Whole-body predictors of wrist shot accuracy in ice hockey: A kinematic analysis by way of motion capture

By

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Contents

Abstract

The purpose of this study was to identify joint angular kinematics that correspond to shooting accuracy in the stationary ice hockey wrist shot. Twenty-four subjects participated in this study, each performing 10 successful shots to four shooting targets. An eight-camera infra-red motion capture system (240 Hz), using passive reflective markers, was used to record motion of the joints, hockey stick, and puck throughout the performance of the wrist shot. A multiple regression analysis was carried out to examine whole-body kinematic variables with accuracy scores as the dependent variable. Results indicate that no one body region predominated as a predictor of accuracy across all four shooting targets since the wrist shot's general movement pattern required that one or more of the body's joints modulate its movement amplitude, rate and timing to achieve an accurate outcome. Significant accuracy predictors were identified in the lower limbs, torso and upper limbs. An accurate outcome was associated with the following characteristics: The lower body seemed to provide a stable base for support, but also contributed to initiation of movement in the form of weight transfer towards the intended target. We propose that the trail leg seemed to offset rotational motion that could potentially upset the stability of the system if not properly managed. Additionally, angular kinematics at the pelvis, spine and thorax appeared to orient the trunk such that the upper limbs can optimally function to achieve an accurate outcome, and also undoubtedly contributed to force production. And finally, accuracy was associated with more dynamic use of the lead arm specifically at the wrist and shoulder.

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Abrégé

L'objectif premier de cette étude était d'identifier les mouvements caractéristiques du corps des joueurs de hockey correspondant à la précision de tirs du poignet stationnaire à travers différents niveaux d'habiletés. Un total de vingt-quatre sujets ont fait partie de l'échantillon. Chacun d'eux ont dû réussir correctement dix lancers dans chacune des quatre différentes cibles. La performance des sujets a été évaluée en mesurant la cinématique du corps, du bâton et de la rondelle à l'aide de marqueur réfléchissants qui ont été filmé à l'aide d'un système d'analyse du mouvement composé de huit caméra infrarouge (Vicon®), le tout étant enregistré à 240 Hz. Avec le niveau de précision comme variable dépendante, une analyse de régression multiple a été effectuée avec les variables cinématiques de toutes les articulations. Les résultats ont démontrés qu'il n'y a pas de prédicteurs universels à travers les différentes cibles considérant qu'une ou plusieurs articulations peuvent ajuster leurs vitesses, amplitudes et séquences pour effectuer un lancer précis. Des prédicteurs important ont été identifiés dans les membres inférieurs, le tronc ainsi que dans les membres supérieur. Les membres inférieurs semblent permettent une base de support stable ainsi qu'un transfert de poids efficace en direction de la cible visée. De plus, la jambe arrière permettrait de contrer le momentum angulaire qui pourrait débalancé le système en équilibre. Le déplacement angulaire du tronc (pelvis, thorax et colonne lombaire) permet d'orienter de façon à ce que les membres supérieurs puissent bouger de façon optimale en plus de contribuer à la production de force transmisse à la rondelle. Pour terminer, la précision semble être associée à un contrôle plus dynamique du poignet et de l'épaule du membre supérieur contrôlant le haut du bâton.

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Chapter 1: Introduction

1.0 Introduction

With a player registration count of 545 363 and over 4.5 million people involved in minor hockey across Canada (Hockey Canada, 2007)—excluding several thousand players involved in recreational, summer, and adult leagues—hockey is an integral part of Canadian culture with nearly one sixth of its population directly involved in the sport. The game of ice hockey has evolved considerably since its origins, as a result of notable improvements to protective equipment, rules, facilities, as well as the modern training of athletes.

In ice hockey, the stick is used for controlling the puck position, shooting the puck into the opposing team's net (Villaseñor-Herrera et al., 2004), making or receiving passes, and taking face offs. The stick is also used for defensive purposes such as blocking passes, stick checking, and finally for (illegal) acts such as slashing, tripping, hooking, and cross checking. The two most commonly used shooting techniques in ice hockey are the wrist and slap shots. The wrist shot is generally accepted as the more accurate of the two with typical velocities of 20 m/s (72 km/h) compared to the slap shot at 30 m/s (108 km/h) (Woo et al., 2004). It should be noted that these velocities are dependent on whether or not the shooter is standing still or skating at the time of the shot. With a shorter movement time required, the wrist shot is also more effective for fast execution. Wu et al. (2003) suggested that shooting outcome is influenced by several factors such as skill level, body strength, stick material properties, and ice surface conditions. The wrist shot is without a doubt one of the most important skills in ice hockey as it influences the scoring outcome of numerous games each year. Several studies have investigated stick material properties (Lomond et al, 2007; Worobets et al, 2006; Villaseñor et al, 2004; Wu et al, 2003; Pearsall et al, 1999), but limited research has been done in the area of shooting kinematics; more specifically, quantification of three-dimensional whole-body kinematics. In recent years, two studies have conducted detailed measures of stick and body kinematics. Woo and colleagues (2004) investigated upper body and stick kinematics of 5 elite and 5 recreational hockey players in the stationary slap shot. They found distinct movement sequences displayed by the elite group characterized by maximum angular velocities in the body moving from the core to the extremities, whereas lower caliber shooters lacked this ordered sequence. Michaud-Paquette and colleagues (2009) characterized stick and puck kinematics in wrist shot execution. Notably, they identified important accuracy predictors, such as the changes in pitch and yaw (see operational definitions) and the concurrent stick bend among others. Unlike Woo's study, unknown are the upper limb joint movements and their respective intra-limb and inter-limb coordination patterns (including wrist flexion and wrist [forearm] pronation/supination), which determine stick orientation. In other words, the outstanding question is *what* whole body kinematic variables are adjusted in the wrist shot to bring about appropriate stick orientation and ultimately accurate puck trajectories? Further investigation to determine kinematic behaviors that predict accuracy are relevant and warranted.

1.1 Nature and scope of the problem

In recent years, advancements in technology have allowed researchers to collect reliable kinematic data precisely and efficiently. Despite these remarkable advancements, there is a limited scope of biomechanical ice hockey research available in the literature. Motion capture methods on ice have proven problematic due to difficulties obtaining an adequate field of view and lighting issues, which have made it very difficult to carry out a precise three-dimensional description of on-ice hockey skills (Lafontaine et al, 2007). The use of a controlled laboratory setting provides the opportunity to precisely describe three-dimensional full-body kinematics of the ice hockey wrist shot. In kinematic analysis, we are concerned with the motion characteristics and analysis of motion from a spatial and temporal perspective without regard to the forces producing these motions.

In the present study, subjects performed a shooting protocol on synthetic ice in a laboratory setting, to permit control of camera placement, appropriate lighting, and also reduce the risk of damage to expensive and fragile motion capture equipment. Furthermore, the use of the laboratory setting made collecting data for a larger sample size (24) possible in a time and cost efficient manner. Synthetic ice shares similar properties to real ice but with a higher coefficient of friction (reported μ at ≈ 0.28, Viking® ice) providing a viable alternative to real ice for the purpose of studying shooting tasks.

1.2 Rationale

The primary objective of a wrist shot is to project the puck with maximal velocity and accuracy to score on the opposing goaltender (Michaud-Paquette et al, 2009). With no wind up required, the wrist shot can be released much faster than the slap shot, increasing the probability of deceiving defending players and goaltenders alike. With the increased speed of the game at elite levels, the ability to release the puck with minimum movement time, maximum velocity and accuracy is a highly valuable skill. Although several authors have provided descriptions of whole-body kinematics during the stationary slap shot using both two and three-dimensional methods (Lomond et al, 2007; Woo et al, 2004; Wu et al, 2003; Polano, 2003; Pearsall et al, 1999; Doré and Roy, 1973) little research has been conducted on the wrist shot. To date, no studies have examined whole body kinematics of the wrist shot and how these might influence resulting accuracy outcomes. However, a recent study by Michaud-Paquette and colleagues (2009) identified important kinematic predictors of wrist shot accuracy external to the body. Notable accuracy predictors among these variables were: blade's heel velocity (fig. 1.2), the position of the puck relative to the blade heel, puck release velocity, blade heel velocity, shaft bend, release roll, and changes in blade orientation angles. At the moment of shot release (SR), the puck becomes a projectile in motion. Given the above, and motor control research suggesting that skilled athletes are able to compensate at the end of a task for other shooting parameter variability that may have otherwise led to inaccuracy (Button et al, 2003), we aimed to analyze the angular kinematics of the wrist shot at SR as well as the change in angular kinematics from shot initiation (SI) to SR. Shooting techniques may vary from one subject to the next from SI to SR. Therefore, the main purpose of this study is to identify the common fundamental whole-body kinematic variables that correspond with accurate shooting techniques.

1.3 Objectives and hypotheses of proposed research

More specifically, using a regression analysis, the objective of this study is to identify variables that may predict wrist shot accuracy using three-dimensional whole-body kinematic analysis. A second objective of this research is to extend previous work by Michaud-Paquette and colleagues who characterized the kinematics of stick behaviour as they relate to shooting accuracy in wrist shot execution. This study is the first of its kind to fully investigate whole body kinematics that may predict shooting accuracy for the wrist shot and is exploratory in its nature. Woo et al., (2004), demonstrated specific movement sequencing during execution of the slap shot, and it is anticipated that a similar sequencing may be observed during accurate wrist shot performance. Similarly, given that we witness a bi-pendular motion in the wrist shot as seen in field hockey research by Bretigny and colleagues (2007) and that these segments differ in their contribution to the wrist shot, we anticipate the identification of differing upper-body accuracy predictors from lead to trail side. This bi-pendular motion and the associated segmental accelerations used to produce stick velocity in field hockey relates to similar golf findings discussing the 'summation of speed principle', which suggests that to maximize the speed of the club head at the distal end of the system (Burden et al., 1998), the golf swing should start with movements of more proximal segments. Additionally, Michaud-Paquette et al postulated that greater wrist involvement may be witnessed among the more accurate shooters based on research by Button et al, (2003). Given the above stated, the following hypotheses were put forth:

H1. We expect the kinematic accuracy predictors identified in the upper body will differ from the lead to trail side.

H2. Based on previous research by Woo et al. (2004), it is expected that similar kinematic patterns will be observed in the wrist shot with movements showing proximal to distal organization.

H3. Based on previous findings (Button et al., 2003; Michaud-Paquette et al., 2009), we expect to observe greater wrist involvement in shooters achieving higher accuracy scores.

H4. It is expected that accuracy scores will differ significantly from the bottom targets to the top targets based on research by Michaud-Paquette and Colleagues (2009) who found accuracy scores for the top targets to be approximately 20% lower than those for the bottom targets.

1.4 Limitations and delimitation of the study

Even though there are several advantages associated with in-lab testing, there are inherent limitations associated with the study.

Limitations

1- All experiments were conducted at room temperature (22 to 24°C);
2- Experiments were conducted in a controlled laboratory setting on synthetic ice (the synthetic ice—Viking®— is made up of polyethylene and is lubricated with a silicon spray. The surface shares similar properties to real ice with a higher coefficient of friction);
3- The shooting conditions were not performed under a real game situation;
4- The shooters did not wear hockey gloves in this study due to the chosen marker placement;

The present study is subject to the following delimitations:

Delimitations

1- Only male subjects participated in this study;
2- Only stationary wrist shots were evaluated in this research;
3- One blade pattern was used;
4- The net was set 4m from the puck's initial location;
5- The subjects' wore their own hockey skates;

1.5 Operational Definitions

Events defining the wrist shot

Shot initiation (SI): occurs when the subject's stick begins its forward motion.

Shot release (SR): occurs when the puck's linear acceleration is equal to zero.

Shot end (SE): occurs when the stick blade changes directions in the Y-axis

Phases defining the wrist shot

Blade/puck contact phase (CP): defined by the period of time between SI and SR.

Follow through phase (FT): defined by the period of time between SR and SE.

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

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

Stick shaft: The straight portion of the hockey stick (fig. 1.2).

Toe: the furthermost end of the blade (Figure 1.2, Pearsall and Turcotte, 2007)

Lie: the angle formed between the blade and the shaft when the blade is flat on the ice. A #5 is a lie angle of 45°. Each increment up or down corresponds to a change of 1.5°. Higher numbers indicate a smaller angle between the blade and the shaft, while smaller numbers indicate a larger angle. Lie angles are typically rated on a scale from 4 to 8. As a general guide, lower lie angle sticks are used for players who skate low to the ice and carry the puck out in front whereas lies of 7 and 8 are for players who skate upright and carry the puck close to their skates (fig. 1.2, Pearsall and Turcotte, 2007).

Blade curve (pattern): refers to the shape of the curve in the blade provided during manufacturing, which may be for left-handed or right handed players. (Pearsall and Turcotte, 2007)

Contra side: Refer to the opposite/contra lateral side to the subject shooting side (fig. 3.4) e.g. Right side of the net for a left-handed shooter (Michaud-Paquette et al, 2009)

Ipsi side: Refer to the same/ipsi lateral side as the subjects shooting side (fig. 3.4) e.g. left side of the net for a left-handed shooter (Michaud-Paquette et al, 2009)

Angular orientation and displacement of the blade in the three planes (fig. 1.1)

Yaw: angular rotation around the Z-axis

Pitch: angular rotation around the X-axis

Roll: angular rotation around the Y-axis

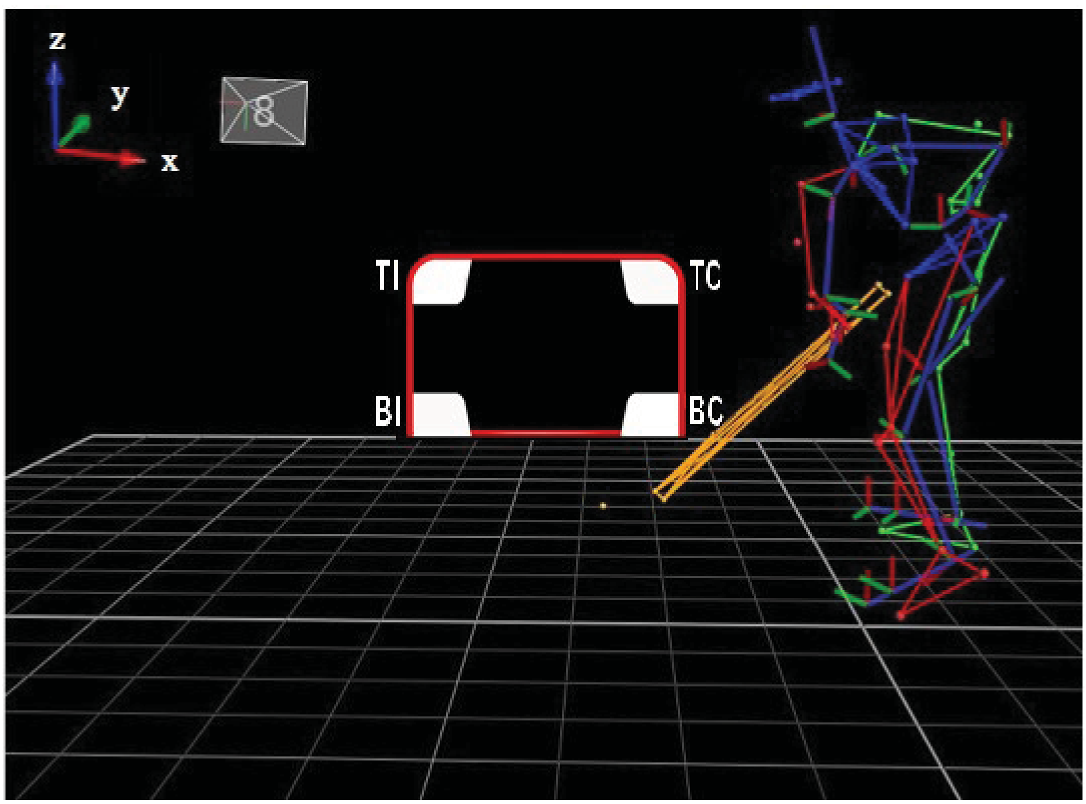


Fig. 1.1: Posterior view of the experimental set up along with the global coordinate system. Targets: TC (top contra), BC (bottom contra), TI (top ipsi), and BI (bottom ipsi) for a left-handed shooter

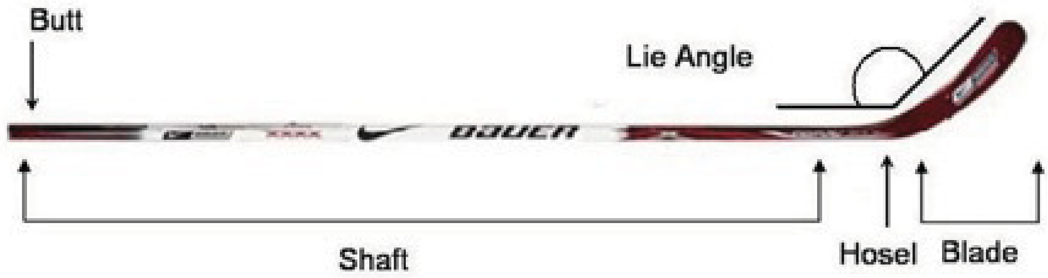


Fig. 1.2: The basic components of a hockey stick

1.6 Contribution to the field

Given the offensive importance of the wrist shot, it will be very beneficial to investigate how accurate players manipulate technical shooting parameters to increase accuracy and ultimately offensive success. Furthermore, it is anticipated that the identification of parameters for accurate shooting mechanics in ice hockey will provide a foundation for future coaching feedback tools. For instance, real time quantification of movement yielding kinematic output parameters may be used to give feedback for proper skill execution. A better understanding of such parameters may also contribute to an increased effectiveness in the performance of the wrist shot and also serve as a building block for future ice hockey research regarding body mechanics. The application of this biomechanical knowledge could be relevant to the innovation of new coaching strategies, strength training methods, as well as ergonomic design and engineering considerations in the manufacturing of ice hockey equipment.

Chapter 2: Review of Literature

2.0 Review of literature

Limited research has been conducted to describe the kinematics of ice hockey shooting skills partly due to technical limitations. The majority of biomechanical ice hockey research, regarding shooting skills, has focused on the slap shot. Despite the wrist shot's prevalence and strategic importance in offensive play, a comprehensive quantitative evaluation of optimal body movement patterns has not been undertaken. In spite of this fact, it is possible to derive insights from kinematic research conducted in sports/skills that share analogous movement patterns such as golf, field hockey, and also ice hockey slap shot research. Therefore, a review of the elements involving kinematic analysis of wrist shot accuracy requires that we explore research of similar nature in ice hockey and in other sports. The following review of literature will examine: The evolution of the hockey equipment with a focus on the hockey stick, important ice hockey shooting skills, previous three-dimensional kinematic research in sport, ice hockey research, and relevant motor control and accuracy findings as they relate to ice hockey shooting kinematics.

2.1 The evolution of hockey equipment

Many changes to ice hockey equipment design have been implemented over the years to enhance performance, protection, and aesthetics (Pearsall et al., 1999). The development of the commercially used hockey stick is believed to have begun with the first nations; the first commercial sticks, made by Mi'kmaq, were made of hornbeam—also called ironwood in a testament to its strength and durability—(Dowbiggin, 2001).

Hockey stick manufacturing has since progressed from solid wood, to two and three-part wood sticks, to fiberglass/wood hybrid sticks, followed by aluminum shafts with blade inserts (1980s), to similar composite shafts (1990s), to the most popular stick in recent years, which is the one-piece composite hockey stick (Pearsall et al., 2007). The curve of the typical hockey stick, in use today, was accidentally discovered by Stan Mikita after an incident in which he broke his stick. He noticed an increased velocity and ability to raise the puck, where subsequently the popularity of the curved blade hockey stick emerged in the mid 1960s and today is standard (Dowbiggin, 2001). These improvements in the engineering of the ice hockey stick have arguably improved manipulation of the puck, increased shooting and passing velocities, and increased precision of these skills. Conversely, the accuracy and ability to execute the backhand shot may be slightly diminished with a curved blade (Michaud-Paquette, 2009).

2.2 Ice hockey skills

Pearsall, Turcotte, and Murphy (2000) proposed that hockey skills include the general movement patterns of skating, stick handling, and checking. These three skill sets, proposed to encompass the physical skills performed in ice hockey, can be divided into subcomponents; within the scope of this study, stick handling and shooting can further be separated into subcategories as seen in figure 2.1. Goaltending skills represent an entirely different category of skills and will not be discussed in this review.

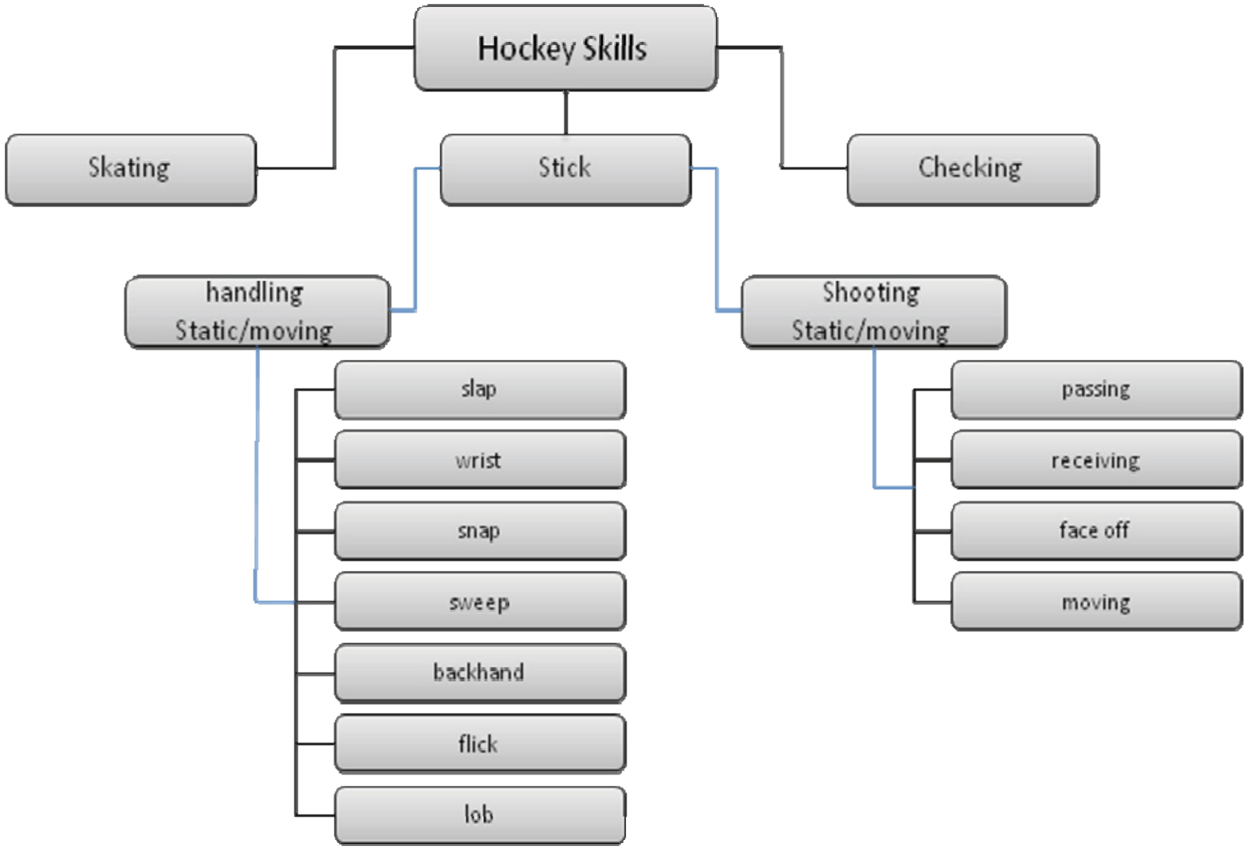


Fig. 2.1: Hockey related skills (adapted from Pearsall et al., 2000)

2.3 Three-dimensional kinematic analysis in sports

Professional sports have become a huge part of North American culture, which has a trickledown effect to competitive and recreational sports alike. Elite professional hockey players often obtain celebrity status, are paid millions of dollars, and are revered by a large fan base. This has increased incentive for young hockey players to make it to the National Hockey League, as well as increased competition among current players to keep their jobs, obtain a lucrative contract, and to win. With the ever expanding drive to gain a competitive edge in sports, the use of motion capture technologies have emerged providing for valid, reliable, and in depth quantification of movement. This type of analysis affords us with the possibility of a better understanding of elite skill performance– the challenge lies in the interpretation of the data. A study by Woo and colleagues (2004) analyzed upper body and stick kinematics of 5 elite and 5 recreational ice hockey players while performing static slap shots on an artificial ice surface. Using an electromagnetic tracking device, fifteen sensors were placed on each subject to record upper-body and stick kinematics. The results indicated significantly faster ($p < 0.05$) blade velocities in the elite group of subjects (29.14 m/s) compared to the recreational group (26.46 m/s). This difference between the groups was explained by dissimilar movement sequences. The elite group displayed a movement sequence characterized by maximal angular velocities in the body moving from the core to the extremities, as well as significantly faster blade velocities. Recreational players displayed different movement patterns with far less temporal organization. This raises an important question: are there distinguishable kinematic differences in the performance of the ice hockey wrist shot across differing skill levels (i.e., high versus low accuracy)?

In the sport of golf, the literature suggests that proficient golfers initiate the backswing by simultaneous rotation of the upper torso, upper extremities, and club away from the address (starting) position, followed by some degree of pelvic rotation (Hogan & Wind, 1957; Myers et al., 2008). Professionals often refer to this independence between the upper torso and pelvic rotation as the “x-factor” or “segmental separation” (McLean & Andrisani, 1997). Using an eight-camera Peak Motus motion capture system and a sampling rate of 200 Hz, Myers et al. (2008) investigated three-dimensional kinematics of upper-torso and pelvic rotation and velocity, as well as torso-pelvic separation and velocity in one hundred recreational golfers. They found that increased separation of the upper-torso and pelvis appear to contribute to increased ball-velocity.

A golf analysis performed by McTeigue et al. (1994) confirmed that the upper body begins rotating away from the flag (target) before the hips in the backswing; yet, at the start of the downswing, the hips began rotating back towards the flag before the upper body followed by the club. These findings concur with the 'summation of speed principle', which states that, to maximize the speed of the club head at the distal end of the system, the golf swing should start with movements of more proximal segments (Burden et al., 1998). This principle may tend to be more variable in the sequencing of movements of the wrist shot in a game situation since its performance may be taken from a variety of start positions with the shooter's hips and shoulders facing differing locations. Therefore other methods to gain accuracy and velocity may be present in the wrist shot. However, in the current study, subjects were delimited to shooting at a four targets from the same shot location repeatedly, increasing the possibility of witnessing consistent techniques in sequential events.

In the sport of ice hockey, the relative position, distance, and height of the shooting targets are rarely identical, along with the added challenge of moving obstacles that may impede attempts to score. In contrast to hockey, given the repetitive nature of the golf swing and the closed environment in which this movement takes place, advancements in motion capture have afforded golf researchers the ability to effectively capture the entire motion of the golf swing. Although the impact duration and projectile vary considerably from hockey to golf—wrist shot impact duration between stick and puck was found to be ~180 ms as compared to the impact duration in golf between the club and the ball at ~10 ms (Michaud Paquette et al., 2009) — we can draw reasonable comparisons when it comes to the importance of the club/blade orientation and the resulting trajectory of the projectile. Williams and Sih (2002) investigated the clubface orientation and impact location during the golf swing. Similar to the blade reference orientation of the present study (pitch, roll, and yaw) the variables/terms loft, tilt and open or closing of the clubface are often used in golf. Twenty-eight right-handed golfers, with handicaps ranging from 0 to 36 performed 14 shots with a driver and a 5-iron. Trials were captured using three motion analysis video cameras (200 Hz), and coordinates of the clubface were calculated using direct linear transform. The results suggested the importance of traveling direction of the clubface, the orientation angles of the clubface relative to its traveling direction, and the frictional interaction of the clubface with the ball during impact. Not surprisingly, subjects with high variability of clubface orientation and impact location on the clubface were likely to show high inconsistency in shot direction and spin. Michaud-Paquette and colleagues (2009) concluded that, contrary to the short impact time in a golf shot, the puck is not impacted so much as it is guided forward by means of steering with the stick's shaft and cradling in the blade's concave front profile. This presumably allows increased time for perceptual feedback, and ultimately corrective measures to accurately guide the puck to the intended target. To put accuracy into perspective, when performing the wrist shot 4m from the target (0.35m x 045 m), the window of error in blade orientation was found to be ±2.85° in the yaw and ±2.5° in the pitch (fig. 2.2) Michaud-Paquette et al. (2009)

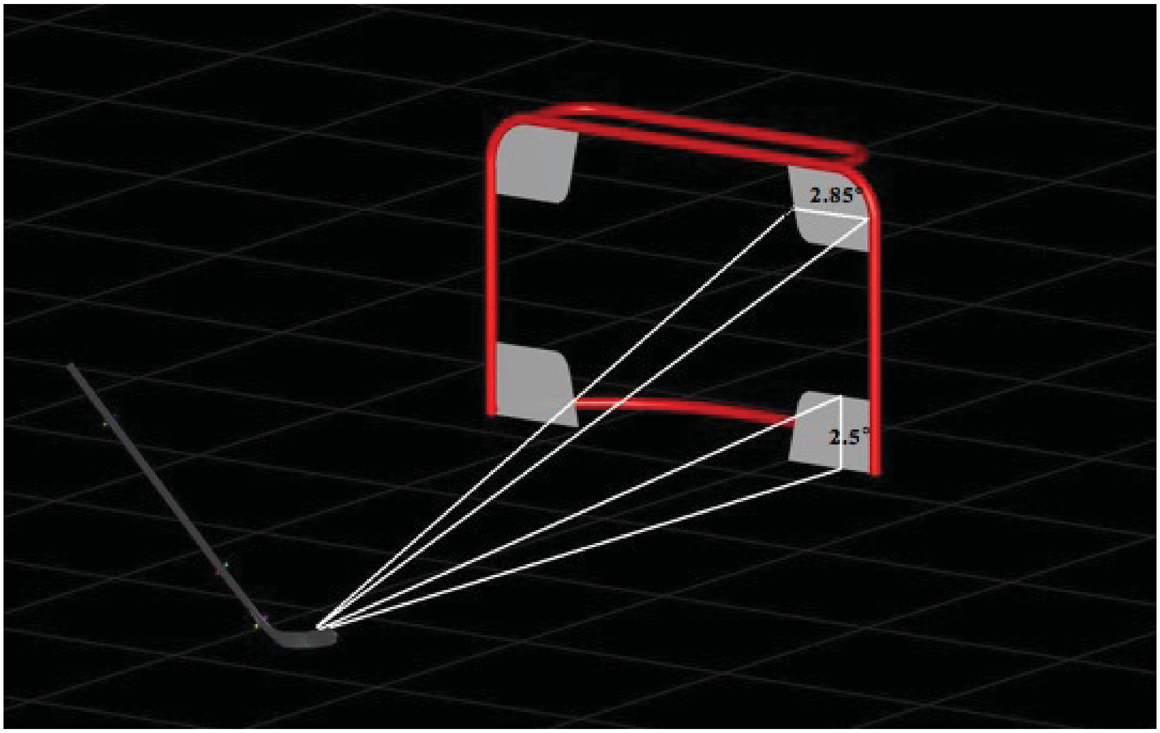


Fig. 2.2: Pitch and yaw margin of error for hitting an accuracy target from 4m (adapted from Michaud-Paquette et al., 2009)

In another example of analogous movements, a field hockey study compared the classic drive and the short grip drive techniques among expert female subjects (N=10) with the use of a five camera motion capture system (Bretigny et al., 2007). The results indicated a shorter duration and amplitude in the short grip drive coupled with inter-limb dissociation on the left side in both shot techniques, whereas the right side was in-phase (note that all field hockey sticks are right handed). The literature describes the coordination of the upper-body limbs as a succession of segmental accelerations, proceeding from the most proximal to the most distal and serving to maximize the stick speed at ball impact (Faque et al., 1987; Bretigny et al., 2007).

Although unknown at this time, it is reasonable to expect that the torso involvement, pelvic and torso rotation / separation, as well as time sequencing of segmental accelerations may be important components of an effective wrist shot and consequently important components of shooting accuracy since the gross movement patterns are comparable in nature to the above mentioned skills. Henceforth, we wish to investigate if these variables may contribute to the accuracy of an ice hockey wrist shot.

2.4 Hockey stick properties

If we recognize that the hockey stick is used as a passive tool to propel the puck, we can view the stick as a mechanical energy reservoir (Minetti, 2004) during shooting tasks where, if used properly, it acts in a 'catapult' or cantilever like fashion. Villaseñor-Herrera et al. (2004) stated that the stick swing energy is converted in part into elastic potential energy within the stick's shaft and continues during the blade-puck contact phase (CP) in the slap shot (fig. 2.3). As the stick shaft subsequently unbends (i.e. recoil), the elastic potential energy of the stick is converted back into kinetic energy, which is transmitted in part or in whole to the puck and gives additional impulse to propel the puck. Accordingly, the stick elastic (bend) energy was strongly related with the final puck velocity in the slap shots taken in this study. These physical principles also hold true in the wrist shot, yet in a slightly different manner.

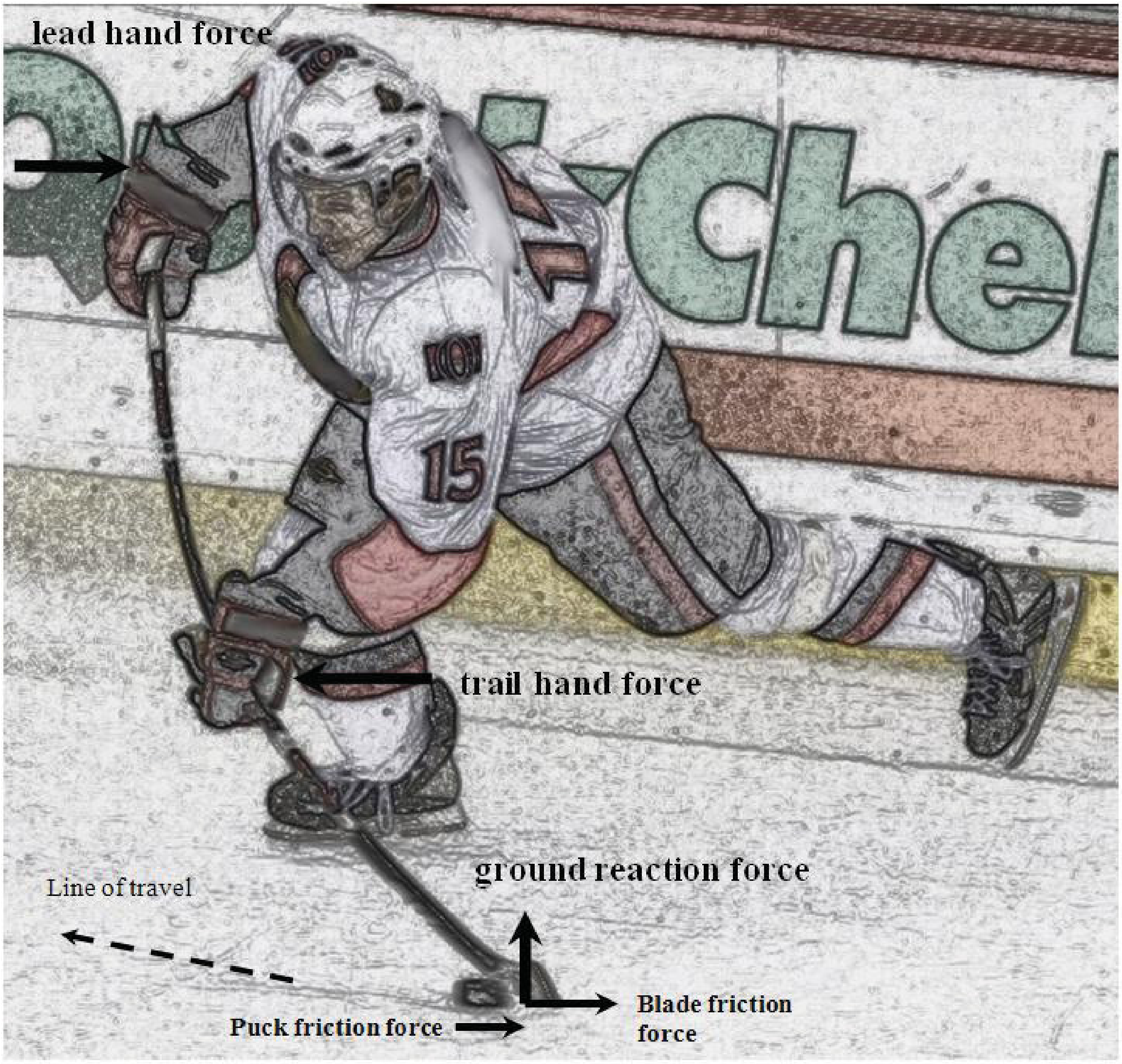


Fig. 2.3: Main external forces involved in ice hockey shot (adapted from Villaseñor-Herrera, 2004)

A study examining the shaft stiffness and its effect on shot velocity during a slap shot yielded results indicating that although lower shaft stiffness elicited significant advantages with respect to shot velocity, the subject characteristics are more important in determining shot velocity than the stick characteristics (Pearsall et al., 1999). In this study, six elite male ice hockey players performed slap shots on a synthetic ice surface with four sticks of different shaft stiffness designated as medium (13 KNm^{-1}), stiff (16 KNm^{-1}), extra (17 KNm^{-1}), and pro stiff (19 KNm^{-1}). The mechanics of the slap shot were evaluated by recording initial ground reaction forces and stick deformation from high-speed filming and puck velocity from a radar gun. With markers along the shaft of the hockey stick, kinematics were obtained by digitizing marker locations with Ariel Performance Analysis System™.

A similar study by Worobets and colleagues (2006), further investigated the relationship between shaft stiffness and puck speed with mechanical energy considerations in the slap shot and wrist shot. Thirty composite hockey sticks were subjected to mechanical cantilever bend testing to determine the shaft stiffness of each stick. Eight of these thirty sticks were chosen in the sample and tested with five varsity hockey players. Eight infra-red high-speed digital video cameras (480 Hz) recorded slap shot and wrist shot testing. For the wrist shot, puck velocities were significantly influenced by shaft stiffness. Generally speaking, more flexible sticks were able to store more elastic energy for subsequent transfer to the puck resulting in increased wrist shot velocities; however, stiffness only explained half the variance in wrist shot puck velocities ($r^2 = 0.52$). This emphasizes the evident importance of the athletes' manipulation of biomechanical variables in shooting. In addition, the stored elastic energy in the shaft was inversely related to stiffness properties. Conversely, Worobets and colleagues found shaft stiffness to have a no significant influence on puck speeds in the slap shot.

Lomond et al. (2007) investigated three-dimensional movement profile of the blade during stationary slap shot as a function of player skill level. In this study, performances were evaluated by simultaneous capture of the stick's lower shaft and blade with high-speed video (1000 Hz), the time of stick-ground contact with two uniaxial forceplates, and time of blade-puck contact with a uniaxial accelerometer mounted in the puck. Looking at temporal events of the slap shot, results indicated a "rocker-phase" in which a clear tendency to load the blade from the toe to the heel occurred in the elite group. Also, the elite group demonstrated a significantly longer ground contact phase. This is consistent with Woo's study (2004), where elite players performed the typical shot motion with greater horizontal translation towards the target than recreational players. Thus, elite players have the opportunity for a longer blade-puck contact time during the slap shot (Villaseñor-Herrera et al. 2004).

2.5 Motor control and accuracy

In ice hockey, the ability to shoot the puck with optimal velocity and accuracy is a decisive factor in the overall performance of an ice hockey player (Hoerner, 1989). A shooter can be very accurate, but without the supporting velocity will have little chance of beating an elite goaltender. With that said, the speed-accuracy trade-off proposes, with respect to Fitts' law, that accuracy is compromised when the skill requires rapid execution (Sachalikidis & Salter, 2007; Magill, 2001), and conversely, that speed is sacrificed when accuracy of a skill is the focus. More specifically, Fitts' law takes into account the time needed to acquire the target, the width of the target, and the distance to the target, along with logarithmically related spatial error (Fitts, 1954). Unknown are the applications of this law to this study where an implement (the hockey stick) is used yielding a more complex system. Given the above, ice hockey players must find a way to optimally maximize velocity and decrease movement time, in many instances to get a shot on net, while attempting to be accurate. This is a common challenge in elite sport with competing tasks. Furthermore, many tasks in which accuracy of a skill is the primary goal, humans tend to show increasing constraints (i.e. reduced movement) over the number of joints recruited (i.e. degrees of freedom) and their respective movements through practice (Button et al. 2003).

Investigating movement variability in basketball free-throws, Button and colleagues found that experienced shooters showed patterns with greater joint involvement from the elbow and wrist joints, but with high intertrial movement consistency. Hung and colleagues (2008) proposed that any change in timing or amplitude of one joint motion (in a motion incorporating several joints) relative to the others would result in a different pattern of joint coordination. These findings suggest that skilled athletes in a wide variety of tasks are able to compensate at the end of their motion for other parameters, occurring early in a discrete skill execution that may have otherwise led to inaccuracy. In addition, Button and colleagues stated that greater wrist involvement in experienced players was evident and resulted in improved shooting accuracy in the basketball free throw. Given the evident importance of the wrists in the ice hockey wrist shot, special attention should be directed to investigating whether or not similar differences / adaptations are seen in ice hockey players as they develop their shooting technique.

A 2008 study by Hung et al. sampled six novice Frisbee players to examine intrinsic shape and variability of end point path in the learning of a multi-joint throwing task. In accordance with previous research (Gentile, 1998; Hikosaka, 2002), Hung and colleagues found that performers rapidly develop a movement topology to achieve the task goal in the early stage of learning while efficient dynamic control develops more gradually and does not become evident until the later stages of skill learning.

2.6 The wrist shot

In the wrist shot — where the hockey stick is used as a passive tool to amplify power as well as to control, manipulate, and propel the puck — the stick blade begins in contact with the puck, and then the stick is moved forward in a pushing action to propel the puck (Wu et al., 2003). This shot is terminated by a vigorous pronation of the wrist at the trail arm, with the hand situated near the mid-point of the shaft; and a backward, dynamically stabilizing movement of the lead hand, situated at the knob of the stick (Naud and Holt, 1975). Naud and Holt (1975) investigated the contact and release points of the slap and wrist shots, in two former professional hockey players, with the use of a high speed camera at 200 Hz. In order to examine these points, the blade of the hockey stick was divided into 10 equal parts ranging numerically from -5 to 5 with the center of the blade being the 0 point. In the wrist shot, they found the contact point (calculated at the center of the puck) occurring near the heel, and the release point near the toe with an average length of travel equal to 0.21m compared to the slap shot where the contact point was often near the center of the blade with the release point occurring at the toe and a 0.15m average length of travel. These findings may seem trivial; however, they relate strongly to accuracy, blade-puck contact time, and perceptual feedback believed to be present in the wrist shot as compared to the slap shot.

From a strength and conditioning perspective, Emmert (1984) provided a qualitative description of the slap shot. He divided the slap shot into three distinct phases:

backswing, action (downswing, preload, and load), and the follow through phase. Emmert identified the trail arm to be the one providing the power to the slap shot, and the lead arm to be the stabilizer. He also stressed the importance of core strength in the trunk muscles and highlighted the action of muscles such as the anterior deltoid, pectoralis major, triceps, latissimus dorsi, external and internal obliques of the trail side in the CP. Examining the wrist shot in a simplistic manner, it is composed of the action, puck release, and follow through phases (slap shot components), eliminating the back and down swing components; therefore, it is reasonable to assume that the muscle groups used are very similar, if not the same.

Table 2.1: Summary of puck velocities [km/h (mph)] reported in previous research (adapted from Pearsall et al, 2000)

				Wrist	
Study	Method	Velocity	Age	Skate	Standing
Alexander et al. 1963	Ballistic	Impact	Adult	117 (73)	97 (60)
Alexander et al. 1964	Ballistic	Impact	Varsity	114 (71)	
Cotton 1966			Adult	90 (56)	81 (50)
Furlong 1968	Stop Watch	Avg	Pro's Adult	163 (102)	
Chau et al. 1973	Cine	Instant	Junior B	143 (99)	132 (92)
Roy et al. 1974	Cine	Avg	Pee-Wee	81 (50)	64 (40)

Table 2.1 provides a summary of early attempts at analyzing shooting mechanics via various methods as outlined above. Testing thirty players, Alexander et al, (1963) recorded slap and wrist shot velocities from a stationary stance as well as in stride; they found a low correlation between static grip strength and the speed of the shot, suggesting that other variables are likely to have a stronger influence on shooting outcome such as the subject's technique or perhaps strength of other muscle groups. A separate study by Alexander et al, (1964) recorded four players performing the skating slap shot with the use of a high-speed camera. The results indicated that a resistance training emphasizing

the upper body strength (i.e., muscle groups believed to be important to both the wrist and slap shots—muscles of the hand, arm, and shoulders) resulted in an increased mean shot velocity in comparison to control subjects. Cotton (1966) found higher average velocities for the wrist and slap shots of 90 and 100 km/h, respectively when the subjects were skating. Using manual stop watches, Furlong (1968) found that professional players recorded greater velocities for skating wrist and slap shots—164 km/h and 174 km/h (Pearsall et al, 2000). Chau et al, (1973) collected velocity data of Junior B hockey players with the use of two high-speed video cameras (400 Hz and 750 to 1000 Hz) to record skating and standing wrist shot velocities. Finally, Roy et al, (1974) also used high-speed cinematography (200 to 500 Hz) to calculate puck speeds for the wrist and slap shots skating and standing. Not surprisingly, table 2.1confirms that velocity values are considerably lower when the subjects shoot from a standing position. These increased values can most likely be attributed to the transfer of kinetic energy from the player to the stick, and ultimately to the puck.

Finally, one of the primary objectives of this study is to extend the findings of Michaud-Paquette and colleagues (2009), who investigated the three-dimensional movement patterns of the ice hockey stick and puck during the performance of the wrist shot in relation to accuracy with the use of a six-camera, Vicon Mx system (Vicon®). Twenty-five healthy male subjects were tested in this study. The research group found accuracy scores for the top targets to be approximately 20% lower than those for the bottom targets. This was attributed to the higher difficulty of a three-dimensional trajectory required when shooting at the top-corners as opposed to the bottom-corners, in which case Michaud-Paquette stated the players could hit the targets by sliding the puck along the ice surface. This study also shed light on important stick and puck predictors of accuracy in the wrist shot: For the bottom corners, the principle predictors were the blade's heel velocity and the position of the puck relative to the blade heel, which explained 36% and 40% of the variance in overall accuracy using multiple regression analysis. For the top corners, puck release velocity, blade heel velocity, shaft bend, release roll, and changes in blade orientation angles (for pitch and yaw) significantly predicted accuracy. These six parameters explained 76% of the variance related to shooting accuracy for the top corners. Furthermore, in an effort to unambiguously refer to angular kinematic stick orientations in which ice hockey player must account for, Michaud-Paquette et al., (2009) proposed pitch, roll, and yaw to correspond to rotation about the X, Y, and Z axes respectively (fig. 2.4). This reference system of stick blade orientation was adopted in the current study.

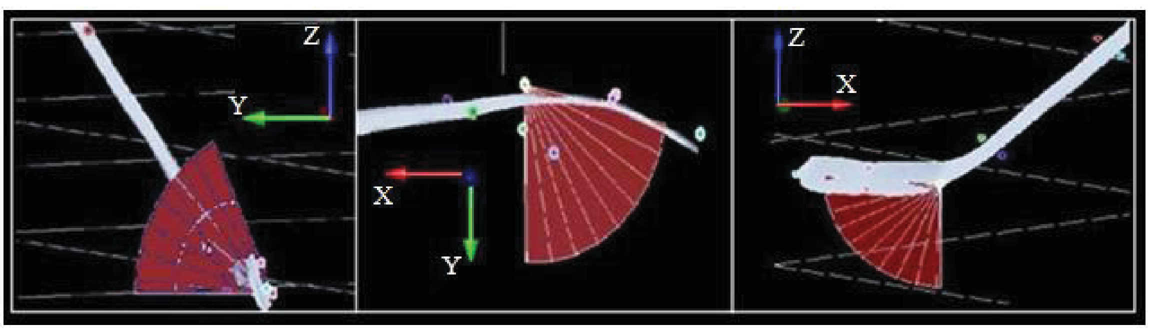


Fig. 2.4: Angular orientation and displacement of the blade in the three planes: Pitch, Yaw, and Roll respectively (adapted from Michaud-Paquette et al. 2009)

Given the research highlighted in this chapter, it is apparent that various parameters, both internal and external to the body, influence the accuracy outcome of a wrist shot. The results of Michaud Paquette et al (2009) and the fact that the hockey stick is the end-effector in the wrist shot, suggest that the stick blade orientation is a strong predictor of puck trajectory. However, given that the body is the actuator of movement, it is necessary to conduct a whole body kinematic analysis during wrist shot execution to determine how the shooter behaves to bring about changes in orientation of the stick blade that would result in accurate puck trajectories.

Chapter 3: Methods

3.1 Test Sticks

Two one piece carbon-fibre, composite Bauer Vapor XXXX (Bauer Hockey Inc, St-Jérome, Canada) hockey sticks with a P92 blade and an 87 flex shaft were used in the testing protocol. Both sticks were instrumented with six reflective markers (9mm) (Vicon, Oxford, UK) along the shaft (fig. 3.1). A layer of blue masking tape was used to cover the stick shaft to avoid undesirable reflection of the stick in motion capture. For ease of reference, the markers were assigned numbers 1 through 6 beginning at the superior end of the shaft.

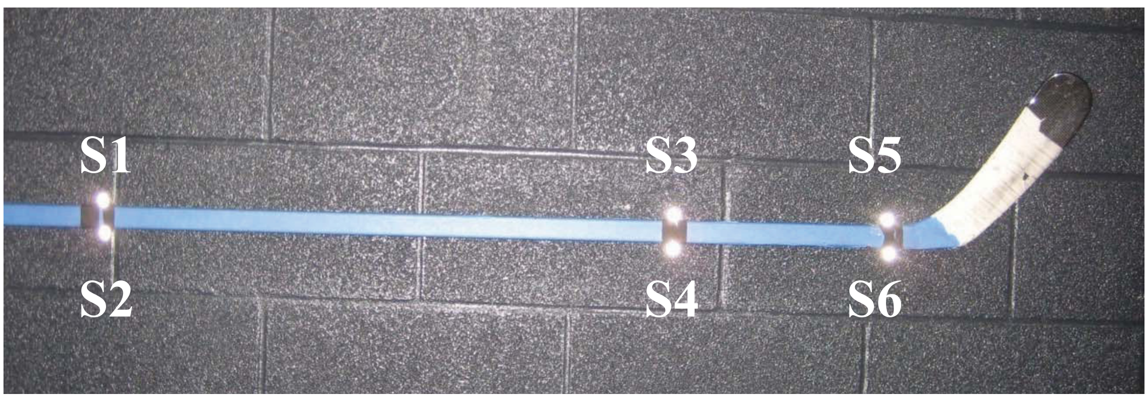


Fig. 3.1: Photograph of the left handed stick used for in experimental testing, with all six reflective stick markers visible

3.2 Subjects

A sample of twenty-four subjects participated in this study. Young, healthy male subjects were recruited representing a cross-section of hockey players ranging from high accuracy (HA) to low accuracy (LA) shooters. At the time of testing, subjects did not present any physical injuries that could prevent them from performing the proposed protocol. Fifteen subjects were right handed shooters and ten were left handed. All 3D data for right-handed shooters were subsequently transformed to left-handed data to facilitate data comparison and analysis. Subjects had levels of ice hockey experience varying from recreational to university (Canadian Interuniversity Sport –CIS), as well as professional. All subjects signed a consent form prior to participation and agreed to do so as volunteer participants. Ethical approval for this study was renewed from the McGill University's ethics committee (REB #713-1006—Appendix II).

3.3 Testing apparatus

An eight-camera, Vicon Mx system (Vicon®, Oxford, UK) was used to record kinematic data. The cameras were placed on tripods as well as wall mounted in fixed locations around the experimental setup in such a way that the whole body, stick, and puck kinematics were suitably captured (fig. 3.3). The camera configuration was chosen to minimize marker obstruction in data capturing (i.e. at least two cameras must record the marker positions in each frame), as well as to avoid equipment damage due to threat of errant pucks. A frame rate of 240 Hz was determined to have the appropriate temporal resolution to capture the movement speed of reflective markers on the subject, stick, and puck; this frame rate was based primarily on previous wrist shot accuracy research (Michaud-Paquette et al., 2009). The experimental protocol took place in the McGill biomechanics laboratory on a synthetic (Viking®, Toronto, Canada) ice surface of $60.8m^2$ as subsequently presented in figure 6 a. Four targets (each 0.3m x 0.3m) were framed by a durable wood surface covering the hockey net (figure 3.4). One reflective marker was fastened to the puck so that its trajectory and velocity could be obtained (fig 3.2). Since the main focus of this research was whole-body kinematics, a modified marker configuration was chosen, based on Michaud-Paquette et al's. study (2009), to record fundamental stick kinematics while avoiding unnecessary processing time.

Fig. 3.2: A hockey puck with a reflective marker

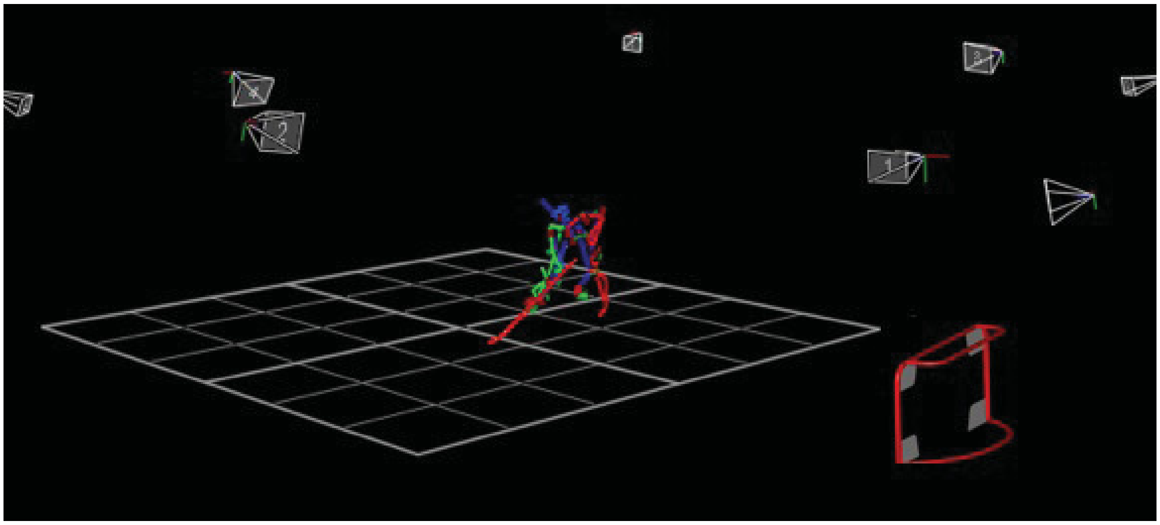


Fig. 3.3: A Vicon image of a subject within the experimental camera set up

3.4 Testing Protocol

3.4.1 Pre-testing measurement

Initially, each subject met the research team, then read and signed a consent form agreeing to the terms of participation. During this time, the subject had the opportunity to address any questions or concerns with the primary researcher. Prior to testing, the subject was outfitted with tight fitting spandex pants to permit proper marker placement, a constant marker position throughout trials, and thus minimizing shifting of markers. Anthropometric measurements of each subject were recorded as input for ensuing Vicon® Plug-in-Gait™ calculations. The measurements taken were: leg length, knee width, ankle width, shoulder offset, elbow width, wrist width, hand width, height, and mass. Furthermore, grip strength data for each hand was compiled to determine the correlation between accuracy and the shooter's grip strength.

3.4.2 System calibration

Prior to each capturing session, all eight Vicon® cameras were calibrated in order to set the system's origin, and to optimize strobe intensity and resolution of each camera. The capture area was dynamically calibrated using a 5 marker Wand & L-Frame and was accepted if the residual error was under 0.2mm. The three-dimensional origin was set using the Ergo Cal L-Frame (9mm) to determine the floor plane orientation. The subjects then performed a "T-pose", and were statically calibrated such that a three-dimensional body model could be reconstructed in Vicon Nexus 1.3 (Vicon®) prior to experimental tasks. A dynamic calibration ensued with the subject producing motion at each joint prior to beginning the experimental tasks. These procedures vastly improved auto labeling (i.e. Nexus software automatically attributes detected markers to specific body model points without manual intervention from the researcher) and dramatically reduced processing time.

3.4.3 Experimental task

The puck's starting position was set 4m from the shooting targets; the starting positions for all trials were consistent according to the subject's handedness (figure 3.4). In communications with the subject, these targets were referred to as top left, top right, bottom left, and bottom right in reference to where the subject was standing. Fourteen mm passive reflective markers were placed on the subject according to the Vicon® Plug-in-Gait™ marker placement (Appendix I). The subjects wore their own skates, no hockey gloves, and were provided an instrumented hockey stick, corresponding to their handedness. One of the four targets was identified for the shooter to aim at prior to each shot, and the order of target identification was randomized. The subjects were asked to perform ten successful shots with a maximum of twenty attempts per target to establish an accuracy score, which was defined by equation 3.1. A successful trial consisted of a wrist shot that passed through the identified accuracy target. A member of the research team tabulated and categorized each shot as accurate or non-accurate (i.e. puck passed within or missed target). The subject was verbally instructed to start from a comfortable position with shoulders perpendicular to the net and attempt to hit the target as many times as possible in the specified protocol with near maximal velocity as though attempting to beat a goaltender. Additionally, the subjects were told to only "draw the puck" in the forward and/or lateral direction in each trial.

Accuracy % = (# successful shot) / # shots)*100 equ. (3.1)

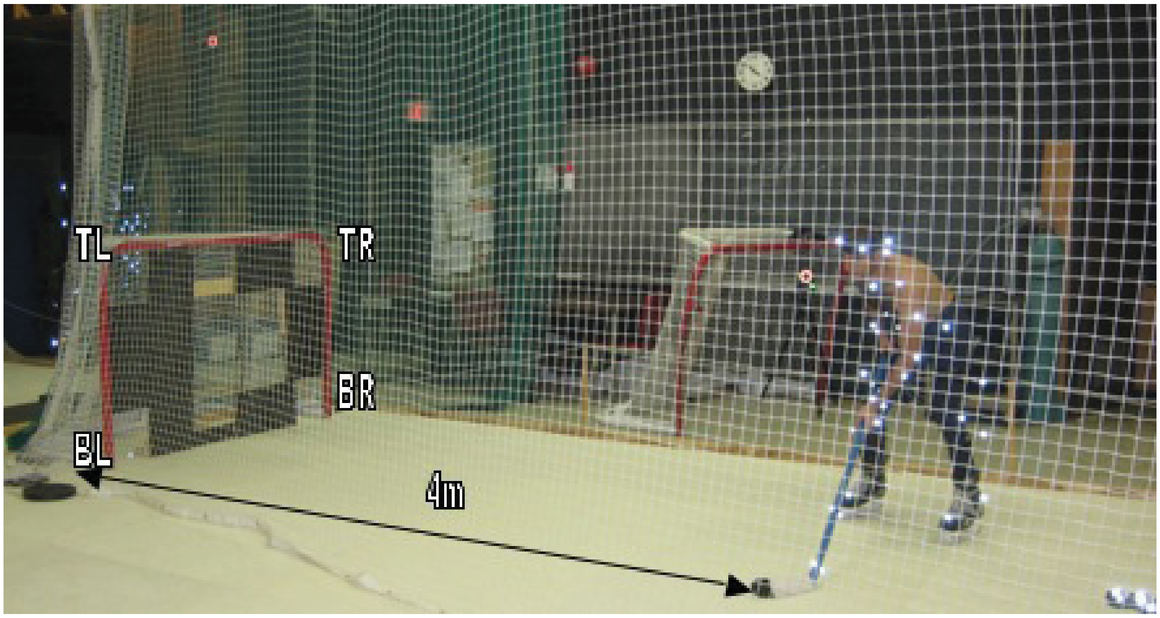


Fig. 3.4: Experimental set up for testing in the McGill Biomechanics laboratory. Accuracy targets, top left (TL / TI) bottom left (BL / BI), top right (TR / TC), and bottom right (BR / BC), are shown each measuring 0.3m x 0.3m

3.5 Data Processing

Reconstructed three-dimensional coordinates of all reflective markers were recorded using Vicon® Nexus 1.3. Data were then exported into Vicon® IQ 2.5 to obtain three-dimensional spatial coordinates for the whole-body, stick, and puck. The recorded spatial coordinates were subsequently used to calculate relative segment orientation angles as well as global coordinate orientation angles. Calculations and marker placement were chosen based on previous research performed in the McGill Biomechanics laboratory (Michaud-Paquette et al, 2009; Dixon et al, 2008). When a marker was not seen by at least two cameras in any frame due to convergence of reflective markers or missing data in the volume space, gaps were interpolated with a cubic spline when smaller than 20 frames. Once all trials were properly labeled, the resulting C3D files were used to calculate specified Plug-in-Gait™ angular output. C3D files were then converted into structured arrays to allow efficient processing of three-dimensional data in Matlab® (version R2007b) (MathWorks Inc., Natick, MA, USA) software. Shot initiation (SI) was recognized when the puck moved in the forward direction, the shot release was calculated at the moment where the puck's maximum velocity was reached (signifying cessation of external contact to the puck), and the shot end was calculated as the point where the linear velocity of the stick changed directions in the y-axis.

3.6 Data analysis

3.6.1 Angle and velocity measures

From the raw marker coordinates recorded, the Plug-in-Gait model calculates relative angular displacements at each joint with respect to a floating coordinate system defined at each joint center with respect to a local coordinate system. These angular displacements are expressed in X, Y, and Z components, and were calculated for all IV's as specified in table 1.1. Supplementary to these joint angles, the Plug-in-Gait model also calculates angular displacements of the thorax, spine, and head as segments. Global angular orientation of the pelvis and shoulder were calculated with respect to the net's plane in Matlab®. A global orientation of 0° at the pelvis or shoulders would correspond to the subject facing perfectly perpendicular to the net (fig. 3.5), and an angle of 90° would correspond to the subject facing the net (fig. 3.6). Furthermore, due to the complexity of the shoulder girdle movements and its anticipated importance in accuracy, shoulder angles were calculated in relation to the thorax orientation using a manually built algorithm (Matlab®).

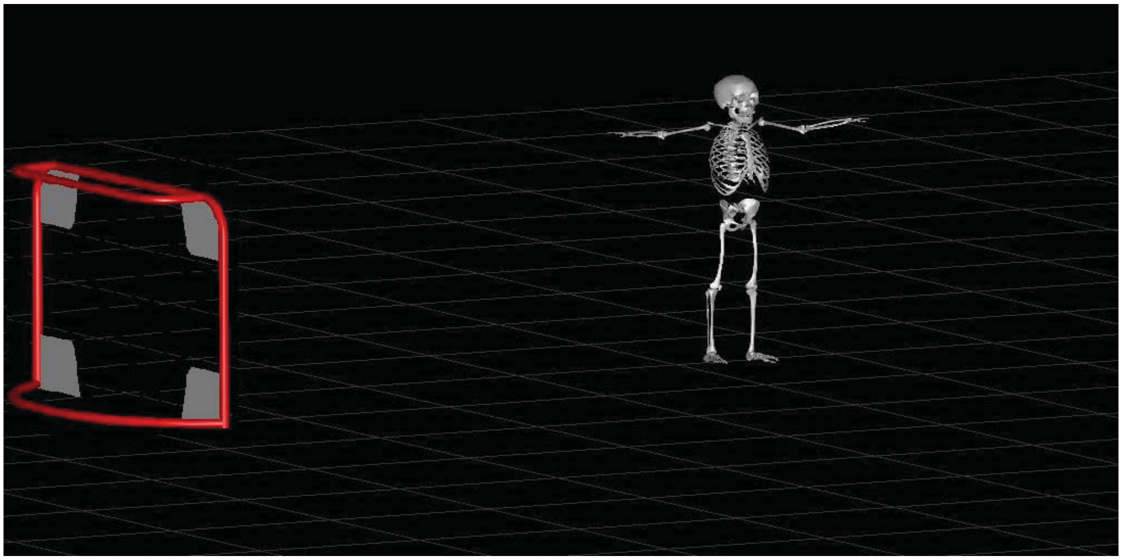


Fig. 3.5: Image of neutral (0°) global orientation angle at shoulders and pelvis for left handed shooter

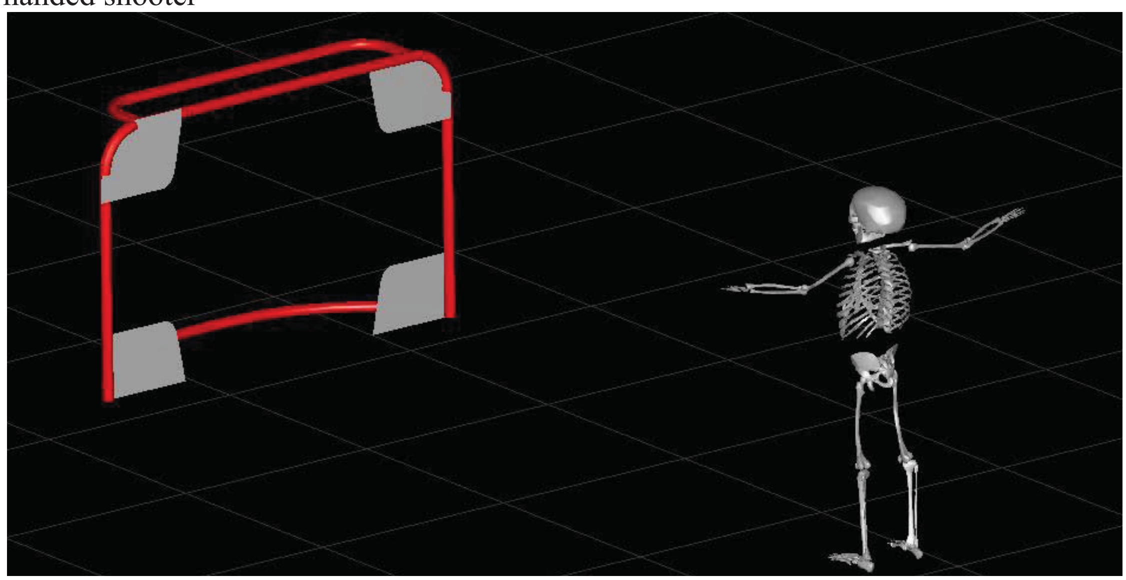


Fig. 3.6: Image illustrating global orientation of shoulders and pelvis at 90°

Angular orientation of the stick blade was calculated for pitch (rotation about X-axis), yaw (rotation about Z-axis), and roll (rotation about the Y-axis) with the raw marker data from the six hockey stick markers. And finally, the puck's velocity was calculated by taking the derivative of the raw marker displacement.

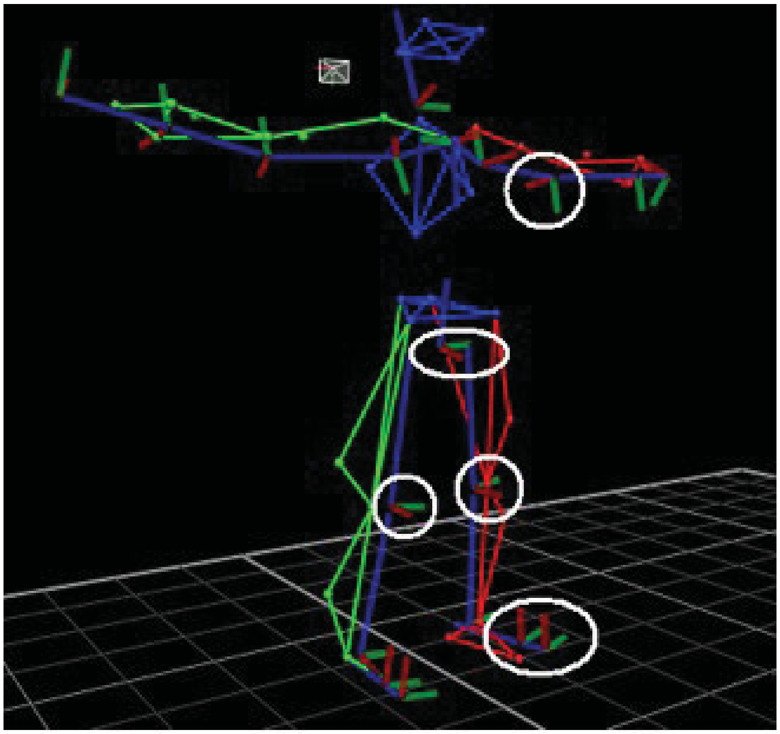


Fig. 3.7: Vicon image with Plug-in-Gait local axes highlighted with circles. Red, green, and purple axes correspond to X, Y, and Z respectively

3.6.2 Statistical analysis

Multiple regression analysis was performed and applied to the dependent variable (accuracy) as well as the independent variables (kinematics data of whole-body) to determine which independent variables best predicted accuracy. Kinematic variables were analyzed at shot release (SR) as well as the delta (delta/Δ angle = change in angle) angles for these variables from SI to SR (figure 3.8). All statistical analyses were performed using SPSS© 17.0 (SPSS Inc., Chicago, Illinois, USA) and Matlab® software. Furthermore, a one-way ANOVA was performed to examine differences in the mean accuracy among separate accuracy targets. Descriptive statistics, including mean, standard error, maximum, minimum, and range were also generated.

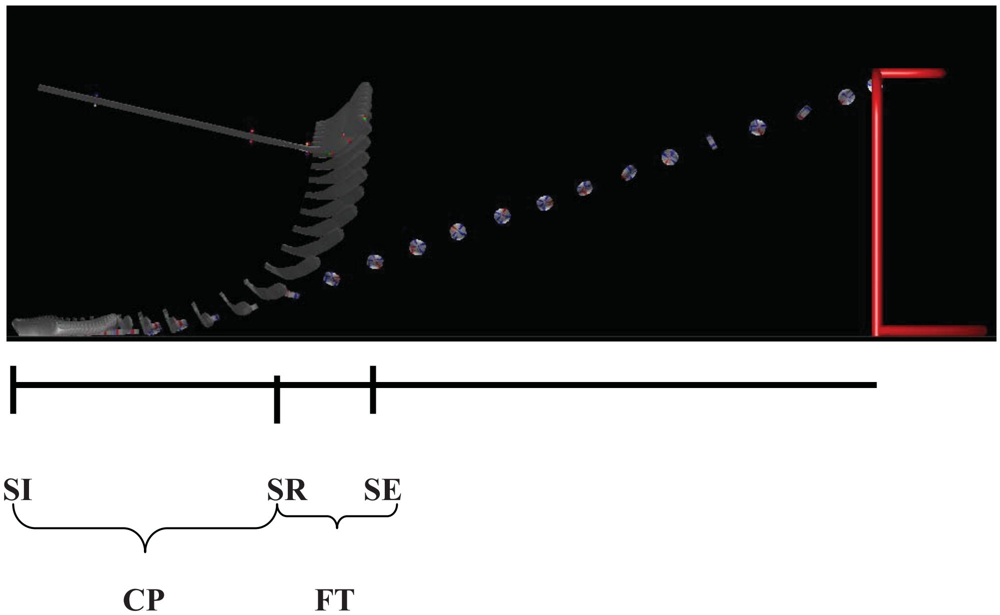


Fig. 3.8: Wrist shot events shot initiation (SI), shot release (SR), and shot end (SE). Wrist shot phases blade/puck contact phase (CP) and follow through (FT) (adapted from Michaud Paquette et al, 2009)

3.7 Independent (IV) and dependent variables (DV)

The dependent variable of this study is the accuracy score as defined in equ. (3.1) per subject. Table 1.1 provides a summary of the DV and IV's considered in the study.

Table 3.1: Kinematic dependent and independent variables

Variables	**Per trial**	**Per target**	**Per subject**
Dependent variable			
Accuracy Score			
	High and low accuracy	accuracy (%)	accuracy (%)
Independent variables			
Trail side: lower body			
Ankle			
LAnkX	Flexion/extension	Mean ± SE	Mean ± SE
LAnkY	Inversion/eversion	Mean ± SE	Mean ± SE
LAnkZ	Internal/external rotation	Mean ± SE	Mean ± SE
Knee			
LKneeX	Flexion/extension	Mean ± SE	Mean ± SE
LKneeY	Abduction/adduction	Mean ± SE	Mean ± SE
LKneeZ	Internal/external rotation	Mean ± SE	Mean ± SE

Hip				
	LHipX	Flexion/extension	Mean ± SE	Mean ± SE
	LHipY	Abduction/adducstion	Mean ± SE	Mean ± SE
	LHipZ	Internal/external rotation	Mean ± SE	Mean ± SE
Lead side: lower body				
Ankle				
	RAnkX	Flexion/extension	Mean ± SE	Mean ± SE
	RAnkY	Inversion/eversion	Mean ± SE	Mean ± SE
	RAnkZ	Internal/external rotation	Mean ± SE	Mean ± SE
Knee				
	RKneeX	Flexion/extension	Mean ± SE	Mean ± SE
	RKneeY	Abduction/adduction	Mean ± SE	Mean ± SE
	RKneeZ	Internal/external rotation	Mean ± SE	Mean ± SE
Hip				
	RHipX	Flexion/extension	Mean ± SE	Mean ± SE
	RHipY	Abduction/adduction	Mean ± SE	Mean ± SE
	RHipZ	Internal/external rotation	Mean ± SE	Mean ± SE
Pelvis				
	PelvisX	Anterior/posterior Tilt	Mean ± SE	Mean ± SE
	PelvisY	Pelvic list	Mean ± SE	Mean ± SE
	PelvisZ	Pelvic rotation	Mean ± SE	Mean ± SE
Trail side: upper body				
Shoulder				
	LShouldX	Flexion/extension	Mean ± SE	Mean ± SE
	LShouldY	Abduction/adduction	Mean ± SE	Mean ± SE
	LShouldZ	Internal/external rotation	Mean ± SE	Mean ± SE
Elbow				
	LElbowX	Flexion/extension	Mean ± SE	Mean ± SE
Wrist				
	LWristX	Flexion/extension	Mean ± SE	Mean ± SE
	LWristY	Radial/ulnar deviation	Mean ± SE	Mean ± SE
	LWristZ	Pronation/Supination	Mean ± SE	Mean ± SE
Lead side: upper body				
Shoulder				
	RShouldX	Flexion/extension	Mean ± SE	Mean ± SE
	RShouldY	Abduction/adduction	Mean ± SE	Mean ± SE
	RShouldZ	Internal/external rotation	Mean ± SE	Mean ± SE
Elbow				
	RElbowX	Flexion/extension	Mean ± SE	Mean ± SE
Wrist				
	RWristX	Flexion/extension	Mean ± SE	Mean ± SE
	RWristY	Radial/ulnar deviation	Mean ± SE	Mean ± SE
	RWristZ	Pronation/Supination	Mean ± SE	Mean ± SE

Trunk			
Thorax			
ThoraxX	Flexion/extension	Mean ± SE	Mean ± SE
ThoraxY	Pronation/Supination	Mean ± SE	Mean ± SE
ThoraxZ	Internal/external rotation	Mean ± SE	Mean ± SE
Spine			
SpineX	Flexion/extension	Mean ± SE	Mean ± SE
SpineY	Pronation/Supination	Mean ± SE	Mean ± SE
SpineZ	Internal/external rotation	Mean ± SE	Mean ± SE
Global Orientation			
Should_global	Angular displacement	Mean ± SE	Mean ± SE
Hip_global	Angular displacement	Mean ± SE	Mean ± SE
Delta variables (calculated from SI to SR)			
Trail side: lower body			
Ankle			
ΔLAnkX	Flexion/extension	Mean ± SE	Mean ± SE
ΔLAnkY	Inversion/eversion	Mean ± SE	Mean ± SE
ΔLAnkZ	Internal/external rotation	Mean ± SE	Mean ± SE
Knee			
ΔLKneeX	Flexion/extension	Mean ± SE	Mean ± SE
ΔLKneeY	Abduction/adduction	Mean ± SE	Mean ± SE
ΔLKneeZ	Internal/external rotation	Mean ± SE	Mean ± SE
Hip			
ΔLHipX	Flexion/extension	Mean ± SE	Mean ± SE
ΔLHipY	Abduction/adduction	Mean ± SE	Mean ± SE
ΔLHipZ	Internal/external rotation	Mean ± SE	Mean ± SE
Lead side: lower body			
Ankle			
ΔRAnkX	Flexion/extension	Mean ± SE	Mean ± SE
ΔRAnkY	Inversion/eversion	Mean ± SE	Mean ± SE
ΔRAnkZ	Internal/external rotation	Mean ± SE	Mean ± SE
Knee			
ΔRKneeX	Flexion/extension	Mean ± SE	Mean ± SE
ΔRKneeY	Abduction/adduction	Mean ± SE	Mean ± SE
ΔRKneeZ	Internal/external rotation	Mean ± SE	Mean ± SE
Hip			
ΔRHipX	Flexion/extension	Mean ± SE	Mean ± SE
ΔRHipY	Abduction/adduction	Mean ± SE	Mean ± SE
ΔRHipZ	Internal/external rotation	Mean ± SE	Mean ± SE
Pelvis			
ΔPelvisX	Anterior/posterior Tilt	Mean ± SE	Mean ± SE
ΔPelvisY	Pelvic list	Mean ± SE	Mean ± SE
ΔPelvisZ	Pelvic rotation	Mean ± SE	Mean ± SE

Trail side: upper body			
Shoulder			
ΔLShouldX	Flexion/extension	Mean ± SE	Mean ± SE
ΔLShouldY	Abduction/adduction	Mean ± SE	Mean ± SE
ΔLShouldZ	Internal/external rotation	Mean ± SE	Mean ± SE
Elbow			
ΔLElbowX	Flexion/extension	Mean ± SE	Mean ± SE
Wrist			
ΔLWristX	Flexion/extension	Mean ± SE	Mean ± SE
ΔLWristY	Radial/ulnar deviation	Mean ± SE	Mean ± SE
ΔLWristZ	Pronation/Supination	Mean ± SE	Mean ± SE

Lead side: upper body			
Shoulder			
ΔRShouldX	Flexion/extension	Mean ± SE	Mean ± SE
ΔRShouldY	Abduction/adduction	Mean ± SE	Mean ± SE
ΔRShouldZ	Internal/external rotation	Mean ± SE	Mean ± SE
Elbow			
ΔRElbowX	Flexion/extension	Mean ± SE	Mean ± SE
Wrist			
ΔRWristX	Flexion/extension	Mean ± SE	Mean ± SE
ΔRWristY	Radial/ulnar deviation	Mean ± SE	Mean ± SE
ΔRWristZ	Pronation/Supination	Mean ± SE	Mean ± SE
Trunk			
Thorax			
ΔThoraxX	Flexion/extension	Mean ± SE	Mean ± SE
ΔThoraxY	Pronation/Supination	Mean ± SE	Mean ± SE
ΔThoraxZ	Internal/external rotation	Mean ± SE	Mean ± SE
Spine			
ΔSpineX	Flexion/extension	Mean ± SE	Mean ± SE
ΔSpineY	Pronation/Supination	Mean ± SE	Mean ± SE
ΔSpineZ	Internal/external rotation	Mean ± SE	Mean ± SE

Global Orientation			
ΔShould_global	Angular displacement	Mean ± SE	Mean ± SE
ΔHip_global	Angular displacement	Mean ± SE	Mean ± SE

Chapter 4: Results

Following is a presentation of the kinematic data captured for twenty-four subjects who performed trials across the four shooting conditions. This chapter provides descriptive statistics for accuracy scores, multiple regression models best predicting shooting accuracy in the present experimental protocol, followed by example angular kinematics for accuracy predictors.

4.1 Accuracy Scores

Accuracy scores were calculated as the percentage of successful trials in which the subject hit the identified shooting target. These scores were generated and summarized for each shooting condition as well as for the overall scores for all subjects (n=24). Table 4.1 provides a summary of descriptive statistics for all four shooting targets along with Pearson correlation coefficients (r) versus overall accuracy scores, multiple regression coefficients of determination (R^2), and F probability statistic values (p) indicating the significance of each prediction model. The prediction equations for each corner were significant ($p < 0.001$). Furthermore, a one-way ANOVA revealed significant differences between the mean accuracy scores for the top targets (37.54% —TC and 43.00% —TI) compared to the bottom targets (61.50% —BC) and 66.40% —BI) ($p \leq 0.05$). The corresponding mean accuracy scores for each separate shooting target with standard error and significant differences are displayed in figure 4.1. The r values for the top corners (0.78—TC and 0.82—TI) suggest that shooters accuracy scores at the top targets are more highly correlated with overall accuracy scores in comparison with the bottom corners (0.69 (BC) and 0.54 (BI)).

Table 4.1 Descriptive statistics: Mean accuracy scores, standard error, maximum, minimum, Pearson correlation (r), range, model p-value, and significant differences between corners and overall accuracy scores

Parameter	Bottom contra (BC)	Bottom ipsi (BI)	Top contra (TC)	Top ipsi (TI)	Overall
Mean	61.50	66.40	37.54	43.00	49.74
SE	5.25	4.23	4.34	4.12	3.66
Sig. Differences	TC, TI	TC, TI	BC, BI	BC, BI	N/A
Max	100.00	100.00	90.10	83.30	93.00
Min	5.00	30.00	10.00	5.00	15.00
Range	95.00	70.00	80.10	78.30	78.00
r	0.69	0.54	0.78	0.82	N/A
R^2	0.95	0.61	0.98	0.73	N/A
p	<0.001	<0.001	<0.001	<0.001	N/A

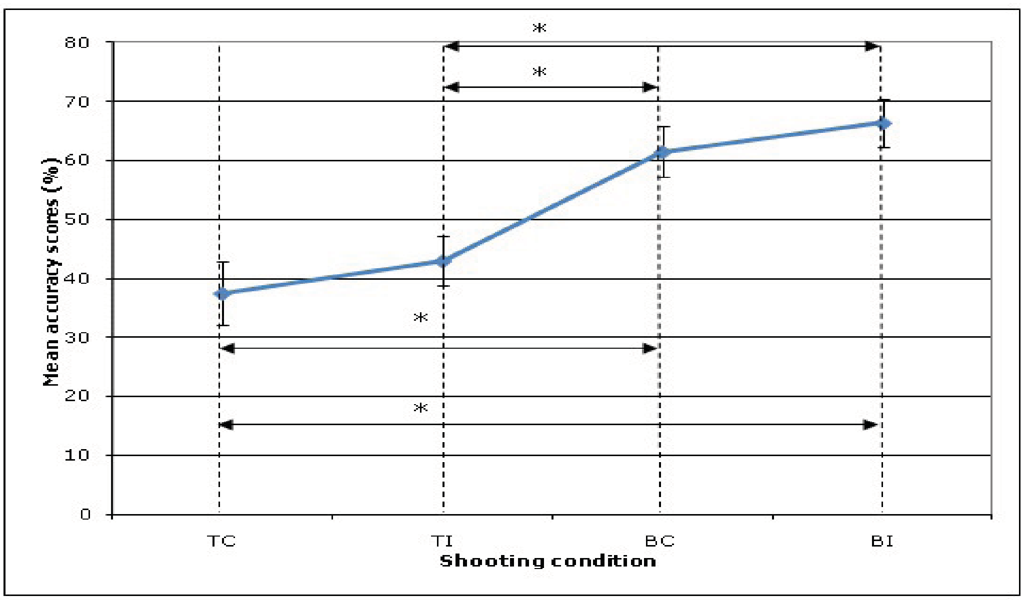


Fig. 4.1: Mean accuracy scores for the four shooting targets with statistical significance illustrated by * ($p \leq 0.05$).

4.2 Multiple Regression Analyses

Multiple regression analyses were performed on all kinematic variables (IV) at SR as well as on their change in angle (Δ) from SI to SR with overall accuracy scores as the DV. The step method criteria using the probability of F with a specified entry of 0.05 and a removal of 0.10 were chosen (SPSS, Inc., version 16.0). For the bottom ipsi (BI) corner, three kinematic shooting parameters explained 61.3% of the variance in overall shooting accuracy scores. These variables were the RWristZ, PelvisZ, and PelvisX. The R^2 along with the change in R^2 (ΔR^2) and P-values corresponding with each model are presented in tables 4.2 to 4.5.

Table 4.2 Results of multiple regression analysis yielding important predictors of shooting accuracy for the bottom ipsi accuracy target

Model	**Bottom ipsi predictors**	**R^2**	**ΔR^2**	**P**
1	RwristZ	0.285	0.285	0.013
2	PelvisZ	0.466	0.181	0.004
3	PelvisX	0.613	0.147	0.001

For the BC target, seven kinematic shooting variables explained 94.5% of variance in accuracy scores. The variables RWristZ , LAnkX , ΔLWristX, RShouldY, ΔLHipX, ThoraxY, and ΔThoraxY rendered a prediction model with a significance level of $p < 0.001$.

Table 4.3	Results of multiple regression analysis yielding important kinematic predictors of shooting accuracy for the bottom contra accuracy target			
Model	**Bottom contra predictors**	**R^2**	**ΔR^2**	**P**
1	RWristZ	0.389	0.389	0.003
2	LAnkX	0.632	0.242	0.003
3	∆LWristX	0.712	0.080	0.044
4	RShouldY	0.799	0.087	0.018
5	∆LHipX	0.875	0.076	0.008
6	ThoraxY	0.918	0.042	0.018
7	∆ThoraxY	0.945	0.027	0.024

The regression equation for the TI corner suggested that the RShouldY, the RWristZ, the ∆PelvisX, and the ∆ LWristZ can explain 73.2% of the variance in the overall accuracy scores ($p<0.05$) as displayed in Table 4.4.

Table 4.4	Results of multiple regression analysis yielding important kinematic predictors of shooting accuracy for the top ipsi accuracy target			
Model	**Top ipsi predictors**	**R^2**	**ΔR^2**	**P**
1	RShouldY	0.238	0.238	0.029
2	RWristZ	0.400	0.162	0.047
3	∆PelvisX	0.537	0.137	0.045
4	∆LWristZ	0.732	0.195	0.005

For the TC target, 97.7% of the variance in shooting accuracy scores were explained by nine kinematic shooting parameters (Table 4.5): RShouldY, ΔLHipX, ΔLElbowX, SpineX, LShouldZ, ΔPelvisZ, ΔLKneeZ, LAnkX, and RElbowX.

Table 4.5 Results of multiple regression analysis yielding important kinematic predictors of shooting accuracy for the top contra accuracy target

Model	**Top contra predictors**	**R^2**	**ΔR^2**	**P**
1	RShouldY	0.240	0.240	0.0240
2	ΔLHipX	0.392	0.152	0.048
3	ΔLElbowX	0.600	0.208	0.008
4	SpineX	0.725	0.125	0.016
5	LShouldZ	0.813	0.088	0.018
6	ΔPelvisZ	0.886	0.073	0.010
7	ΔLKneeZ	0.921	0.035	0.032
8	LAnkX	0.956	0.035	0.009
9	RElbowX	0.977	0.020	0.010

Table 4.6 provides a summary of the change in R^2, revealing the variance each variable accounts for in its corresponding prediction equation.

Table 4.6 Summary of multiple stepwise regression results yielding the change in the coefficient of determination for accuracy predictors

	BC	BI	TC	Ti
	ΔR^2	ΔR^2	ΔR^2	ΔR^2
RWristZ	0.389	0.285		0.162
LAnkX	0.242		0.035	
ΔLWristX	0.080			
RShouldY	0.087		0.240	0.238
ΔLHipX	0.076		0.152	
ThoraxY	0.042			
ΔThoraxY	0.027			
PelvisZ		0.181		
PelvisX		0.147		
ΔLElbowX			0.208	
SpineX			0.125	
LShouldZ			0.088	
ΔPelvisZ			0.073	
ΔLKneeZ			0.035	
RElbowX			0.02	
ΔPelvisX				0.137
ΔLWristZ				0.195
Overall R^2	**0.945**	**0.613**	**0.977**	**0.732**

From the regression model, the unstandardized beta coefficients (β) were calculated for SR and Δ variables, and are listed in table 4.7 along with their respective constants. These beta coefficients were used to build regression equations for each shooting condition and are given in equations 4.1, 4.2, 4.3, and 4.4.

Table 4.7 Unstandardized Beta coefficient values for accuracy predictors in all four prediction equations along with their constants

	BC	BI	TC	TI
	B	B	B	B
RWristZ	0.675	0.725		0.712
LAnkX	-1.745		-0.789	
ΔLWristX	-1.098			
RShouldY	-1.557		-3.625	-1.622
ΔLHipX	-0.713		-1.473	
ThoraxY	0.709			
ΔThoraxY	-0.355			
PelvisZ		-0.990		
PelvisX		1.705		
ΔLElbowX			1.845	
LSpineX			-0.658	
LShouldZ			-1.220	
ΔPelvisZ			-1.098	
ΔLKneeZ			-0.802	
RElbowX			0.379	
ΔPelvisX				2.041
ΔLWristZ				-1.056
Constant	**50.274**	**-80.882**	**153.645**	**103.269**

$$BC = 0.675RWristZ - 1.745LAnkX - 1.098\Delta LWristX - 1.557RShoulderY - 0.713\Delta LHipX + 0.709ThoraxY - 0.355\Delta ThoraxY + 50.274 \quad \text{equ. (4.1)}$$

$$BI = 0.829RWristZ + 0.555Hip\_Global - 53.891 \quad \text{equ. (4.2)}$$

$$TC = -3.625RShouldY - 1.473\Delta LHipX + 1.845\Delta LElbowX - 0.658SpineX - 1.220LShouldZ - 1.098\Delta PelvisZ - 0.802\Delta LKneeZ - 0.789LAnkX + 0.379\ RElbowX + 153.645 \quad \text{equ. (4.3)}$$

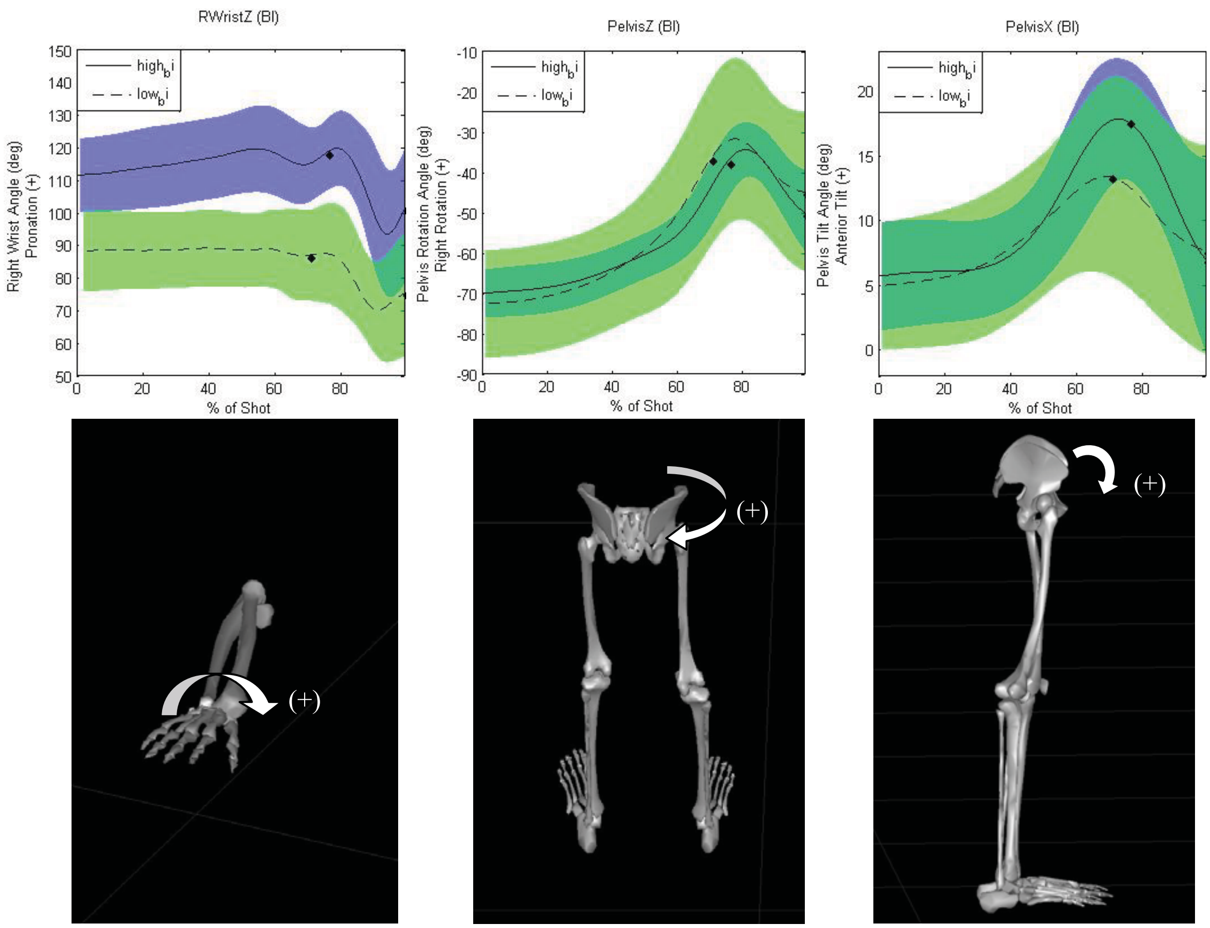
$$TI = 0.712RWristZ - 1.622RShouldY + 2.041\Delta PelvisX - 1.056\Delta LWristZ + 103.269 \quad \text{equ. (4.4)}$$

4.3 Kinematic predictors of accuracy

This section provides representative mean angular kinematic graphs for predictors of wrist shot accuracy. To help with the interpretation of the data, and to differentiate desirable from non-desirable kinematic behaviour, graphs were generated for significant predictors of accuracy, using data from the five most accurate shooters and the five least accurate shooters. This was done solely to discern the kinematic tendencies of highly accurate shooters compared to those that were less accurate and was not part of the main statistical analysis. All kinematic angles are in reference to anatomical position.

For ease of reference, shooters with accuracy scores above 50% will be distinguished as accurate or high accuracy shooters, and shooters with scores equal to or below 50% will be considered low accuracy shooters. The variables included below were chosen based on their inclusion in each of the four regression models for all shooting targets. Figure 4.2 provides an illustration of a subject's whole-body kinematics from SI to SR with the help of motion capture data. The graphs included in figures 4.3 through 4.6 display the identified mean angular joint displacement for the X, Y, or Z components, from SI (0%) to SE (100%). SR typically occurred between 60-80% of the shot execution—identified by the black dot for high and low groups. Noticeable kinematic differences for the bottom ipsi corner at SR can be clearly seen for the RWristZ with ≈ 25° more pronation at the lead wrist in accurate shooters, and for PelvisX with ≈5° more anterior tilt at SR (figure 4.3). For the PelvisZ, although the mean angles at SR are similar for the selected shooters, a considerably larger standard deviation (indicated with coloured zones along the mean; grey (green) for low accuracy and dark grey (purple) for high accuracy shooters) was observed in the low accuracy shooters at SR and throughout the entire shot execution.

Fig. 4.2: a composite image of a subject's whole-body motion from shot initiation (SI) to shot release (SR)



a) b) c)

Fig. 4.3: A graphical representation of the accuracy predictor's mean angular kinematics at the bottom ipsi (BI) target for subjects who achieved the five highest and five lowest accuracy scores in addition to corresponding anatomical reference figures. Arrows illustrate the type of motion that will result in increased graphical values. BI accuracy predictors: a) RWristZ (pronation), b) PelvisZ (right pelvic rotation), c) and PelvisX (anterior pelvic tilt)

For the BC target, the most evident differences at SR were seen again in the RWristZ with nearly 30° more pronation in accurate shooters (fig. 4.4). On average, accurate shooters display more plantarflexion for LAnkX at SR and this was especially evident in follow through phase (FT). Accurate shooters seem to perform wrist shots with their lead shoulder in a more adducted position (RShouldY) than low accuracy shooters. ThoraxY suggests that high accurate shooters show less lateral flexion of the thorax when shooting at the BC target. For delta variables, we witness a ≈ 12° increase in range of motion (ROM) of the ΔLWristX for the accurate shooters suggesting more flexion and extension of the wrist.

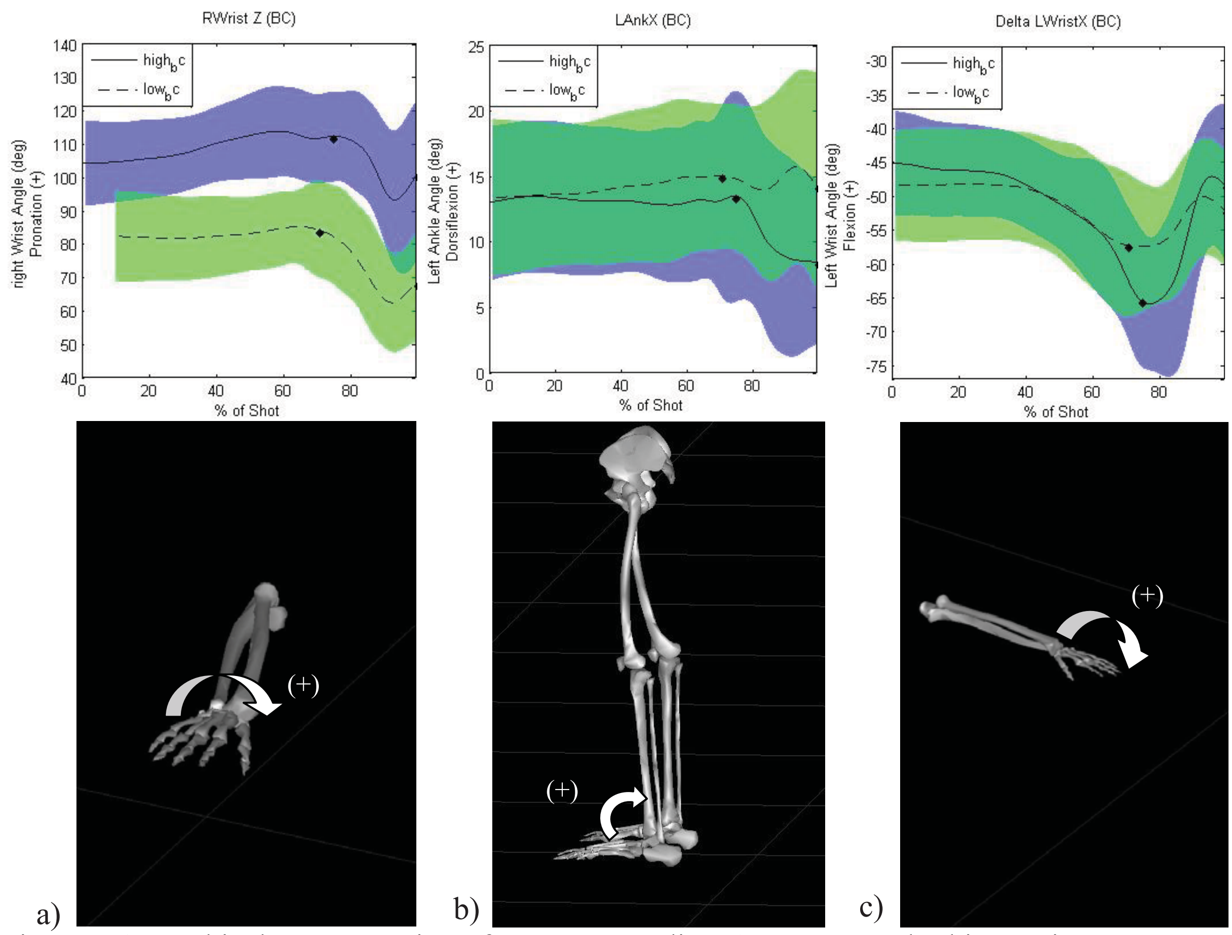


Fig. 4.4: A graphical representation of accuracy predictor's mean angular kinematics at the bottom contra (BC) target for subjects who achieved the five highest and five lowest accuracy scores in addition to corresponding anatomical reference figures. Arrows illustrate the type of motion that will result in increased graphical values. BC accuracy predictors: a) RWristZ (pronation), b) LAnkX (dorsiflexion), c) ΔLWristX (flexion), d) RShouldY (abduction), e) ΔLHipX (flexion), and f) ThoraxY and ΔThoraxY (left lateral flexion)

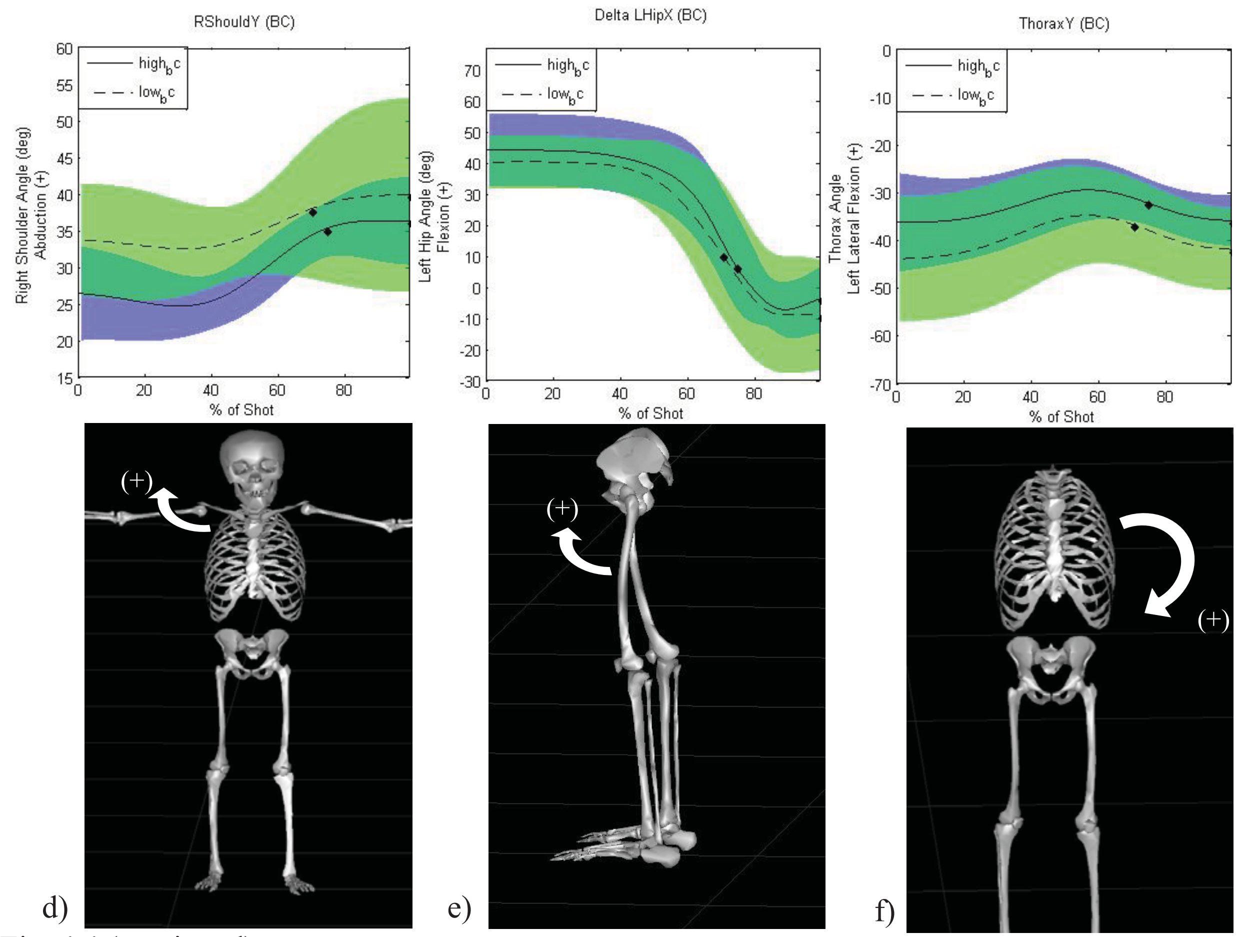


Fig. 4.4 (continued)

At the top ipsi corner, the RWristZ variable once again appeared in the regression model with the accurate shooters showing approximately 20° more pronation at the lead wrist than low accuracy shooters (figure 4.5). The RShouldY reveals ≈ 8° more adduction than for accurate subjects. For delta variables, low accuracy subjects showed a smaller ROM (≈ 5°) in anterior pelvic tilt at ΔPelvisX, in addition to showing a smaller ROM for the ΔLWristZ (≈ 8°).

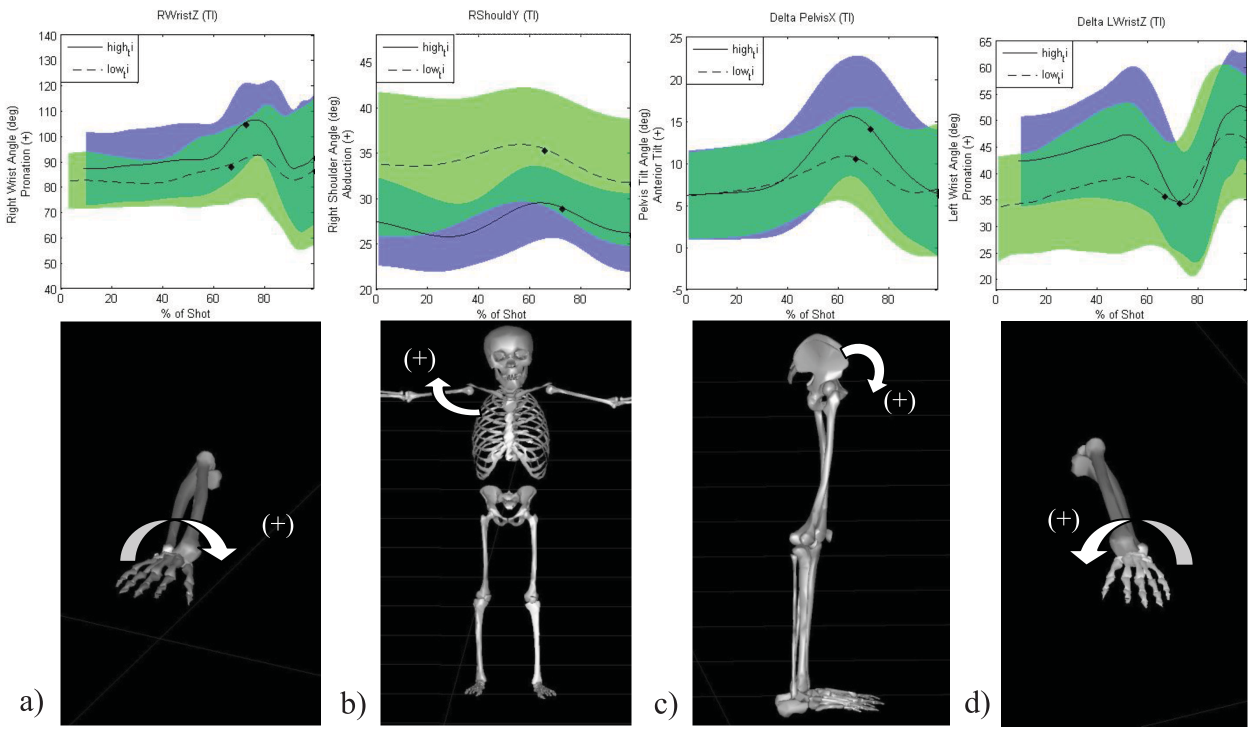


Fig. 4.5: A graphical representation of accuracy predictor's mean angular kinematics at the top ipsi (TI) target for subjects who achieved the five highest and five lowest accuracy scores in addition to corresponding anatomical reference figures. Arrows illustrate the type of motion that will result in increased graphical values. TI accuracy predictors: a) RWristZ (pronation), b) RShouldY (abduction), c) ΔPelvisX (anterior pelvic tilt), d) ΔLWristZ (pronation)

Finally, figure 4.6 provides the TC accuracy predictors. We witness more abduction for RShouldY in low accuracy subjects (≈ 8°) at SR with a much larger standard deviation when compared to the accurate shooters. A notable difference is also present at the trail ankle angle for LAnkX between accurate and non-accurate subjects' mean angles. Furthermore, the LShouldZ graph suggests more internal rotation of the trail shoulder for the low accuracy shooters at SR.

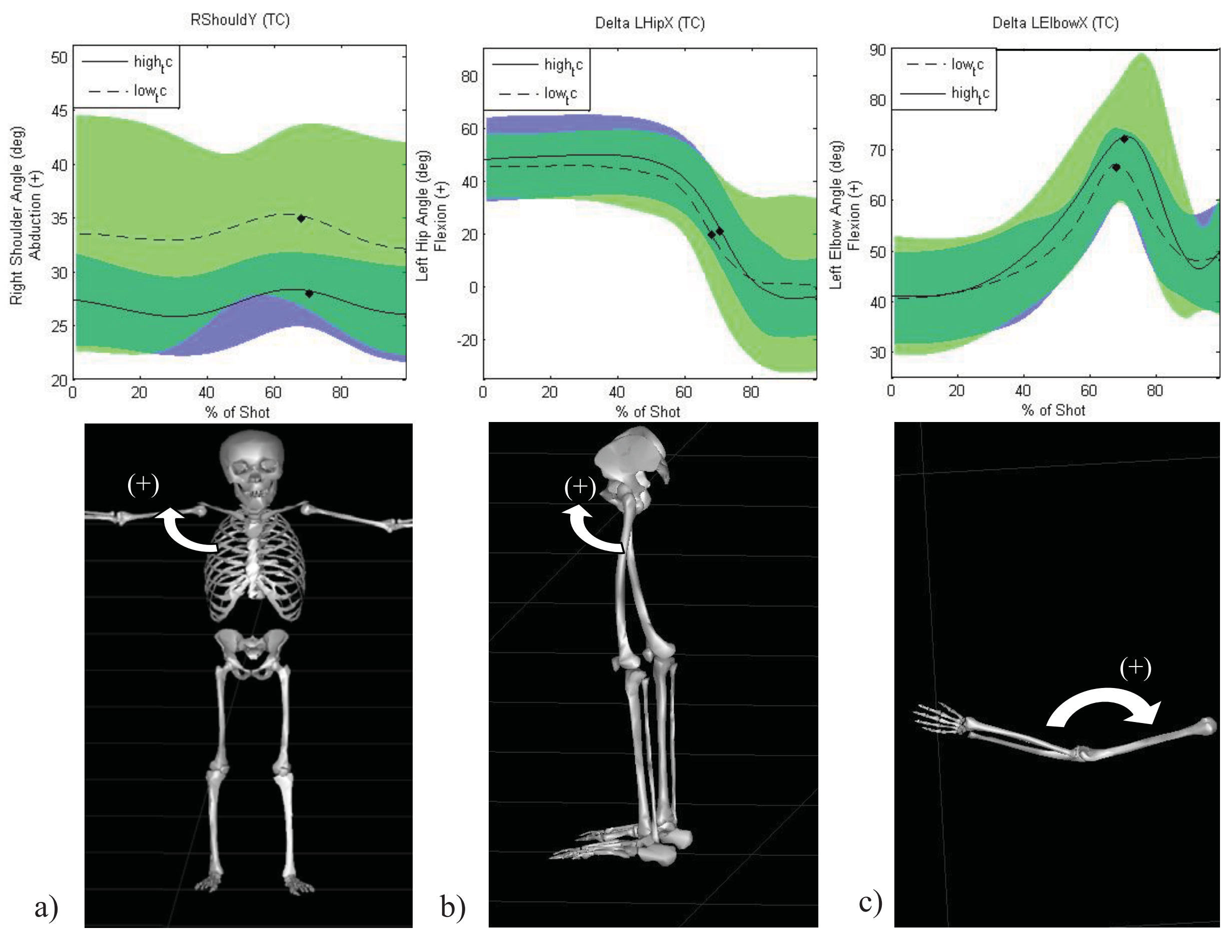


Fig. 4.6: A graphical representation of accuracy predictor's mean angular kinematics at the top contra (TC) target for subjects who achieved the five highest and five lowest accuracy scores in addition to corresponding anatomical reference figures. Arrows illustrate the type of motion that will result in increased graphical values. TC accuracy predictors: a) RShouldY (abduction), b) ΔLHipX (flexion), c) ΔLElbowX (flexion), d) SpineX (flexion), e) LShouldZ (external rotation), f) ΔPelvisZ (right rotation), g) ΔLKneeZ (external rotation), h) LAnkX (dorsiflexion), and i) RElbowX (flexion)

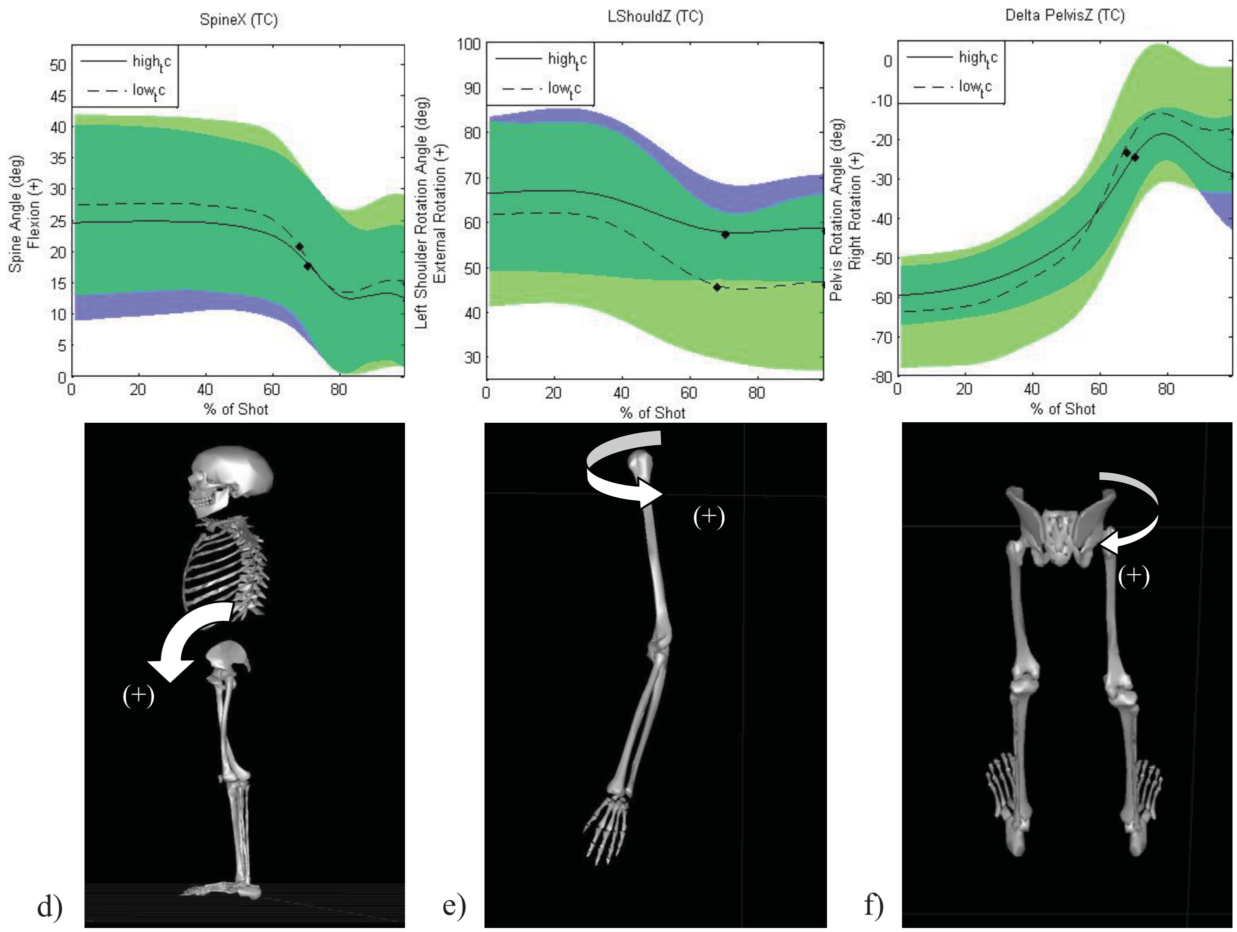


Fig. 4.6 (continued)

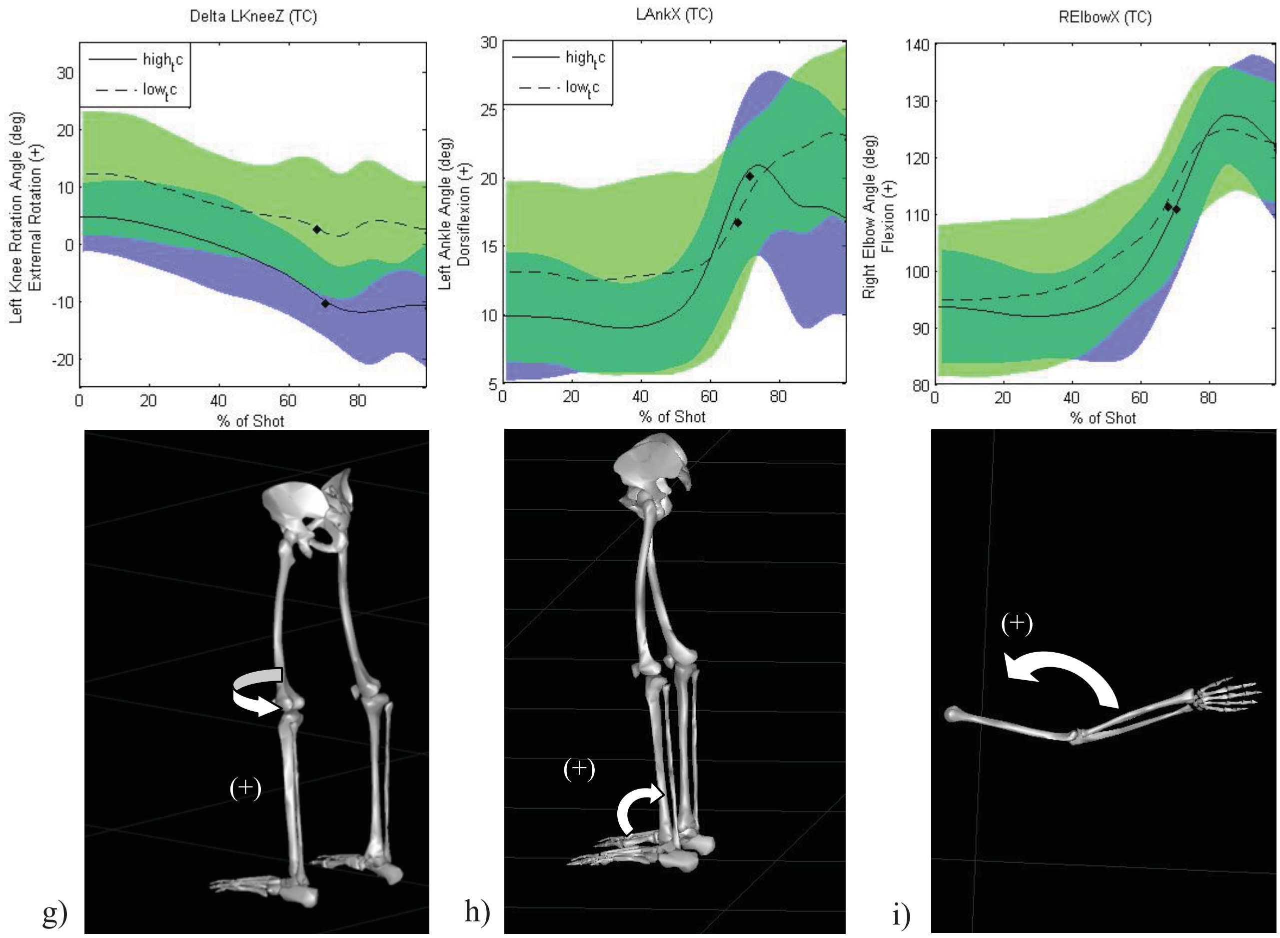
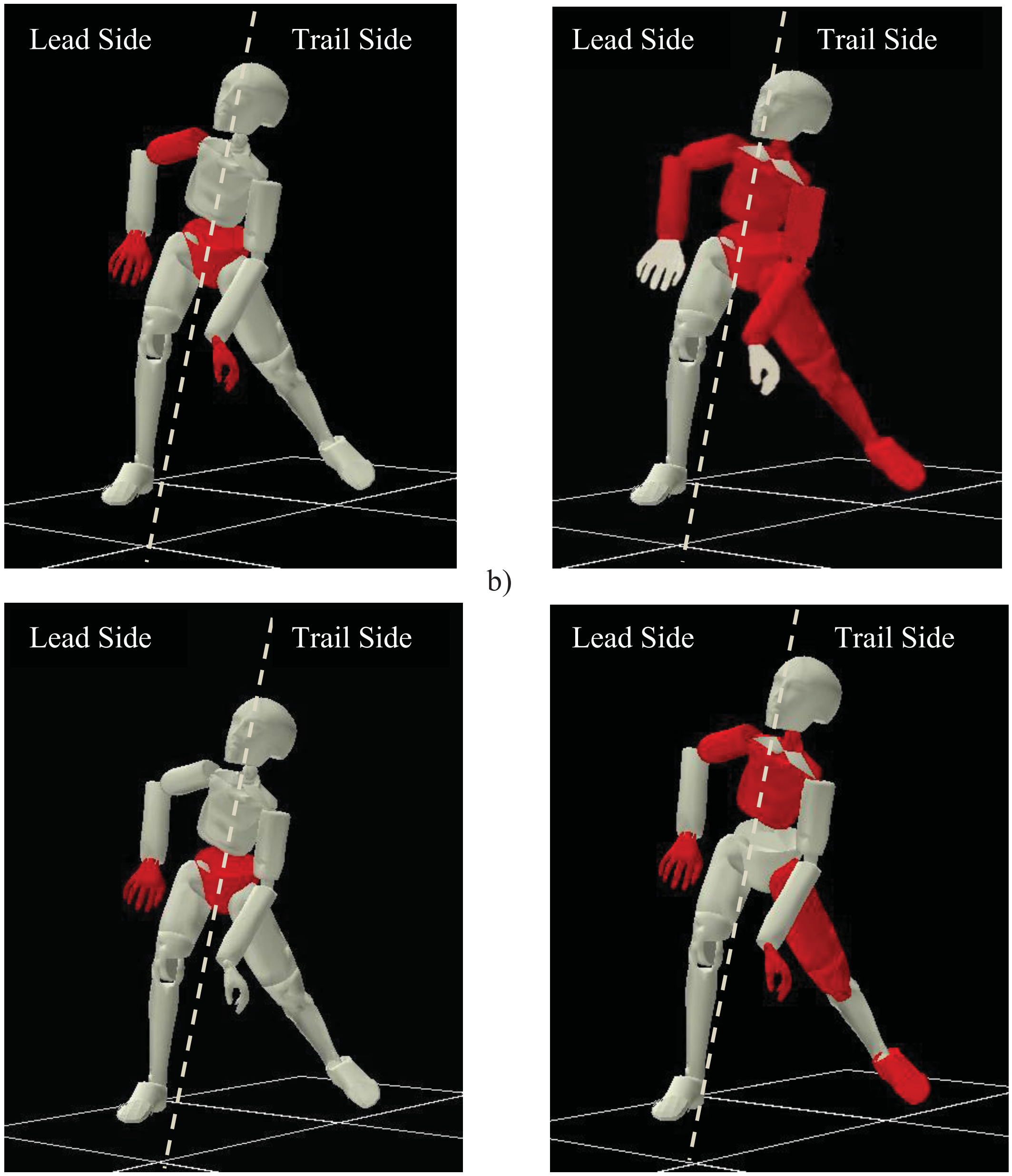


Fig. 4.6 (continued)

Chapter 5: Discussion

In summary, this study successfully identified important predictors associated with wrist shot accuracy (refer to visual summary of these predictors as presented in fig. 5.1). The results suggest that an accurate outcome is associated with the following characteristics: The lower body seems to provide a base for support, but also contributes to the initiation of movement, in the form of weight transfer towards the intended target. We also propose that the lower trail limb may serve to offset rotational motion that could upset the stability of the system if not properly managed. The angular kinematics present at the pelvis, spine, and thorax, appear to orientate the trunk such that the lead and trail limbs can optimally function to achieve an accurate wrist shot. These trunk variables undoubtedly contribute to the force generation necessary in the wrist shot as well in addition to their accuracy implications. Moving to the upper limbs, an accurate outcome was associated with a more dynamic use of the lead arm, specifically at the wrist and shoulder. Similar to many complex motor tasks, the wrist shot involves numerous interacting components or degrees of freedom, of which, it is the mastery of these degrees that results in a stable coordinated movement (Stergiou et al., 2001). More specifically, it appears that in order to be accurate, shooters may aim to learn to constrain degrees at the shoulder, while affording the opportunity for greater involvement at the elbow and wrist joints.



a) b) c) d)

Fig 5.1: visual summary of kinematic accuracy predictors for all four shooting conditions: a)Top ipsi corner, b) Top contra corner, c) bottom ipsi corner, and d) bottom contra corner

To put into perspective the challenge that shooters face to hit a target as in the current protocol, the puck's release vector had to fall within an average trajectory envelope of ±2.02° of horizontal and ±2.07° of vertical dispersion (figure 5.2). Given that the window size of the four targets are effectively the same, differences in scoring probability by target depend on the relative release height and location of the puck to the target. To adapt to each target's height and location coordinates, the wrist shot's general movement pattern needs to be modified, that is, one or more of the body's joints needs to modulate its movement amplitude, rate and timing. By comparing across the spectrum of low to high accuracy shooters, the regression analysis identified those body joints and their modulated kinematics (i.e. technique) that most correspond to shot accuracy. As it turns out, no one body region predominated as a predictor of shot accuracy for all targets. Rather, different joints were identified from the legs, torso and arms.

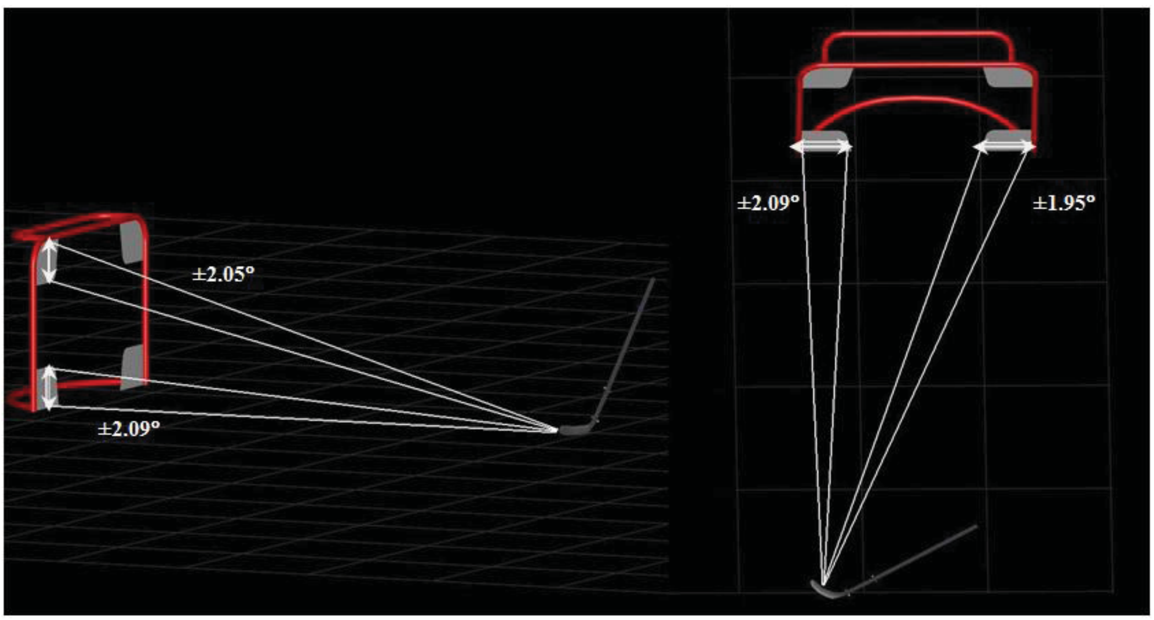


Fig. 5.2: Horizontal and vertical dispersion error margin. It is necessary to remain within this trajectory envelope to intercept the target from a distance of 4 m

When evaluating body mechanics, it is important to remember that the body is not a rigid block but a complex, flexible system formed by multiple segments tied together by muscles surrounding joints (Alpini et al., 2008). It may help to think of the muscles (or the resulting joint angles) as the actuator in this system, which is the cause of motion in the shooting task, and the stick as the effector, which acts in response to stimulus in a series of energy transfers moving from various body segments to the stick, and finally to the puck (Minetti, 2004). In other words, the body ultimately dictates the behaviour of the hockey stick and thus the resulting trajectory of the puck. A hockey player theoretically has fourteen major joints that must be accounted for with three components of motion (x, y, and z), yielding a system with roughly 42 degrees of freedom. The Plug-in-Gait™ model calculates angular displacement values for the major joints of the body in addition to the orientation of the pelvis, spine, and thorax, while excluding more intricate joints of the body. Hence, to identify the key body movements corresponding to shot accuracy is a complex and daunting challenge.

The purpose of this study was to identify the whole-body kinematic variables that best predict wrist shot accuracy. Additionally, kinematics of the stick were used to characterize shot technique. The current study contained a sample of twenty-four subjects of varying skill levels. A normal distribution of accuracy scores was observed with a mean of 49.74%, ranging from 15% to 93% (Appendix I).

Similar to the findings of Michaud-Paquette et al. (2009), regardless of the subjects' proficiency, a main effect was found for target heights; that is, measures for bottom to top corners were significantly different ($p \leq 0.05$) with mean scores of 63.95% and 40.27% respectively. By that account, the 23% "handicap" for top corners implies a great motor control challenge exists for the player. Previous work in this area suggested that shooting at upper targets requires the shooter to compensate for a three-dimensional trajectory (pitch, yaw, and forward distance) as opposed to a simpler two-dimensional trajectory when aiming for low targets, wherein the target can be intercepted by applying the appropriate impulse vector to the puck (Michaud-Paquette et al., 2009). It appears that to hit the top targets requires more challenging stick/blade orientation and displacement technique than bottom targets. Also worth noting, comparison of accuracy scores by lateral position point out an increased difficulty in hitting targets located contra-laterally to the shooters starting position (i.e. cross body) as compared to ipsi-lateral. Though not significantly different, the mean accuracy for BC was 5.46% lower than BI, and TC was 4.9% lower than TI. Furthermore, the regression equations were able to explain more variance for the contra-lateral side (94.5% at BC and 97.7% at TC) than the ipsi-lateral side (61.3% at BI and 73.2% at TI). From the previous study by Michaud-Paquette and colleagues (2009), they found that 36% (BC) to 40% (BI) of the accuracy variance at the bottom corners were explained by stick behaviour; however, by including body kinematics a much higher percentage of variance was explained for the bottom corners (61.3% (BI) to 94.5 (BC)), and top corners (73.2% (TI) to 97.7 (TC)). Evidently, both stick and body movements reveal a lot about future shot success. To frame the following discussion, movements within the three body regions (that is, lower limbs, torso, upper limbs) will be evaluated.

From the kinematic data, the regression analysis identified lower-body variables of importance corresponding to accuracy outcome, particularly for contra-lateral targets: these were the trail ankle, knee, and hip. Before making sense of the specific nature of these joint movements, the role of the lower limbs as elucidated by other authors will be presented. In general, two mechanical functions have been noted: postural stabilization and weight transfer. The first function seems obvious. If you compromise stability due to poor dynamic control of the base of support then movement control of superior segments will also be compromised. Indeed, Alpini et al. (2008) highlighted the unique postural challenge that hockey players face, stating that maintaining postural stability involves coordination of limbs, the trunk and head by means of a sensorimotor antigravity network. This challenge is complicated by the low surface friction created by the ice. The second function, weight transfer or weight shift, involves a transition of greater body weight support from the trail to lead limb during the task's execution. From other sports such as golf, field hockey, and baseball, researchers have described similar weight transfer behaviour as part of a summation of segmental accelerations from the legs to the trunk core to the upper extremities such that optimal speed and trajectory of a projectile may be achieved (Milburn, 1982; Bretigny et al, 2008; Welch et al, 1995). In the current study, this behaviour was exhibited clearly by the higher accuracy shooters but to a lesser degree for lower caliber shooters; in fact, the latter subjects' attempt to transfer weight often led them to loss of balance. Therefore, lower body movements must fulfill the concurrent functions of dynamic stability and weight transfer.

Most related to shot accuracy were the trail ankle, knee, and hip. For instance, for both contra-lateral prediction equations, increased accuracy corresponded to greater plantar flexion of the trail ankle for the BC corner, and greater dorsiflexion for the TC target at SR. The ankle of trail leg had great importance at the BC corner, explaining 24.4% of the accuracy variance in comparison to a low weighting at the TC (3.5%). Interestingly, an increased accuracy was associated with greater ankle plantarflexion near and after SR, suggesting the presence and importance of weight transfer and forward momentum of the body from the trail to the lead foot in the direction of the target.

Similarly, the change in angle at the trail hip (ΔLHipX) was a recurring accuracy predictor, in this case for both the BC and TC corners. Thus, a greater ROM at the trail hip was predictive of accuracy when shooting at these corners. One interpretation of these findings is that the extension of the trail leg served to counteract the forceful rotations occurring at the pelvis and torso in addition to angular acceleration of the upper limbs (fig. 5.3). Unlike golf and baseball, where the players have cleats to initiate and/or negate their rotational momentum, hockey players must find other means to offset such axial movements. The counter motion of the trail hip assisted in maintaining stability (that is, angular momentum) within the horizontal plane that in turn assisted in control of body balance. Finally, greater accuracy corresponded to increased internal rotation at the trail knee. Potentially, this was interrelated to the trail foot being anchored to the ice for the early phases of the shot combined with the rotation of the pelvis and torso toward the target.

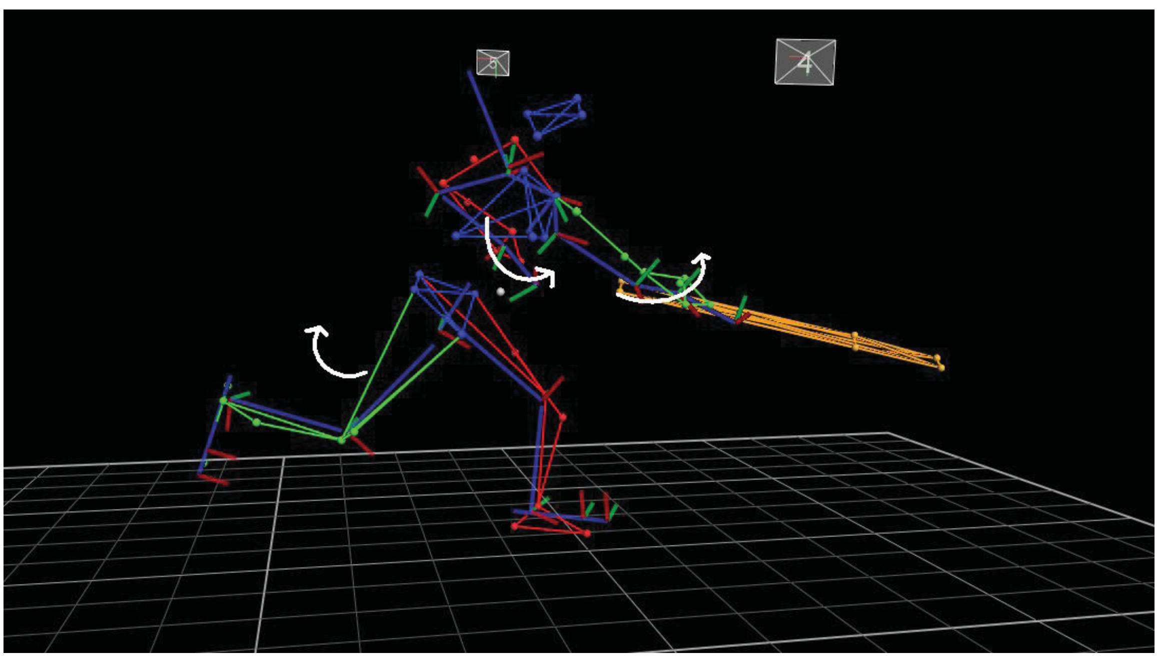


Fig 5.3: three-dimensional image of a high accuracy shooter. Extension at the trail hip seems to counter the rotation occurring in the upper-body as well as maintain balance

Therefore, it appears that the lower body kinematics serve as the underlying base of support for the entire system in the wrist shot in addition to its contribution to the transfer of weight to the lead foot promoting optimal upper body kinematic parameters. Furthermore, it is reasonable to speculate that the forward momentum of the body generated by weight transfer also contributes to the velocity of the wrist shot, which is a very important factor in the context of competitive play.

Trunk segments

The second body region of focus is the body's trunk (or often referred to as the core in athletics training), here comprised of the pelvis, spine and thorax segments. Extensive research in golf has characterized rotational behaviour of the pelvis and shoulders (thorax) as part of the aforementioned segmental acceleration sequences (Myers et al., 2009). Golf research has suggested that segmental separation (that is, decoupling trunk segments) results in increased storage and utilization of elastic energy in the associated muscles. This can be explained by the stretch shortening cycle (SSC), which states that a muscle that is eccentrically loaded prior to concentric contraction results in an increase of force and power production compared to an isolated concentric or eccentric contraction (Myers et al., 2007; Ettema et al., 1992; Komi, 1984). In ice hockey, Woo and colleagues (2004) observed that during slap shots, the movement sequence was characterized by maximal angular velocities in the body moving from the core to the extremities, providing evidence that the SSC may also play a role in ice hockey wrist shot as well as the slap shot. Similarly, in this study of the wrist shot, the rotation of the pelvis precedes rotation of the upper body. Consequently, the pelvis and thorax are, with no great surprise, strong contributors to the mechanics of wrist shot execution. In addition to the sequencing, the specific segment orientations within the trunk correspond to accuracy, as evidenced within the predictive regression equations generated. For instance, the variable PelvisZ (axial rotation) contributes substantially to the accuracy functions for the BI corner (18.8%) and at the TC corner (7.3%). The data suggest that accuracy is associated with consistent and optimal levels of pelvic rotation toward the target. Separation of the top and lowest accuracy shooters demonstrates this phenomenon as we witness lower standard deviations and ranges of motion in accurate shooters. Other variables such as anterior tilt of the pelvis (pelvisX), and thorax side tilt or lateral flexion (ThoraxY, ThoraxΔY) were also identified as strong predictors of accuracy. In general, the latter kinematic behaviour of the trunk's segment have a substantial influence on accuracy, presumably by modulating between the motions of the lower body (stability and weight transfer) and upper body (orientation to target, bi-pendular swing of arms as well as stick stroke).

Upper limbs

As noted earlier, the combined movement of various body segments ultimately determine the stroke path of the stick, and finally to the puck's projection (Minetti, 2004). Motor control of these numerous segments into a coherent and effective general movement pattern is daunting. In general, the wrist shot exhibits a sequential acceleration of segments, beginning from the lower limbs through the trunk to the upper limbs. The former are responsible for dynamic stability and amending body orientation towards the target. Finally, the last segments to determine accurate guidance of the puck via the stick are the upper limbs.

Prior literature suggests that when accuracy is a key objective, humans tend to constrain the system over a large number of degrees of freedom in order to increase consistency of task results (Glazier and Davids, 2009). Although conventional views of skilled athletic performance have often described the movement system as invariant, Button et al. (2003) provided contradicting evidence, which proposed that skilled basketball players showed greater wrist and elbow involvement (distally) with less involvement at the shoulder (proximally) in basketball free throw execution. This suggests a highly flexible system subject to varying degrees of constraint depending on the task and task conditions presented to subjects.

These theories agree with the current results, indicating that in order to be accurate during wrist shot execution, shooters showed more constraint over movement at the lead and trail shoulder joints, and conversely more angular involvement at the elbow and wrist joints. For instance, for the lead shoulder (RShouldY), a more adducted shoulder angle was observed (i.e. the arm anchored closer to the body) with a considerably lower standard deviation for high accuracy shooters. As well, accurate shooters displayed less trail shoulder internal rotation (LShoulderZ) ROM. The former variable explained 24 and 23.8% of the accuracy variance at the TC and TI corners, respectively, and 8.7% for the BC corner, while the latter variable explained 8.8% of the variance at the TC corner. Thus, 33.3% of the variance in overall accuracy at the TC target is explained by such constraint of degrees of freedom at the shoulders. For the upper targets, RShoulderY possessed the greatest prediction weighting on accuracy (table 4.6), implicating this variable with puck lift for top targets. In other words, this variable's apparent importance when shooting at the top targets may directly or indirectly help to provide puck lift into the upper portion of the net.

When shooting at the TC target, the regression equations indicate that the trail elbow flexion (ΔLElbowX) was a predictor of accuracy explaining 18.8% more variance than the lead elbow (RElbowX) flexion at SR (table 4.6). The data provide evidence that accuracy is associated with greater change in trail elbow flexion from SI to SR (i.e. more flexion of elbow). This is congruent with the hypothesis put forward by Michaud-Paquette et al. (2009) stating that larger elbow flexion angles may be required in high caliber shooters since they tend to draw the puck into the body more and that this may also result in adduction of the arms into the body accompanied by a freeing of the wrists for greater involvement in shot execution. Although beyond the scope of this study, extensive visual inspection of the current data seems to support the notion that high accuracy (i.e. high caliber) shooters tend to "draw" the puck into the body early in the CP.

The hockey stick is used as a passive tool to amplify and control movement and ultimately propel the puck. In the wrist shot, the stick blade begins in contact with the puck, the stick is moved forward in a pushing action to project the puck, and the shot is terminated by a vigorous pronation of the trail arm about the wrist, and a backward, dynamic stabilizing movement of the lead hand (Wu et al, 2003; Nault and Holt, 1975). When considering the lead forearm pronation-supination (RWristZ) component was a heavily weighted variable in the regression equations for three of the four shooting conditions; the regression equations suggest that the lead wrist pronation can predict 38.9%, 28.5%, and 16.2% of the variance at the BC, BI, and TI corners, respectively.

While accuracy is associated with greater pronation, the exception to this rule was the RWristZ at the TI corner. This seems to be due to greater need for supination of the lead wrist to reach the top corners, which would directly contribute to appropriate pitch angle of the blade when "scooping" the puck to the top targets. Michaud-Paquette et al. (2009) proposed this "scooping" phenomenon, such that a considerable amount of change in the blade's pitch angle was needed throughout the contact phase in order to reach the top targets. The regression results indicate that the RWristZ component was the most significant predictor of accuracy for the bottom corners. Interestingly, the shooters that attained higher accuracy scores showed what seemed to be adaptations of the wrist angles from corner to corner, and especially when comparing top to bottom targets, whereas the lower accuracy shooters showed very little difference in their wrist profiles across corners.

Further investigation of the wrist variables entered into the TI regression equation reveals notable interaction between the lead and trail wrist components (fig. 4.5). First, we see the rotational components of both forearms (pronation/supination) entering into the regression equation explaining 35.7% of the variance at the TI target. The most recent research suggests that accurate shooters tend to begin the wrist shot by cradling the puck near the center of the blade, and that the puck is moved forward by steering the shaft and blade's front profile (Michaud-Paquette et al, 2009), where subsequently the puck is essentially rolled from the center of the blade laterally until its release towards the intended target. This was described previously as a "flick" by Michaud-Paquette et al. (2009), where a large and rapid change in *blade angl*e (pitch and yaw) and *stick bend* *recoil* was seen near the end of contact phase corresponding to large increase in pronation at the trail wrist—at ≈ 50-70% of the shot.

Investigating the interaction between the pronation/supination of the two wrists, we witness that as accuracy increases, the trail wrist pronation increases from ≈ 0-55% of the shot, which seems to keep the wrist cocked and permit a larger ROM as we see from ≈ 55-95% of the shot. This angular profile of the trail wrist seems to correspond to a cradling of the puck for much of the CP, followed by rolling of the puck towards the lateral portion of the stick blade (near the end of CP), and finally the subsequent forceful "flicking" of the puck with follow through corresponding to the rapid dip from 45º to 30º and back up to nearly 55º as exemplified in accurate shooters (fig. 4.5). Since this dramatic increase in pronation occurs near and/or post SR, it seems to be a very important phenomenon influencing accuracy. However, it appears as though a very small portion of the trail wrist "flick" actively contributes to the flight of the puck, and a great deal of the motion is simply a follow through or a deceleration of the "flick" directly proportional to the high angular accelerations generated to launch the puck.

The intricate dialogue that must occur between the two wrists / forearms as well as the entire lead and trail limbs are due to their interconnection via the hockey stick. In support of this notion, when the kinematic data of high accuracy shooters are extracted and compared to low accuracy shooters, generally speaking, the result is an increased ROM and wrist involvement. Both WristZ graphs show greater slopes in accurate shooters suggesting increased angular velocity. These results agree with previous research suggesting that greater wrist involvement can lead to greater power and accuracy (Minetti, 2004; Button et al, 2003).

Additionally, at the trail wrist, high accuracy shooters had a tendency to show more change in angle for the flexion/extension component when shooting at the BC target. Specifically, the data suggest that in order to be accurate, shooters tended to flex and extend the trail wrist more than low accuracy shooters. Intuitively, this trail wrist angle is related to a corresponding angle present at the lead wrist. We have established that the top targets necessitate a greater blade pitch angle, which would then imply that lesser blade pitch angles would be necessary to hit the bottom targets. Thus, to be accurate at the BC corner, the data and regression results suggest the necessity for more pronation at the lead wrist and more extension at the trail wrist. Accordingly, an increase in extension at the trail wrist would seem to serve as a means to maintain lower puck trajectories while maintaining the integrity of the shooting motion. Thus, in order to hit the BC targets, shooters should focus on attaining high pronation angles at SR for the lead wrist and a high ROM at the trail wrist with considerable extension angles.

This study confirms the importance of three-dimensional movement analysis in hockey. With such intricate movements throughout the body, two-dimensional motion capture methods do not sufficiently describe a skill such as the wrist shot. Included below is a comparison of the postural differences for a high and low accuracy shooter of similar size with the help of three-dimensional motion capture technology
(fig. 5.4).

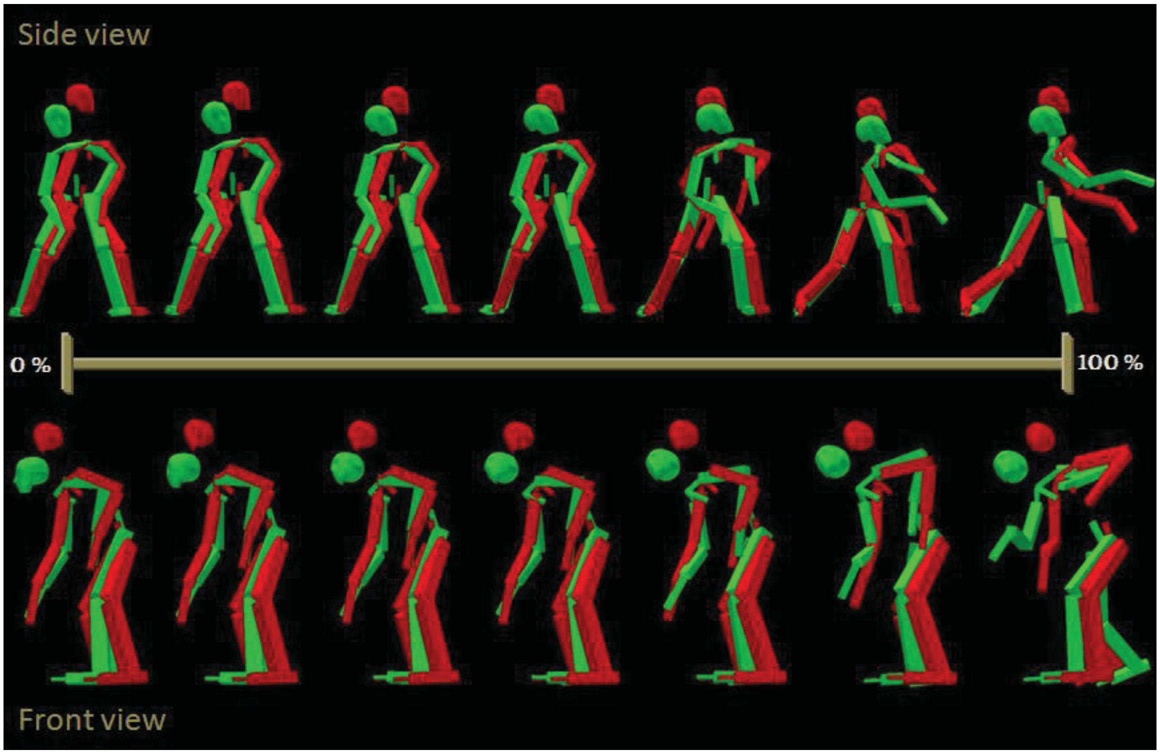


Fig 5.4: a composite image of the shooting sequence. In light gray (green), we have a high accuracy shooter, and in dark gray (red), we have a low accuracy shooter. Notable kinematic differences exist in the lower limbs, thorax, and upper limbs

If we look closer at the regression results 94.5% of the variance could be accounted for by seven parameters at BC, and 97.7% of the variance was explained by nine parameters at TC. For the ipsi side, 61.3% of the variance at the BI corner was accounted for by three kinematic parameters, and finally, 73.2% of the accuracy variance was explained by four kinematic parameters. Although no significant accuracy differences were found from contra to ipsi-lateral sides, the regression results suggest that shooting to the contra-lateral side may impose a more complex segmental arrangement and different synergies between the limbs may be found between shooting sides. Therefore, further research into this area will be necessary to understand the dynamic sequencing of the wrist shot kinematics.

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Appendix

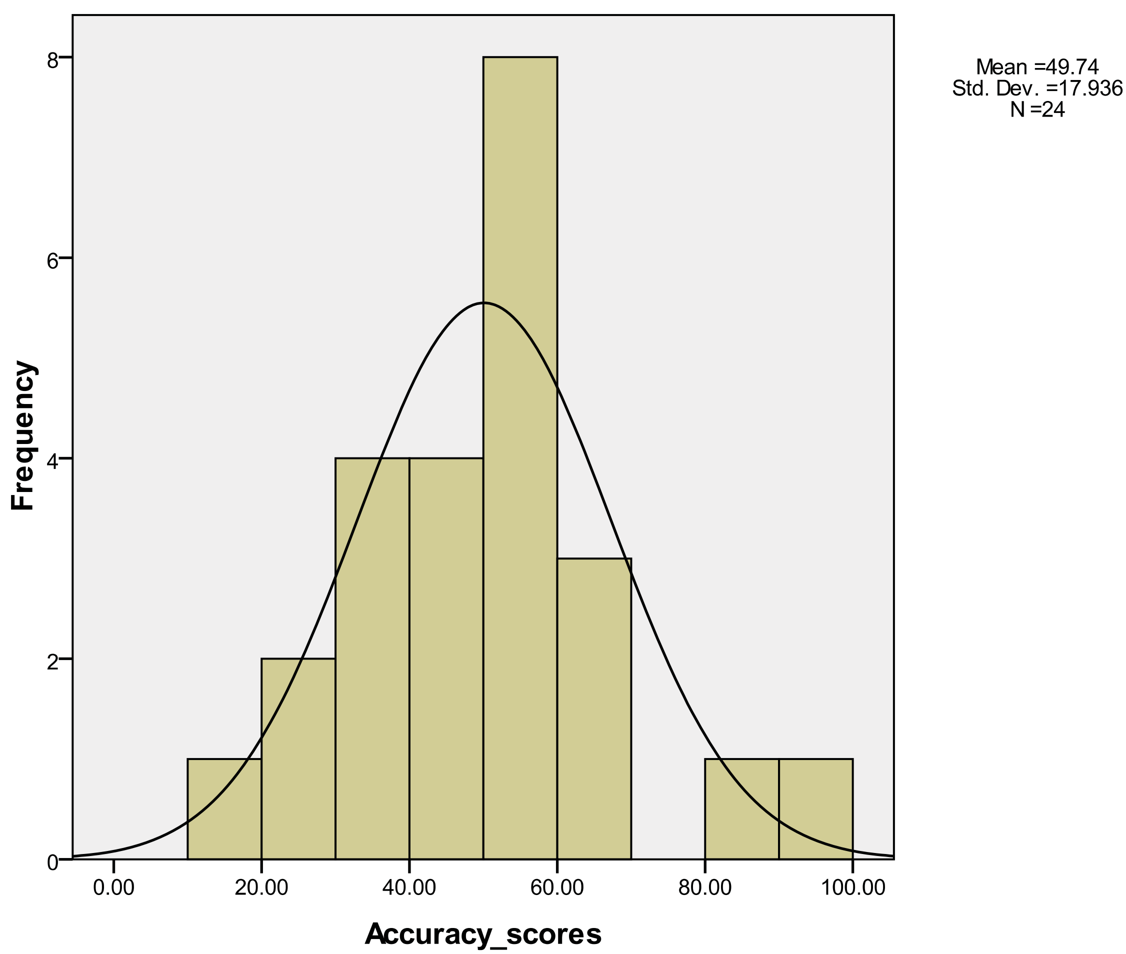
Appendix I – Accuracy score distribution

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Accuracy_scores	24	15.00	93.00	49.7375	17.93616
Valid N (listwise)	24				

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Accuracy_scores	.104	24	.200*	.983	24	.950



Appendix II – Consent form

INFORMATION AND CONSENT DOCUMENT

Investigator: Patrick M. Magee M.Sc. candidate
René A. Turcotte Ph.D.
Biomechanics Laboratory, Department of Kinesiology and Physical Education, McGill University

Statement of Invitation

You are invited to participate in a research project conducted by the above named investigator. This research project will be performed in the Biomechanics Laboratory of the Department of Kinesiology and Physical Education, McGill University, located at 475 Pine Ave West, Montréal, Québec H2W 1S4. You are asked to come to one experimental session that will each last from 1-2 hours. I greatly appreciate your interest in my work.

Purpose of the Study

The purpose of this study is to investigate stick and whole body kinematic data related to successful wrist shot execution.

Your participation in this study involves:

1. Providing informed consent prior to the experimental session,
2. Providing data concerning your physical attributes and hockey experience (e.g., height, gender, age, and different anthropometric segment measurements, years of experience in hockey, level of play),
3. Being outfitted with spandex clothing in order to obtain optimally accurate kinematic data.
4. Completing 10 successful shooting trials on four targets with a maximum of twenty attempts per target, wearing ice hockey skates and full body reflective marker set on an artificial ice surface while manipulating a hockey stick and puck.

Risks and Discomforts

It is anticipated that you will encounter no significant discomfort during these experiments. There are no risks associated with these experiments. An experimenter will be present at all times during the sessions.

Benefits

There are no personal benefits to be derived from participating in this study. Documenting the kinematic differences in shooting mechanics between skill levels will optimistically help increase the understanding, coaching, and performance of the wrist shot in the sport of ice hockey.

Confidentiality

All the personal information collected during the study you concerning will be encoded in order to keep their confidentiality. These records will be maintained at the Biomechanics Laboratory by Dr. René A. Turcotte for 5 years after the end of the project, and will be destroyed upon the expiration of this time frame. Only members of the research team will be able to access them. In case of presentation or publication of the results from this study nothing will enable your identification.

Inquiries Concerning this Study

If you require information concerning the study (experimental procedures or other details), please do not hesitate to contact *Patrick M. Magee*, at the numbers or addresses listed at the top of this document, at (514) 588-0099 (mobile), or at patrick.magee@mail.mcgill.ca

Responsibility clause

In accepting to participate in this study, you will not relinquish any of your rights and you will not liberate the researchers nor their sponsors or the institutions involved from any of their legal or professional obligations.

Consent

Please be advised that your participation in this research undertaking is strictly on a voluntary basis, and you may withdraw at any time.

A copy of this form will be given to you before the end of the experimental session.

Appendix III– Ethics certificate

McGill University

ETHICS REVIEW
RENEWAL REQUEST/FINAL REPORT

Continuing review of human subject research requires, at a minimum, the submission of an annual status report to the REB. This form must be completed to request renewal of ethics approval. If a renewal is not received before the expiry date, the project is considered no longer approved and no further research activity may be conducted. When a project has been completed, this form can also be used as a Final Report, which is required to properly close a file. To avoid expired approvals and, in the case of funded projects, the freezing of funds, this form should be returned 3-4 weeks before the current approval expires.

REB File #: 713-1006
Project Title: Physics of projectile accuracy in wrist shots
Principal Investigator: Patrick Magee, MSc candidate
Department/Phone/Email: Kinesiology & Physical Education; 09976
Faculty Supervisor (for student PI): David Pearsall, PhD, Associate Professor

1. Were there any significant changes made to this research project that have any ethical implications? ___Yes __x__No
   If yes, describe these changes and append any relevant documents that have been revised.

2. Are there any ethical concerns that arose during the course of this research? ___ Yes _x__ No. If yes, please describe.

3. Have any subjects experienced any adverse events in connection with this research project? ___ Yes _x__ No
   If yes, please describe.

4. __x__ This is a request for renewal of ethics approval. (see attached progress report)

5. ____ This project is no longer active and ethics approval is no longer required.

6. List all current funding sources for this project and the corresponding project titles **if not exactly the same** as the project title above. Indicate the Principal Investigator of the award if not yourself.

NSERC CRD grant CRDPJ 363586-07

Principal Investigator Signature: P Magee Date: 20 Aug/08

Faculty Supervisor Signature: DJ Pearsall Date: 20 Aug/08
(for student PI)

For Administrative Use **REB:** ___REB-I __x__REB-II ___REB-III

____ The closing report of this terminated project has been reviewed and accepted

__✓__ The continuing review for this project has been reviewed and approved

____ Expedited Review ____ Full Review

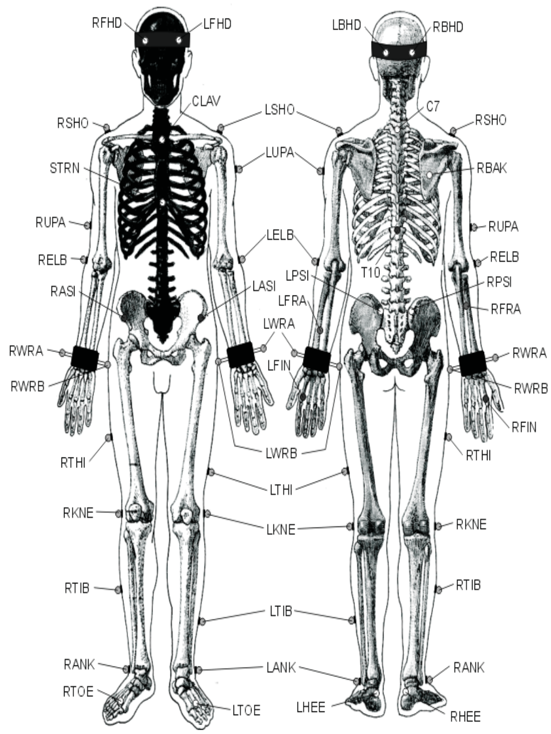
Signature of REB Chair or designate: L McNeil Date: Sept 29, 2008

Approval Period: Oct. 17, 2008 to Oct 16, 2009

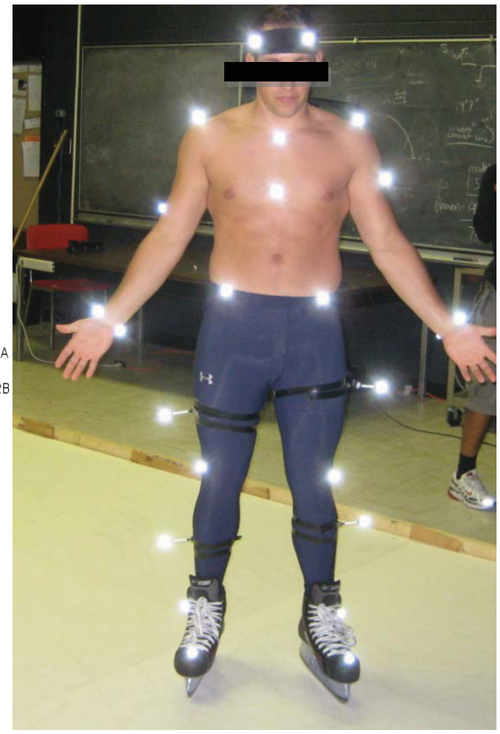
******NOTE NEW MAILING ADDRESS******
Submit to Lynda McNeil, Research Ethics Officer, 1555 Peel Street, 11th floor, fax: 398-4644 tel:398-6831

(version 12/07)

Appendix IV – Plug-in-Gait marker placement



a) Vicon® Plug-in-Gait



b) Vicon® Plug-in-Gait on subject

Appendix V – Accuracy score sheet

Shooter: ________________

Handedness: ________________

Top Left

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

Top Right

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

Bottom Left

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

Bottom Right

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

S = successful

U = unsuccessful

Appendix VI – Overall accuracy scores per subject

Wrist Shot Accuracy Scores		
Subject	**Handedness**	**Accuracy score**
1	Right	50
2	right	38.5
3	right	80.0
4	right	38.6
5	right	15.0
6	left	26.4
7	left	46.6
8	right	20.0
9	left	52.9
10	left	59.7
11	left	53.7
12	left	41.3
13	right	52.5
14	left	62.5
15	right	59.4
16	right	45.3
17	left	32.9
18	right	37.3
19	left	69.0
20	left	42.3
21	right	54.5
22	right	67.8
23	right	54.5
24	right	93.0