The dynamic interaction of hand grip and ice hockey stick flexion during slap shots and wrist shots

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Abstract

This study synchronized previously used technologies (Zane, 2012, Hannon, 2010) to examine the dynamic interaction of hand grip and ice hockey stick flexion during slap shots and wrist shots. Eighteen adult male subjects (11 high caliber, HC, and 7 low caliber, LC) ice hockey players were tested. Subjects performed five stationary wrist shots and five stationary slap shots using three hockey stick shafts of different stiffness' (77, 87, and 102) on a synthetic ice surface. Grip forces at the stick-hand interface were recorded at 1000 Hz using 32 piezo resistive sensors and stick flexion was measured at two locations (mid and lower shaft) using sets of strain gauge pairs about the shaft's major and minor axes.

Grip force and strain were found to differ between the calibers, such that HC showed higher forces and stick flexion than LC during both wrist and slap shots. While stick model stiffness affected the extent of strain flexion (highest for 77 flex, lowest for 102 flex), stick stiffness did not significantly affect the forces seen at the hands, nor the shooting velocity. Peak strain in the minor axis (about half the magnitude of the major axis) typically occurred 10 to 20 ms before peak strain about the major axis, indicating a complex 3D dynamic bend and possibly torsion shot dynamics. In terms of grip, individual shooters displayed remarkable consistency in their grip "force signatures" yet there was wide inter-subject variability. Correlation analysis was also conducted on both slap shot and wrist shot groups. In general, bi-manual grip force coupling was evident across all subjects. Further study is warranted using these combined measures to better understand the dynamics between the player's hand and the ice hockey stick during other skill tasks.

Résumé

Ce projet a combiné des technologies précédemment utilisées (Zane, 2012, Hannon, 2011) dans le but d'éxaminer l'interaction dynamique entre les forces appliquées par la main sur le bâton et les forces de flexion du bâton lui-même lors du lancé frappé et du tir du poignet. Dix-huit sujets adultes mâles, tous joueurs de hockey (11 de haut calibre, HC et 7 de bas calibre, LC), ont été étudiés. Les sujets ont réalisés cinq lancés du poignet et cinq lancés frappés d'une position stationnaire, en utilisant trois bâtons de différente rigidité (flex 77, 87 et 102). Le tout fût réalisé sur une glace synthétique en laboratoire. Les forces d'adhérence du bâton appliquées par la main furent enregistrées à une fréquence de 1000Hz en utilisant 32 capteurs piézo-électriques. La flexion du bâton fût mesuré à deux endroits (milieu et bas du manche) par l'entremise d'un ensemble de jauges de déformation installé en pair sur les axes majeur et mineur du manche.

La déformation du bâton et les forces appliquées au niveau de la main varient dépendamment du calibre du joueur, tel que la déformation et les forces appliquées au bâton étaient plus importantes pour les joueurs de haut calibre, autant pour le lancé frappé que pour le tir du poignet. La raideur du bâton a eu une influence sur la flexion du bâton (plus important pour un flex de 77, plus bas pour un flex de 102), mais ceci ne semble pas influencer les forces mesurées au niveau des mains ou encore la vitesse de la rondelle après un tir. La déformation maximale sur l'axe mineur (environ la moitié de l'amplitude de la déformation sur l'axe majeur) apparait en général 10 à 20 ms avant la déformation maximale sur l'axe majeur, ce qui indique une flexion dynamique complexe en 3D et possiblement la présence de torsion dynamique en parallèle. En terme de force appliquer par les mains sur le bâton, chaque joueur a affiché une bonne uniformité pour reproduire leur propre "signature", ne variant pas beaucoup de tir en tir.

Malgré cette “signature” propre à chaque joueur, il y a beaucoup de variation entre les joueurs. Une analyse de corrélation a aussi été réalisé pour les lancés frappés et les tirs du poignet. En général, un couplage des forces appliquées au bâton par les deux mains a été démontré. Il serait intéressant de poursuivre ce genre d’étude en combinant les deux types de mesure dans l’idée d’avoir une meilleure compréhension des forces dynamiques présentes entre les mains et le bâton, et ce pour différente tâches propres au hockey.

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Introduction

Despite the popularity of hockey, and the importance of the hockey stick as the primary tool for a variety of tasks in the sport, there is still a limited understanding as to how a stick behaves when shooting thanks to the interaction provided by the hands. One reason for this is that, during a game, hockey skills are not always performed in a predictable way. Skills are subject to player perception, decision-making and reaction time; this makes skill level a function of timing and execution, rather than just one or the other (Pearsall, Turcotte, & Murphy, 2000). In a controlled setting, this study looked to identify the "grip force profiles" (the forces imparted on the stick by the hands during a shot) created by elite and novice shooters, the "stick flex profiles" (how the stick bends during the shot) these players created when shooting using sticks of varying stiffness, and the dynamic interaction between these two factors. Synchronizing technologies previously used to measure "grip force profiles" (Zane, 2012) and "dynamic flex profiles" (Hannon, 2011), we were provided insight towards the relationship between these variables, as well as how that relationship changed between shooting caliber and stick stiffness.

Literature Review

The Hockey Stick

While ice hockey sticks were originally made of just wood, over time they have been made with fiberglass, aluminum, and, now, carbon fiber composites ((Hoerner, 1989),(Pearsall & Turcotte, 2007)). Modern composite sticks are manufactured through a variety of techniques, and are either constructed as true one-pieces, or fused from two pieces, with remarkable consistency (Pearsall & Turcotte, 2007). Sticks feature a shaft, a butt end, a hosel, a lie angle, and a blade. Figure 1 illustrates these features. Stick shafts come in different levels of stiffness, can be square or rounded along their edges, and may come with a rubberized grip applied by the manufacturer. The stick blade has a toe, a heel, a top edge, a bottom edge and a curve (Pearsall & Turcotte, 2007). Blades may come in a variety of shapes and curves, though these dimensions must adhere to the rules of the governing league in which the user plays.

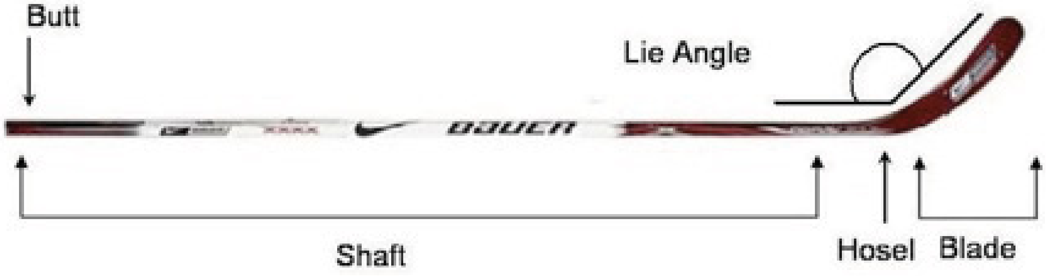


Figure 1 : The basic components of a hockey stick (Magee, 2011)

Hockey Canada and the National Hockey League (NHL) use the same standards for legal stick dimensions. The maximum length of a stick shaft for both governing bodies is 63 inches, with exceptions made for players above 6 foot 6 inches in height; these players may use a 65-inch stick. The blade of a stick can be a maximum length of 12.5 inches from heel to toe; the maximum height of a blade is 3 inches, where the minimum can be no less than 2 inches. The curve of the stick blade cannot be greater than ¾ of an inch at any point along the blade (("National Hockey League Official Rules 2012-2013," 2012), ("Referee's Case Book/ Rule Combination 2012-2014," 2012)). The International Ice Hockey Federation (IIHF) have slightly different rules in regards to stick dimensions, thanks primarily to use of the metric system. A hockey stick shaft may be no longer than 163 cm, no wider than 3 cm and no thicker than 2.5

cm. A stick blade may be no longer than 32 cm, and no taller than 7.5 cm; it may be no shorter than 5 cm ("IIHF Rulebook," 2010).

Stick skills in hockey

The hockey stick acts as an extension of the player's arms, and is used as the primary tool for the player to interact with the puck. To use a stick effectively and efficiently a player must coordinate the important aspects of skating (angle of propulsion, angle of forward inclination, power and length of stride) with agility, coordination, flexibility and strength (Hoerner, 1989). While the role that the stick plays in a hockey game isn't exclusively to shoot the puck, shooting is the primary means in which a player may score a goal for his or her team; the slap shot, the wrist shot, the snap shot, the sweep shot, the backhand, the flick, and the lob are all varieties of shots. When classifying "stick skills" one must also include puck handling with shooting, which encompasses passing, pass receiving, face offs, and moving. Factors that influence the performance of these skill tasks include the participants themselves (who range in age, gender, and experience), equipment (which is subject to age and condition), and, environments (which includes the playing surface, the playing context, the games rules, etc.) (D. Pearsall et al., 2000)

Shooting in hockey

There have been traditionally six different approaches taken towards measuring shooting velocity in hockey: impact velocity, average velocity, instantaneous velocity, maximal velocity, radar and integration of accelerometer data (Reed, 1979). While there are a variety of shots used by players to propel the puck, the two most commonly used shots are the "slap shot" (SS) and the "wrist shot" (WS) (Montgomery, Nobes, Pearsall, & Turcotte, 2004). In 2004, Montgomery and his research team conducted a study of 10 NHL hockey teams over 9 games. They found that defenseman used slap shots 54% of the time when shooting, in comparison to using their wrist shot 23 % of the time. Centers used slap shots 25 % of the time, and wrist shots 29% of the time. Wingers used slap shots 26% of the time and wrist shots 37% of the time (Montgomery et al., 2004).

When taking a SS, a player draws their stick back, forcibly slaps the ice, and then makes contact with the puck. There are six phases to the SS: the backswing, the downswing, the preloading phase, the loading phase, the release and the follow through (Villasenor, Turcotte, & Pearsall, 2006). Slap shots are typically performed with a wider grip than wrist shots, with hands roughly 40 to 60 cm apart (Wu et al., 2003). Roy & Dore (1976) found that the maximum velocity of the upper body is reached just prior to puck impact when taking slap shots. Examining the differences in shooting between pre and post-pubescent players, they saw that older players were more apt to rely on technique than brute force to propel the puck, while younger players tried to use whatever strength they had rather than a refined technique; Peewee-aged players shot significantly differently than midget-aged and adult players, but the midget-aged and adult players were not significantly different in how they shot the puck. Younger players may not have been strong enough to effectively harness the potential energy of the hockey sticks to increase their shot velocities, like older players were (Roy & Doré, 1976).

Woo and fellow researchers (2004) took a different approach to Roy & Doré when comparing elite and recreational hockey when taking slap shots. Their study involved placing 15 EMG sensors on each subject, as well as using Ultratrak ® (Polhemus Inc., Burlington VT, USA) motion capture technology to collect kinematic data. Findings showed that Elite players achieved higher translational velocity (13.14 m/s) than recreational players (9.08 m/s), as well as greater stick blade velocity (29.14 m/s VS 26.46 m/s), greater shot velocity (29.14 ± 1.39 m/s VS

26.46 ± 0.66 m/s), and less angular displacement velocity (16.00 m/s VS 17.38 m/s). The peak angular velocity movement sequences were different between the two tiers of players, where elite players started their shots from the trunk and recreational players started their shots from the shoulder (Woo, Loh, Turcotte, & Pearsall, 2008).

Lomond, Pearsall and Turcotte (2007) looked at the movement of the stick blade during slap shots, and the differences in execution of the shot between elite and recreational shooters. Using high speed camera and force plate, researchers noted that the timing and sequence of events of the shot were important in dictating performance, much like other “striking tasks”. Dividing trials into three phases, toe-to-heel contact, stick loading, and blade-ground contact, there were some distinct differences found in how the blades reacted for elite and recreational shooters; Elite shooters spent significantly less time in toe-to-heel contact and stick loading then the recreational group did, but spend a significantly longer time in blade-ground contact. Both groups saw a tendency during toe-to-heel contact to load the blade from to heel, creating a ‘rocker’-like effect. Stick construction did not result in altered blade orientation during shooting (Lomond, 2007).

More quickly executed than the slap shot, a wrist shot involves the player rapidly sweeping the puck forward, terminating the shot with a snap of the wrist and follow through. According to Hoerner (1989), an effective shot involves quickness, speed, power and accuracy.

Michaud-Paquette, Pearsall & Turcotte looked to identify the technique of an accurate wrist shot in 2008. Two caliber groups used the same patterned stick covered with VICON markers, shooting against the four corners of the net, 4 meters away. Subjects shot at each target until they had scored successfully 10 times, or had attempted 20 shots. Subjects were more accurate shooting at bottom corners, hitting the target 65% of the time, than the upper corners, hitting the target only 45% of the time (Yannick Michaud-Paquette, Pearsall, & Turcotte, 2008). This can be explained by the fact shooting along the ice is essentially a 2 dimensional task, where shooting at the top corners involves an additional trajectory component. High caliber shooters had a tendency to bring the puck closer to their bodies prior to release, while recreational shooters would more so just push the puck forward; this may have been to allow greater freedom for the wrist to manipulate the puck and increase control. Low caliber shooters saw their stick motion more resemble a pendulum (Yannick Michaud-Paquette et al., 2008).

Another study similar in nature was undertaken in 2011 to identify the joint angular kinematics that corresponded to accurate wrist shots (Y. Michaud-Paquette, Magee, Pearsall, & Turcotte, 2011). Using VICON motion capture technology (Vicon ®, Oxford, UK), each subject was required to perform ten successful shots at four shooting targets. Multiple regression was used to examine the relationship between kinematic variables and shot accuracy. Characteristics such as the stability of the base of support, momentum cancellation, trunk orientation and dynamic control of the lead arm were all seen as important traits when optimizing accuracy (Y. Michaud-Paquette et al., 2011).

Wu et al. (2003) looked to examine the effects that sex, strength, size, skill and stick constructions had on the performance of slap shots and wrist shots. Both male groups shot harder than females, for both the slap shot and the wrist shot. The shaft of the stick deflected more for skilled players during both wrist and slap shots, despite the fact strength and attack angle of the groups remained comparable. Within groups, shot velocity correlated most to height, mass, bench and grip strength for both shots. Attack angle also greatly correlated with puck velocity (Wu et al., 2003).

Beam Theory

Humans can use passive devices (such as hockey sticks) to enhance their physical capabilities when participating in sport. In hockey, the stick stores and releases elastic energy when shooting, adding to the power already contributed to the shot by the human body (Minetti, 2004)

Deflections occur in beam structures when a load is applied, as seen in hockey sticks when a shot is being taken. Equal and opposite impulse forces are exerted between the beam and the object applying the force, as seen between the hand and the stick or the stick and the puck (Hibbeler, 2007). Castigliano's Theorem is a simple way to describe how a beam deforms when a load is applied. The theorem states "when forces act on elastic systems subject to small displacements, the displacement corresponding to any force, collinear with the force is equal to partial derivative of the total strain energy with respect to that force" (Eq. 1).

$$\delta_i = \frac{\partial v}{\partial F_1} \qquad \text{(Eq.1)}$$

The displacement at the point of application of the force F_1 is described by ∂_i , in the direction of F_1 (Budynos, 2006)

Stretch, torsion, transverse shear in two directions, and bending in two directions are six variables that are responsible for static strain energy (Hodges, 2006). Fatigue and inertia must also be considered in dynamic analysis (Eq.2). Equation 2 takes into consideration these factors and applies them to Castigliano's Theorem when the equation is double integrated $\frac{dv}{dx} = 0$ is relative to the length of the beam in the x axis, M represents the moment of the beam, E is the modulus of elasticity, I is the inertia about that axis, and v is the deflection of the beam (Budynos, 2006).

$$\frac{d^2v}{dx^2} = \frac{M}{EI} \qquad \text{(Eq.2)}$$

Equations 1 and 2 illustrate that there are many variables that lead to deformation, and many combinations of these variable may lead to a desired deformation. In modern study, it is common to use strain gauges to measure such deformation. In hockey sticks, the ability for a stick to bend or deform is given as a rating of flex.

Beam theory and the hockey stick

Hockey sticks are available in a variety of curves and shaft stiffness's. Despite this, it is difficult to compare sticks by their labeled properties because between manufacturers there is no industrial standard used to measure shaft stiffness (Reed, 1979). The coefficient of rigidity is one measure of stiffness that describes a given load placed on an object divided by the displacement in the object created by the load. Shaft stiffness can also be determined by the three point-bending test, with a center and/or cantilever loading protocol. The amount of bend along the major axis is measured and then used to determine the stick stiffness (Reed, 1979). The less a stick bends during the test, the stiffer the stick is.

When two-off axis forces are applied to an object, bending occurs, where on one side of the object there is tension stress, and on the other side of the object there is compression stress (McLester, 2008). A bending moment occurs along the length of the beam, and the point of application of the force will see the largest magnitude of bend. The amount of bend will decrease as distance from the point of application increases (Figure 3) (Hibbeler, 2007). When a hockey player shoots the puck, the bottom hand can be considered the point of application of the force.

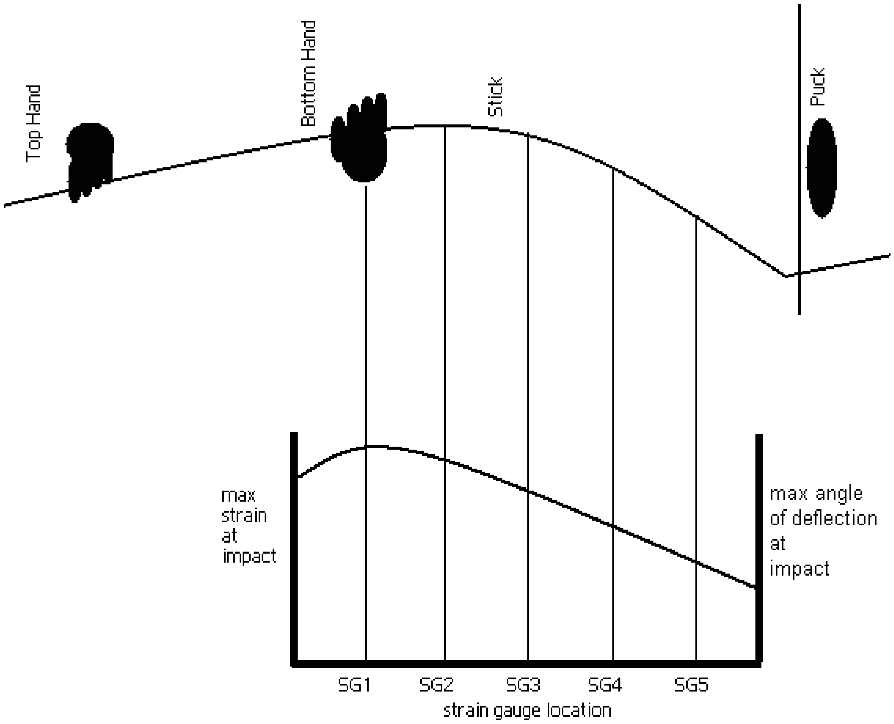


Figure 2 : Typical strain profile at five strain gauge locations during maximum deflections during impact with surface (Hannon, 2010).

There is still much to understand in regards to how the stick reacts when a puck is shot. Bending is visually apparent and most occurring along the major axis of the stick (Pearsall & Turcotte, 2007), but there is also bending that occurs along the minor axis of the stick. Magee et al. (2008) developed a strain gauge system for use on hockey equipment, including hockey sticks. Strain data from the system allowed for levels of strain to be measured along different points of the shaft according to temporal pattern. Bending and temporal strain patterns of sticks were similar to those seen in a dynamic cantilever test. Strain rates were different for slap shots and wrist shots, though shafts generally saw similar strain levels at the same locations; the gauges highest up the stick saw the most strain, while the gauges closest to the blade saw the least (MaGee, 2008).

With sticks offered in a variety of flexes, it is no surprise there has been research into how these flexes affect shooting. One such study was conducted to see if there were any correlational effects between shaft stiffness and puck velocity during a slap shot (D. Pearsall, Montgomery, Rothsching, & Turcotte, 1999). While more flexible shafts saw the greatest deflection, maximum shot velocities did not significantly differ between sticks. In a similar study by Worobets, Fairbairn, & Stefanyshyn (2006), researchers assigned stiffness values to eight different sticks after they had been loaded in a machine. Each participant took five wrist shots and five slap shots with each stick. Higher stick stiffness was found to be related to lower wrist shot velocity, though there was no significant relation in slap shots (Worobets, Fairbairn, & Stefanyshyn, 2006).

Villasenor, Turcotte & Pearsall looked to examine the recoil behavior of hockey sticks using VICON motion capture technology (Vicon ®, Oxford, UK) and a triaxial accelerometer. Results of their study showed that elite shooters use their sticks differently than recreational shooters do. Elite shooters' sticks begin to bend right at puck contact, and bending lasts for 28.8% of puck contact time. The elite shooters stick is already in recoil before the recreational players stick even begins to bend. The recreational shooters stick only bends for 18.2 percent of puck contact, then recoils until puck contact is lost. The Elite players stick is finished recoil by the time puck contact is terminated, where the recreational players is not (see Figure 4). Elite shooters flexed their sticks to a greater angle and translated horizontally forward with the puck more, as opposed to merely rotating in the forward direction, which was more apparent in recreational shooters (Villasenor et al., 2006).

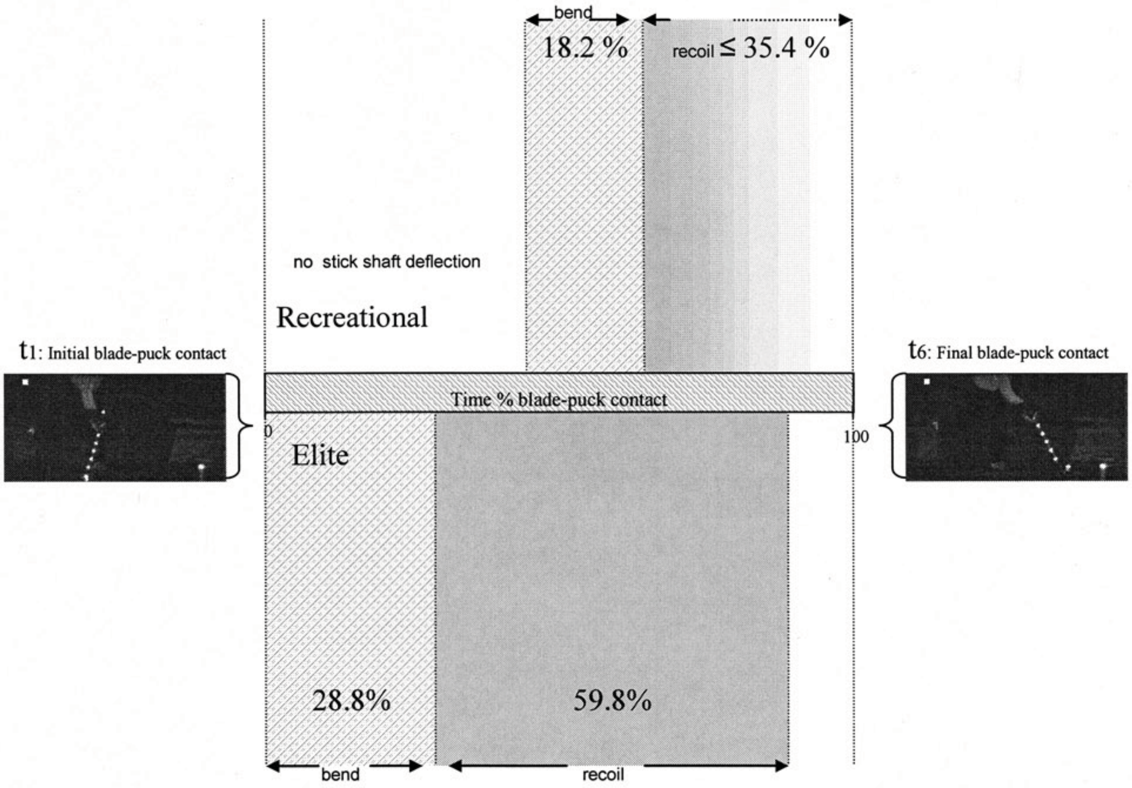


Figure 3 : The average percentage of time spent in bend and recoil during puck-blade contact, for elite and recreational shooters (Villasenor et al., 2006)

Related to the Villasenor study, Hannon and her research team (2011) looked to examine what she described as "dynamic strain profiles" in sticks of different stiffness, between players of different skill levels, during both slap shots and wrist shots. Using sticks with flex profiles of 77 and 102, they measured shot kinematics and stick deformation using strain gauges and VICON motion capture technology (Vicon ®, Oxford, UK). Results showed that high caliber (HC) subjects created greater deflection throughout the shaft of the stick during slap shots than low caliber (LC) subjects did. The 77 flex stick deformed more in the lower shaft then the 102 flex stick did. The time to peak strain was shorter for HC players than LC players. There was no significant different between grip width, lower hand placement, and stance width between the two subject populations. There were no major difference found between velocity of either shot between stick models (Hannon, Michaud-Paquette, Pearsall, & Turcotte, 2011).

Hannon’s findings support the thoughts of Worobets, who stated,“ how the athlete loads the stick has as much influence on puck speed as stick construction” (Worobets et al., 2006). They were also consistent with Dore & Roy (1976) who found that when shooting, puck velocities were more sensitive to the shape of a force graph rather than the maximum forces actually generated. They also found that individuals could consistently replicate the same force patterns (Doré & Roy, 1976).

Shooting implement studies in other sports

Strain gauge technology has been used in a variety of sports to evaluate equipment and shooting implements. In 1992, Milne & Davis places strain gauges on the shaft of a golf club, testing three golfers of various handicaps. Investigating the “kick point” of clubs, researchers looked at “the shape of the bent shaft at impact”(Milne, 1992). While manufacturers claim the ability to create a kick point at different points along the shaft, it remains unclear as to if these kick points are functional towards the better execution of shots. These kick points affect the “feel” experienced by players, a level of comfort when using the equipment that may be as much a psychological advantage as a biomechanical one (Milne, 1992). Results of the study showed that there was not a dramatic difference for any of the golfers when using the differently constructed clubs. The strain gauges also helped clearly identify three distinct phases of the swing by observing measured torques; the top of the swing where the shaft bends backward, approximately 130 ms before impact where a momentum transfer takes place and the shaft straightens before bending forward, and at impact itself, where the shaft absorbs some of the energy of the shot as vibration and imparts the rest on the ball. Taking into account the behavior of the shafts at each of these points, as well as the individual golfers technique, it appears possible to design a shaft optimized to maximize shot effectiveness for a golfers swing through changing the flexibility, kick point and feel of the shaft (Milne, 1992).

It is theorized in golf that shaft stiffness should increase club head speed and alter clubface orientation at impact. MacKenzie and Sprigings (2009) used a 3D forward dynamics model of a golfer and flexible club during downswing to analyze this theory. A genetic algorithm optimized the coordination of the model's muscle, torque generators, to maximize club head speed. Four different shaft stiffness's were entered into the program to examine its effects on club head speed and club head orientation. The models torque generators were modified 3 times to represent three different types of golfers; slow, medium and fast. The various club stiffness's and segments used in the simulation were determined by using a vise and actual driver, as well as motion capture technology. As swing speed increased, so did the lag deflection of the club; within each swing speed, lag deflection increased with shaft flexibility. The golfer who was fastest and had the most flexible club saw the most dynamic loft and dynamic close; the slowest and stiffest saw the least. There were no meaningful differences in club head speed between golfers and clubs. Optimized simulations for fast swings speeds see that any non-rigid shaft can contribute up to 4% of total club head speed. Researchers concluded that trying to pair golfers with a shaft of a given stiffness was not a practice that would create meaningful improvement in a players game (MacKenzie, 2009).

In 2012, Betzler took two golf clubs, one ladies flex and one extra stiff flex, and made them as similar as possible in most respects. Players were unaware of what variable was being considered in the study, and the clubs were rigged with strain gauges and motion capture markers. The more flexible club saw slightly higher ball speeds and club-head speeds. The stiffer club saw a marginal increase in lead bending at impact (Faul, 2007).

In lacrosse, Crisco (2009) conducted a study to better understand how lacrosse sticks propel a lacrosse ball; if it were merely a passive extension then the ball shoot speed would be equal to speed at the tip of the stick. Not only did the ball come out faster than predicted for both male and female players, 3.5 m/s faster for males and .7 m/s faster for females, there was also a noted difference between speeds generated by stick models. Researchers were unable to identify what factors caused the increase in shot velocity. Shafts may have bent and released potential energy, as seen in shooting in hockey, but they believed the shafts were too stiff for this to be true. The plastic heads bending may also have been releasing potential energy, though all the heads were similar, making this unlikely. The increase might have been a function of the speed of the stick. One male shot with both male and female sticks, shooting harder than all the females, but still quite similarly to what was predicted. This lead researchers to believe that perhaps the increase in ball speed was due to the difference between male and female sticks rather than gender, and that the deeper pockets of the men’s sticks may have influenced shot speed (Crisco, 2009)

Kwan (2010) undertook a study looking at the strain badminton racquets underwent during a stroke. The amount of strain imposed by the players ranged widely, but the timing of the strokes were very similar. Lighter strokes saw lower peak deflection during both forewing and backswing. The racquet with the higher frequency gave a slightly shorter stroke (Kwan, 2010).

Hands and Grip

With the point of contact between a hockey player and a hockey stick being limited to the hands, it is important to understand the anatomy of the hand. The healthy hand features four fingers and a thumb, where each of these digits have a carpometacarpal (CMC) joint and a metacarpophalangeal joint (MCP); fingers also have two interphalangeal joints (IP), while the thumb only has one (Levangie, 2001).

The human hand features roughly 30 degrees of freedom (DoF). This is because the proximal and distal IP joints of each finger each have one DoF, and the MCP joint has two degrees of freedom; each finger has 4 degrees of freedom. The thumb itself has 5 DoF, thanks to one from the IP joint, and 2 each from the MCP joint and the trapeziometacarpel (TM) joint. 6 degrees of freedom are from translation and rotational motions of the palm, where each rotational motion offers 3 degrees of freedom (J. Lin, Wun, Y., & Huang, T.S., 2000).

Napier (1956) was the first person to use the terms power grip and precision grip to describe how the hand can hold an object. A power grip involves the ring and little fingers, assisted by the middle and index fingers, pressing against the palm of the hand. Any precision required for the grip is provided by the thumb and index finger. A precision grip is a grip between the terminal pad of the fingertips and its opposing thumb pad. The size of the object dictates how many fingers are required for the task. The precision grip and the power grip are not mutually exclusive; they can overlap in tasks and there are many phases within each grip (Napier, 1993). Because there is an inverse relationship between force generated by the hand and wrist range of motion, whatever task a person undertakes must feature a balance between the two factors (Komi, 2008).

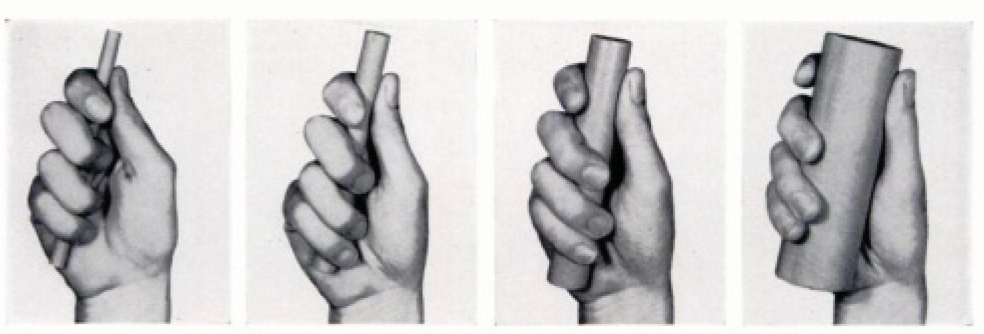


Figure 4 : an arbitrarily chosen series of postures illustrating some of the phases of the power grip complex.

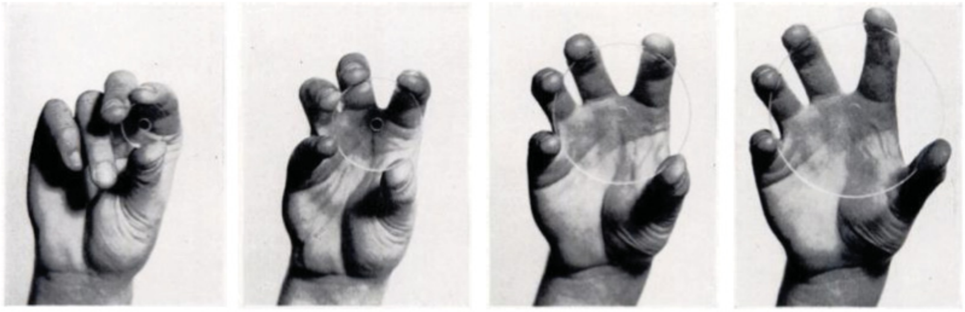


Figure 5 : an arbitrarily chosen series of postures illustrating some of the phases of the precision grip complex.

In the context of playing hockey, it is important to understand how the hand functions when conducting prehensile activities- either using a power grip or precision handling grip.

Holding the hockey stick

In hockey, a player may shoot left or right handed, each shooting side is a mirror of the other; a left handed shooter has their left hand lower on the stick shaft, with their right hands on the butt of the stick. A right shooter is the opposite of this (see Figure 6). The top hand remains relatively stationary during the course of a game, but the bottom hand of the player may move up and down the shaft given the task that the player must undertake. While there have been limited studies that looked at the contributions of the hands during shooting tasks, one such study was conducted by Zane, in 2012, at McGill University. Measuring force with 32 FSA sensors, she was able to identify unique grip signatures of individuals taking both slap shots and wrist shots. There was a correlation between forced generated by the hands and shot velocity, but high velocities were attained through a variety of grip patterns (Zane, 2012).

There are a variety of different “power grips”, but the grip most applicable to studying how a hockey player holds their hockey stick is the “cylindrical grip”. A cylindrical power grip involves the fingers forcefully flexing around an object, while the thumb also adducts and flexes, wrapping around the object (Levangie, 2001).

Figure 6 : The lower hand for a left hand shooter (left) and a right -handed shooter (right) (Zane, 2012).

Grip strength

Grip strength indicates the strength and functionality of a hand. It has also been noted that upper limb posture plays a role in the maximum producible handgrip force (Roman-Liu, 2003). In terms of gender, it has been consistently shown that men can exert more grip strength than females. While this has something to do with the fact that females have a smaller physiologic cross-sectional area of muscle than males (Morse, 2006), females also tend to have a smaller percentage of their lean body mass located in the upper body (Miller, 1993). Kong & Lowe (2005) found that the female grip was 58 % that of what men could produce. Similar studies have found values in a similar range, from 51% to 69% (Kong, 2005).

In 2007, Leyk et al. looked at the grip strength of men and woman, as well as high level female judo and handball athletes. They found that 90% of females produced less force than 95% of the males. They also found that there was a disparity greater than 200N in terms of mean maximal hand-grip strength between sexes (Leyk, 2007).

In the search for optimal strength, a variety of cylinders have been used as handles, due to the shapes simplicity and practicality in everyday life. When testing maximum grip force on cylindrical aluminum handles of different diameters, Kong & Lowe (2005) found that optimal handle diameter was 19.7 % of the subject's hand length. Studies by Pheasant & O'Neill (1975), Edgren et al (2004) and Kong & Lowe (2005) have all seen that the optimal cylindrical size to maximize grip strength force is an inverted parabolic function. Pheasant & O'Neill (1975) believed that grip was weaker on small handles due to inadequate surface contact, and weaker on larger handles because of limitations of the hand muscles themselves. Kong & Lowe (2005) saw that subjects in their studies exerted greater total finger forces with smaller diameter handles than the largest diameters despite similar EMG activity. These findings support the idea of optimization in terms of handle design, but it still remains unclear how objects of different shapes are affected in scaling handle designs.

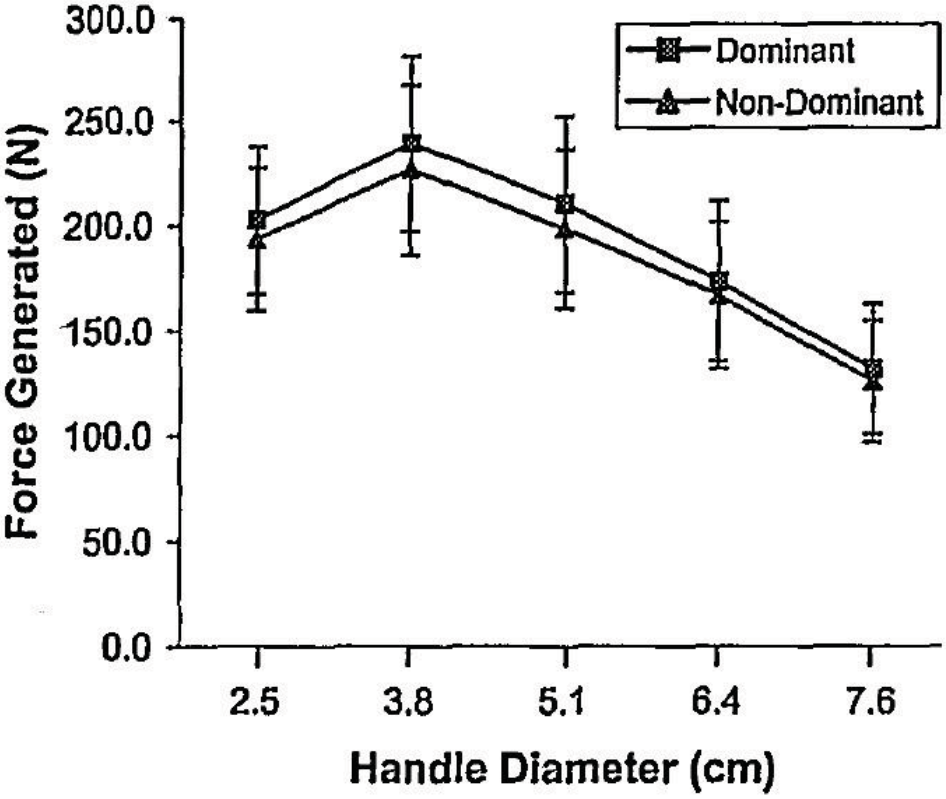


Figure 7 : Maximal voluntary contraction (MVC) grip force as a function of handle diameter (Edgren et al., 2004).

Most studies have examined grip force as a unidirectional quantity, but Edgren et al. (2004) considered both magnitude and direction of grip strength, while looking at hand exertion properties while grasping cylinders of various sizes. Not only did force angle increase as hand size increased, but force vectors directed away from the palm for large cylinders, while towards the palm for smaller handles(Edgren, 2004).

Total and Individual Finger forces

When looking at the forces created by the hands, research has been done looking at the sum of the forces as well as the contributions of the individual fingers. Kong & Lowe (2005) consider individual finger force as the sum of the four phalangeal segment forces for a given finger (distal, middle, proximal and metacarpal), while the total finger forces would be the sum of the individual finger forces of the one hand.

Amis (1987) looked at the forces exerted by individual fingers during the grasping of cylinders of different sizes. Each finger showed similar patterns in the way forces were distributed among the three phalanges, where the largest forces were always seen on the distal pads; middle and proximal pads had lower forces that were similar to one another. The proportions of force created by the phalanges were approximately the same for the whole range of cylinders tested (Amis, 1987). Kong & Lowe (2005) saw that the distal phalange created 41.6% of the total grip finger force, while the middle phalange accounted for 23.7%, the proximal phalange 19.0% and metacarpal phalange created 15.7 %, respectively.

When looking at the contributions of individual fingers during griping tasks, different researchers have found different results. An et al. (1978) found that the index, middle, ring, and little fingers contributed 32%, 33%,21 %, and 14% of total grip force, respectively; Radhakrishnan & Nagaravinda (1993) found 31 %, 33%, 22%, and 14% (Radhakrishnan, 1993), where Kong & Lowe (2005) found 24.9%, 34.8%, 26.5% and 13.8 %

When a finger is maximally isometrically contracted, there is involuntary muscle activity involved in the other fingers; this is called enslaving (Zatsiorsky, 1998). Zatsiorsky and his research team had subjects press force sensors as hard as possible, using every possible combination of one to four fingers. It was found that slave fingers, the fingers not directly in contact with the surface being pushed, still produced between 10.9 and 54.7 % of their MVC in the single finger task. Levels of engagement in the enslaved fingers increased the closer the finger was to primary fingers used, and the enslaving effect is nearly symmetrical across the hand.

De Monsabert (2012) conducted research that was meant to identify muscle and joint forces during a power grip task. An instrumented device featured a handle and pressure map; it led to the determination of the forces seen at 25 areas of the hand. Subjects maintained a maximal power grip for 6 seconds with their strong hand, raising the device to a comfortable height. Joint angles were found from synchronized kinematic data using motion capture technology. All of this information was placed in a model featuring 23 degrees of freedom and 42 muscles to estimate muscle and joint forces. Greater forces were seen at the distal phalanges of the long fingers than the middle and proximal phalanges. 66% of the force was applied to the fingers, the other third was applied to the palm. Mean hand force was 804 + or – 117.9 N. For the thumb the most proximal areas applied the most force (De Monsabert, 2012). This study found new quantifications for the level of muscle load sharing, co-contraction levels, and the biomechanics of the hand.

Fatigue and Grip

Many tasks, both recreational and professional, require a sustained grip force to maximize control and performance of the task (Blackwell, 1999). Hockey is no different; it is therefore important to understand the effects of fatigue on the hands. Muscle fatigue can be thought of as a decline in the desired contractile force of the muscle (Vollestad, 1997).

The findings of Blackwell et al. (1999) considered maximum absolute grip force and the electromyography (EMG) activity of the flexor digitorum superficialis (FDS) when contracted at 60-65% of maximum voluntary contraction. While fatigue of FDS did not changes as a function of grip size, it was found that absolute forces were greatest at medium sized handles rather than for large or small handles (Blackwell, 1999). Damion and his colleagues (2000) looked at muscle fatigue in the hands by examining maximal isometric force of the hands four fingers for one minute. Using two exercises to create fatigue in two different portions of the finger, it was found that total force production of the four fingers was reduced by 43% when it was produced by the portion of the hand that was the focus of the fatiguing exercise. Total force production dropped 23% even when the generating site of the force was not the focus of the fatiguing exercise. Single-finger tests saw force reduced by 23% of MVC for all of the fingers, thanks to fatigue. The sum of each fingers MVC was larger than the sum of the total MVC of the four hands when acting in unison (Danion, 2000).

Position of Upper Limb

The orientation of the upper limb plays an important role in grip strength and maximum voluntary contraction (Roman-Liu, 2003). As mentioned previously, there is an inverse relationship between force generated by the hand and wrist range of motion, so whatever task a person undertakes , they must have a balance between the two factors in order to maximize performance (Komi, 2008). Hallbeck (1994) looked at the forces measured when extending and flexing the wrist, which are generated by muscle groups within the hand and the forearm, and by the wrist dedicated muscles. It was ultimately found that posture, as well as force direction, as well as digit strength, affects the magnitude of external force generated. The average extension force and flexion forces were significantly different for both men and women (Hallbeck, 1994).

Hazleton (1975) examined the ability of each finger to exert force in five different wrist orientations: neutral, volar flexion, dorsi flexion, ulnar deviation, and radial deviation. While the forces values varied at each position, the fingers were proportional with how much force they created relative to one another at each wrist orientation; On average, at the distal phalange, the index, long, middle (ring) and little finger contributed 25.7, 33.0 , 23.6 and 17.2 % to total force, respectively (Hazelton, 1975). Morse et al. (2006) examined variables that could affect grip force and torque, finding wrist angle the most important factor; mean maximal grip forces for males and females occurred at 70 degrees wrist flexion. Mathiowetz et al. (1985) found that grip strength was much stronger with 90 degrees of flexion than fully extended (Mathiowetz, 1985). Marley & Wehrman (1992) reported a significant decrease in maximum grip strength when the forearm was pronated (Marley, 1992). Roman-Liu (2007) looked at an extensive variety of arm orientations rather than just elbow orientations. That study found that the greatest handgrip force was created at 45 degrees horizontal abduction, 180 degrees arm flexion, 45 degree medial rotations, 135 degree elbow flexion, 0 degree wrist adduction/abduction, 15 to 0 wrist extension, and either 60 degree forearm pronation, or 30, 60 and 70 degrees supination.

Lin, McGorry, and Chang (2012) undertook a study to investigate the influence of posture on the pushing force generated by subjects. 31 subjects took part in the study. A testing apparatus was created to limit the contributions of the muscles not of focus; during pilot testing it was clear that pushing capacity was influenced by the interaction of the trunk and lower limb postural strategies, participant weight, and friction. Handles were tested at 0, 45, and 90 degree rotations. The handles were tested parallel to the frontal plane, and featuring a 15 degree anterior tilt. The hands were placed 80% and 125% of the bi-acromial breadth of the average US adult. Normalized push strength was found to be significantly affected by handle rotation and the interaction of handle distance. The 0 degree rotation handle saw less force generated than the 45 degree and the 90 degree configurations, and there was no significant difference between the 45 degree and 90 degree conditions. Compared to the standard configuration of horizontal handle, no frontal tilt and 31 cm handle distance, the 45 degree rotation with 15% tilt saw the greatest improvement in force generation, at 6.7 %. Men pushed significantly harder than women (J.-H. Lin, McGorry,R.W. & Chang, C.-C., 2012).

Lin (2013) and fellow researchers conducted an experiment investigating static, one-hand pulling strength using four handle heights and three pulling directions. Pull heights featured to fixed heights, and two relative heights. Pulling directions included across the body, in front of the body, and from the same side of the body. Load cells were placed on the testing apparatus to measure the force applied and participants all used the same style of shoe, and their dominant hands for testing. Other than keeping their feet parallel, and not using their second hand, they could adjust their degrees of freedom however they chose. Pulling strength was maximized where loads were on the same side of the body, and where heights remained below 61 cm from the floor. Men pulled with more force than women. Age was a significant factor in pulling force for men, but not women (J.-H. Lin, McGorry,R.W. & Maynard, W., 2013).

Instrumentation for testing grip

There have been various methods of trying to measure force created by the hands and fingers in the past. While Nikonovas et al. (2004) reported that the most widely used took for assessing grip strength is the Jamar dynamometer, he and his researchers developed a unique system for measuring forced generated at the hand surface. Using Tekscan Flexiforce TM Sensors (Tekscan Inc., Boston, MA) placed all across the hands, in a manner that did not interfere with normal hand function, with Tegaderm Transparent Dressing TM(3M St. Paul, MN) (Nokonovas,

2004) . Leyk et al. (2007) used a simple hand grip-ergometer (Leyk, 2007), and Morse et al. (2006) used an isokinetic wrist dynometer that controlled wrist angle and angular velocity.

King & Lowe, like Nikonovas et al. (2004) used FlexiForce ^{TM} sensors on a glove to evaluate total grip force and individual phalange force. Gloves of different sizes were used to ensure precise fit for subjects of different hand sizes. Total hand force could not be found due to the club being in contact with parts of the hand that did not feature a sensor. Schmidt et al. (2006) used the same sensors attached directly to the grip of a standard golf driver (Schmidt, 2006). Komi created a more elaborate method of using these sensors, first attaching 31 sensors to strategic locations on two gloves, but also using Tekscan 9811 ^{TM} matrix sensors (Tekscan Inc. Boston, MA) directly on the handle of the golf club to measure total grip force. Determining the optimal placement of sensors when measuring grip, depending on the unique tasks, will ultimately lead to a better and more accurate understanding of the grip forces being created.

Budney (1979) used a steel shafted golf club instrumented with three transducers that responded to grip pressure. Optimal locations were determined via measurement of each of the subjects(Budney, 1979). Eggeman & Noble (1985) developed a strain gauge transducer they used to determine the mean grip and force on a baseball bat during swings (Eggeman, 1985). Keller et al. (2000) developed a dynamic grasping system that could measure wrist angle in relation to the grasping force of each finger and thumb (Keller, 2000).

Applications in Sports

Many sports that involve an instrument acting as an extension of the arms have had grip, and its importance, examined. In sports such as lacrosse, golf, tennis, cricket, and baseball, slight differences in grip and wrist position can greatly affect performance outcomes, and differentiate the recreational from the high-level athlete (Hume, 2005).

In hockey, Reed et al (1979) examined upper body strength within junior and professional hockey players They found that for both populations right hand grip strength was greater than left hand grip strength, regardless of shooting side (Reed, 1979) .Similarly, Wu et al. (2003) looked at slap shots and wrist shots, examining the effects of different stick types against skill level and strength levels. They found that grip strength for skilled women was greater than unskilled women (*M*= 40.3 N, *SD*= 3.5 N vs. *M*=33.5 N, *SD*= 3.9 N), and greater for skilled men as compared to unskilled men (*M*= 59.0 N, *SD*= 11.6 N vs. *M*=57.5 N vs. *SD*=9.1 N).

In baseball, Eggeman & Noble (1985) measured the grip forces exerted on the bat during a swing. They concluded that while the top hand pushed the bat towards the ball, the bottom hand guided the bat prior to ball contact. Batters remained firm in their grip of the bat until just before ball contact.

Szymanski examined the effects of 12 weeks of wrist and forearm training on a number of key variables that influence fatting effectiveness in baseball. Two groups of high school players each performed a total body resistance program, where three days a week the second group also performed wrist and forearm exercises. Wrist and forearm strength was measured before and after training. Linear bat velocity (BV), center of percussion velocity (CV), hand velocity (HV) and time to ball contact was also measured before and after using motion capture technology. Both groups saw significant improvement in wrist and forearm strength, as well as increases in linear BV, CV, and HV. Both groups made significant increases in their squat and bench press strength. Results suggested that resistance-training program can increase BV, CV, and HV among players, but resistance training does not have to involve wrist and forearm specific strengthening; this was because there were no significant differences between the results of the two groups after training (Szymanski, 2006).

Hatze (1976) conducted research in tennis and found that a tight grip not only increased impulse imparted on the ball, but also increased the power of the stroke. A tight grip increased the vibrational shock absorbed by the hand, thus reducing slippage of the racquet. In another study, a machine was designed by researchers to test various degrees of grip on a tennis racquet, allowing angled impacts at any point on the racket face (Choppin, 2010). A tighter grip reduced the outbound ball angle. There is a clear outbound angle distinction between no grip and grip, but not the two levels of reduced grip. The further the ball contacts the racquet from center, the less speed, accuracy and flight seen by the ball. A tighter grip reduces angle deviation of the ball. The rebound velocity of a ball is less affected by grip than rebound angle. Researchers claimed it was more advantageous to have a firm grip when playing tennis (Choppin, 2010).

There have been a variety of studies that have looked at grip in golf. Hume et al. (2005) analyzed the role of biomechanics in maximizing distance and accuracy when shooting. Looking at a “strong grip” and “weak grip”, they saw that a strong grip allowed the players to more readily release the hands during downswing and impact, increasing club head speed. While this grip offered greater chance of miss-hits, a “weak grip” offered more club face control at the expense of slower hand speeds. In 2008, Komi et al. measured the grips of 20 right handed shooting golfers of various skill levels. Each golfer was found to have a very consistent and repeatable grip force signature. Like Eggeman & Noble (1985) saw in baseball, many golfers used their left hands to maintain a grip until impact, where grip would jump again just after impact, and decrease during follow through. On golfers’ right hands the middle and ring finger were typically the dominant hands controlling the club during takeaway and backswing; force generated by the index, middle and ring fingers on the right hand peaked just after impact.

In 2005, Kong used a force glove measurement system to measure the contributions by individual portions of the hand (fingers and phalanges). Different size gloves were used to avoid the effect of hand size placed in the same glove. In addition to Force and EMG readings, participants were asked to rate comfort during each trial on a scale of 1-7. Comfort levels were higher for mid-size handles (30, 35, and 40 mm). The largest handle was designated the most uncomfortable (50mm); Men preferred the 35 mm, women preferred the 40 mm. Women generated about 57.6% as much force as men during testing. Depending on the diameter of the handle, different fingers contributed the highest levels of force. Forces were greater in small handles and these factors are inversely related (Kong, 2005).

Testing environments

While ice hockey is typically played in arenas on ice, previous testing has showed that other surfaces can prove as an adequate alternative when studying the sport. Stidwell, Pearsall and Turcotte (2010) looked at skating kinematics and kinetics on ice, comparing them to those found when skating on an artificial ice surface. None of the kinetic factors investigated were found to be significantly different, though subjects were found to have extended their knees by 4 degrees more when skating on synthetic ice compared to when they skated on natural ice. Ownership of an artificial surface leads to savings in potential ice rental costs, and room temperature testing conditions allows for the use of temperature sensitive technologies, making artificial ice testing an appealing alternative to on- ice testing. (Stidwill, Pearsall, & Turcotte, 2010).

Nomenclature

Toe-up (TU) – In the minor axis, the same side as the blade's toe.

Toe-down (TD) - In the minor axis, the same side as the blade's heel.

Leading side (LD) - One direction of the major axis, the same side as the blade's front face.

Lagging side (LG) - One direction of the major axis, the same side as the blade's back face.

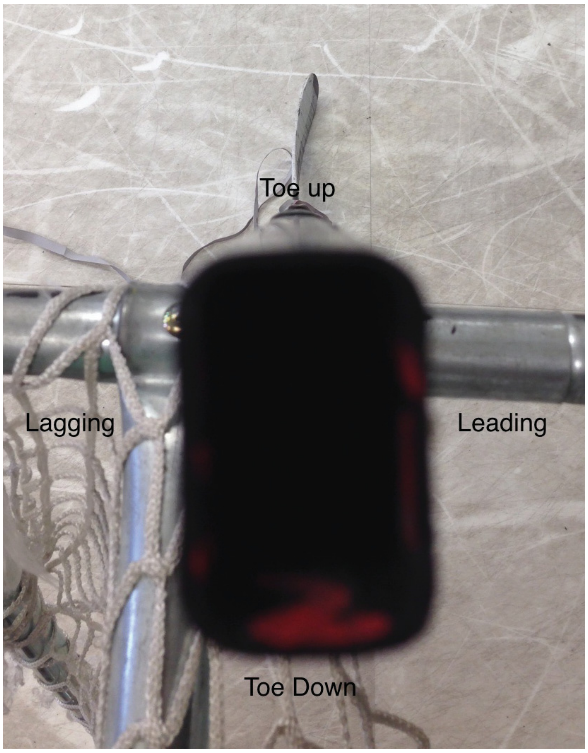


Figure 8 : The four faces of the stick shaft

Upper hand (U) - the subject's higher hand, placed highest on the stick, near the butt end.

Lower hand (L) - the subject's lower hand, placed nearest to the middle of the shaft.

Flex Profile - the number assigned to a hockey stick by the manufacturer to describe how stiff the shaft is; higher numbers imply a rigid shaft, while lower numbers indicate a shaft that is less so.

Dynamic Strain Profile - the dynamic change in magnitudes of the strain measured by instrumented strain gauges on the shaft of the hockey stick during the course of a shot.

Grip force profile - the unique pressure created on the four sides of the shaft by the interface between each hand and the shaft of the stick.

Peak Stick strain - The highest level of strain (in microstrain) experienced at the strain gauge (SG) location during shot execution.

Peak Grip force - The highest force (in Newtons) exerted against the Force Sensor Array (FSA) stick sensors during shot execution.

Player Caliber - Skill level was stratified according to previous highest level played. The two skill levels created were designated as high caliber (HC) and low caliber (LC).

Wrist shot (WS) - a shot that involves the player rapidly sweeping the puck forward, terminating the shot with a snap of the wrist and follow through.

Slap shot (SS) - a shot that involves a player drawing their stick back in the air, then forcibly slapping the ice and puck.

Rationale and Hypotheses

The goal of this study was to understand the interface of the hockey stick and the hands of the players who used them. Previous study had looked at the forces generated by the hands when shooting (Zane, 2012). Other previous study looked at the dynamic strain response of various stick stiffness when taking wrist shots and slap shots (Hannon, 2010). Taken together, the relationship between grip force and stick deflection were examined.

Slap shots and wrist shots differ in their execution and timing. While the two shots are both important in playing hockey, they are used strategically differently, and therefore were examined independently of one another in this study. Grip force and stick strain, we hypothesized, would be affected by player caliber and stick shaft stiffness. The originally predicted effects of player caliber on each shot, based on the findings of Hannon (2010) and Zane (2012), can be found below:

1) Player Caliber would affect both strains and grip forces such that HC shooters would generate larger magnitudes than LC shooters, within each shot type.
2) Within both shooting calibers, individual shooting techniques would lead to distinct grip force signature groups. While individuals consistently produce replicable force patterns, force patterns would vary amongst most shooters.

The predicted effects of stick stiffness on each shot type, based on the findings of Hannon (2010) and Zane (2012), can be found below:

3) When examining grip force differences by stick stiffness, force would not change for either variety of shot.
4) In terms of strain by stick stiffness, we expected to see greater levels of strain for less stiff sticks for the SS and WS about both major and minor axes, respectively.

The predicted interaction between strain and force measures, based on the work of Hannon (2010) and Zane (2012), as well as pilot testing, can be found below:

5) Grip forces will be highly related to force measures, regardless of shot type and stick stiffness.

Limitations

- FSA sensors cannot be placed on the entire surface of the stick thanks to FSA resolution limitations. This includes the corners of the shaft of the stick, and the edges directly beside the corners where there might be contact made with the hands.
- Testing took place in a laboratory setting at room temperature, as opposed to a rink setting.
- Only four sets of strain gauges were placed on each test stick. Due to the placement of these gauges, FSA sleeves could only be placed at so wide of a grip.
- Players were unfamiliar using sticks when they were not their regular model or length.
- The two hands were held in a fixed position on the stick when the shooters shot, which is somewhat different than during game play where the bottom hand has freedom to move up and down the shaft.
- Having only the materials to equip left-handed sticks for testing, we were limited to recruiting only left handed shooters.

Delimitations

- Only male shooters between the ages of 21-29 were observed
- Only one blade pattern and stick model, in three different flexes, were used for testing.
- Subjects wore hockey gloves when shooting
- Testing occurred while subjects stood stationary.
- Subjects wore skates provided by the lab.

- Due to the length of the sticks, only shooters between the heights of 5ft 8 and 6 ft. 2 were recruited

Methods

Participants

This study featured eighteen male subjects between the ages of 21 to 29. Eleven participants previously played what was classified as “high level’ hockey (Junior hockey or higher), while seven participants played what was classified as “recreational. These shooters were separated as “high caliber” (HC) and “low caliber” (LC), respectively. Participants were recruited from the McGill Varsity hockey team, McGill intramural hockey teams and local recreational players. Only left-handed shooters were able to participate in testing, due to equipment limitations. Both forwards and defensemen were permitted to test, but not goaltenders. Prior to testing, subjects were required to read and sign a consent form in accordance with the Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans. The also answered a variety of questions in regards to their personal and playing history.

Equipment

Three left handed Bauer x60 model sticks were used for this study. Each stick featured a different flex rating: 77, 87, and 102, respectively. Each stick was instrumented with 4 pairs of 350Ω, 0.125 inch long strain gauges (Vishay). Each of the strain gauge pairs were connected to half-active Wheatstone bridges using an excitation voltage of 2V ± 2%. When force was applied to the stick and there was bending of the strain gauge, the amount of voltage running through circuit changed. The gauges circuitry was powered using an analog/digital amplifier that also recorded the output voltages from each circuit (DataLog MWX8, Biometrics Ltd., Ladysmith, VA.). This analog output was recorded to a MicroSD (Lexar $^{\text{TM}}$ by Micron Consumer Products Group, Inc., Milpitas, CA) card and transferred manually to a local computer for post-processing analysis. Thin flexible wires were used to connect the amplifier, the Wheatstone bridges, and the strain gauges so that loose cables did not interfere with shot execution. The amplifier and bridges were attached to a modified set of shoulder pads in order to avoid clutter (See Figures 9 and 10). Each gauge pairing was bound directly to each stick shaft to measure the linear deformation of both the minor (SG2, SG4) and major (SG1, SG3) axes of the hockey stick at two distinct locations along the shaft (see Figures 11, 12 and 13). SG1 was placed 1150 mm up from the blade on the major axis of the sticks, while SG2 was placed at the same distance on the minor axis of the stick. SG3 was placed 550 mm up from the blade on the major axis of the sticks, while SG4 was placed at the same distance on the minor axis of the stick.

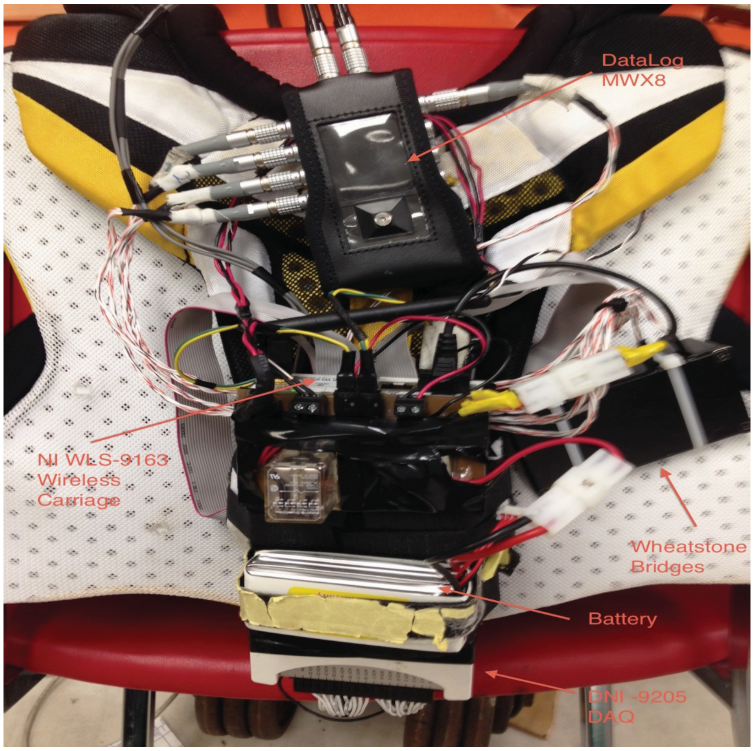


Figure 9 : Outfitted backpack, featuring DataLogger, amplifiers, Wheatstone bridges, DAQ Wi-Fi Carriage and analog module, and battery

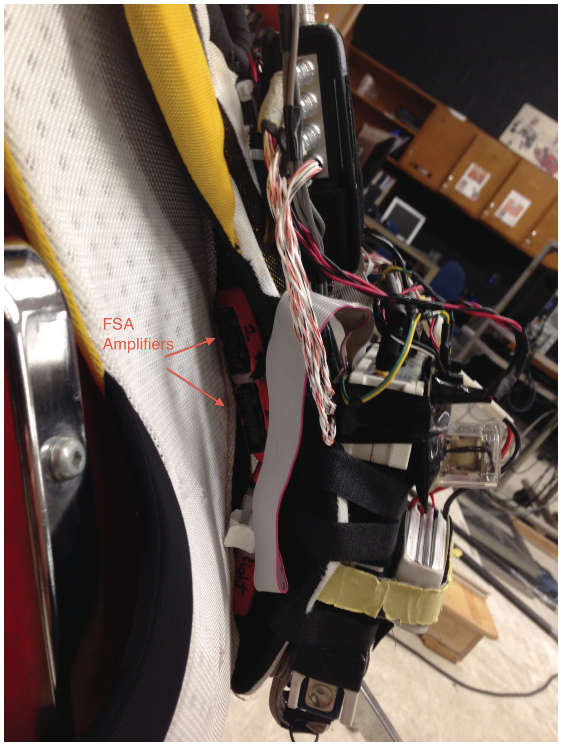


Figure 10 : Placement of FSA amplifiers resting on spine of equipped shoulder pads.

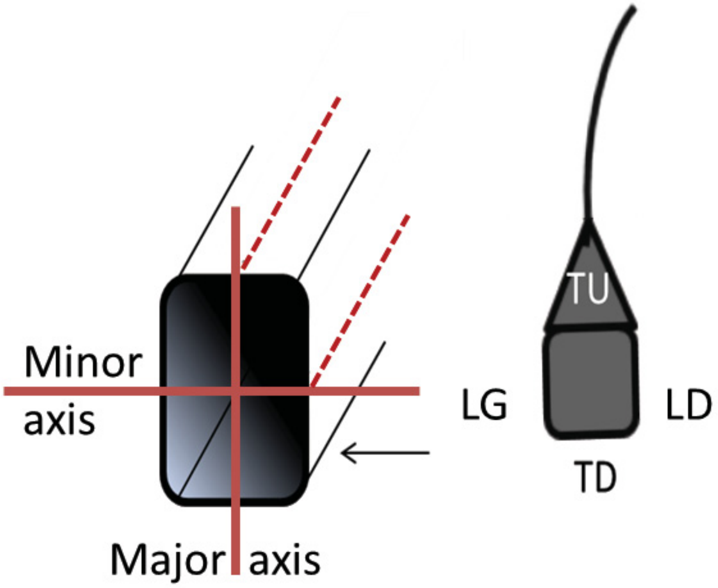


Figure 11 : The orientation of the major and minor axes on the stick. The minor axes coincides with the Toe Up and Toe Down stick faces. The major axis coincides with the Leading and Lagging stick faces.

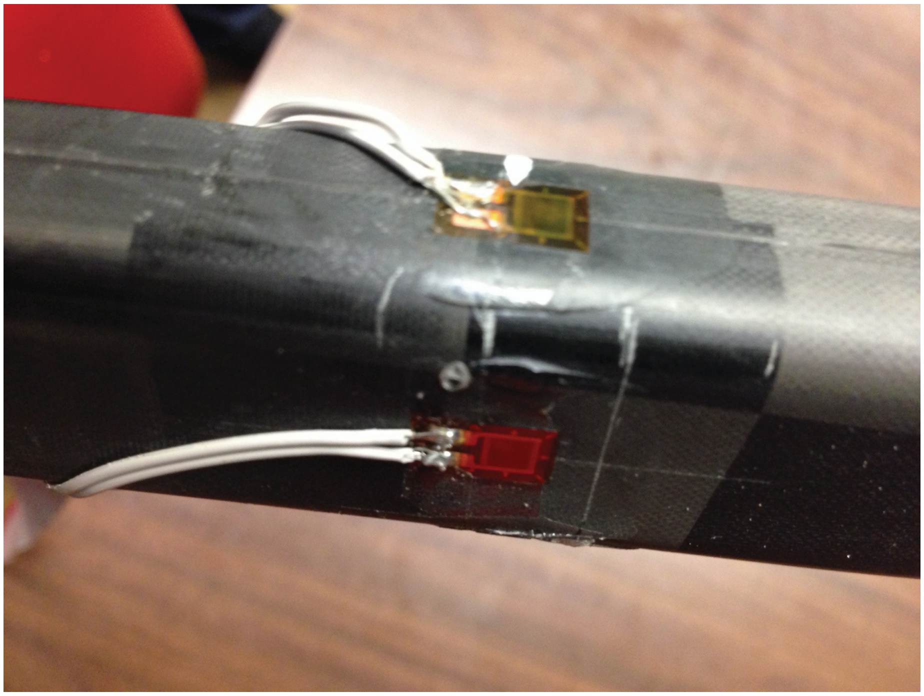


Figure 12 : Half of the major and minor axis strain gauge pairings.

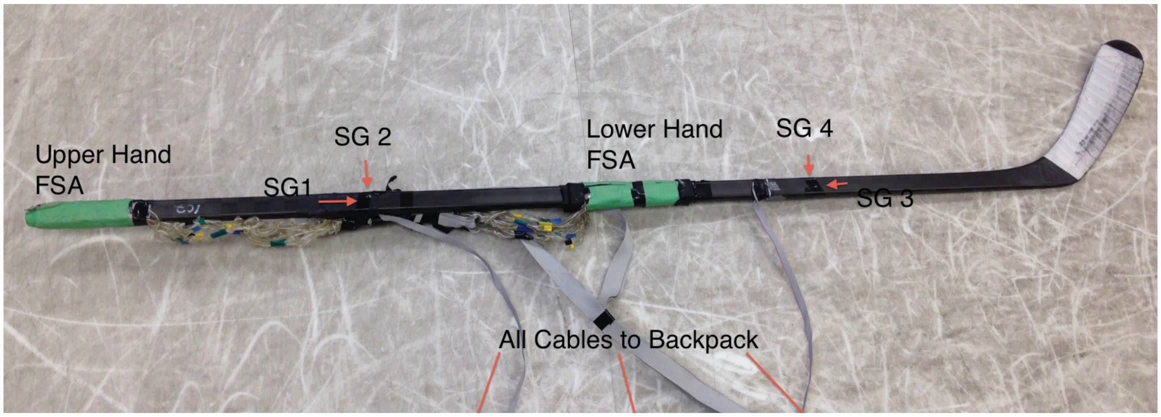


Figure 13 : Testing stick outfitted with FSA sensors and Strain gauges

Force Sensing Array (FSA) sensors (ISS-O) (Vista Medical, Winnipeg, Manitoba) were selected to measure grip force for this task, due to success in similar shooting experiments (Zane, 2012). While the sensors are 1.7 cm x 1.5 cm in surface area, their active sensing area is 0.64 cm x 0.64 cm (Zane, 2012). These thin, flexible piezo resistive force sensors were appropriate for our testing purposes because they were extremely thin and lightweight, durable with a Teflon coating, and could collect to a frequency of up to 10 000Hz. Sensors were connected to long, ribbon cable (UL Style 2651 300 Volt Max, Phalo Corporation, Manchester, NH) and tethered through the subjects elbow pad that lead to the 32 channel amplifier (see Figure 14). In turn, the amplifier was in series with a data acquisition device (NI-9205) that was inserted in a Wi-Fi capable carriage (NI WLS-9163, National Instruments, Austin, TX) linked via Wi-Fi connection to a computer using LabVIEW™ 2013 (National Instruments®, Austin, Texas) software to record sensors' voltages. The amplifier and DAQ board were driven by a 5V DC Lithium-ion battery.

Figure 14 : Ribbon cable from strain gauges and FSA tethered to elbow pad to reduce interference during shooting tasks.

Following the configuration created by Zane (2012), 16 sensors were used to measure force at the lower hand, and 16 sensors located at the butt-end of the stick were used to measure the force of the upper hand. Each set of 16 sensors covered 68 cm^2 on the shaft of the stick (see Figure 15).The lower hand sensors mounted onto a removable sleeve that could be placed up and down the shaft (to accommodate both slap shot and wrist shot hand positions) and was easily removed. The upper hand sensors were placed on a sleeve that remained stationary at the butt end of the stick (see Figure 16). Each sleeve was made of black polymer plastic shrink wrap (Shenbo Electronics Co. Ltd.). Velcro straps were in place to anchor the sleeve's position on the shaft, but additional electrical tape was used to secure the sleeve's position along the shaft without effecting testing results. Sensors were protected from hand moisture with a layer of ClingWarp (Glad, The Clorox Company of Canada, LTD.) and masking tape.

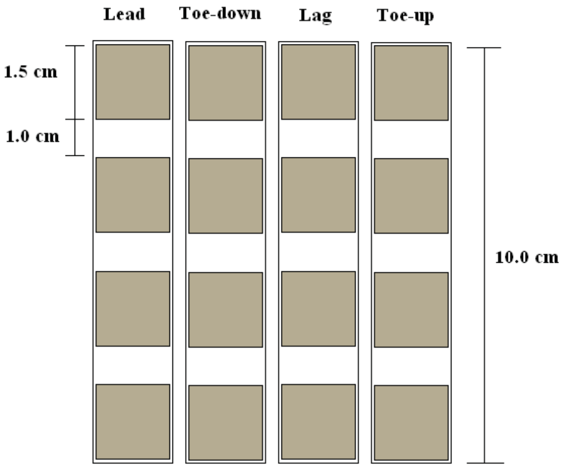


Figure 15 : Sensor configuration layout for both the mid-shaft and butt-end region of the stick (adapted from Zane, 2012).

Figure 16 : Sensor configuration for lower hand on stick (adapted from Zane, 2012)

Figure 17 : Sensor configuration for upper hand on stick (adapted from Zane, 2012)

The synchronization of the FSA system and Strain Gauge system was achieved using a common TTL pulse that was recorded in both systems the instant that a common trigger was pressed. Both system signals were synchronized on MATLAB® (MATLAB 2013a , MathWorks, Boston) during post processing.

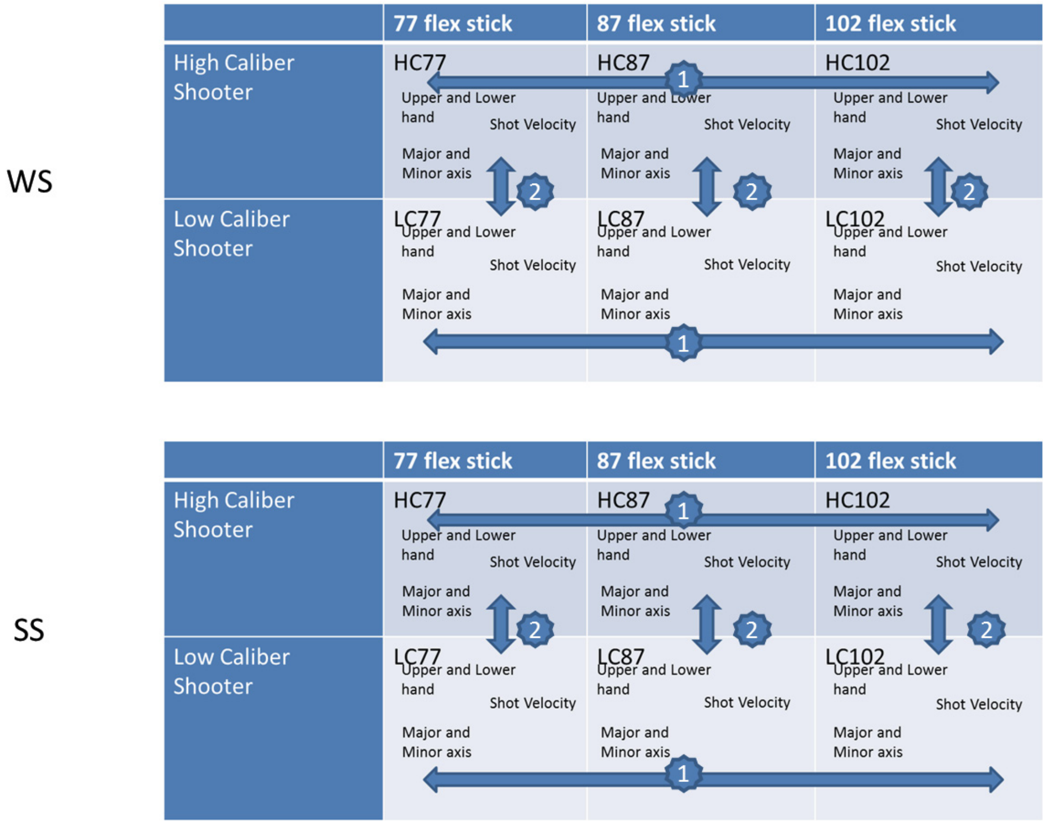
Calibration of the strain gauges was conducted through a shunt calibration technique, the morning of each day prior to testing. A known voltage went through the bridge and the calibration box lowered the resistance to set intervals, simulating the strain gauge response. This data was applied to trial data in post-processing in MATLAB® (MATLAB 2013a , MathWorks, Boston) .

Each FSA sensor was calibrated using a quasi-static stepwise calibration. Force was applied to each sensor's sensing area using a square piece of plastic underneath a wooden platform on top of which 1 kg weights were placed. All of this was placed on top of a force plate (4060-10, Bertec, Columbus, OH). To account for creep, which occurred thanks to material deformation, each sensor was loaded with increasing weight, but unloaded completely before each incremental increase. Values from the sensor and the corresponding weight allowed a relationship between voltage and force determined for each sensor. Also during this process, the sensor measurement error was calculated for each sensor, currently within the range of ± 5 N.

An artificial ice surface (Viking®, Toronto, Canada) at the Ice Hockey Research Group biomechanics lab at McGill University was used for this experiment, due to the cost associated with renting ice time at another location. The surface was installed over top of a concrete leveled floor and level (Stidwill et al., 2010). The testing area was9.5 m by 5.7 m (14.15 m^2), and housed only the subject, test pucks, and a regulation hockey net.

Experimental setup

This study employed a research design with categorical variables. The independent variables included shooter caliber (high/low) and stick stiffness (77, 87, and 102 flex) for both slap shots and wrist shots. This design (Calibre$_2$ x Stiffness$_3$) was analyzed using a mixed methods repeated measures ANOVA (see Figure 17). Correlation analysis was conducted between grip force and strain measures, within slap shot and wrist shot groups.



WS

	77 flex stick	87 flex stick	102 flex stick
High Caliber Shooter	HC77 Upper and Lower hand Shot Velocity Major and Minor axis	HC87 Upper and Lower hand Shot Velocity Major and Minor axis	HC102 Upper and Lower hand Shot Velocity Major and Minor axis
Low Caliber Shooter	LC77 Upper and Lower hand Shot Velocity Major and Minor axis	LC87 Upper and Lower hand Shot Velocity Major and Minor axis	LC102 Upper and Lower hand Shot Velocity Major and Minor axis

SS

	77 flex stick	87 flex stick	102 flex stick
High Caliber Shooter	HC77 Upper and Lower hand Shot Velocity Major and Minor axis	HC87 Upper and Lower hand Shot Velocity Major and Minor axis	HC102 Upper and Lower hand Shot Velocity Major and Minor axis
Low Caliber Shooter	LC77 Upper and Lower hand Shot Velocity Major and Minor axis	LC87 Upper and Lower hand Shot Velocity Major and Minor axis	LC102 Upper and Lower hand Shot Velocity Major and Minor axis

Figure 18 : The comparisons that took place in this experiment. (1) A comparison of all the stick models used for both the slap shot and the wrist shot, and (2) a comparison between high caliber shooters and low caliber shooters for both the WS and the SS

The primary dependent variables examined in this study were the peak grip force (N) exerted on each face of stick, as well as the peak micro strain (micro μ) experienced by the stick.

From conducting an a priori power analysis using G*Power 3 software (G*Power version 3.1.9, Dusseldorf University, (Faul, 2007), Dusseldorf, Germany), and using SG1 results between sticks from pilot testing, it was calculated that a minimum of 6 subjects were required to obtain a power level of .8 in this experiment.

Experimental Protocol

Each morning, prior to testing, equipment was checked and maintained to ensure proper function. Instrumented sticks were calibrated using a shunt calibration box prior to each testing session. After obtaining consent from the subject, descriptive data pertaining to each subject's mass, height, playing history, equipment used, hand length, and hand breadth were collected. Each subject will also performed three maximum grip strength trials for both their left and the right hands using a dynamometer.

Subjects were then advised to put on the testing equipment. When fully outfitted, the subject would stand on the artificial ice surface while wearing skates, the instrumented shoulder pads, a pair of elbow pads, and a pair of gloves provided by the lab. They also held one of the instrumented sticks (see Figures 19 and 20).The subject was given a brief warm-up period to familiarize themselves with the testing environment and equipment. The shooters were asked to practice standing wrist shots and slap shots (five shots of each) with an instrumented stick to become comfortable with the tethered cable during the shot. During this period, a comfortable location of the lower hand FSA sleeve was established for both varieties of shot. Measurements between both sensor sleeves were recorded for both shot types, and kept consistent to ± 100 mm throughout the remainder of testing.

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Figure 19 : Front view of fully outfitted subject

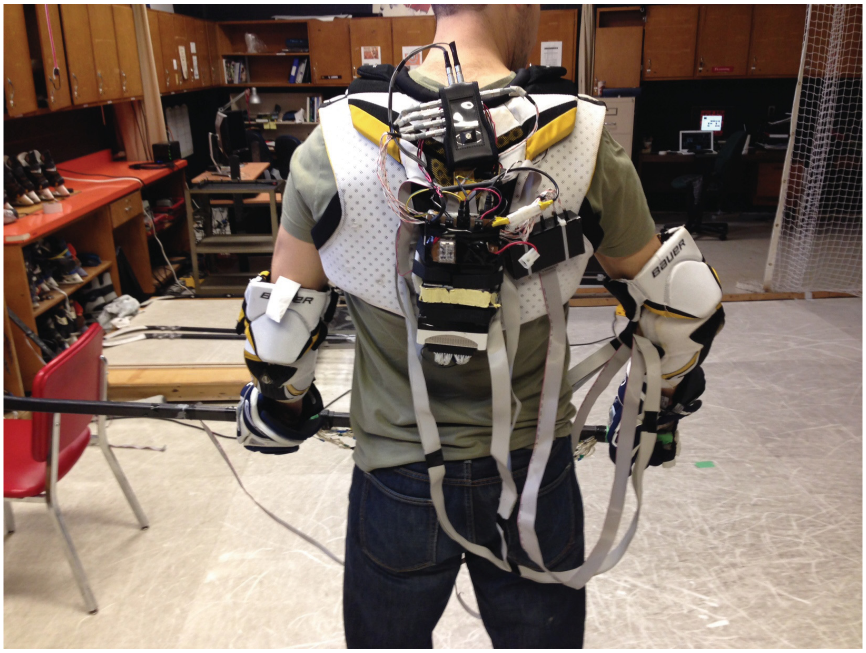


Figure 20 : Back view of outfitted subject

After completing their practice shots, testing began. Recorded trials began with subjects holding the instrumented stick standing 3.5m from the net, and at a 90° orientation. Shots continued until five good trials had been captured for the WS. Following WS trials, the lower FSA sleeve was moved to the recorded SS hand position and five acceptable trials were captured. The same protocol was repeated using the other flex model variations of the stick (77, 87, and 102 flex, resulting in a total of 15 acceptable slap shots and 15 acceptable wrist shots being taken). The order of stick model tested was randomized for each shooter. During each shot, a radar gun was used to measure shot velocity.

Research timeline

Each subject took approximately 60 minutes to test. The steps that were used in testing are listed below:

- 10 minutes for weight, height, hand size measurement, and grip strength test
- 5 minutes for subject to put on skates
- 5 minute warm-up and accommodation period
- 10 minutes stick model 1, 5 acceptable wrist shots, 5 acceptable slap shots
- 5 minutes to change stick model and FSA
- 10 minutes stick model 2, 5 acceptable wrist shots, 5 acceptable slap shots
- 5 minutes to change stick model and FSA
- 10 minutes stick model 3, 5 acceptable wrist shots, 5 acceptable slap shots

Data acquisition, processing and analysis.

LabVIEW™ Version 11.0 (National Instruments®, Austin, Texas) software was used to collect data from all 32 sensors for each trial in .abc format. A DataLOG MWX8 was used to collect strain data from the stick, recording directly to a Micro SD card. Data was then manually converted from .rwx to .log format using DataLog software (Version 8.00, Biometrics Ltd.).

MATLAB (Ver 7.14.0.739, R2012a, MathWorks, Inc., Massachusetts, USA) software was used to process data over eleven different step. First, FSA data had to be converted from .abc format to .zoo format, strain data had to be converted from .log format to .zoo format, and the force data and strain data had to by synchronized and combined into one file. All none combined files were deleted at this point to avoid clutter. Next, force data had to be zeroed using a baseline from testing and converted to Newton's using a calibration file. Strain gauge data had to be converted to micro strain using stick calibration files, after which, the data had to be filtered, the stick side variables had to be calculated from the data recorded by the individual sensors, and the strain gauge data had to be flipped in both the minor and major axis. Finally, to allow the comparison of the dynamic grip force and strain measure between trials, a 601 ms window around each shot trial's ground contact window was identified based on registering the time of peak strain as the 301st frame of the window. This 301st frame was either the peak of SG1 or SG3, depending on hand location of the shooter.

SPSS Statistics (IBM Corporation, Somers, U.S.A.) was used to perform statistical analyses of dependent variables extracted from the force-time and strain-time data according to our experimental setup (see page 48). Variables extracted were local minimums and maximums occurring within “shot windows”. Note that the timing of strain and force measures could not be analyzed due to the lack of homogeneity created by the time registration used when creating our “shot windows’.

Skill Level groups

Subjects were divided into two groups defined as High Caliber (HC) and Low Caliber (LC) based on the level of their previous hockey experience. The HC and LC shooting groups were similar by years of experience, height, mass, hand length, hand breadth, grip strength, or grip distances when shooting. However, significant differences were found between SS and WS shooting velocities, as well as subject age (Table 1).

Table 1 : Descriptive statistics based on caliber of player (x ± SD) and corresponding ANOVA F, p values.

Variable	HC	LC	F	*p*
Age	22.9 ± 2.2	26.4 ± 2.8	9.153	.008*
Years' Experience	18.0 ± 2.2	15.0 ± 7.2	1.702	.211
Height (cm)	181.7 ± 4.9	183.1 ± 2.7	.474	.501
Mass (kg)	84.8 ± 7.1	78.8 ± 8.3	2.674	.122
Left Hand Length (cm)	19.5 ± 1.0	19.2 ± 0.9	.385	.544
Right Hand Length (cm)	19.4 ± 0.9	19.2 ± 0.8	.261	.616
Left Hand Breadth (cm)	8.8 ± 0.4	8.7 ± 0.4	.353	.561
Right Hand Breadth (cm)	8.8 ± 0.3	8.6 ± 0.4	1.600	.224
WS Grip Distance (cm)	32.9 ± 4.5	30.7 ± 4.4	1.037	.324
SS Grip Distance (cm)	52.5 ± 5.5	50.3 ± 6.5	.580	.457
Grip Strength Left Hand (kg)	56.3 ± 7.3	55.3 ± 5.2	.102	.753
Grip Strength Right Hand (kg)	54.8 ± 6.2	55.1 ± 5.5	.007	.932

*$p < 0.05$

Results

Grip force analyses and stick strain analyses for both wrist shots and slap shot (n=18) trials will be presented. SPSS Statistics (Ver. 21.0, SPSS Inc., Chicago, Illinois, U.S.A.) was used to perform statistical and correlational analyses of dependent variables extracted from the force-time and strain-time data.

Results for Slap shots

Between Sticks

Repeated measures ANOVAs were performed to determine if within the caliber groups there were differences between shot velocity, peak grip force levels, peak stick strain, and timing at which those peaks occurred during the different stick conditions. There were no significant differences between SS velocities within stick conditions (see Figure 21), and there were no significant differences for either shooting caliber when looking at peak grip forces during SS within the different stick conditions. There were no significant differences found between peak force times thanks to the effect of different shooting techniques.

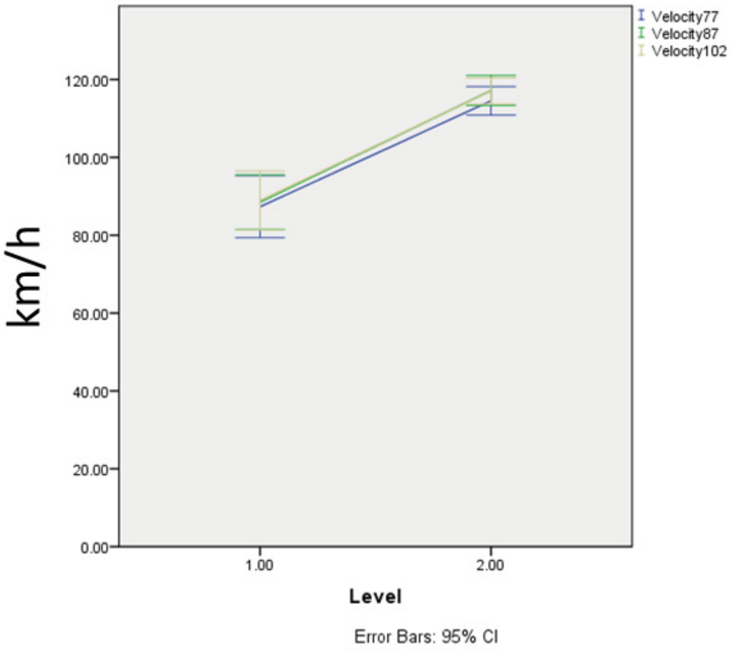


Figure 21 : LC (1) and HC (2) average slap shot velocity

When examining peak strain for each of the four SGs, each of the four gauges saw significant differences between stick model ($F(2,15) = 19.319$, $p = .000$, $F(2,15) = 20.316$, $p = .000$, $F(2,15) = 11.989$, $p = .000$, $F(2,15) = 7.327$, $p = .002$). As predicted, sticks with the lower stiffness ratings saw, on average, higher peak strain (see Table 2 and Figure 22). Using pairwise comparison for each strain gauge and stick, we were able to identify which sticks were significantly different than the others (see Table 3). At SG1, each stick differed in the amount of strain it saw. At SG2, stick 77 was different than stick 102, and stick 87 was different than stick 102. At SG3, stick 77 was different than stick 87 and 102, but stick 87 and 102 were not significantly different. At SG4, only stick 77 and 87 were significantly different.

Table 2 : Average peak strain (micro µ) and Standard Deviation for each SG, for each stick, SS.

	Group	Mean	Std. dev.
SG177	LC	1492.1	180.3
	HC	2437.1	232.3
SG187	LC	1395.0	174.6
	HC	2283.7	197.0
SG1102	LC	1343.0	178.8
	HC	2171.9	186.2
SG277	LC	722.0	159.3
	HC	1100.8	186.4
SG287	LC	705.8	177.4
	HC	1024.7	182.7
SG2102	LC	613.2	164.3
	HC	981.1	137.6
SG377	LC	1473.1	240.0
	HC	1860.8	188.3
SG387	LC	1342.0	258.8
	HC	1714.6	228.3
SG3102	LC	1290.1	178.1
	HC	1671.8	165.5
SG477	LC	603.8	83.5
	HC	840.0	182.5
SG487	LC	556.6	114.8
	HC	728.1	166.2
SG4102	LC	552.3	115.2
	HC	781.6	152.7

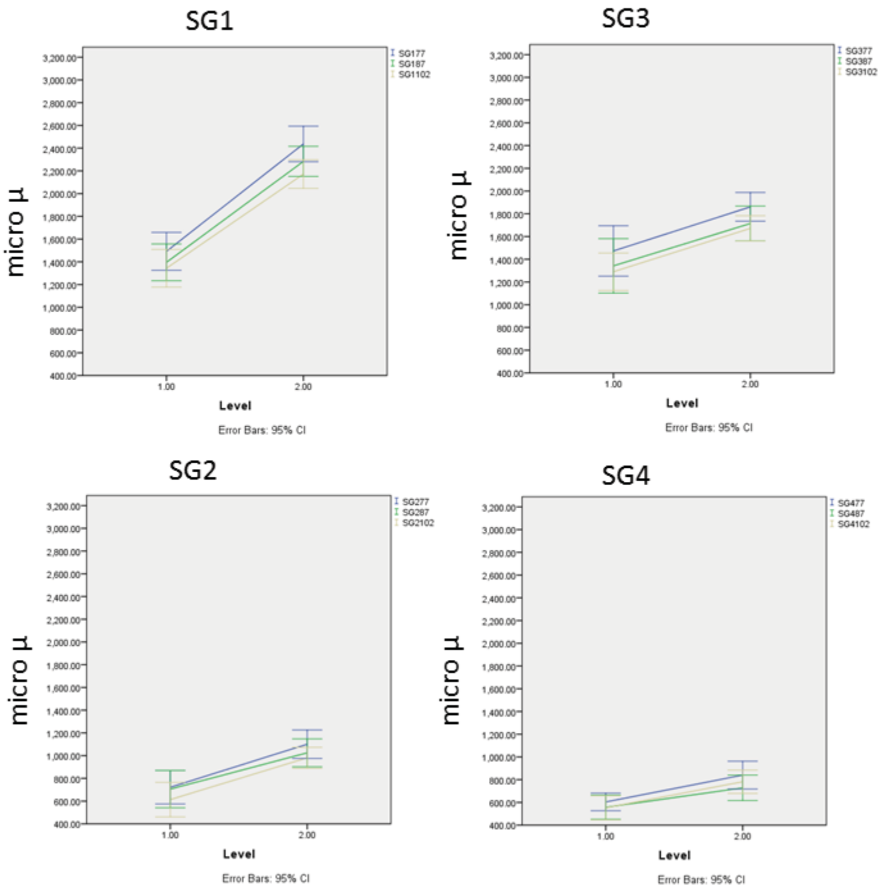


Figure 22 : Peak strain (micro µ) in each SG pairing for LC (1) and HC (2) shooters, SS.

Table 3 : Pairwise comparisons between the 77, 87 and the 102 sticks at each SG, SS.

SG1		Mean Diff.	Std. Err.	*p* Value
77	87	125.2	36.7	*.011
	102	207.1	33.6	*.000
87	102	81.9	30.0	*.044

SG2		Mean Diff.	Std. Err.	*p* Value
77	87	46.1	27.6	.343
	102	114.2	20.0	*.000
87	102	68.1	22.1	*.021

SG3		Mean Diff.	Std. Err.	*p* Value
77	87	138.7	29.9	*.001
	102	186.0	29.2	*.000
87	102	47.3	31.9	.472

SG4		Mean Diff.	Std. Err.	*p* Value
77	87	79.6	24.4	*.015
	102	55.0	22.2	.074
87	102	24.6	16.5	.465

* $p < 0.05$;

Between Caliber

As predicted, HC shooters achieved significantly higher peak velocities with their SS than LC shooters did (see Table 4).

Table 4 : SS velocities based on caliber of player (x ± SD) and corresponding ANOVA F, p value

Variable	HC	LC	F	*p*
Slap Shot Velocity (km/h)[a]	116.3 ± 4.9	88.3 ± 8.0	86.229	.000*

* $p < 0.05$; [a] HC, n= 11; LC , n= 7

In terms of peak force, there were minimal differences between high caliber and low caliber shooters on the upper hand faces, while on the lower hand the LLD, LTD, and LTU saw significantly different forces between calibers (see Table 5). The differences in peak force time for the different faces were negligible between calibers.

Table 5 : Upper and Lower hand stick faces' average peak force (N), Std. Dev., Corresponding ANOVA F Value, and p value for LC (1) and HC (2) shooters, SS.

Face	Group	Mean	Std Dev.	F	p Value
ULG	LC	18.0	8.5	2.842	.111
	HC	12.1	6.4		
ULD	LC	30.6	17.7	2.024	.174
	HC	22.4	6.1		
UTU	LC	24.8	15.6	2.942	.106
	HC	36.0	12.1		
UTD	LC	26.4	15.3	.877	.363
	HC	31.5	7.6		
LLD	LC	16.0	8.0	5.045	.039
	HC	27.8	12.3		
LLG	LC	12.1	4.7	1.079	.314
	HC	14.3	4.2		
LTD	LC	18.7	6.3	4.660	.046
	HC	26.7	8.3		
LTU	LC	38.6	7.7	5.962	.027
	HC	48.4	8.6		

In terms of strain, HC shooters saw higher peak strain than LC shooters at each SG pairing, as expected from previous research (Hannon, 2010; Villasenor, 2006). SG1 and SG3 saw greater strain than SG2 and SG4, though we also see that SG2 saw more strain than SG4 (see Table 6). It should also be noted that the timing for max peak strain of the major and minor axes gauges differed between HC and LC shooters. In general peak strains of the minor axes consistently occurred before the major axis gauges by 10 and 20 ms for the LC and HC shooters, respectively (see Figure 23 and Figure 24).

Table 6: Stick strains by average peak strain (micro µ, Std. Dev,) Corresponding ANOVA F value, and p value for LC (1) and HC (2) shooters, SS.

Gauge	Group	Mean	Std Dev.	F	p Value
SG1	LC	1410.0	175.5	105.3	.000
	HC	2297.6	180.8		
SG2	LC	680.4	162.5	21.2	.000
	HC	1035.5	157.8		
SG3	LC	1368.4	215.1	16.2	.001
	HC	1749.1	182.8		
SG4	LC	570.9	99.5	10.1	.006
	HC	783.2	157.1		

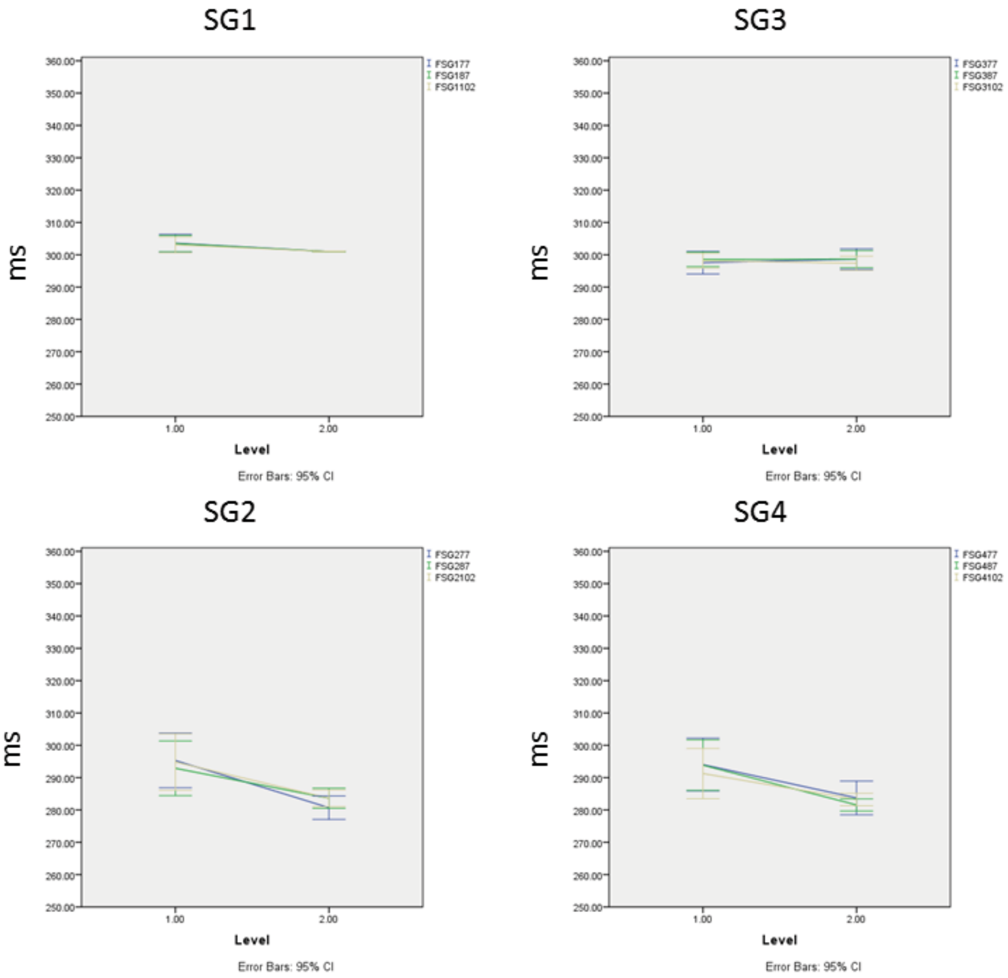


Figure 23 : Average frame number of peak strain for each SG, for LC (1) and HC (2) shooters, SS.

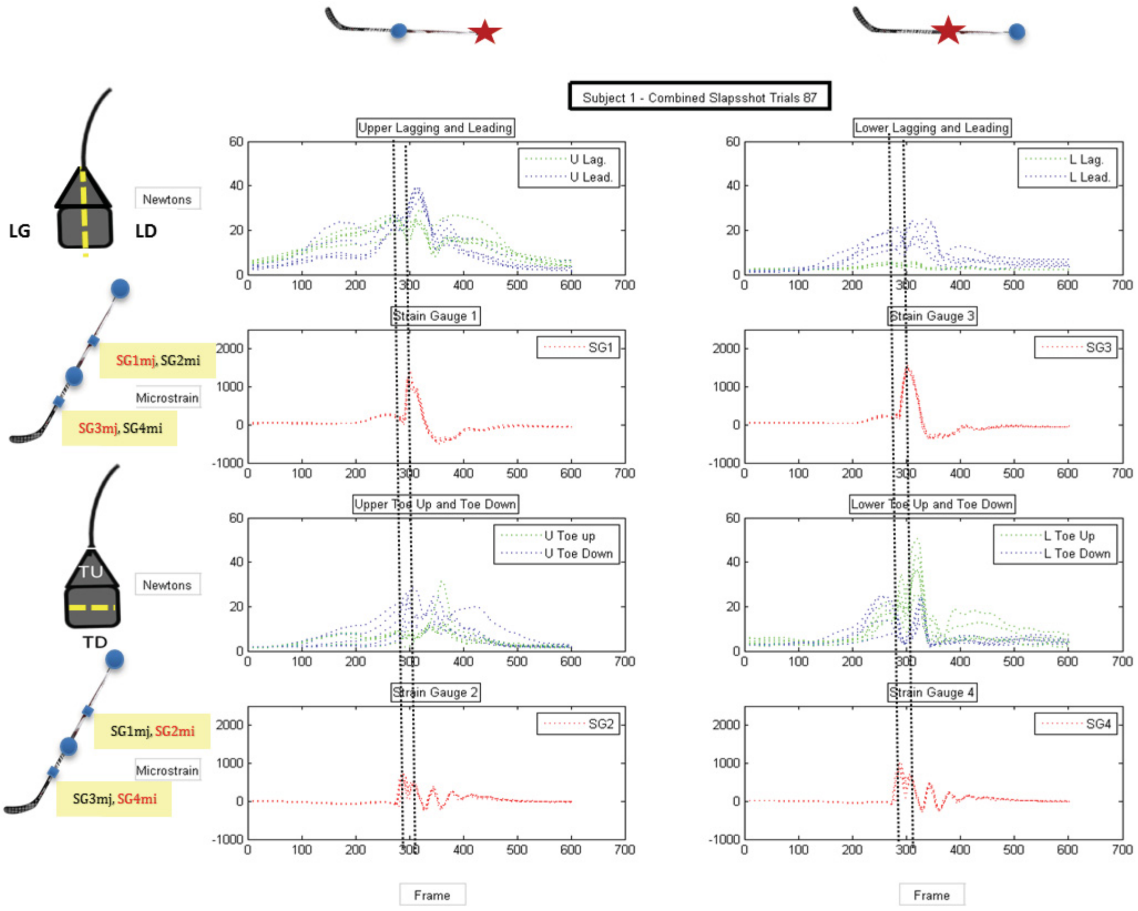


Figure 24 : Five SS trials for Subject 1 depicting differences in peak strain between major and minor axis strain gauges (see vertical dashed lines identifying time difference interval).

As seen by Zane, (2010) qualitatively, we also saw that there was very little change in grip forces and stick strain between each subject and condition. We also saw that some shooters saw similar patterns in their grip force patterns to other shooters when shooting. This allows us to separate subjects into different shooting types, much like how Komi (2008) saw different groups when examining drives in golf. In general, four slap shot grip force styles were observed.

Group one shooters, exemplified here by Subject 1 (see Figure 25), saw moderate force levels on all faces of the stick, with especially large spikes in force in the ULG, ULD, and LTU faces around the time of maximum strain (highlighted by shaded rectangles).

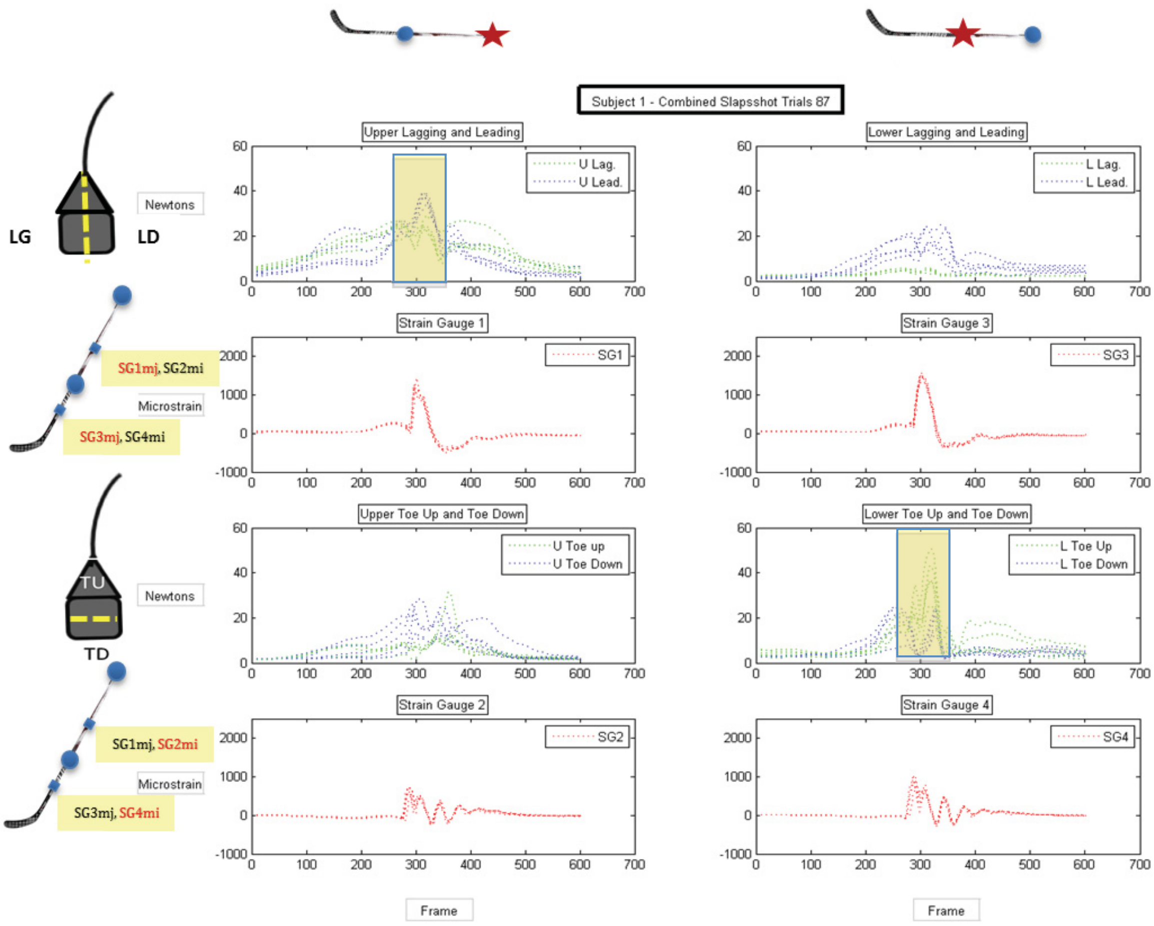


Figure 25 : Five slap shot trials performed by Subject 1.

Group two, exemplified here by Subject 10 (see Figure 26), saw moderate to higher forces on the lower hand when shooting, especially on the LTU face. On the upper stick faces, there were lower forces seen in the LD and LG faces, while larger forces were seen in the TU and TD faces, especially just after max strain (see shaded regions in Fig 26).

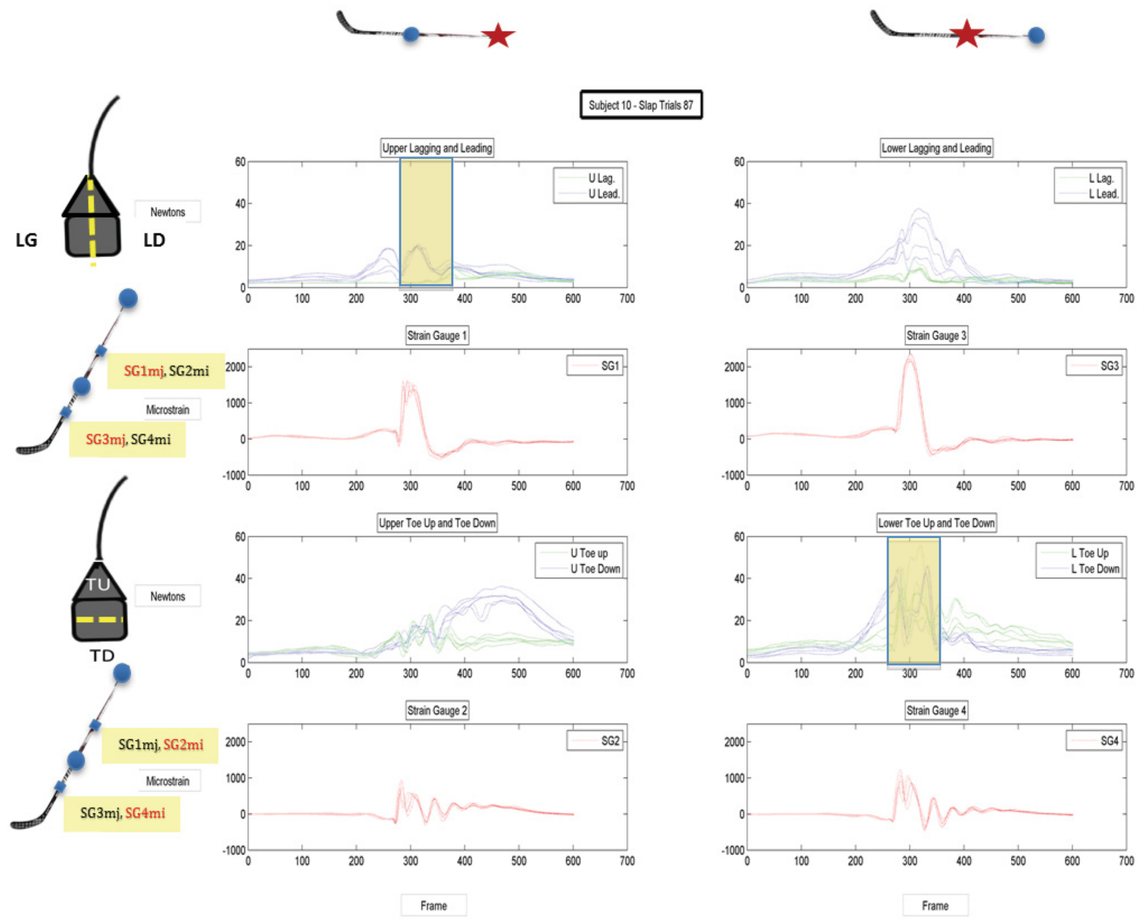


Figure 26 : Five slap shot trials performed by Subject 10.

Group three, exemplified by Subject 12 (see Figure 27), saw minimal levels of force occurring on the LLD and LLG faces (see shade rectangle regions in Fig 27). Moderate to large forces were seen both at the upper and lower TU and TD faces, especially at the LTD face, where there was a definite peak in force that occurred around the time of max peak strain.

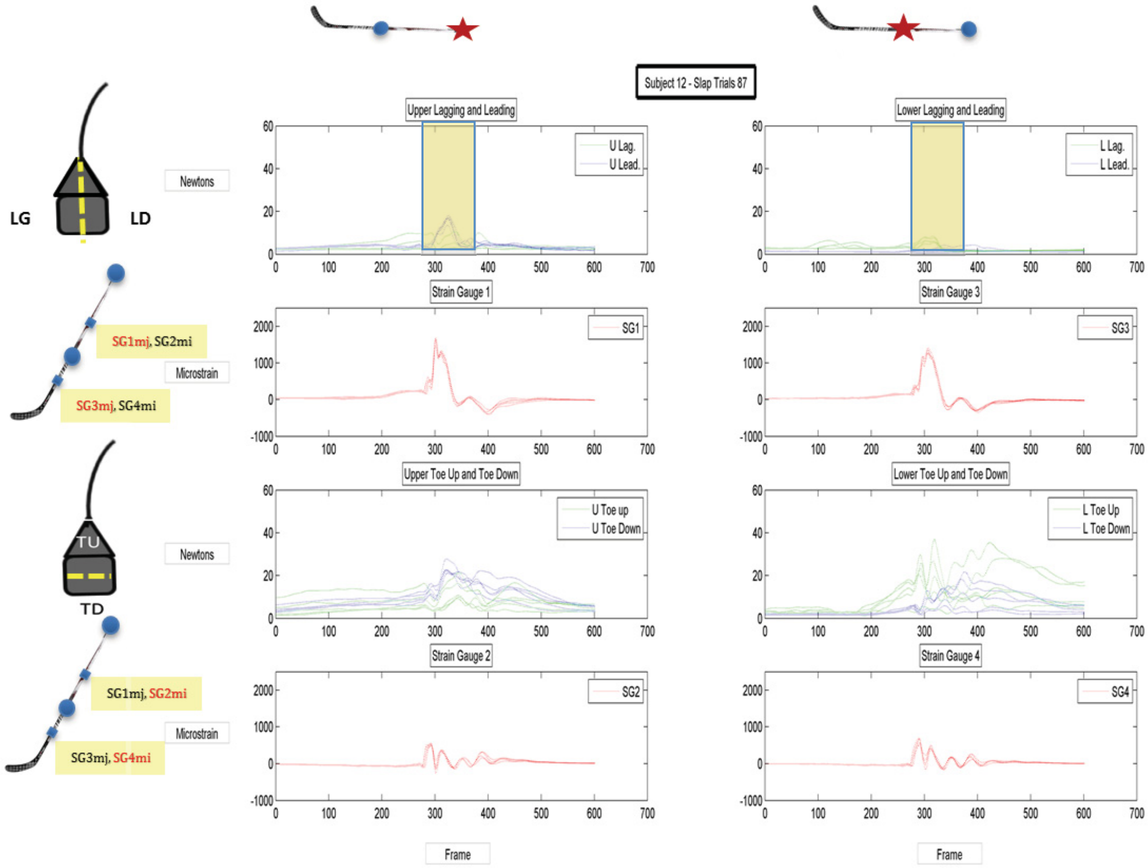


Figure 27 : Five slap shot trials performed by Subject 12.

The final group of subjects (see Figure 28) saw moderate forces occur at most faces of the stick during shooting. What makes them a unique group is the large LLD force that occurred at max peak strain of the stick, nearly the same time we saw our peak in LTU face of the stick (see shaded rectangles in Fig 28).

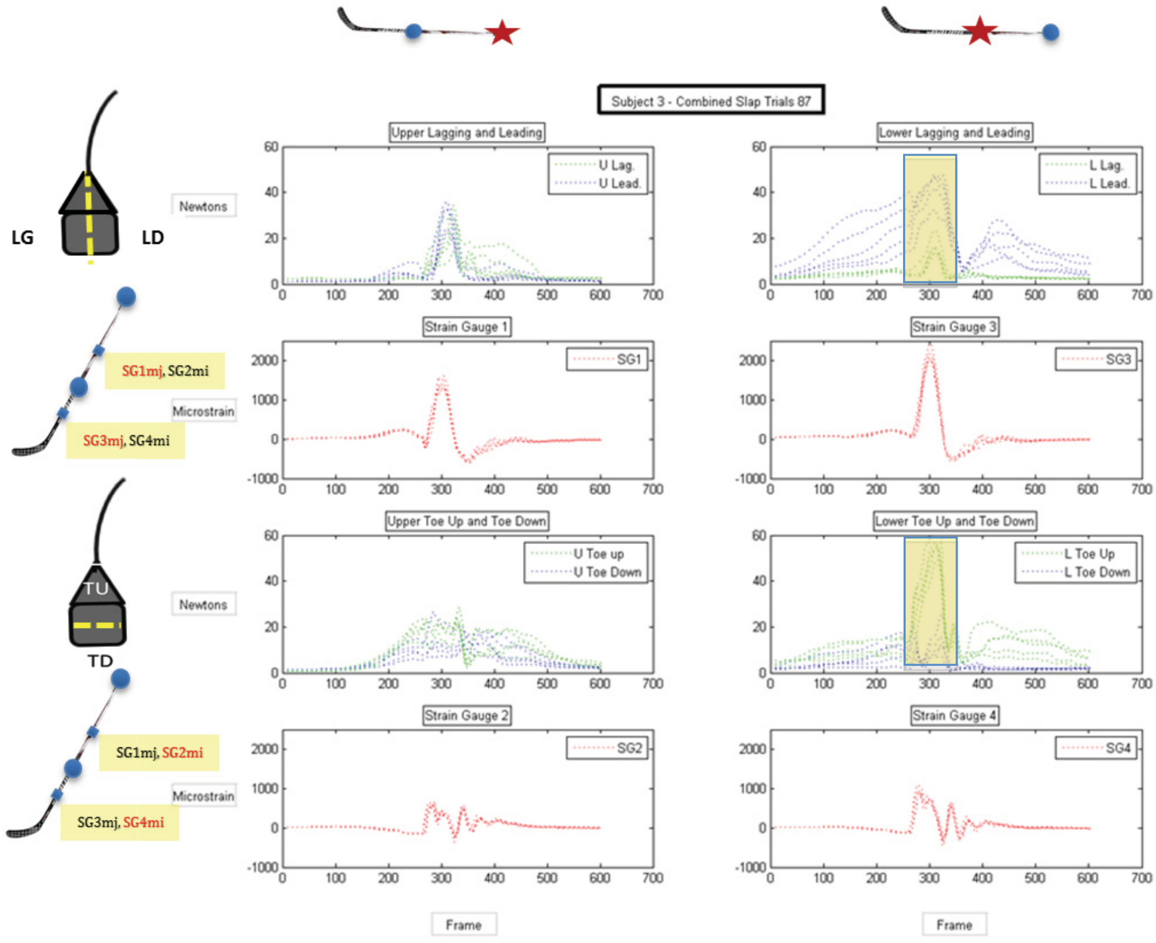


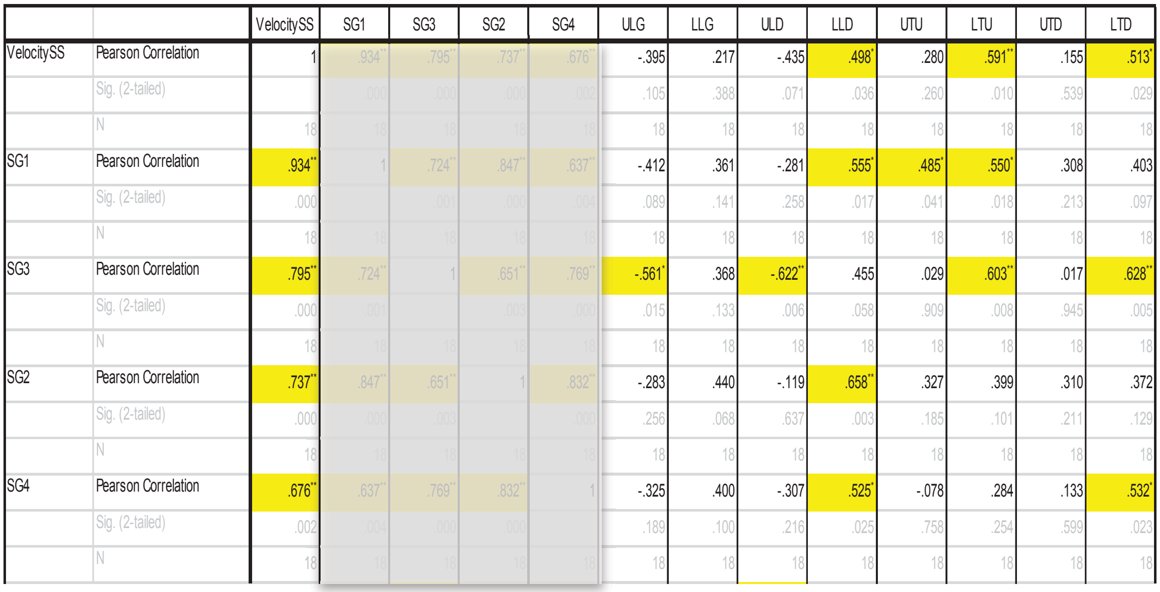
Figure 28 : Five slap shot trials performed by Subject 3.

These shooting groups, which feature both HC and LC shooters, see both distinct differences and similarities. These similarities show the many possibilities for different techniques, and that no one shooting style is completely mutually exclusive from another. Running ANOVA's to compare variables between group's leads to further validation of this point. Group one shooters see significantly greater ULD forces than group two and three, but not group four. Group two shooters saw significantly higher LLD forces than group three but none of the other groups. Group three shooters saw significantly lower LLD forces than group two and four, but not group one. Group four saw a LLD force significantly higher than group one and four, but not group two.

Correlation Analysis

Correlational analysis showed that shot velocity was closely related to levels of strain at each SG (see Table 7 and Figure 29). Shooting velocity was also related closely to forces at the LLD, LTU, and LTD faces. With respect to strain measures in relation to grip face forces, several significant r scores were identified ($p<0.05$), though these varied between strain gauge locations.

Table 7 : Correlation Analysis of Slap Shots.



		VelocitySS	SG1	SG3	SG2	SG4	ULG	LLG	ULD	LLD	UTU	LTU	UTD	LTD
VelocitySS	Pearson Correlation	1	.934**	.795**	.737**	.676**	-.395	.217	-.435	.498*	.280	.591**	.155	.513*
	Sig. (2-tailed)		.000	.000	.000	.002	.105	.388	.071	.036	.260	.010	.539	.029
	N	18	18	18	18	18	18	18	18	18	18	18	18	18
SG1	Pearson Correlation	.934**	1	.724**	.847**	.637**	-.412	.361	-.281	.555*	.485*	.550*	.308	.403
	Sig. (2-tailed)	.000		.001	.000	.004	.089	.141	.258	.017	.041	.018	.213	.097
	N	18	18	18	18	18	18	18	18	18	18	18	18	18
SG3	Pearson Correlation	.795**	.724**	1	.651**	.769**	-.561*	.368	-.622**	.455	.029	.603**	.017	.628**
	Sig. (2-tailed)	.000	.001		.003	.000	.015	.133	.006	.058	.909	.008	.945	.005
	N	18	18	18	18	18	18	18	18	18	18	18	18	18
SG2	Pearson Correlation	.737**	.847**	.651**	1	.832**	-.283	.440	-.119	.658**	.327	.399	.310	.372
	Sig. (2-tailed)	.000	.000	.003		.000	.256	.068	.637	.003	.185	.101	.211	.129
	N	18	18	18	18	18	18	18	18	18	18	18	18	18
SG4	Pearson Correlation	.676**	.637**	.769**	.832**	1	-.325	.400	-.307	.525*	-.078	.284	.133	.532*
	Sig. (2-tailed)	.002	.004	.000	.000		.189	.100	.216	.025	.758	.254	.599	.023
	N	18	18	18	18	18	18	18	18	18	18	18	18	18

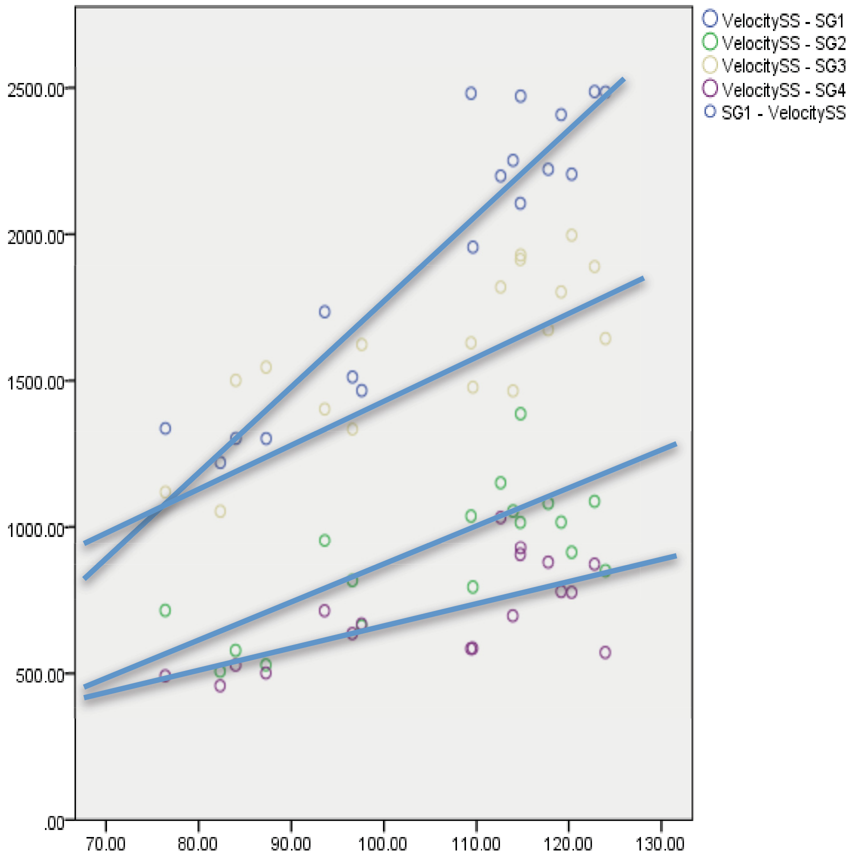


Figure 29 : Shot velocity (km/h) by Strain (micro µ) for each SG, SS.

Results for Wrist shots

Between Sticks

Repeated measures ANOVAs were performed to determine if within the caliber groups there were differences between shot velocity, peak grip force levels, peak stick strain and timing at which those peaks occurred during the different stick conditions for WS. When comparing peak velocity and peak grip forces, the WS, like the SS, saw no significant differences between stick conditions. Shooters shot with roughly the same velocity, using similar grip forces, when using the different stick. Stick model had no effect on the timing of peak grip forces.

When examining peak strain for each of the four SGs, each of the four gauges saw significant differences between stick models. As predicted, and similar to the findings of Hannon (2010), sticks with the lower stiffness ratings typically showed higher peak strain, while sticks with the higher stiffness rating typically saw lower strain levels (see Table 8 and Figure 30). Using pairwise comparison for each strain gauge and stick, we are able to identify which sticks are significantly different than the others (see Table 9). Each SG saw significant differences between stick 77 and stick 87, as well as stick 77 and stick 102. SG1, in addition to these significant differences, saw a significant difference in peak strain between stick 87 and stick 102.

Table 8 : Average peak strain (micro µ) and Std. dev. for each stick at each SG, WS.

	Group	Mean	Std. dev.
SG177	LC	830.4	143.8
	HC	1684.5	295.4
SG187	LC	731.0	167.5
	HC	1489.7	318.2
SG1102	LC	643.8	77.3
	HC	1389.1	326.6
SG277	LC	354.9	153.7
	HC	646.5	131.7
SG287	LC	266.2	148.7
	HC	598.2	115.9
SG2102	LC	239.5	103.4
	HC	586.9	150.4
SG377	LC	1230.4	298.5
	HC	2209.4	308.8
SG387	LC	1071.3	298.5
	HC	1892.1	370.5
SG3102	LC	937.3	163.0
	HC	1721.1	320.0
SG477	LC	503.3	254.1
	HC	820.4	156.4
SG487	LC	339.9	219.2
	HC	663.6	123.0
SG4102	LC	392.7	221.2
	HC	748.7	139.6

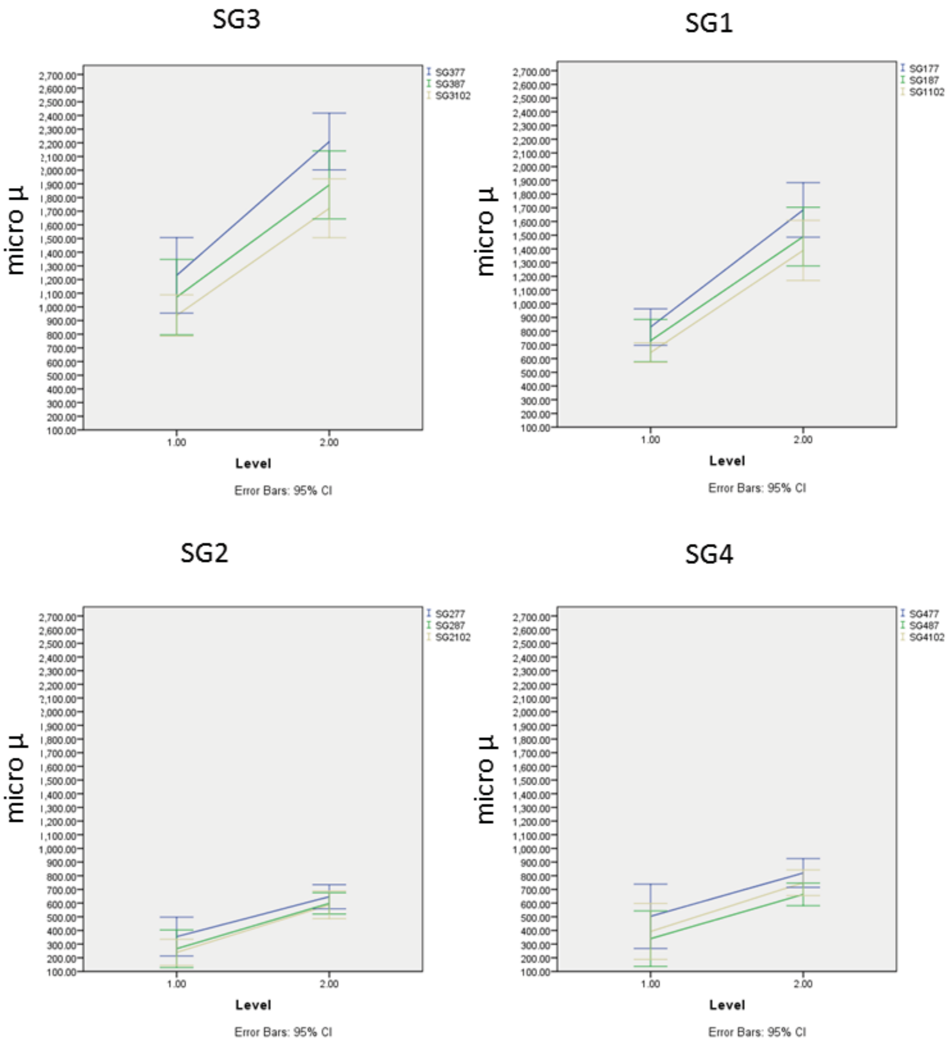
Table 9 : Pairwise comparisons between the 77, 87 and 102 sticks during WS.

SG1		Mean Diff.	Std. Err.	p Value
77	87	147.1	21.8	.000
	102	241.0	24.4	.000
87	102	93.9	35.0	.049

SG2		Mean Diff.	Std. Err.	p Value
77	87	68.5	20.4	.012
	102	87.5	20.1	.002
87	102	19.0	26.7	1.000

SG3		Mean Diff.	Std. Err.	p Value
77	87	238.2	27.4	.000
	102	390.7	33.9	.000
87	102	152.5	47.3	.016

SG4		Mean Diff.	Std. Err.	p Value
77	87	160.1	23.5	.000
	102	91.2	19.1	.001
87	102	-68.9	29.4	.096


SG3

SG1

SG2

SG4

Figure 30 : Average Peak Strain (micro µ) for each SG, LC (1) and HC (2) shooters, WS.

The timing in which the minor axis and major axis saw peak strain was found to be significantly different between sticks (*F* (2, 15) = 6.963, *p* = .003). Open further examination through pairwise comparison, it is seen that there are significant differences between the 77 stick and the 102 stick, and the 87 stick and 102 stick in terms of the timing of peak strain in the major and minor axis (see Figure 31).

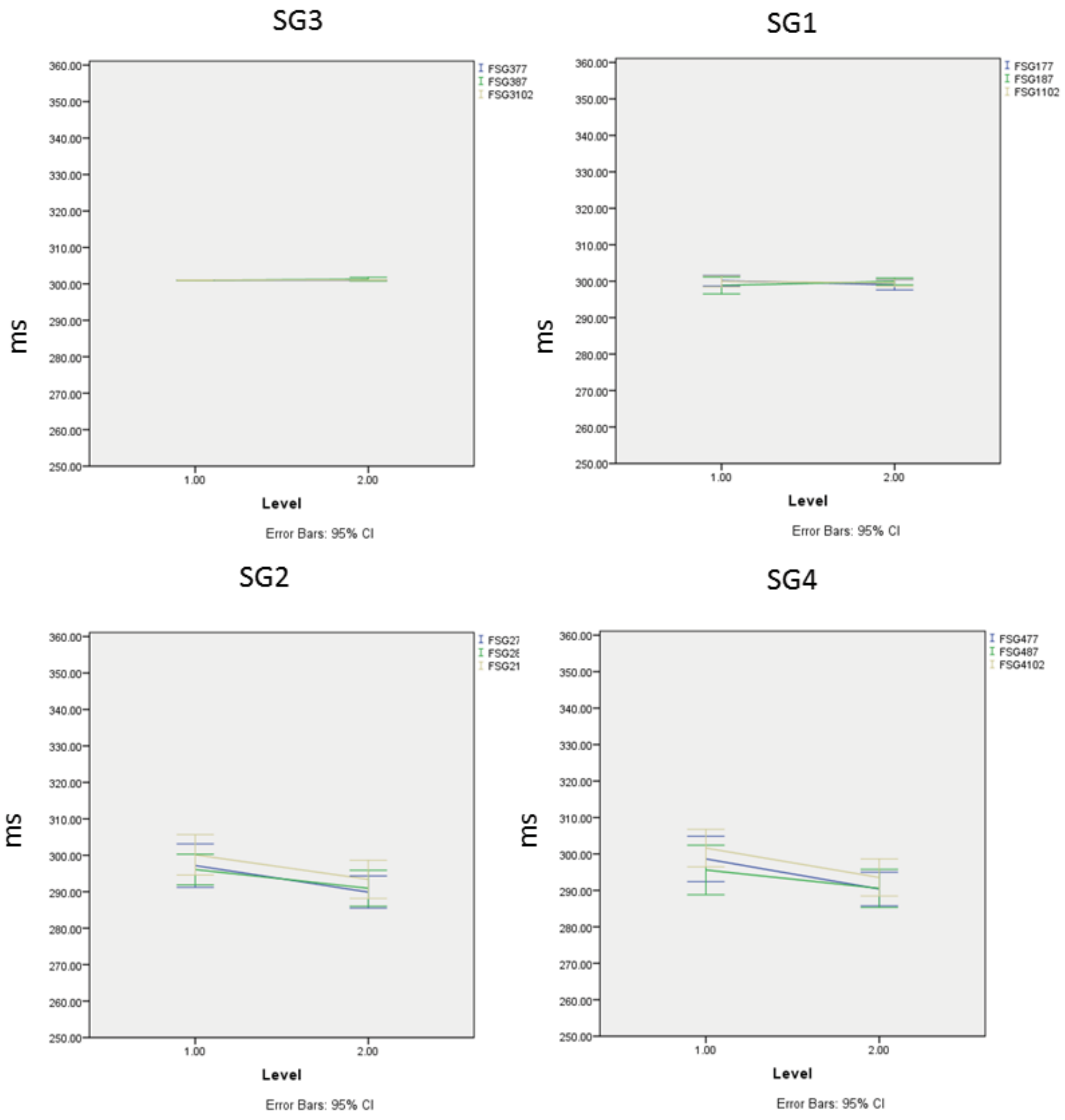


Figure 31 : Average frame number of peak strain for each SG, for LC(1) and HC(2) shooters, for each stick, WS.

Between Caliber

From our comparison through ANOVA, we see that HC shooters achieved significantly different velocities with their WS than LC shooters did (see Table 10 and Figure 32).

Table 10 : WS velocities based on caliber of player (x ± SD) and corresponding ANOVA F, p value.

Variable	HC	LC	F	*p*
Wrist Shot Velocity (km/h)^b	95.1 ± 6.0	69.3 ± 11.1	39.733	.000*

* $p < 0.05$; b HC, n= 11; LC, n= 7

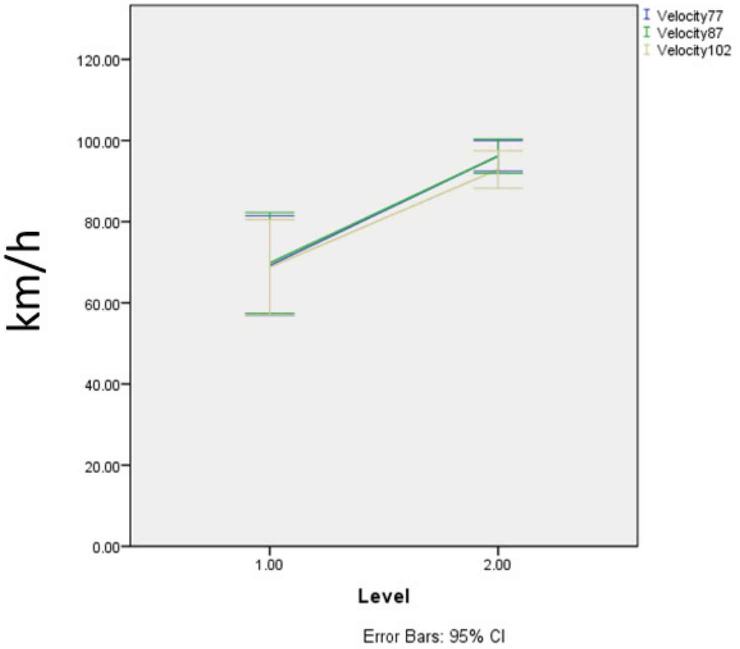


Figure 32 : LC (1) and HC (2) average wrist shot velocity.

In terms of peak grip forces, the only force that we can definitively say differs between HC and LC shooters is the UTU face. This is because statistical comparison is made difficult due to large differences in variance between the two caliber groups thanks to different technique (see Table 11). There was no effect of caliber on the timing of peak grip forces.

Table 11 : Upper and Lower hand stick face forces average peak force, Std. Dev. Corresponding ANOVA F Value, and p Value for LC (1) and HC (2) shooters, WS.

Face	Group	Mean	Std Dev.	F	p Value
ULG	LC	17.5	7.9	.270	.611
	HC	15.1	10.0		
ULD	LC	24.9	4.6	4.558	.049
	HC	33.8	10.4		
UTU	LC	13.3	4.7	4.990	.040
	HC	24.2	12.2		
UTD	LC	11.4	2.7	.836	.374
	HC	13.0	4.2		
LLD	LC	13.3	6.4	5.643	.030
	HC	22.2	8.4		
LLG	LC	18.1	13.1	1.890	.188
	HC	25.6	10.1		
LTD	LC	16.4	2.5	.356	.559
	HC	18.2	7.7		
LTU	LC	38.6	9.2	.466	.505
	HC	43.5	17.2		

For WS, HC shooters saw higher peak strain than LC shooters at each SG pairing, like seen in previous research (Hannon, 2010; Villasenor, 2006). SG1 and SG3 saw greater strain than SG2 and SG4, though we also see that, unlike the SS, in WS SG3 saw more strain than SG1 and SG4 saw more strain than SG2 (see Table 12). For WS, like SS, it should be noted that the timing for max peak strain of the major and minor axes gauges was significantly different between HC and LC shooters. LC shooters saw peak strain achieved in the minor axes approximately 4 ms before the major axes s, HC shooters saw the minor axis achieve peak strain around 11 ms before max strain in the major axis. The same effect of placing the stick completely down before sweeping forward, though not as large as in SS, is still a prevalent trend in WS (Figure 33).

Table 12 : Stick strains by average peak strain (micro µ), Std. Dev,) Corresponding ANOVA F Value, and p Value for LC (1) and HC (2) shooters, WS.

Gauge	Group	Mean	Std Dev.	F	p Value
SG1	LC	735.1	122.4	41.315	.000
	HC	1521.1	305.5		
SG2	LC	286.8	130.2	29.387	.000
	HC	610.5	119.3		
SG3	LC	1079.6	246.8	36.241	.000
	HC	1940.8	321.8		
SG4	LC	412.0	227.2	16.218	.001
	HC	744.3	125.0		

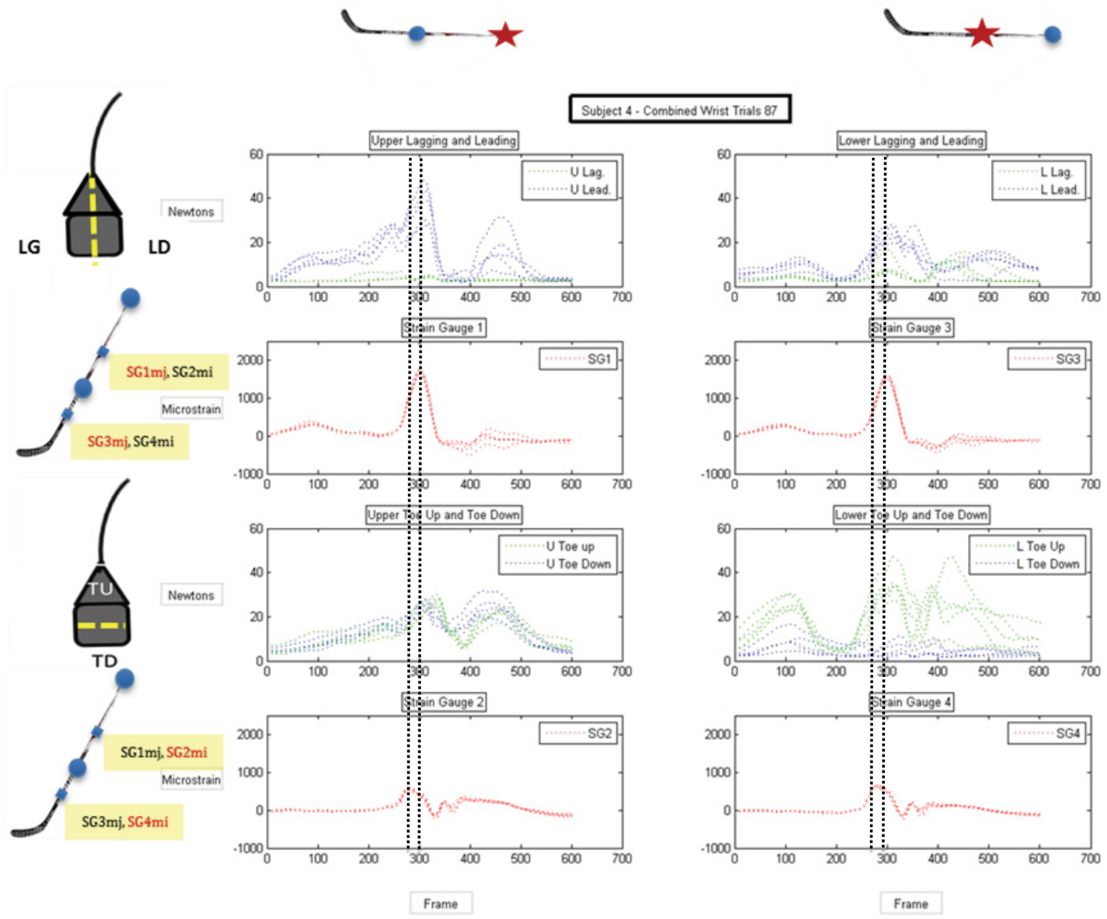


Figure 33 : Five WS trials for Subject 4 depicting differences in peak strain between major and minor axis strain gauges (see vertical dashed lines identifying time difference interval).

Like in SS, shooters and their wrist shot techniques can be divided into common groups; for WS, we can create another four unique shooting groups. These groups do not feature the same players as the SS groups. While two shooters may share similar technique when taking SS, they may take WS completely differently.

Group One, exemplified by Subject 4 (see Figure 34), generally saw larger forces on all stick faces at the time of max strain.

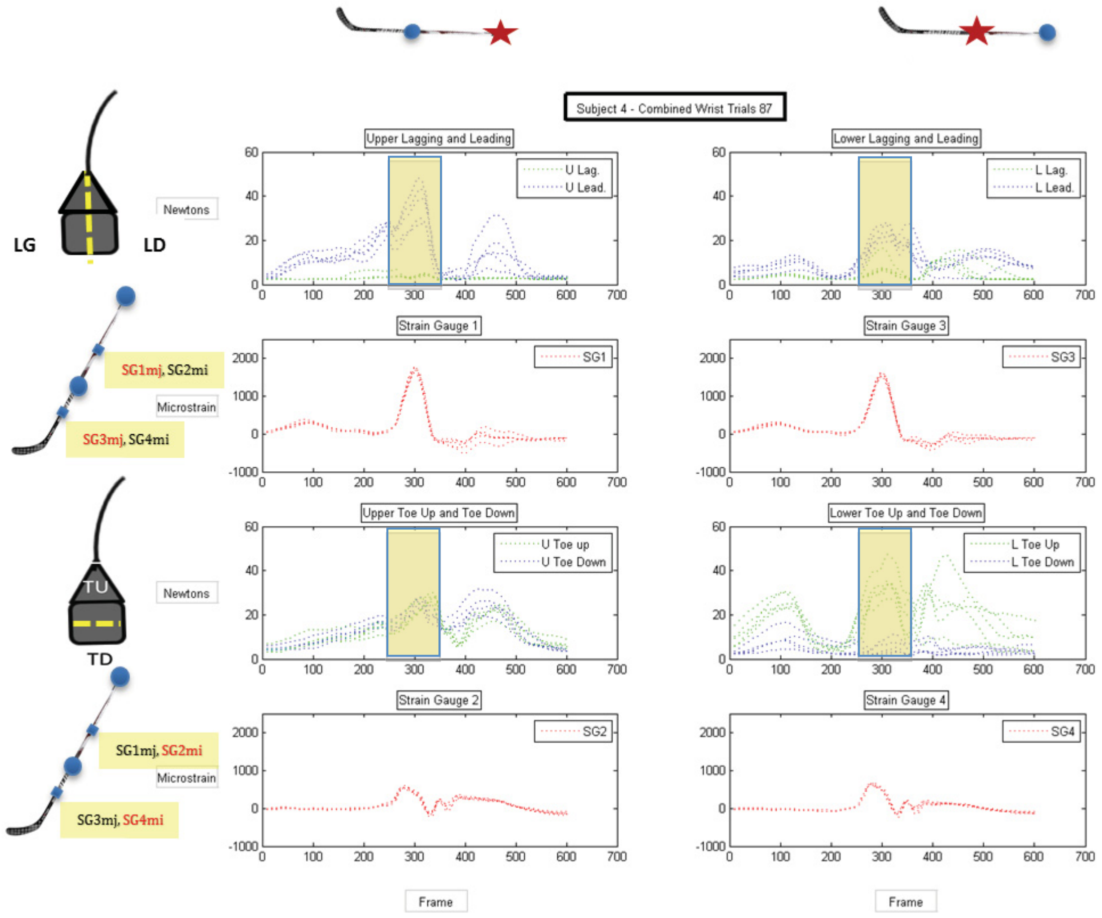


Figure 34 : Five wrist shot trials performed by Subject 4.

Group 2, exemplified by Subject 11 (see Figure 35), saw minimal force at the LLG, LLD, UTU, and UTD faces.

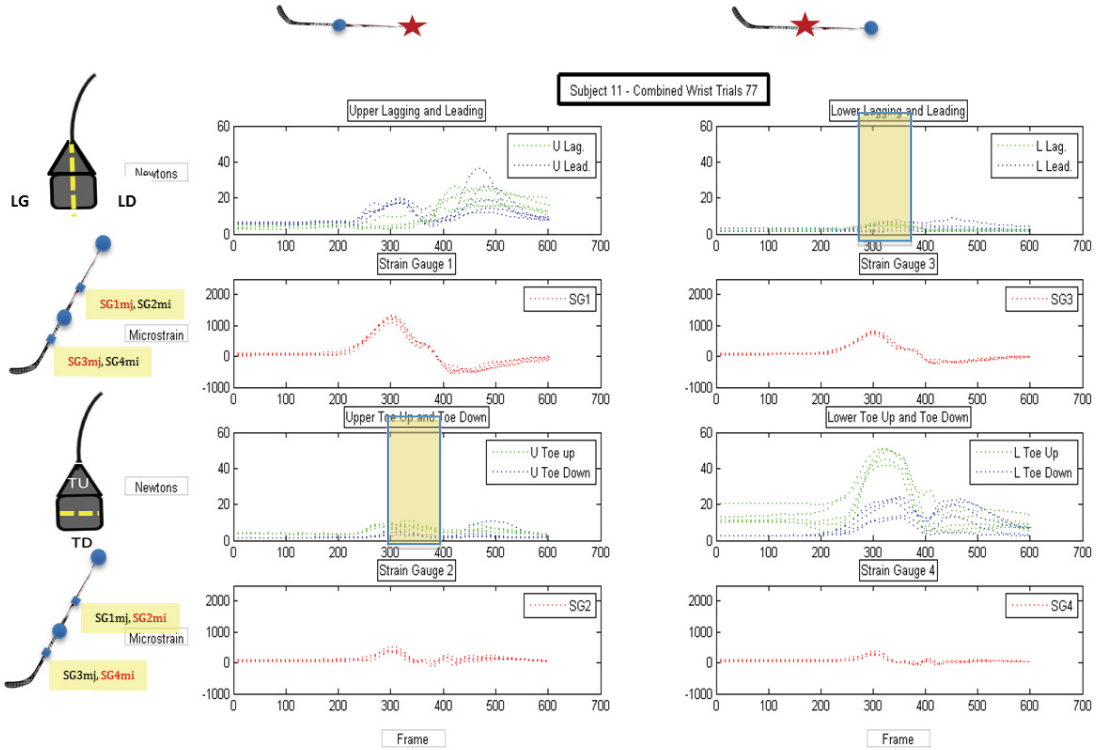


Figure 35: Five WS trails performed by Subject 11

Group 3, exemplified by Subject 17 (see Figure 36), saw moderate forces on all of the stick faces, other than the LLD and LLG faces. Rather than sharp peaks seen directly at max strain in the TU and TD faces.

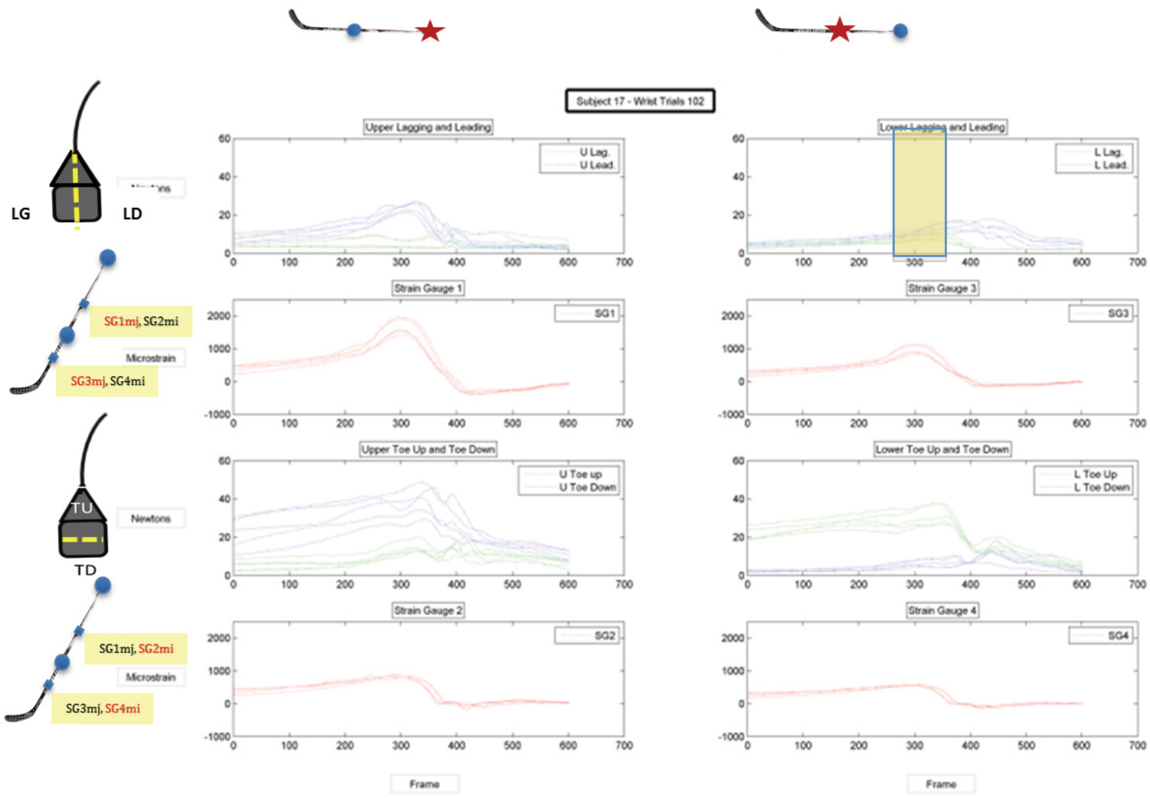


Figure 36 : Five wrist shot trials performed by Subject 17.

Group 4, exemplified by Subject 3 (see Figure 37), sees moderate to high forces on all of the stick faces, except for UTU and UTD. The highest observed forces occurred on the LTU face, though the peak did not occur as sharply as in other shooting types.

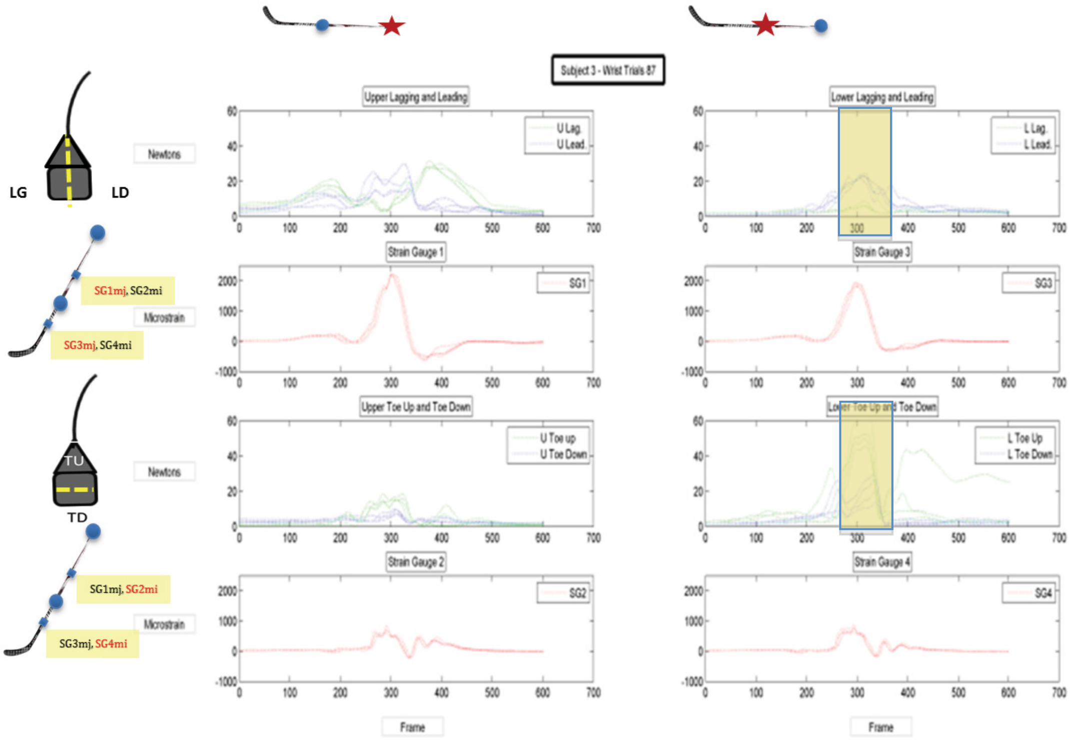


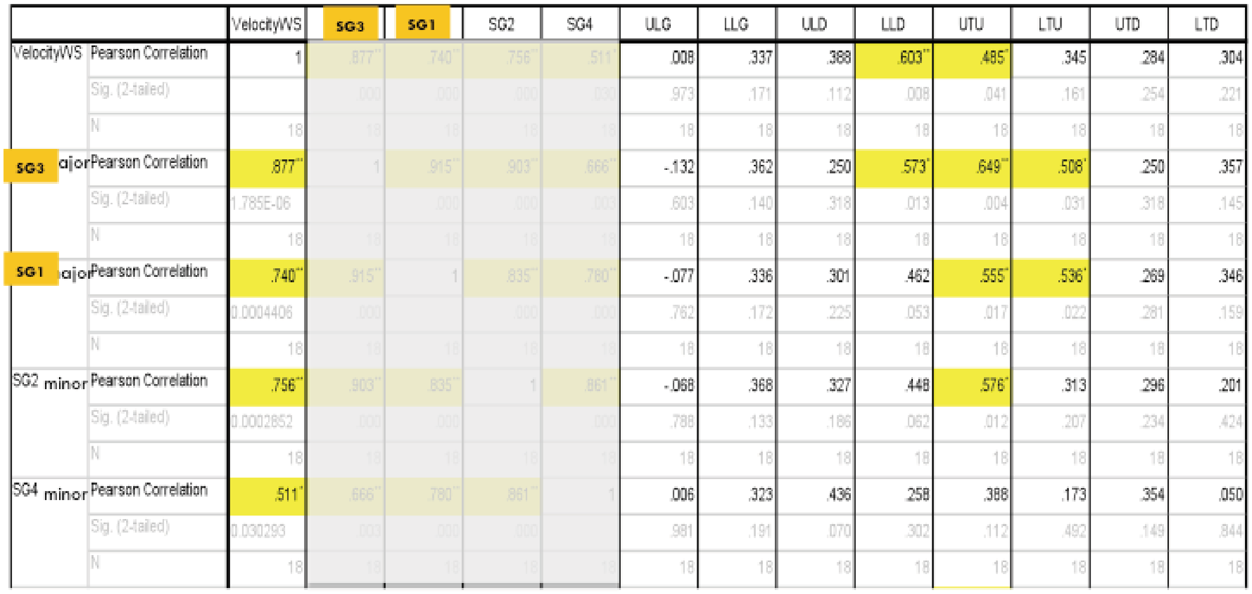
Figure 37 : Five wrist shot trials performed by Subject 3

As seen in SS, no one WS shooting style is completely mutually exclusive from another. Running ANOVA's to compare variables, as well comparing descriptive statistics between groups, leads to further validation of this point. Group 1 shooters see significantly greater UTD forces than group's 2 and 4, but not group 3. There are overlapping traits of these techniques, though. Group 1 was composed of primarily HC players, while group 2 featured only LC players. The other two groups saw a mixture of the shooting calibers.

Correlation Analysis

Correlational analysis, like that of the SS, showed that shot velocity was closely related to levels of strain at each SG (see Table 13 and Figure 38). Shooting velocity was also related closely to force at the LLD, UTU faces. With respect to strain measures in relation to grip face forces, several significant r scores were identified ($p<0.05$); for example, SG3 measures were significantly related to grip face force at LLD, UTU, and LTU.

Table 13 : Correlaion Analysis for Wrist Shots.



		VelocityWS	SG3	SG1	SG2	SG4	ULG	LLG	ULD	LLD	UTU	LTU	UTD	LTD
VelocityWS	Pearson Correlation	1	.877**	.740**	.756**	.511*	.008	.337	.388	.603**	.485*	.345	.284	.304
	Sig. (2-tailed)		.000	.000	.000	.030	.973	.171	.112	.008	.041	.161	.254	.221
	N	18	18	18	18	18	18	18	18	18	18	18	18	18
SG3 ajor	Pearson Correlation	.877**	1	.915**	.903**	.666**	-.132	.362	.250	.573*	.649**	.508*	.250	.357
	Sig. (2-tailed)	1.785E-06		.000	.000	.003	.603	.140	.318	.013	.004	.031	.318	.145
	N	18	18	18	18	18	18	18	18	18	18	18	18	18
SG1 ajor	Pearson Correlation	.740**	.915**	1	.835**	.780**	-.077	.336	.301	.462	.555*	.536*	.269	.346
	Sig. (2-tailed)	0.0004406	.000		.000	.000	.762	.172	.225	.053	.017	.022	.281	.159
	N	18	18	18	18	18	18	18	18	18	18	18	18	18
SG2 minor	Pearson Correlation	.756**	.903**	.835**	1	.861**	-.068	.368	.327	.448	.576*	.313	.296	.201
	Sig. (2-tailed)	0.0002852	.000	.000		.000	.788	.133	.186	.062	.012	.207	.234	.424
	N	18	18	18	18	18	18	18	18	18	18	18	18	18
SG4 minor	Pearson Correlation	.511*	.666**	.780**	.861**	1	.006	.323	.436	.258	.388	.173	.354	.050
	Sig. (2-tailed)	0.030293	.003	.000	.000		.981	.191	.070	.302	.112	.492	.149	.844
	N	18	18	18	18	18	18	18	18	18	18	18	18	18

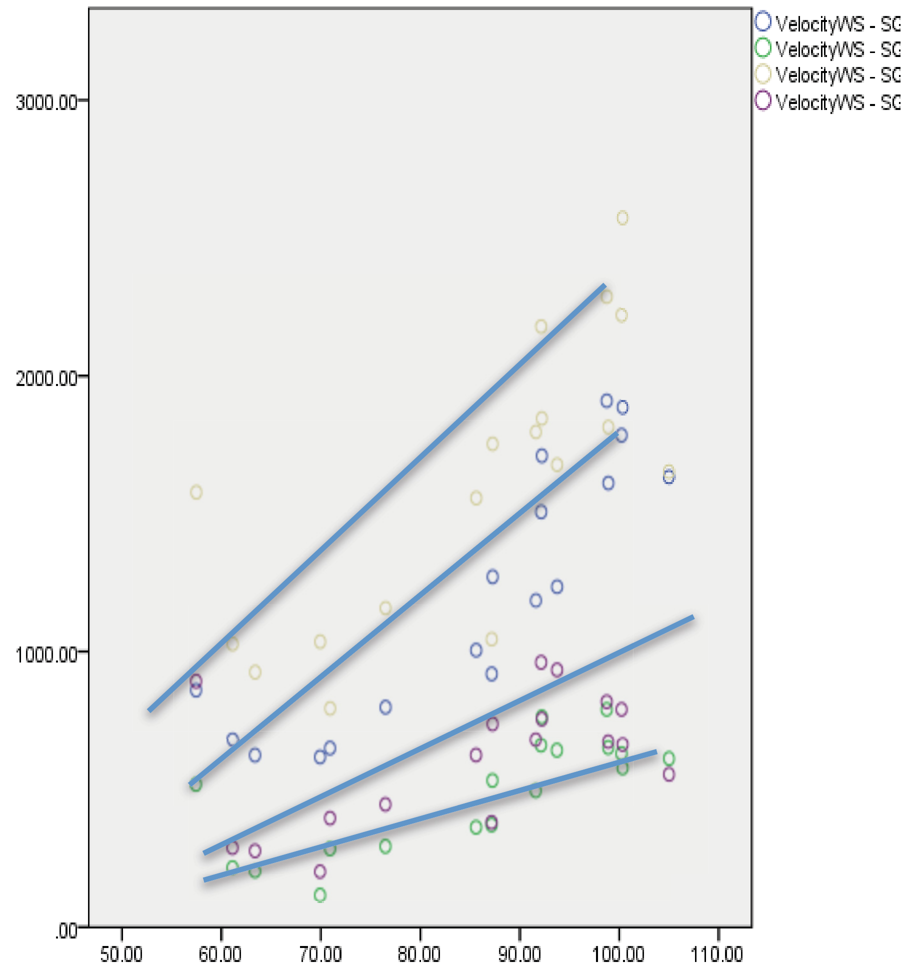


Figure 38 : Shot Velocity (km/h) by Strain (micro µ) for each SG, WS.

Discussion

Like the work by Hannon in 2010, and Zane in 2012, this study saw strain gauges and FSA sensors measure stick strain and hand-stick interface forces for the duration of both SS and WS. Measuring both of these variables concurrently, it was the hope of this researcher to better understand the interaction of the variables in both HC and LC shooters. The observed forces, it should be noted, were not strictly grip forces of the hand created by the fingers and palm. The forces observed also include the forces imparted on the stick by the upper limbs and body as well as the reactive forces of the blade during ice contact (Zane, 2012).

Two cohorts of shooters (HC male and LC Male) executed SS and WS with three sticks of different stiffness rating (77, 87, and 102 flex). Shooting velocities for the HC and LC shooters were somewhat higher than those previously reported for stationary shooting (Hannon, 2010; Pearsall et al., 1999; Pearsall et al., 2007; Roy et al., 1974; Roy et al., 1976; Zane, 2012), but not by a shocking amount. Also, like what was previously reported, player caliber was found to significantly affect shooting velocity in both SS and WS. Velocity was not significantly affected by shaft stiffness for either shot in either caliber group, neither were peak grip forces at the stick-hand interface for either shot type. This is consistent with what was found by Pearsall et al. (1999), Wu et al. (2003), Hannon (2010) and Zane (2012). The findings of Worobets et al. (2006) contradict what was found for WS, but not SS.

Player shooting technique offered a lot of variability to force, strain and time values in this study. While techniques could be grouped, and shooters could repeat their own shots with remarkable consistency, no two shooters executed their shots the exact same way. Technique similarities could be seen between LC and HC shooters the same, enforcing the idea that there is no one to effectively shoot the hockey puck. Many techniques shared aspects of its nature with other shooting techniques. Commonalties seen by shooters and differences between HC and LC are touched upon later in this discussion.

High caliber shooters saw higher levels of stick deflection than low caliber shooters, where the stick models of the lowest flex rating saw the highest degrees of strain, and the highest flex rating stick experienced the lowest level of strain. These findings are in agreement with what was seen by Wu et al. (2003) and Hannon (2010). Though each individual shooter had the choice of distance between their hands for both types of shots, combining all of these shooters into the high and low caliber groups saw the distance between hands for both groups as non-significant, nor was grip strength or body size found to be any different.

Slap shots

As previously noted, HC shooters shot slap shots faster than LC shooters, regardless of stick model used. Strain seen by sticks during SS was unique, and is illustrated in Figure 24. Strain in the major axes witnesses a small peak (backswing) followed by a large, sharp, peak (ice contact to max strain), and then a small negative peak (stick recoil). Strain in the minor axes sees a sharp peak (ice contact to max strain) followed by a dampening sinusoidal pattern (stick recoil). To this researcher's knowledge, this is the first time strain has ever been measured in the minor axis of the hockey stick during shooting tasks. This means that these depictions of stick behavior in the minor axis provide new information and a better understanding of stick behavior during the SS. Also, seeing that peak strain occurs in the minor axis prior to the major axis, and that HC sees greater levels of peak strain, timings provides some insight into one factor that may help separate HC shooters from LC shooters. HC players put greater emphasis not only bending the stick more in the minor axis, they also do it earlier, which helps them achieve greater puck velocities.

When examining the effect of skill level on grip forces during the SS, the LTU, LTD, UTD and UTU faces showed greater forces when HC shooters were shooting rather than LC shooters; the LLD face also typically saw more forces. Despite this, only the LTU, LTD, LLD faces were seen to be significantly different between calibers. This differs from the findings of Zane (2012) who found differences between peak grip force for HC and LC shooting males on every stick face except LTU.

When observing all SS in general, the TU and TD faces, as well as the ULD face, saw the most significant force values during peak strain. These dual hand forces were noted by Zane's (2012) theory of force coupling. In this instance, the LTU forces created the bottom hand are coupled with the large reaction forces at UTU, UTD, and ULD at the top hand (see Figure 37). Together, this force couple both controls the sticks spatial position and create a third ground reaction force. The resulting three point forces create the shaft deflection. The minimal force seen at the lower lag face of the shaft was unexpected. Possible explanations may be related to the stick shaft spatial orientation during initial to mid ground contact wherein the minor axis is not parallel to the shot direction due to the blade's arc path (Lomond et al., 2007). Further, the lower hand may apply the bulk of the force closer to the edge of the LLG face, rather than the center of the face. A conceptual rendering of the respective face force vectors during the shots phases (shaft downswing, bend, recoil) is shown in Figure 39: the approximate magnitudes of these vectors correspond to the general measures observed.

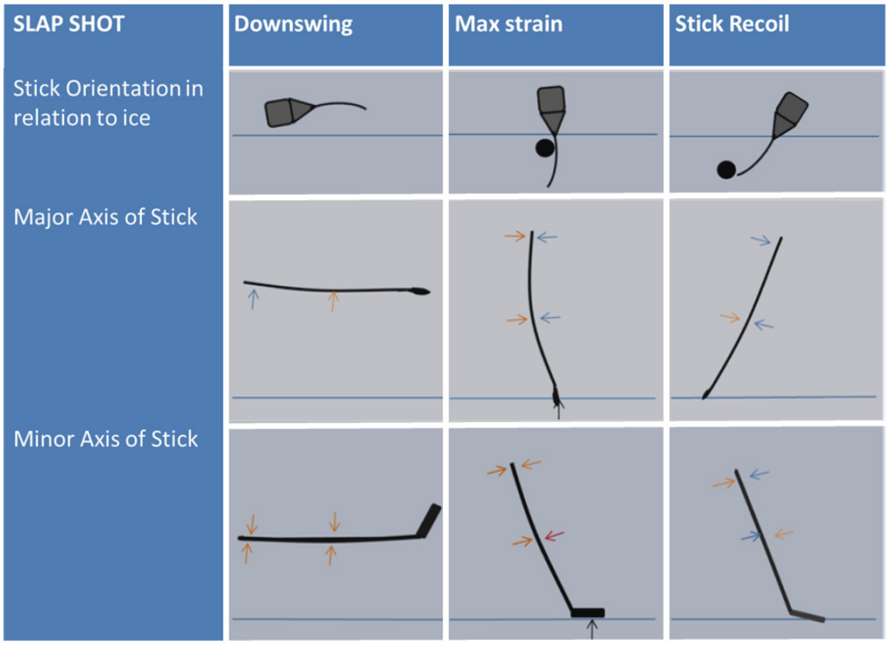


Figure 39 : Common trends when examining the force and strain created by subjects during SS

Taking the correlation analysis into account, the levels of strain at each SG were highly related to the velocities seen with SS. Given previous findings by Hannon (2010), and knowing that HC shooters typically achieved high levels of strain and shot velocity, these findings support previously established hypotheses. High forces seen at the stick faces LLD, LTU, and LTD correlated with higher shot velocities, supporting the findings of Zane (2012). Contrary to prior assumption, stick face forces seen at LLD and LLG did not strongly correlate to higher levels of strain for SG in the Major axes (SG1 and SG3). This implies that the movement of the stick during the shot is not exclusively a back-to-front sweep, and that forces are occurring elsewhere on the stick to create the bend required to propel the puck. Further study is warranted to examine this phenomenon, providing better insight towards the path of the stick through space when shooting.

Wrist shots

Like SS, HC shooters were able to attain higher velocities than LC shooters when performing WS. Dynamic shaft strains were seen during WS (see Figure 34). Strain in the major axes began with a small peak, as the puck begins to be swept by the stick, followed by a steep peak, and a small negative peak. Unlike the SS, which showed strain peaks as visually very sharp and short events, the WS occurs over a longer period of time and is much more gradual and rounded. Strain in the minor axis acts similarly to the major axis, in that strain sees a smooth transition from positive peak to negative peak in recoil. Like in SS, HC players put greater emphasis on not only bending the stick more in the minor axis during WS, but they also do it earlier, which helps achieve greater puck velocities. With significant differences in peak strain between the minor and the major axis between the 77 flex and 87flex stick models and the 102 flex stick model, it is interesting to note there was still no significant difference in shot velocity between sticks.

In terms of grip forces, these measures were generally higher for HC shooters than LC shooters. The UTU face was the only face that showed significantly differences between shooting calibers (F (2, 15) = 5.643, p = .0030). In WS, much like the SS, the TU and TD faces, as well as the ULD face, saw the largest forces during peak strain. This is a function of weight transfer to bend the shaft. Like in the SS, during the WS, large LTU forces at the lower hand were coupled shortly later by with upper hand forces at UTU, UTD, and ULD faces. While a majority of the strain occurs in the major axis, again no significant forces at the LLG stick face were observed. This begs the question of where is the force that is creating this large major axis strain? As way of explanation similar to the SS, the stick shaft during the WS does not move solely linearly through space: off-axis shaft orientation during initial ground contact and torsion created by the drag of the blade. Consequently, a majority of the lower hand force may be closer to the edge of the LLG/LTU faces (that were not detected by the sensor array positioned at the center of the LLG face). Hence, LLG force estimates may be underestimated. Further study with expanded force sensor surface covering is warranted. A conceptual rendering of the respective face force vectors during the shots phases (shaft downswing, bend, recoil) is shown in Figure 40: the approximate magnitudes of these vectors correspond to the general measures observed.

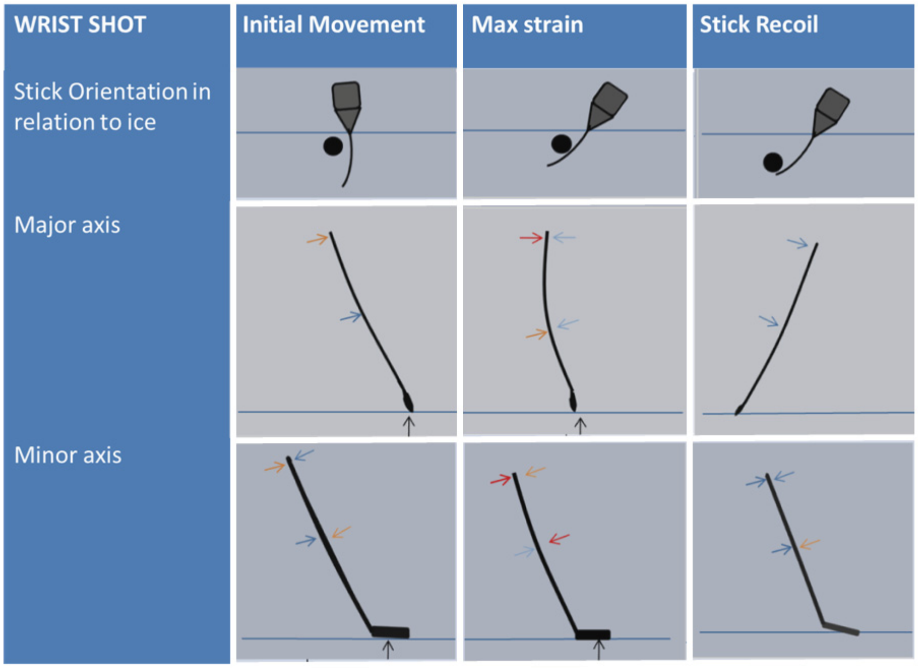


Figure 40: Common trends when examining the force and strain created by subject when taking WS.

From the correlation analysis, the levels of strain at each SG were highly related to the velocity seen with WS, much like SS. Hannon (2010) previously saw that HC shooters typically achieved high levels of strain and shot velocity, and these findings support those previously found. High forces seen at LLD and UTU correlated with shot velocities, supporting the findings of Zane (2012), though fewer grip force faces were directly related to shot velocity. This may be due to differences in shot technique. Stick face forces seen at LLD strongly correlated to higher levels of strain for SG3, though LLG did not. As seen with the SS, this implies that the movement of the stick during the shot is not exclusively a back-to-front sweep through space. As with SS, future study is required in WS to reveal the sticks path through space when shooting, while also examining the grip forces at play.

Conclusions

This study demonstrated that not only is it feasible to measure forces at the hand-stick interface, and measure stick strain during shooting tasks in ice hockey, but also that these technologies can be synchronized, and the relationship between these variables can be observed. Force measures were generally seen as higher for HC shooters than LC shooters. While strain was observed lowest for the sticks of the highest stiffness rating, stiffness rating did not have an effect how observed forces at the hand-stick interface, nor shot velocity.

While grip strength is a strong predictive relationship in regards to shot speed, an equally important indicator of shot performance is the player's caliber and technique, as previously reported by Zane (2012) and Roy et al. (1976). Dynamic grip forces of the upper and lower hands about the stick shaft are not easily predicted. Indeed, different "dynamic force signatures" (or forces seen throughout the process of a shot) produced by individual's own techniques and anthropometrics. Nonetheless, four general grip coupling patterns for each shot type were suggested in the above results. Stemming from the prior work by Hannon (2010) and Zane (2012), this study has provided a unique insight into concurrent bimanual grip forces and the stick shaft deflection about both major and minor axes. In particular, the substantial deflection about the minor axis (and peak flex timing differences from the major axis seen in slap shots) demonstrates that shooting dynamics cannot be simply modeled as a two-dimensional phenomenon. Further study using these measurement techniques should be pursued; for example, to assess other hockey skills from stick handling tasks, to “one-timer’ scenarios and pass reception.

Stick strain was highly related to shot velocity for both WS and SS, as were grip forces at several stick face locations. Stick strain and grip forces were seen to be related at some faces, though it was expected that the relation would be stronger between the forces seen at the lower hand and the strain gauges about the major axis. Future study is required to fully understand the interaction between stick strain and grip forces, due to the dynamic changes of stick orientation during the shooting process in both SS and WS.

In addition, expanded study including full body and stick motion capture would aid in better understanding of the hand-stick interface during shooting. Ultimately, insights provided by these studies can be extended to improve player skill and training development.

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