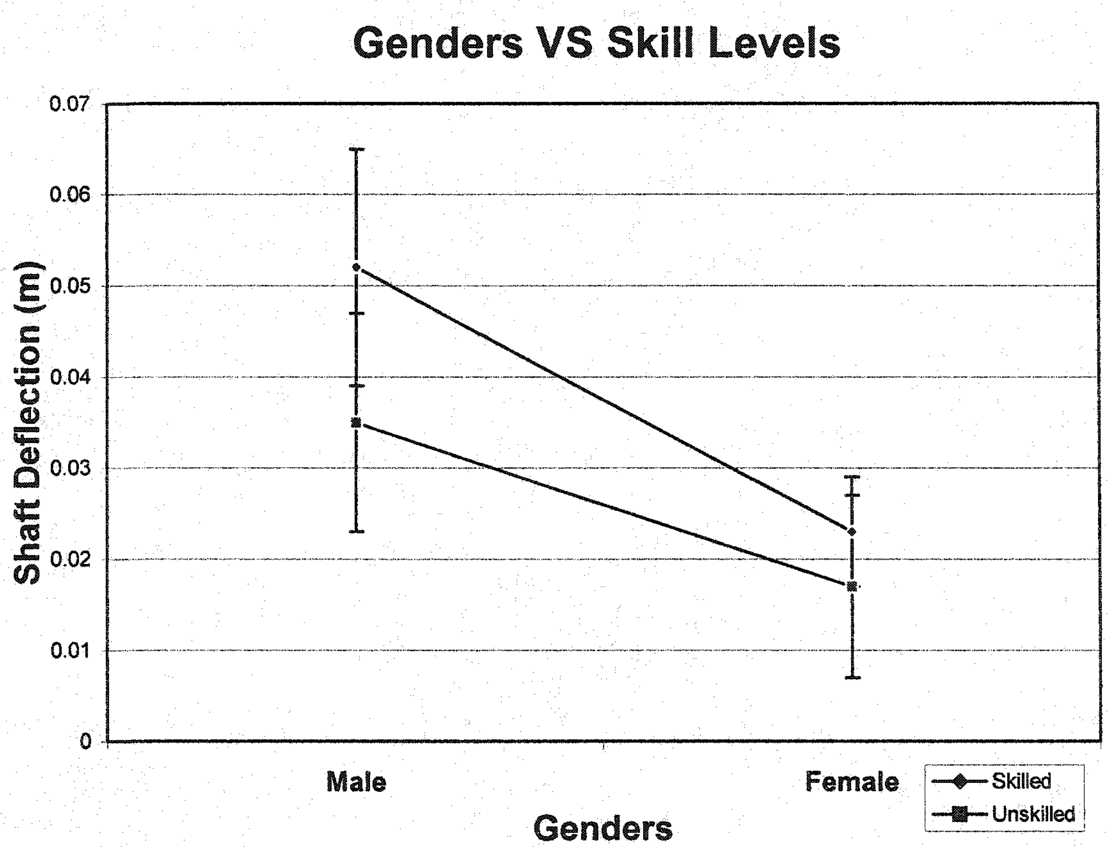

Figure 11. Wrist shot: shaft deflection between genders (male and female) and skill levels (skilled and unskilled).

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