Acceleration Characteristics of Forward Skating

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ABSTRACT

The purpose of this study was to quantify kinetic and kinematic variables in ice hockey forward acceleration tasks as well as to compare two skate models: a regular ice hockey skate (SKATE) and a skate with a modified flexible tendon guard (SKATE FTG). Twelve adult male subjects performed four acceleration trials with each skate model. Strain gauges on the blade permitted direct skate push-off force estimates while body accelerations (forward-backwards) were estimated from a sensor placed on the player's back. The results demonstrated the feasibility to quantify bilateral skating dynamics. In terms of single and double support time, the combined left and right stride estimates approximate 80% and 20% of the skating stride, respectively. Overall, there were no significant differences between skate models in terms of time to complete the skate task or average stride rates. Significant contact time differences between the right SKATE and right SKATE FTG (0.41 vs 0.36s) contributed to greater impulse and power output were observed; however, the opposing effect of air resistance did not permit substantial time improvements over the 54 m skating distance.

ABRÉGÉ

Le but de cette étude était de quantifier les variables cinétiques et cinématiques pour une tache de patinage en ligne droite ainsi que de comparer deux modèles de patins: un modèle de patin de hockey conventionnel (SKATE) et un patin avec un protège-tendon souple modifié (SKATE FTG). Douze sujets adultes masculins ont effectué quatre essais d'accélération avec chaque modèle de patin. Les jauges de contrainte sur le support de lame ont permis d'estimer les forces de réaction au sol tandis que les valeurs d'accélérations (accélération et décélération) durant la phase de propulsion ont été estimés à partir d'un capteur placé sur le dos du joueur. Les résultats ont démontré la faisabilité de quantifier les forces dynamiques bilatérales. Les résultats ont confirmés la faisabilité de mesuré les forces dynamiques lors de tâches de patinage sur glace. Les valeurs temporelles de simple et de double-support combinant les patins droit et gauche sont approximativement 80 % et 20% d'une foulée complete. Dans l'ensemble, il n'y avait pas de différences significatives entre les modèles de patins en termes de temps pour compléter la tâche ni de différence entre les fréquences de foulée moyenne. D'importantes différences de temps de contact entre le patin droit SKATE et le patin droit SKATE FTG (0,41 vs 0.36s) ont contribué à une plus grande impulsion et

puissance de sortie ont pu être observés, mais l'effet opposé de résistance de l'air n'a pas permis des améliorations substantielles de temps sur la distance de 54 m de patinage.

Chapter 1: Introduction

1.1 Introduction

Much of what we know about skating biomechanics has developed through speed skating research (Ingen Schenau, De Boer, & De Groot, 1988). Past research in this sport has primarily concentrated on the kinematics and kinetics of forward skating with the aim of increasing performance through optimizing acceleration and achieving maximum velocity (de Koning, Thomas, Berger, De Groot, & Van Ingen Schenau, 1995).

To best understand speed skating technique, de Boer at al. examined the pattern of moments of force and power output at the ankle, knee and hip joints using strain gauges placed between the shoe and blade of the skates (de Boer, et al., 1987). They discovered that the body's center of mass accelerates from the point of push-off force as a result of the rotating segments such as the flexion and extension of hip, knee and ankle. The peak in push-off force occurs in the early phase of knee extension (115º) but the absence of plantar flexion means that the effective knee extension range is very small (115º-150º) (de Boer, et al., 1987). This results in a short and explosive extension of the knee joint. The power output in the push-off is mainly generated by the monoarticular extensor muscles (gluteus maximus and vastus medialis). It seems the power is transported from the hip to the knee by the bi-articular rectus femoris. Initially during push off, the hip has the largest moment however it decreases over time while the net moment in the knee and ankle joints increase over time (de Boer, et al., 1987).

Further analysis of speed skaters acceleration technique revealed that the speed skating start resembles a transition from running to gliding. Analysis of the different techniques used for propulsion demonstrate substantial differences in the push-off mechanics between the second and eighth strides (de Koning, et al., 1995). The second skating stride resembled a running stride as the push-off force was applied against a fixed point. However, in the eighth stride the skate glided during push-off thus executing a more lateral push-off. During the running like push-off the rotational velocity of the leg is a greater contributor to the body center of mass forward velocity than the extension velocity of the leg. However, the increasing leg extension during the gliding technique helps to obtain the higher velocities (de Koning, et al., 1995).

Speed skating research such as that conducted by de Boer et al. and de Koning et al. provided important insights that may be translated to ice hockey, as the gross skating movement patterns are similar between skating contexts. Forward skating is a biphasic movement, which consists of alternating single and double support phases (Marino, 1977). In previous research, Marino concluded that while skating at maximum velocity a player experiences a gliding phase during the single support period and a propulsion phase during the double support period. Eighty percent of the skate stride is spent in single support and 20% in double support. The results of Marino's research indicate that as velocity increases, the stride rate also increases but the single and double support times decrease. Therefore, in the acceleration phase, the number of times force is applied is the most important factor not the amount of force applied per stride (Marino, 1977).

A hockey player's ability to accelerate at a high intensity for two or three strides is a fundamental skill required in the game of ice hockey. In 1989, Hoshizaki used 2D cinematography to analyze forward skating and found the acceleration phase consisted of the first three strides, at which point maximum velocity was maintained with a forward skating stride (Hoshizaki, Kirchner, & Hall, 1989). With this in mind, Marino examined the kinematics of the front power start. The highest acceleration occurred immediately after the first overt movement and lasted for 1.25 seconds. Positive acceleration lasted for the first 1.75 seconds however was then followed by periods of deceleration (Marino, 1979). The deceleration occurred when maximum velocity had been reached and subsequently gliding phases alternated with propulsive phases. However, velocity continued to increase beyond the initial start stride. If positive acceleration lasted for the initial three or four strides it is evident that it is possible to apply propulsive force in both the single and double support phases (Marino, 1977).

To maximize acceleration the propulsive limb must be moved through a full range of motion (ROM) while maintaining stride rate. In further analysis of the hockey start, Lafontaine (2007) used 3D video cameras to track the skater's movement to investigate how ankle and knee kinematics evolve from the start to maximum velocity during forward acceleration tasks. The results indicated that the knee and ankle ROM increased with every stride as the velocity increased. The skate boot kept the ankle in dorsiflexion throughout the acceleration task; however, eversion increased with velocity. The increased rear foot eversion allowed skaters to apply force to the ice surface perpendicular to the tangential glide path, thus helping to increase velocity during the subsequent contralateral foot support (Lafontaine, 2007). These findings were supported by Pearsall et al. (2001) when electrogoniometers were used to measure ankle kinematics in forward ice hockey skating. Maximum eversion was exhibited just prior to push-off to facilitate the optimal blade to ice contact orientation to elicit the desired resultant force vector.

The importance of ankle range of motion was initially illustrated with the concept of the klapskate. In 1996, Ingen Schenau et al. designed an articulated speed skate allowing the blade to pivot about a hinge joint mechanism below the front boot attachment. This skate (termed the klapskate due to the “klap” sound heard following the blade’s spring return after each push off) permitted a more powerful plantar flexion and in turn a longer push-off phase that could not be performed in the traditional, Norwegian style speed skate (Ingen Schenau, De Groot, Scheurs, Meester, & De Koning, 1996). When examining jumping and running mechanics, Ingen Schenau realized that plantar flexion contributed a great deal of force. Furthermore, Ingen Schenau argued if speed skaters could perform both full knee extension and plantar flexion they would generate a greater work stroke, therefore increasing skate speed potential.

Subsequent research conducted in 2000 by Houdijk et al. compared the push-off mechanics in speed skating of conventional skates and klapskates. The findings of the study demonstrated that speed skaters using the klapskate produced an increase in mean power output of 25 W over the conventional skates; thus translating into a 5% increase in velocity when using the klapskate (Houdijk, De Koning, De Groot, Bobbert, & Van Ingen Schenau, 2000). Furthermore, the stroke frequency was higher (from 1.30 to 1.36 strokes*s^{-1}) and the total work per stroke was 11 J greater with the klapskate. The researcher highlighted that one reason for the increased power output in the klapskate was that during the push off phase, specifically in the final 50ms, the force was directed perpendicular to the blade through greater knee extension and ankle plantar flexion.

Can similar changes to speed skates be applied to ice hockey skates? The more assorted skills required in the latter, such as rapid changes of directions and stops, preclude an articulated blade due to lack of stability. However, potentially other ergonomically inspired design modification for ice hockey skates may be considered. For instance, hockey skate manufacturers have been interested in the effects of ice skating performance after increasing the range of motion in skate boots.

To accurately evaluate the biomechanics of skating researchers had to overcome the technical challenges of measuring force during on-ice skating. In 2010, Stidwill et al. developed a portable force measurement system, which successfully performed a kinetic analysis of vertical and medial-lateral forces produced during on-ice skating; thus allowing us to evaluate the kinetic changes due to an increased range of motion in the skate boot (Tyler J. Stidwill, et al., 2010). In the study, propulsive forces were measured using strain gauges attached to the outside of the right skate blade. In addition, electrogoniometers measured dynamic knee and ankle movements during forward skating. On the ice subjects performed forward start, acceleration and constant velocity skating tasks. The strain gauge values produced had a high linear relationship with known force values.

Subsequently, Lachine (2010) compared the push-off force, during on-ice acceleration trials, between the regular skate (known as the SKATE) and the modified skate (known as the SKATE FTG), which had a more flexible tendon guard. The right skate, of both skate types, was instrumented with the force transducer system Stidwill developed as well as the electrogoniometers (Lachaine, 2010; Stidwill, Turcotte, Dixon, & Pearsall, 2010). The flexible tendon guard in the SKATE FTG allowed for a statistically significant increase in plantar flexion and net plantar/dorsiflexion range of motion (Lachaine, 2010). The SKATE FTG also had significantly higher medial-lateral peak and average forces during acceleration phase but not the constant velocity phase. Some of the increased force production was believed to be a result of the increased contribution of the calf muscles at the end of the push off and a fuller knee extension, which was also supported by Ingen Schenau's theory on the use of the klapskate and due to the incomplete knee extension seen in the traditional skate. The SKATE FTG also provided a 14 to 20% increase in work and power output however, it did not result in a higher skating velocity (Lachaine, 2010). According to Marino (1977) the stride rate is the determinant factor for velocity and subsequently, Lachaine et al. demonstrated that the stride rate and contact time were similar between skate types thus leading to similar skating velocities. Although the SKATE FTG does not prove to have statistically significant increases in kinetic variables during the velocity phase its does during the acceleration phase. It is during the acceleration phase of forward skating that medial-lateral average and peak forces, maximal plantarflexion and plantarflexion angle at peak force were all statistically different between skate types.

Some of the increase in force with the SKATE FTG may have been lost due to changes in skating technique adopted when skaters were not accustomed to the increased plantar/dorsi range of motion. Therefore, there were some undesirable changes in kinematics and thus a reduction in mechanical efficiency due to a lack of familiarity. Lachine et al. believed that some of the additional work may have been lost in medial-lateral plane as the skaters experienced a greater sway in center of mass from side to side, while it was more stable in the more familiar SKATE. Therefore, some of the outcomes may be attributed to the participants lack of familiarity with the SKATE FTG.

Baig et al. continued the investigation into the SKATE FTG using a Biodex System 4 Pro dynamometer to measure boot stiffness characteristics in the SKATE and SKATE FTG. As previously seen, the SKATE FTG boot had significantly greater range of motion than the SKATE boot thus allowing greater plantar flexion. However, the increased range of motion did not translate into a greater amount of total work in the SKATE FTG boot (Baig, 2010).

How much do the propulsive forces during on ice skating tasks contribute to the body's acceleration? How can the COM of the body during ice hockey skating be examined? The prior studies cited above have used video image recording to derive kinematic information; however, the inherent limitations with this approach (e.g. very large field of view leading to poor measurement accuracy and the inability to track more than one stride) are a deterrent for large subject sample studies. To avoid this restriction, alternative technologies can be considered. For instance, advances in Inertial Measurement Unit (IMU) hardware and associated software's may provide a solution to direct and unhindered measures of a skater's movements, allowing for estimates of COM progression, in the anterior-posterior, medial-lateral and vertical directions. In the following is a brief review of its research and clinical applications.

Inertial measurement units allow researchers to perform field-testing thus eliminating the need for camera-based systems such as Vicon. The IMU combines three sensors, an accelerometer, gyroscope and magnetometer to capture and analyze three-dimensional orientation and acceleration. The present study has chosen to analyze only the accelerometer data for this particular thesis.

Accelerometers have been used in gait laboratories for many years because they are small, they do not restrict movement, they do limit data collection to the lab environment and they cost very little compared to other equipment commonly used in gait laboratories (Kavanagh & Menz, 2008). The accelerometer operates by assigning tangential or linear acceleration vectors to the body it is attached to and detects rotational and translational accelerations of the moving body (Kavanagh & Menz, 2008). However, one limitation when using an accelerometer to analyze gait is that the direction of movement cannot be determined, therefore it is easiest to interpret the data when the movement is cyclical and in a straight line (Kavanagh & Menz, 2008).

The recommend location when using only one triaxial accelerometer is to attach it over the L1-L3 spinous process as it closely reflects the lower trunk accelerations during walking (Bergamini, et al., 2012; Kavanagh & Menz, 2008; Moe-Nilssen, 1998). This location is beneficial as it has low transverse plane rotation relative to axial rotation of the pelvis and thorax. Consequently this is a reliable location to directly measure acceleration of the upper body in healthy individuals (Moe-Nilssen, 1998).

Bergamini (2011) used a single inertial measurement unit (IMU) to identify foot strike and foot-off instants of time in maximal sprint runs. (Bergamini, et al., 2012). The IMU was placed on the lower trunk (L1 level) of each athlete. The study compared the acceleration and angular velocity vectors between amateur and elite athletes. In doing so they illustrated that a single, trunk mounted IMU was suitable in estimating stance and stride duration during sprint running.

In 2011, Stauffer performed a preliminary investigation in the use of accelerometers to measure ski, leg and torso accelerations for Nordic skiers. A custom designed shirt was used to fix the accelerometer to the subjects torso (Stauffer, Onillon, & Vetter, 2011). They determined that the frontal accelerations measured on the torso correlated with the ski accelerations. An unexpected finding was that the center of mass vertical acceleration was almost constant while there was noticeable lateral acceleration. It was hypothesized that there would be minimal to no lateral acceleration with noticeable vertical acceleration. Although these results are preliminary they believe this finding was a result of the accelerometer moving slightly during the trial thus illustrating the importance of securely fastening the accelerometer to the body.

Thus, the goal of this study was to incorporate the use of the portable force measurement system for both skates and the evaluation of trunk acceleration using two skate models, the SKATE and the SKATE FTG.

1.2 Purpose

The purpose of this study was to analyze and quantify kinetic and kinematic variables in ice hockey forward skating tasks. A comparison was made between two skate models, a Regular hockey skate (SKATE) and a modified skate with a flexible tendon guard, known as the SKATE FTG, which allowed for increased dorsi flexion and plantar flexion during skating tasks. The study used an Inertial Measurement Unit (IMU, model:

InertiaCube BT, company: InterSense, location: Billerica, MA) to measure the anterior-posterior (relative to the movement direction) trunk acceleration, while performing a series of on ice skating tasks. In addition, the study aimed to measure the concurrent dynamic forces during the skating tasks using strain gauge force transducers. The acceleration and dynamic forces were evaluated simultaneously in order to examine how much of the skates total push-off force contributed to the forward acceleration of the body. Furthermore, the study evaluated the mechanical work required to move the body's center of mass during forward skating.

1.3 Hypotheses

Based on previous research it is anticipated that the SKATE FTG will provide a performance advantage in a forward acceleration task over the SKATE. Subsequently, the SKATE FTG stride rate will be greater than the SKATE and the contact time will be shorter for the SKATE FTG. Consequently, the use of the SKATE FTG during the performance of the forward acceleration tasks will result in higher peak forces, impulse and power than the SKATE. In addition, it is expected that the SKATE FTG will result in an increase in acceleration and subsequently, a faster time of completion.

1.4 Limitations and Delimitations of this Study

1.4.1 Limitations

Limitations of this study were:

- The tasks were performed in a non-game situation and pre-planned; therefore, to what extent these findings are representative of skating tasks in an open game situation needs to be determined
- The subjects did not use their own personal skates, which may affect their skating patterns.
- The skates were sharpened in a traditional manner before each testing period and therefore, optimal blade sharpness was not controlled for.

1.4.2 Delimitations

The delimitations of this study were:

- The subjects did not wear full ice hockey equipment, thus possibly affecting the kinetics and kinematics of the body.
- Only males subjects were tested
- The subject pool included only forwards and defenseman

Chapter 2: Review of Literature

2.1 History of Hockey

The game of ice hockey dates back to the early 1800s in Windsor, Nova Scotia where a group of students from King's College School played a game called ice hurley (Diamond, 1998). Hurley was a summer time sport typically played with a ball and stick somewhat resembling lacrosse with goal zones, posts and goalkeepers (Diamond, 1998). However, Canada's cold winter conditions provided an added challenge of playing on ice (Pearsall, Turcotte, & Murphy, 2000). The original rules of ice hockey were influenced by cultural roots of English, Scottish, and Irish immigrants. Since the 1800s ice hockey has adapted to incorporate technical equipment designs, extensive training, coaching, and game strategies (Pearsall, et al., 2000).

2.2 Hockey Skills Classification

Hockey is considered an "open" skill which requires players to consistently respond to game cues (Pearsall, et al., 2000). A unique skill set is required to play the game of ice hockey. A player relies on qualities such as speed, balance, agility, accuracy and reaction time in order to skate, check, stick handle and shoot (Pearsall, et al., 2000). Performance in hockey is dependent on a number of factors which include but are not limited to physical condition, individual skill, equipment and environment (Federolf, Mills, & Nigg, 2008; Pearsall, et al., 2000).

2.2.1 Internal Factors Affecting Performance

Ice hockey is a high intensity game that stresses both the aerobic and anaerobic energy systems (Montgomery, 1988). During a 60 minute game, players average about 15 to 20 minutes of play. An average shift typically lasts only 43.1 to 47.1 seconds and at intervals of 4 or 5 minutes (Montgomery, 1988; Montgomery, Nobes, Pearsall, & Turcotte, 2004). An elite hockey player must compete at a high intensity throughout the entire game and thus a great aerobic endurance is necessary to meet the intensity and duration of every shift. A hockey player’s average heart rate during a shift is 85% while their maximum heart rate exceeds 90%.

Due to the physical nature of the game, it is necessary for elite hockey players to have both upper and lower body strength and power (Montgomery, 1988). Hockey players are often mesomorphic as they require anaerobic power and muscular strength to achieve optimal acceleration and maintain maximum skating velocity (Montgomery, 1988). Both type I and type II muscle fibers experience muscle glycogen depletion during a game and subsequently, blood lactate levels are elevated above resting levels. Consequently, a vast amount of current research is directed towards improving the physical condition of hockey players.

2.2.2 External Factors Affecting Performance

The external factors that have the greatest influence on skating performance include: air friction, ice surface and skate properties (Jos J. de Koning, de Groot, & van Ingen Schenau, 1992).

2.2.2.1 Air Friction

Extensive speed skating research has indicated that air friction is affected by a number of factors; two of which include anthropometric measures and the speed skaters body position (Ingen Schenau, De Boer, & De Groot, 1988). Anthropometric measurements such as body mass and body length significantly affect the degree of drag force (Ingen Schenau, et al., 1988). There is conflicting evidence supporting the optimal height and weight to enhance skating velocity however maintaining a low body fat percentage is critical. The skating position which optimizes skating velocity is dependent on three joint angles: trunk, knee and ankle angle (Ingen Schenau, et al., 1988). Most notably, speed skating coaches stress the importance of maintaining a horizontal trunk while racing in order to reduce the drag force. The combination of these joint angles have a significant effect on the overall drag force of the speed skater and consequently, the achieving maximal velocity during a race.

2.2.2.2 Ice Surface

Ice conditions can greatly affect the skating performance during a game of ice hockey. Ice friction is equal to the product of the normal force (N) (i.e. body weight) and the ice friction coefficient (μ) (Ingen Schenau, et al., 1988). The friction coefficient of ice is largely dependent on the temperature at which the ice is maintained. Measuring the effects of friction on speed skating performance has proven difficult in the past. One method of measuring the coefficient of friction has been to place strain gauges on the TUUK of the skate and subsequently measuring push-off force in the horizontal and vertical directions (de Boer et al., 1987; Jos J. de Koning, et al., 1992; Jobse, Schuurhof, Cserep, Schreurs, & Dekoning, 1990). A unique characteristic of skating is that a low coefficient of friction is necessary for gliding while a high coefficient of friction is required for starts/stops and quick changes in direction. The friction coefficient of ice ranges from $\mu = 0.003$ and $\mu = 0.010$ and often changes by 0.001 or 0.002 between periods that the ice is treated (Federolf, et al., 2008; Ingen Schenau, et al., 1988). The low coefficient of ice is the product of the thin semiliquid layer naturally found on the ice and the low temperature maintained in the arena, ranging from -6 to -9 C (Jos J. de Koning, et al., 1992; Pearsall, et al., 2000). The colder ice temperatures also make it easier for the puck to glide along ice surface. Furthermore, the Zamboni helps to maintain the low coefficient of removing a thin layer of ice and depositing a thin layer of hot water (Pearsall, et al., 2000).

2.2.2.3 Skate Properties

The design and construction of the hockey skate are fundamental to a hockey player's performance. Over the years, skates have been constructed by a variety of materials such as polyethylene resins, carbonates and fiber glass in order to decrease the mass of the skate and allow for greater mobility (Pearsall, et al., 2000). Researchers believe that the important characteristics of an ice hockey skate such as radius of curvature, center of curvature and the alignment of the blade with the boot will affect performance of linear skating, turning, and stopping (Pearsall, et al., 2000).

2.2.2.3.1 Boot Stiffness

A great deal of research goes into the hockey skate design to optimize skating performance. In a skate boot, it is critical to have a balance between support and flexibility, while at the same time providing comfort and protection (Turcotte, Pearsall, & Montgomery, 2001). Stability in an ice hockey skate is not only necessary for ankle support but it also allows the hockey player to have complete control while skating. Consequently, the stiffness characteristics of an ice hockey skate are a primary concern for elite hockey players. In 2001, Turcotte et al. developed a protocol to measure the stiffness characteristics of an ice hockey boot. Ankle range of motion was measured using six particular movements including dorsi-flexion, plantar flexion, inversion, eversion and medial and lateral torsion movements (R. A. Turcotte, et al., 2001). Within this study, Turcotte et al. tested the protocol by measuring the stiffness characteristics of the Bauer Supreme 1000 and 5000 and the Bauer Air90. After testing the skate designs in all ranges of motion, the Bauer Supreme 5000 had the greatest stiffness characteristics when compared to the Bauer 5000 and the Air 90. Turcotte et al. concluded that the protocol employed for measuring stiffness characteristics in hockey boots allows manufacturers to test the effects of specific designs and materials prior to production (Turcotte, et al., 2001).

In recent years, skate manufacturers have been interested In the effects of skating performance after increasing the range of motion in skate boots. In 2010, Baig et al., measured boot stiffness characteristics in a Regualr skate (SKATE) and a modified skate (known as the SKATE

FTG), which had a more flexible tendon guard. Initially, the authors established the natural foot and ankle range of motion in a Nike Free 5.0 using a Biodex System 4 Pro dynamometer. Subsequently, the range of motion was compared to the skate types. The shoe and the SKATE FTG had significantly greater range of motion than the SKATE (Baig, 2010). Furthermore, the SKATE FTG boot allowed greater plantar flexion than the SKATE however, this did not translate into a greater amount of total work in the SKATE FTG (Baig, 2010).

2.2.2.3.2 Range of Motion

The introduction of the klapskate and the research surrounding it demonstrated the importance of range of motion. In 1996, Ingen Schenau et al. designed the klapskate which had a hinge placed between the blade and the boot inferior to the metatarso-phalangeal joint. The researchers argued that the klapskate permitted a powerful plantar flexion during the push-off phase that could not be performed in the traditional, Norwegian style speed skate (Ingen Schenau, De Groot, Scheurs, Meester, & De Koning, 1996). The klapskate design allows the skate blade to remain in a horizontal position on the ice during the push off. When wearing the Norwegian style speed skate, skaters were taught to keep their weight on the back of the skate when gliding and pushing off to minimize ice friction.

Consequently, speed skaters were unable to fully extend their knee in the push off phase. When examining jumping and running mechanics, Ingen Schenau realized that plantar flexion contributed a great deal of force. The potential power output from plantar flexion is lost in speed skating if the skater has to pull their leg off the ice prior to full knee extension. Ingen Schenau argued if speed skaters could perform full knee extension and plantar flexion they would generate a great power output, therefore increasing performance.

Ingen Schenau tested the performance of klapskates versus Norwegian style skates using a case control study (Ingen Schenau, et al., 1996). During 1994/1995 speed skating season 11 male speed skaters from the Zuid Holland region of the Netherlands agreed to switch from the Norwegian style skate to the klapskate. The results indicated that the speed skaters using the klapskate improved their performance by a significantly large ($p < 0.001$) 6.2 ± 2.3% while the skaters with the Norwegian style skates improved their performance by 2.5 ± 1.6% (Ingen Schenau, et al., 1996). These results were not only significant but they also provided the necessary frame work for future speed skating research. In 1998 at the Nagano Winter Olympics all speed skaters used klapskates and consequently, all the world records were shattered.

Subsequent research conducted in 2000 by Houdijk et al. examined the biomechanics that contribute to the increased performance in the klapskate. The findings of the study supported Ingen Schenau's research as skaters achieved a 5% increase in velocity when using the klapskate (Houdijk, De Koning, De Groot, Bobbert, & Van Ingen Schenau, 2000). Furthermore, the stroke frequency was higher and the total work per stroke was 11 J greater with the klapskate. This resulted in an increase in mean power output of 25 W when using the klapskate instead of the conventional skates (Houdijk, et al., 2000). The researcher highlighted that one reason for the increased power output in the klapskate was that during the push off phase, specifically in the last 50ms, the force was directed perpendicular to the blade through knee extension and ankle plantar flexion. However, in the conventional skate knee extension is suppressed and prevented from contributing to the power output. Literature provides strong support for increasing speed skating performance with increased ankle range of motion.

2.2.2.3.3 Blade Edge

An ice hockey skate blade is shaped like a rocker and has a radius of curvature that runs from anterior to posterior (Humble & Gastwirth, 1988). The blade of a hockey skate is designed to have sharp medial and lateral edges with an intermediate shallow channel (Humble & Gastwirth, 1988). Optimal sharpness is required of the edges to allow for acceleration, quick changes of direction and smooth stopping (Pearsall, et al., 2000). Most skating tasks are performed with either the medial or lateral edge and rarely does the entire blade run flat along the ice (Humble & Gastwirth, 1988). Acceleration requires an acute angle between the ice and the skate blade so that the medal edge can cut into the ice surface. Quick changes of direction require the lateral edge of the skate blade to provide a pivot point by cutting sharply into the ice.

The ice hockey skate blade design has not changed significantly for decades. However, in 2004, CT Edge patented a new skate blade design that reportedly reduced the coefficient of friction. The new CT Edge blades flare outward on both sides changing the angle of contact between the blade and the ice and furthermore provide a wider contact area between the blade and ice. In 2008, Federolf et al. compared the friction coefficient between the standard blade and the new CT Edge blades designed with blade angels of 4°, 6°, and 8° (Federolf, et al., 2008). The CT Edge blades had a lower friction coefficient than the standard blade and the friction coefficient appeared to decrease as the blade angle increased.

2.3 Skating Mechanics

Most hockey enthusiasts agree that skating is the most important and complex skill required in the game of hockey (Renger, 1994). Much of what we know about skating biomechanics has developed through speed skating research. Speed skating research such as that conducted by Ingen Schenau, de Boer and de Koning has provided important insights into hockey research such as linear movement patterns.

2.3.1 Linear Movement

Linear skating at a constant velocity is a biphasic movement which consists of alternating single and double support phases (G. W. Marino, 1977). Marino stated that while skating at maximum velocity a player experiences a gliding phase during the single support period and a propulsion phase during the double support period. In subsequent research, Pearsall et al. supports this concept but suggests that skating patterns be divided into a support phase and a swing phase (Pearsall, et al., 2000). Additionally, the support phase is subdivided into a single and double support period. Within this concept, propulsion generally begins in the middle of the single support phase due to extension of the knee, hyperextension and abduction of the hip and plantar flexion of the ankle

(Pearsall, et al., 2000). Linear skating is a result of external rotation of the hip and force applied perpendicular to the skate blade.

The understanding of linear movement and the propulsive forces that contribute to the push-off phase in speed skating are critical to improving athletic performance. A seminal piece of research was conducted by de Boer et al. (1987) to understand linear movement in speed skaters. In 1987, de Boer at al. examined the pattern of moments of force and power output at the ankle, knee and hip joints in order to understand the technique and muscle coordination during speed skating (de Boer, et al., 1987). de Boer states that the center of gravity accelerates from the point of push-off force as a result of the rotating segments such as the flexion and extension of hip, knee and ankle. Initially during push off, the hip had the largest moment however it decreased over time while the net moment in the knee and ankle joints increased over time (de Boer, et al., 1987). In a similar study, de Koning et al. (1992) examined the joint moments and powers exhibited during push-off. Using EMG, the muscle activation was measured in ten leg muscles during the push-off phase. It was evident that muscle activation in the leg follows a proximo-distal temporal order as propulsion occurs (J.J. de Koning, deGroot, & Ingen Schenau, 1991).

A study conducted by Song et al. in 1979 illustrated the importance of the relationship between lower limb strength and flexibility in linear skating. The researchers delineate that skating velocity is dependent on strength, flexibility and anthropometric factors such as hip flexion strength, ankle dorsiflexion, hip adduction-abduction flexibility and knee flexion-extension flexibility (Song, 1978). The propulsive limb must be able to move through a full range of motion to maximize skating velocity. Other skating techniques that allow hockey players to obtain maximum velocity included: significant forward lean when the recovery leg touches the ice, placement of the recovery foot directly below the hip, short single support periods, a full knee extension and a blade surface angle of 45 degrees (G. W. Marino, 1983).

The horizontal velocity of linear skating is determined by calculating the product of stride rate times stride length (G. W. Marino, 1977). The results of Marino’s research indicate that as velocity increases, the stride rate also increases but the single and double support times decrease. Therefore, the number of times force is applied is more important than the amount of force (G. W. Marino, 1977).

2.3.2 Angular Movement

A player’s performance in ice hockey is determined by their ability to quickly and frequently make directional changes and consequently, angular skating is a critical component in game of ice hockey. Changing the direction of travel requires centripetal force to be applied to an external axis of rotation (Pearsall, et al., 2000). As this occurs, the skater’s trunk leans into the center of the turn (or axis of rotation). Balance is maintained do to the reactive forces applied at the skate blade. An equal and opposite gravitational force is applied vertically while a horizontal reactive force acts as centripetal force (Pearsall, et al., 2000).

Ice hockey players are often required to make quick directional changes due to the rapid movement of the puck. A small angle between the skate blade and the ice is necessary to achieve quick changes of direction. In addition, blade sharpness is critical to maintaining control while performing quick angular movements as the blade cuts into the ice to provide a pivot point. Directional changes can be achieved by either pivoting while both blades run parallel or through a series of crossovers (Pearsall, et al., 2000). Crossovers have been more widely studied in speed skating as they allow the skater to execute propulsive forces to accelerate while turning. In order to complete this task, the outside leg applies force through the inside edge of the skate blade while the inside leg applies force through the outside edge of the blade (Pearsall, et al., 2000). The skate blade's radius of curvature allows a hockey player to be more agile while performing high velocity turns because the blade maintains contact with the ice surface as the player's center of mass shifts throughout the turn (Pearsall, et al., 2000).

One factor which appears to affect player's angular movements is leg dominance. In 2006, Young et al. determined leg dominance and muscle imbalance affects speeds tests when performing change of direction tasks. Typically the dominant leg is stronger than the non-dominant leg. Therefore, a faster change of direction was most commonly seen when the dominant leg was the outside leg as it contributed the greatest propulsive forces in the turn (Young & Farrow, 2006). For example, skaters that are right leg dominant performed faster directional changes to the left. Similarly, Cowly et al. (2006) found that during cutting maneuvers subjects produced ground reaction forces which were 41.4% greater in their dominant limb than their non-dominant limb.

2.3.3 Starts

A player's ability to accelerate at a high intensity during a hockey is one of the most important skills required. Throughout a game, players are often faced with the task of racing to get to a puck due to the rapid movement of the puck between opponents (G. Marino, 1996). The three most common hockey starts are the straight forward start, crossover side start and thrust/glide or “T” start (Pearsall, et al., 2000). In 1979, Naud and Holt determined that the thrust/glide start produced the greatest acceleration over the first two strides. The thrust/glide technique allowed players to apply push-off force perpendicular to the direction of travel while the push-off force in the front start was applied at a 45 degree angle. Furthermore, the crossover start was the slowest because some of the push-off force was used to propel them vertically (Naud & Holt, 1979).

Other research supports the front power start and the crossover side start as the most effective at achieving high accelerations (G. Marino, 1996; Roy, 1977). In a real game situation, the front start and the crossover side start are most effective because the thrust/glide start requires proper positioning of the feet prior to execution (Pearsall, et al., 2000). The acceleration phase ends after the first three strides at which point maximum velocity is maintained with a forward skating stride (Hoshizaki, Kirchner, & Hall, 1989). Following the initial three strides a player develops a consistent movement pattern where the angle of propulsion decreases and consequently their acceleration decreases (G. W. Marino, 1983).

In 1979, Marino examined the kinematics of the front power start. The highest acceleration occurred immediately after the first overt movement and lasted for 1.25 seconds. Positive acceleration lasted for the first 1.75 seconds however was then followed by periods of deceleration (G. W. Marino, 1979). The deceleration occurred when maximum velocity had been reached and subsequently gliding phases alternated with propulsive phases. However, velocity continued to increase as it required more than 1.75 seconds to achieve maximum velocity. If positive acceleration lasted for the initial three or four strides it is evident that it is possible to apply propulsive force in both the single and double support phases (G. W. Marino, 1979). During the single support phase, the thigh rotates laterally, along with hip and knee extension. Furthermore, the recovery leg is externally rotated with hip, knee and ankle flexion thus allowing immediate propulsion. Consequently, there are no periods of gliding during the initial strides as the strides are short and choppy (G. W. Marino, 1979). Following this realization Marino redefined the ice skating stride with three functional phases: gliding during single support, propulsion during single support, and propulsion during double support. In 1996, Marino et al. highlighted some important predictors of a successful start are a high stride rate, significant forward lean, a low takeoff angle and placement of the recovery foot under the body for the next stride (G. Marino, 1996).

An analysis of speed skaters propulsion technique revealed substantial differences in the push-off mechanics between the second and eighth strides (J. J. de Koning, Thomas, Berger, De Groot, & Van Ingen Schenau, 1995). The second stride resembled a running stride as the push-off force was applied against a fixed point. Consequently, the contribution of the rotational velocity of the leg was a greater contributor to the skater’s acceleration than the extension velocity of the leg (J. J. de Koning, et al., 1995). However, in the eighth stride the skate glided during push-off thus executing a more lateral push-off. As a result the leg extension velocity was more important in increasing the speed skaters velocity rather than the rotational velocity.

2.3.4 Stops

Naud and Holt examined 3 strategies a hockey player may use to stop, turn around and accelerate again during a game (Naud & Holt, 1980). The two methods for stopping were a parallel stop and a skates in-line stop. Subsequently, the two starts examined were the crossover side start and the thrust/glide start. The combination which produced the fastest turnaround was the thrust/glide start following a parallel stop (Naud

& Holt, 1980). This was made possible because following the parallel stop both feet were at a 90 degree angle and subsequently, the rear foot maintained the 90 degree angle during the initiation of the thrust/glide start. When the feet in-line method of stopping was investigated, the subjects tended to glide sideways further.

In 1983, Gagnon, Dore, and Lamontagne used strain gauge force transducers to measure on-ice forces of a parallel stop. During a parallel stop the skater exhibited a horizontal rotation and quick lateral flexion of both skates while force is applied perpendicular to the direction of displacement (Gagnon, Dore, & Lamontagne, 1983). This method allowed skaters to maintain balance while applying large braking forces (Pearsall, et al., 2000).

2.3.5 Backwards Skating

Backwards skating plays an equally important role in ice hockey as forward skating. However, backwards skating is unique to ice hockey and therefore minimal research has been conducted to examine the biomechanics. When it comes to backward skating, greater flexibility is required in the boot of the skate. A hockey skate blade is designed with a curved blade to allow for weight transfer from front to back as required to generate power when backwards skating (Pearsall, et al., 2000). The force generated from backwards skating is less than forward skating because the force is generated with internal rotation of the hip and applied in a lateral and anterior direction. Consequently, the range of motion is not as large as forward skating (Pearsall, et al., 2000).

2.4 Skating Analysis

Our understanding of skating biomechanics has primarily developed from speed skating research. Past research has focused on improving performance through enhancing knowledge of the kinematics and kinetics of forward skating (J. J. de Koning, et al., 1995).

2.4.1 Kinematics

Measuring the kinematics of skating focuses on the movement of the body segments. As previously mentioned, de Boer et al. was one of the first researches to examine the pattern of moments of force and power output at the ankle, knee and hip joints in order to understand the technique and muscle coordination during speed skating (de Boer, et al., 1987). The study used EMG to analyze the muscle coordination in 6 muscles (the gluteus maximus, biceps femoris caput longum, semitendinosus, vastus medialis, rectus femoris, gastrocnemius). The main contention of this study states that the center of gravity accelerates from the point of push-off force as a result of the rotating segments such as the flexion and extension of hip, knee and ankle. De Boer et al. highlighted that the push off skate was lifted from the ice at 150 degrees. Therefore, full extension of the knee could not contribute to the power output and plantar flexion of the foot also did not occur. Initially during push off, the hip had the largest moment however it decreased over time while the net moment in the knee and ankle joints increased over time (de Boer, et al., 1987). Throughout push off, the gluteus maximus was the primary muscle responsible for the generation of power while the quadriceps aided in providing an explosive burst of power before the end of push-off. Subsequently, the knee extension ROM was small and consequently, had to be explosive. De Boer et al. compared this action to a catapult action. During the gliding phase the knee extensors (rectus femoris and vastus medialis) were pre-stretched while the biceps femoris and gastrocnemius were active. Therefore, when the gastrocnemius and biceps femoris turn off there is an explosive extension of the knee joint. The vastus medialis and rectus femoris produce the greatest amount of power at the knee joint.

In 2002, Chang et al. studied the kinematics of the lower limb during forward ice hockey skating on a treadmill. The skating stride of 5 varsity ice hockey players was analyzed at three different velocities. Joint kinematic data was measured at the hip, knee and ankle using electrogoniometry. Chang et al. illustrated that during the push off phase, propulsion was the result of extension at the hip and knee along with plantar flexion at the ankle (R. Chang, Turcotte, Lefebvre, Montgomery, & Pearsall, 2002). Furthermore, increased range of motion was observed at the hip and the knee in conjunction with the increasing velocities. In 2009, Chang et al. further analyzed the kinematics of speed skating by looking closer at the relationship between the hip adductor muscle function and the movement of the hip and thigh. The study highlighted that the adductor magnus exhibited the greatest increase in peak muscle activation and activation time with increased velocity (Ryan Chang, Turcotte, & Pearsall, 2009). Furthermore, there was a significant increase in stride length and stride rate with increased speed. However, this did not result in a significant increase in range of motion at the hip, knee and ankle. With increased speeds there was a significant increase in abduction eccentric contraction which is believed to be the main cause for groin strain (Ryan Chang, et al., 2009).

In 2008, Upjohn et al. compared lower limb kinematics of forward skating between high and low calibre hockey players. The main objective of the study was to develop a more complete understanding of the skating stride using lower limb segment orientation and joint angles. The results of the study highlighted that the high calibre hockey players achieved faster skating velocities than the low-calibre participants despite having similar stride rates (Upjohn, Turcotte, Pearsall, & Loh, 2008). Furthermore, high-calibre participants demonstrated significantly greater stride length and stride width (Upjohn, et al., 2008). This was supported by a greater rate of knee extension and plantar flexion during the propulsion phase while greater rate of hip and knee flexion occurred at weight acceptance.

In further analysis of the hockey kinematics, Lafontaine (2007) investigated how ankle and knee kinematics evolve from a forward skating start to the point where maximum velocity is achieved. The results indicated that the knee and ankle range of motion increased with every stride as the velocity increased. The skate boot kept the ankle in dorsiflexion throughout the acceleration task however, eversion increased with velocity. The increased ankle eversion allowed skaters to apply force in a tangential direction on the ice surface, thus helping to increase velocity (Lafontaine, 2007). These findings are supported by Pearsall et al.'s research in 2001 when electrogoniometers were used to measure ankle kinematics in forward skating stride. At the beginning of the single support phase the skate was dorsiflexed 7.1 degrees and reached a maximum dorsiflexion of 11.8 degrees as the double support phase began (Pearsall et al., 2001). During the swing phase, the ankle plantar flexed from 11.8 degrees dorsiflexion to 1.9 degrees dorsiflexion. Similarly, the ankle eversion increased throughout the push off phase. Maximum eversion occurred at 7.1 degrees just prior to push-off thus demonstrating the need to generate a resultant force on the ice (Pearsall, et al., 2001). As the foot undergoes the swing phase the ankle became inverted prior to the neutral position seen at the gliding phase.

2.4.2 Kinetics

In the past there have been a number of technical obstacles faced when measuring kinetic variables during on-ice skating (Stidwill, Turcotte, Dixon, & Pearsall, 2010). Past speed skating research has measured push-off force using strain gauges (de Boer, et al., 1987; de Koning, et al., 1992; Jobse, et al., 1990). The primary goal of these studies was to measure ice friction and consequently only measured force in the horizontal and vertical direction. Furthermore, the placement of the strain gauge transducers limited data collection on medial-lateral forces.

A portable force measurement system was developed by Stidwill which accurately determined vertical and medial-lateral force components (Stidwill, et al., 2010). In the study, propulsive forces were measured using a strain gauge attached to the outside of the right skate blade. The subjects wore a backpack which contained a microprocessor controlled data acquisition device (Stidwill, et al., 2010). In addition, electrogoniometers measured dynamic knee and ankle movements during forward skating. On the ice subjects performed forward start, acceleration and constant velocity skating tasks. The strain gauge values produced had a high linear relationship with known force values. In addition, the force estimates which were consistent trial-to-trial. The system successfully performed a kinetic analysis of vertical and medial-lateral forces produced during on-ice skating. Subsequently, Stidwill et al. used the strain gauge technology to compare the kinetics and kinematics of forward skating between a synthetic ice and an ice surface (Stidwill, Pearsall, & Turcotte, 2010). The study concluded that only minor difference existed between ice and synthetic ice. When the participants skated on the synthetic ice surface they extended their knee by an average of four degrees more than compared to the ice surface (Stidwill, et al., 2010). The synthetic ice surface had a higher coefficient of friction than the ice surface thus requiring quicker recovery from stride to stride because deceleration occurred more quickly.

In 2010, Lachaine et al. examined how push-off force differed between the regular SKATE and the modified SKATE FTG, which had a flexible tendon guard and eyelet configuration. The right skate of both skate types was instrumented with a force transducer system to measure medial-lateral and vertical forces while a goniometer was installed about the ankle to measure kinematics during skating (Lachaine, 2010). Contrary to Stidwill (2010) the goniometer was placed on the medial side of the shank and on the medial exterior surface of the boot to measure ankle kinematics (Lachaine, 2010). This positioning placed less stress on the goniometer, and decreased the likelihood of breakage during the vigorous acceleration tasks. The results of the test revealed that the SKATE FTG allowed a significant increase in plantar flexion and net plantar/dorsiflexion range of motion however, a greater kinetic output did not result (Lachaine, 2010). Furthermore, the SKATE FTG provided a 14 to 20% increase in work and power output however, it did not result in a higher skating velocity (Lachaine, 2010). The researchers believed this outcome to be a result of the participants lack of familiarity with the SKATE FTG.

2.4.3 Pressure Distribution

In 2001, Turcotte et al. measured plantar pressure patterns exhibited in ice hockey skates during forward skating. Pressure sensors were placed on the insole of the skate boot and subsequently, participants performed forward skating tasks at increasing velocities. The pressure sensors were categorized into four areas: anterior, posterior, medial and lateral. The results indicated that the gliding phase corresponded with a total force plateau prior to the peak force (Turcotte et al., 2001). As velocity increased the plateau region decreased in addition to a decrease in contact time due to the increased stride frequency. When analyzing the anterior to posterior pressure patterns, the force pattern shifted from posterior to anterior as illustrated by a heel strike to toe off support phase (Turcotte, et al., 2001). Subsequently, the anterior foot showed a greater peak force at higher velocities. The medial and lateral pressure patterns exhibited increased medial force as velocity increased thus supporting the research illustrating increased ankle eversion at high velocities (Turcotte, et al., 2001). In 2004, Turcotte et al. compared plantar foot force between skating on ice and on a skating treadmill. Supporting the previous research, Turcotte et al. once again found that as velocity increased so to do the peak forces at the toe-off. When comparing the whole foot force-time patterns at equivalent velocities there was no significant difference found between the ice surface and the skating treadmill (Turcotte et al., 2004). When looking just at the heel loading force it was 30% greater on the treadmill than the ice however, this was likely due to the differences in kinematics and muscle activation patterns (Turcotte, et al., 2004).

Further analysis of plantar pressure was conducted by Dewan using piezo-resistive sensors placed on the foot and ankle to measure pressure distribution during skating (Dewan, 2004). The results highlighted that the plantar medial foot had the highest pressure in the forefoot while the plantar lateral foot had higher pressure in the heel. Subsequently, plantar pressure was found to be greater on the medial side than the lateral side. Medial inside pressure was distributed on the ankle at the beginning of the stride and on the forefoot during push off. The lateral inside pressure was the greatest at the ankle during push-off however, at the end of the stride the lateral metatarsal exhibited higher pressure.

In 2006, Trumper compared in-skate pressure patterns between elite and recreational hockey players during forward crossovers. The elite ice hockey players performed the skating tasks significantly faster than the recreational players. The pressure profiles recorded during the skating tasks illustrated that there was significantly higher peak pressures in the plantar region of the recreational group while the elite players had significantly higher peak pressures in the medial and lateral regions (Trumper, 2006). In both the elite and recreational players there was higher peak pressures on the medial, lateral and plantar surfaces on the inside foot then the outside foot throughout the crossover tasks (Trumper, 2006). However, the influence of skating direction had no direct effect on the pressure profiles or peak pressure.

2.4.4 Task Analysis

Hockey players are assessed by scouts on their ability to perform tasks such as skating, stick handling, shooting and checking. In 2004, Montgomery et al. performed a task analysis on 10 National Hockey League teams and 180 players to quantify the time and frequency of various skating activities. The frequency of starts, stops, crossovers, sharp turns and direction changes were recorded in addition to total forward and backward skating. The average shift times were 44.7 s, 43.1 s and 47.6s for the centers (C), wingers (W), and defensemen (D) respectively (Montgomery, et al., 2004). Based on players position, Montgomery et al. examined the total number of forward starts, crossovers, sharp turns and direction changes and found defensemen performed the greatest number of movements at 270, followed by centers with 258 and lastly wingers at 227 (Montgomery, et al., 2004). In comparison to the other positions, the defensemen performed starts (64.7), stops (43.4) and forward-backward turns (60.8) most often. While the centers performed crossovers and sharp turns most often. The percentage of time spent skating backwards was 4.8% for the C, 5.7% for the W and 19.2 % for the D (Montgomery, et al., 2004). The results of the task analysis illustrate that players skating patterns differ depending on their positions. Consequently, players may benefit on having different skate designs to suit their required tasks.

Chapter 3: Methods

3.1 Subjects

For this study, 12 subjects aged 19-29 participated in the following protocol. Based on power analyses during pilot testing, this was a sufficient sample size for the given variables. Subjects varied in skill level from high to low calibre, from varsity hockey players and those with junior hockey experience, to recreational players and those who solely played in intramural leagues. The subjects were all healthy and capable of completing the required skating protocol. Prior to each testing session, subjects read and signed a consent form in accordance with the Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans. Ethics were approved by the McGill University Research Ethis Board (REB #270-0112). Subjects received no financial compensation for their participation.

3.2 Experimental Protocol

3.2.1 Environment

All testing was done at the McGill University McConnell Arena. The surface of the ice was freshly resurfaced with a Zamboni prior to testing to control for optimal skating conditions.

3.2.2 Setup

The subjects wore the SKATE and the SKATE FTG for the study.

Figure a: Medial and posterior view of the SKATE (Lachaine, 2010)

Figure b: Medial and posterior view of the SKATE FTG with the flexible tendon guard (Lachaine, 2010)

In addition, the subjects wore a helmet for security reasons and gloves and carried a stick to mimic a hockey setting. An Inertial Measurement Unit (IMU) was used to measure the trunk acceleration and was placed on the back of the pelvis at the L1-L3 level. The IMU was connected to a laptop via a Bluetooth receiver. The left and right skate were instrumented with five force transducing strain gauges. Wires from the strain gauges were connected to a box in a backpack containing the data logger and a trigger to start/stop the trials on the ice. The total weight of the backpack was 2.4 kg; prior studies demonstrated that such a weight did not alter skating mechanics (de Boer, et al., 1987). A standing trial was recorded with the strain gauges while the subject applied all their weight on the right foot in a standing position. This was repeated for the left skate. With the subject's mass, it was possible to verify precision of the force transducer system.

3.2.3 Pre-testing

Subjects read and signed the informed consent form which clearly stated the testing protocol. Prior to the maximal effort trials, subjects had 10 to 15 minutes to warm up so they could became familiar with the skates and the equipment. In order to insure the ankle range of motion was consistent between skaters, all subjects were instructed to lace the skates to the top islet (Lachaine, 2010).

3.2.4 Testing

The subjects were instructed to perform a series of forward acceleration trials. Skaters performed four good trials at maximal skating velocity. The subjects will began by standing behind the goal line and started after a verbal command. Following the tester's command to "go", the subject jumped straight up into the air and land on both skates, feet parallel. Subsequently, the skaters accelerated off the goal line by pushing off with either the right or left skate. When the subject reached the far goal line, they came to a complete stop using the parallel stop method and jumped straight into the air. The participants were given 2-3 minutes to recover between trials to avoid fatigue (Lachaine, 2010).

3.2.5 Task

The forward acceleration task was evaluated by having the subjects skate from one goal line to the second goal line at maximum speed. The distance covered was 54.25m. All subjects maintained a linear trajectory while covering the distance. The time to skate from one blue line to the next (15.24m) was measured with timing gates. A camera was placed on the red line on the opposite side of the ice to obtain a sagittal view of the acceleration task.

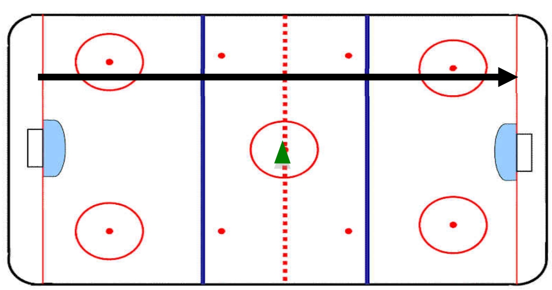

Figure c: The path of the skater during the forward skating task. The arrows represent the skating direction and the green triangles the camera placement.

3.2.6 Start

Each trial consisted of the subjects beginning from a standing position and accelerating as quickly as possible to maximum velocity. The subject began in a standing position, with their knees slightly flexed, feet parallel and approximately 30 centimeters apart (Naud & Holt, 1979). The athletes had the option to initially push off with either their right or left leg.

3.3 Research Design and Independent (IV)/Dependent(DV) Variables

Table 1: Research Design

Variable	Type	Scale	Definition
Skating tasks	Independent Variable	Categorical	(1) Acceleration (2) Maximum speed
Skating type	Independent Variable	Categorical	(1) SKATE (2) SKATE FTG
Vertical force obtained from the strain gauges	Dependent variable	Continuous	- Peak vertical force - Contact time and Stride rate - Impulse = Force x Δ Time - Work = Force x Δ Distance - Power = Work / Time - Single and double

			support (% of skate stride)
Acceleration obtained from the inertial sensor (anterior-posterior)	Dependent variable	Continuous	- Anterior-posterior acceleration/deceleration - Peak positive acceleration/deceleration

3.4 Instrumentation

3.4.1 Inertial Sensors

The inertial sensor used for this study was the InertiaCube BT (company: InterSense, location: Billerica, MA). The dimensions of an inertial sensor are 60 mm x 54 mm x 32 mm and weighs 67 grams. The InertiaCube BT is a wireless inertial sensor, which measures angular rate of rotation, linear acceleration and the earth's magnetic field in three perpendicular axes. The angular range measures all axes in full 360 degrees with a maximum angular rate of 1200 degrees per second and a minimum angular rate of 0 degrees per seconds. The InertiaCube BT reference frame is based on the local geographic frame with the x-axis pointing north, y-axis east and z-axis down.

For this particular study, only the accelerometer data was used. The InertiaCube BT was connected to the computer via a Class 1 Bluetooth receiver, which has a range of 100 feet. The update rate is 180

Hz and it has an average latency of 40ms. The operating temperature ranges from -5° to 50° C.

3.4.2 Strain Gauge Force Transducer

3.4.2.1 The Theory behind the Strain Gauge

The use of strain gauge force transducers is based on Hooke's law of elasticity which states that strain is directly proportional to the applied force (Frederiksson & Akerlind, 2008). This principle is true as long as the elastic limit of the structure is not exceeded (Frederiksson & Akerlind, 2008). The plastic skate blade holder is assumed to be linearly elastic so that when deformation occurs during the skating stride, the blade holder returns to its equilibrium position (Lachaine, 2010). Ultimately, the strain gauge is designed so that it produces electrical resistance proportional to the applied force (Winter, 2005).

The strain gauge is made up of strain sensitive alloy, which is displayed in a foil grid (Micro-Measurements, 2010b). The gauge is connected to a bridge circuit through connective wires and an electrical current is applied. Force acting on the TUUK causes a certain amount of strain within the strain gauge force transducer. Subsequently, the alloy is calibrated such that when it undergoes the smallest of changes it will result in a change in electrical resistance at the bridge circuit (Winter, 2005). Furthermore, a linear relationship exists between the deformation of the skate blade holder and the electrical resistance; consequently, the unbalance of voltages is proportional to material deformation (Winter, 2005).

The strain gauge converts compressive and tensile deformation of the blade holder to microstrain signals, which are subsequently converted to force estimates. Tension in the TUUK causes the alloy in the strain gauge to become thinner and longer resulting in an increase in electrical resistance (Winter, 2005). On the contrary, compression of the TUUK causes the alloy of the strain gauge to become broader and shorter thus decreasing the electrical resistance (Winter, 2005). The relationship between the change in the resistance and the applied strain is known as the gauge factor. The gauge factor is represented by the ratio $(\Delta R/R_o)/(\Delta L/L)$ where ΔR represents the change in electrical resistance, R_o represents the initial unstrained resistance of the gauge, ΔL represents the change in resting length and L represents the initial resting length (Hoffmann). The change in the electrical resistance can be calculated with the help of a Wheatstone bridge circuit.

The Wheatstone bridge circuit compares the known resistance of the gauge with the unknown electrical resistances due to the applied strain

(Hoffmann). The three main types of Wheatstone bridge circuits differ based on the number of active gauges. The Ice Hockey Research Group uses a half active bridge circuit which has two active bridges (Stidwill, et al., 2010). The half active bridge circuit consists of two identical strain gauges and two resistors with equal resistance value (Hoffmann). The two resistors within the bridge circuit change their resistances proportional to the strain acting against them. When there is no applied force and consequently no strain in the blade holder, the bridge is perfectly balanced and therefore, the two resistors are equal and the voltage output is zero (Winter, 2005). However, if a force is applied to the blade holder the transducer undergoes a strain which will result in an unbalance of voltages proportional to the force (Winter, 2005). The strain gauges are paired such that they experience opposite forces; thus, if one experiences compression the other experiences tension. Therefore, both gauges respond more accurately to the strain and thus, increase the response of the bridge to the applied force. Furthermore, paired strain gauges, which act opposite and proportionally to the force, reduce the incidences of error such as that resulting from temperature.

The selection of the appropriate gauge for the task is critical in obtaining accurate and reliable strain measurements (Micro-

Measurements, 2010b). In order to determine which strain gauge will be most compatible with the environment and the operating conditions one must consider the type of strain measurement (i.e. either static or dynamic), the test duration, the accuracy required, the operating temperature and the cyclic endurance (Micro-Measurements, 2010b).

The Ice Hockey Research Group determined that the CEA-series strain gauge (CEA-06-125UW-350) was ideal for measuring the skate blade holder deformation during on-ice skating tasks. The CEA-series is a primarily used for general purpose static and dynamic stress analysis (Micro-Measurements, 2010b). The stain-sensing alloy is made of constantan alloy, which has the ideal combination of properties for many strain gauge applications. An important characteristic of constantan is it's high strain sensitivity or gauge factor and subsequently, it's relative insensitivity to strain level and temperature (Micro-Measurements, 2010b). It is critical that the on-ice temperature does not greatly affect the strain gauge accuracy. Other important characteristics of constantan include a high elongation capability and a good fatigue life (Micro-Measurements, 2010b). A good fatigue life is advantageous when measuring propulsive forces during acceleration skating tasks as the TUUK is constantly undergoing rapid deformation. Constantan alloy is processed for self-temperature compensation such that it matches the test material expansion coefficient (Micro-Measurements, 2010b). The self-temperature compensation strain gauges are assigned a number to represent the approximate thermal expansion coefficient of the structural material in parts per million per degree Fahrenheit (Micro-Measurements, 2010b). The CEA-06-125UW-350 strain gauge was selected based on its self-temperature compensation number 06, as it closely matched the thermal expansion of the nylon plastic in the blade holder. These specific strain gauges are also designed to produce a minimal thermal output. The CEA-series strain gauge has a backing material made of a polyimide, which protects the constantan grid and makes it less sensitive to damage (Micro-Measurements, 2010b). The polyimide is a thin, flexible carrier ideal for small surfaces such as the TUUK. Furthermore, the strain gauges have large cooper-coated tabs, thus providing an optimal attachment for the leadwires (Micro-Measurements, 2010b).

The gauge length and placement are important factors, as the strain measurements must be made at the greatest stress points on the blade holder. The area of maximum strain is typically small and therefore if the strain gauge is to large the strain reading will not highlight the high stress point and rather will average the entire region, resulting in a lower strain measurement (Micro-Measurements, 2010b). The CEA-06-125UW-350 strain gauge has a gauge length of 0.125 inches and has proven effective at measuring the strain of the blade holder (Micro-Measurements, 2010b).

The gauge resistance found in the CEA-series is typically either 120 Ω or 350 Ω. The Ice Hockey Research Group has opted for the 350 Ω strain gauge resistance as it is preferred to reduce heat generation across the gauge, it decreases the leadwire effects such as circuit desensitization and it has a greater signal to noise ratio in the bridge circuit (Micro-Measurements, 2010b). Other important factors of the CEA-06-125UW-350 strain gauge are the strain sensitivity or gauge factor and the strain range. The gauge factor is relatively high at 2.120 +/- 0.5% while the strain range is +/- 5% (Micro-Measurements, 2010b). In addition, the temperature range, which affects the dimensions and resistance of the material is -75°C to 175°C, thus providing a great range for on-ice testing. Two factors, the strain level and the number of cycles measure the fatigue life of a strain gauge. The strain level, measured in με, is ±1500 and the number of cycles is 10^6 (Micro-Measurements, 2010b). These parameters illustrate that CEA-06-125UW-350 is the appropriate strain gauge for on-ice testing.

3.4.2.2 General Strain Gauge Limitations

The Ice Hockey Research Group has determined that a few limitations exist when working with strain gauges. One limitation that is inevitable when working with strain gauges is hysteresis (Sinclair, 2001). Hysteresis occurs when the structural material, such as the blade holder, is not perfectly elastic and consequently the increasing strain during the loading phase is not equal to the decreasing strain during the unloading phase (Sinclair, 2001). Another limitation faced when using strain gauges is temperature (Sinclair, 2001). A change in dimension and resistance can occur as a result of environmental or structural temperature. Consequently, it is critical to select a strain gauge that is suited for the task you are researching. The error due to temperature can be minimized by pairing two identical strain gauges in the bridge circuit. The linearity error of the Wheatstone bridge circuit is another limitation that is difficult to overcome (Hoffmann). When using strain gauges it is assumed that there is a linear relationship between the relative change in the strain gauge resistance and the Wheatstone bridge output voltage (Hoffmann). However, if the relative change of the strain gauge increases by even the slightest percent, the assumption can no longer be made (Hoffmann). This limitation can be minimized by using two active strain gauges in the half bridge circuit that are partnered such that when deformation occurs one strain gauge undergoes compression while the neighbouring strain gauge experiences tension. Additionally, the error due to nonlinearity can be reduced if you do not exceed the strain range of the gauge and it can be ignored as long as the strains being measured are small (Micro-Measurements, 2010a).

3.4.2.3 Strain Gauge Placement on the TUUK

In 2010, Stidwill et al. developed a portable force measurement system using strain gauges to accurately determine vertical and medial-lateral force components during on-ice skating tasks (Stidwill, et al., 2010). The strain gauges required custom calibration to determine the ideal strain gauge placement. Five strain gauges were strategically attached to the blade holder by an adhesive known as cyanoacrylate (Micro-Measurements, 2010b; Stidwill, et al., 2010). One strain gauge was positioned along the longitudinal axis of blade holders beam to measure vertical strain (Stidwill, et al., 2010). The vertical gauge was referenced to a static gauge thus making it a quarter active Wheatstone bridge circuit. A pair of strain gauges was oriented vertically on opposite sides of the anterior post of the TUUK to measure anterior medial-lateral strain (Stidwill, et al., 2010). Similarly, a second pair of strain gauges was oriented vertically on opposite sides of the posterior post of the TUUK to measure posterior medial-lateral strain. Using partnered strain gauges allow us to measure the strain difference on the medial and lateral sides due to torsion in the blade holder (Stidwill, et al., 2010). The configuration of strain gauges on the blade holder allows us to determine an estimate of the ice reaction forces based on the strain measured through vertical, anterior medial-lateral and posterior medial-lateral axes of the TUUK (Lachaine, 2010).

The strain gauges are connected to bridge circuits through connective wires and connect to the DataLOG. The data is collected at 100Hz using a portable 13 bit analog to digital data acquisition system (Stidwill, et al., 2010). The data log is used to power the bridge circuits, to record their signal during testing and supply a 2V +/- 2% excitation voltage to the force transducer strain gauges (Stidwill, et al., 2010). The DataLOG measurement scale was set to 10mV with a resolution of 0.0025mV (Stidwill, et al., 2010).

3.4.2.4 Strain Gauge Calibration

The blade holder is a unique structure made of Nylon 6. An in depth dynamic validation process is required to determine the vertical and medial-lateral strain to force relationship. A lever method is currently used to generate consistent vertical forces on the blade holder (Fortier, 2010). A wooden foot lever has been built that fits inside the skate. Subsequently, it is attached to a loading lever, which allows forces of at least 2000 N to be applied (Fortier, 2010). The skate is placed in an upright position on the force plate so that the blade is directly in contact with the surface. This calibration procedure allows the forces to be distributed evenly across the skate boot. Furthermore, we are able to generate forces that are greater than body weight and thus more closely resemble the ice reaction forces measured during on-ice skating tasks.

For the medial anterior and posterior force calibration, the medial side of the skate blade is placed flat along the force plate so that only the blade of the skate is in contact with the force plate (Fortier, 2010). Similarly, the lateral side of the skate blade is placed facing downward on the force plate for the lateral anterior and posterior calibration. A wooden press was created to fit the shape of the medial and lateral sides of the skate so that a downward force can be evenly distributed to both the anterior and posterior post (Fortier, 2010). The wooden press allows us to apply loads of at least 1000 N. The calibration process includes slow medium and fast loading rates (Fortier, 2010). During the calibration, the strain gauge and the force plate signals are recorded simultaneously. For each skate, a linear regression equation is determined to convert the strain gauge voltage to force. Theoretically, the correlation coefficient between the strain gauge recording and the force plate signal should be equal to 1.00 and it is evident in the Stidwill et al. research that correlation coefficients are very close to 1.00 following the calibration procedure.

3.4.2.5 Limitations Using the Strain Gauge on the TUUK

Despite the high correlation coefficient between the strain gauges and the force plate, there are still a couple limitations with the current strain gauge configuration. First, the strain gauge system does not produce a linear strain-force relationship below 75 N in the medial-lateral orientation and similarly does not produce a linear strain-force relationship below 300 N in the vertical direction (Fortier, 2010). Secondly, the current configuration of the strain gauges do not account for the loads produced through the extreme front or extreme back of the skate blade holder (Fortier, 2010). Although these limitations do exist we do not believe they are statistically significant to the results.

3.4.3 Statistical Methods

A two-way multivariate analysis of variance (MANOVA) was conducted to compare all kinematic and kinetic variables across each leg for the skating acceleration trials. The significance level of $\alpha = 0.05$ was set in order for the results of the statistical analysis to be considered statistically significant (Lachaine, 2010; Stidwill, et al., 2010).

3.4.4 Ethical Considerations

Each subject completed an informed consent form prior to the testing sessions. The form clearly stated that participation in the study is voluntary and that they may withdraw at any point during the study if they feel uncomfortable.

All participants were required to wear a Canadian Standards Association (CSA) approved helmet while performing the on-ice skating tasks. All information collected from the subjects will be kept confidential at the McGill University Biomechanics Laboratory for five years after the completion of the project.

Chapter 4: Results

This study successful quantified both bilateral skating dynamics and the corresponding body accelerations for 12 subjects. Over all, there were no significant difference in gross time measures between skate models during steady state skating, either from time to complete the skating task (i.e. travel distance from blue line to blue line; 1.816 (0.08) vs 1.813 (0.07) seconds for SKATE FTG vs SKATE respectively) nor average stride rates (0.97 to 1.01 strides/sec, Figure d).

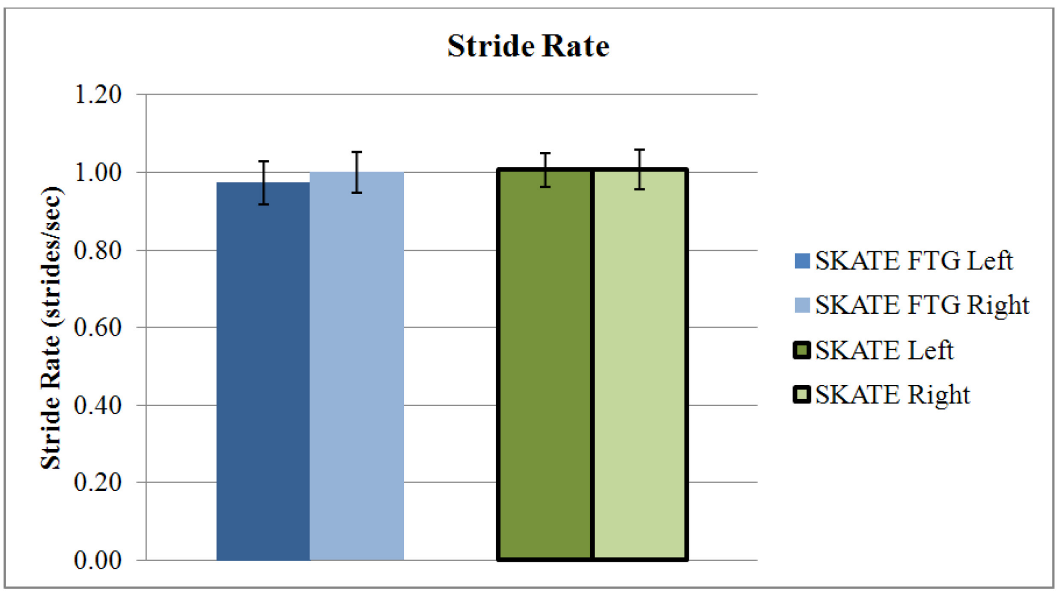

Figure d: Stride rate (± SD) in the forward skating task determined for each skate model and limb side.

However, discrete examination of time parameters within the task revealed some differences of note (Figure e). For example, contact times (of a skate with the ice surface) tended to be greater during steady state skating compared to during the initial skating accelerations (0.36 to 0.41 s versus 0.31 to 0.36 s). With the regular SKATE, these differences were significant particularly on the right side (0.36 versus 0.41 s; p=0.023). Similar left to right contacts times were shown, though the SKATE condition tended to favour 50 ms longer right support than left. The inverse trend was noted for the SKATE FTG (that is, left > right by 10 to 30 ms). Taken together, the interaction between side*skate model revealed a significant contact time difference between the right SKATE and right SKATE FTG (0.41 vs 0.36 s, respectively; p <0.05).

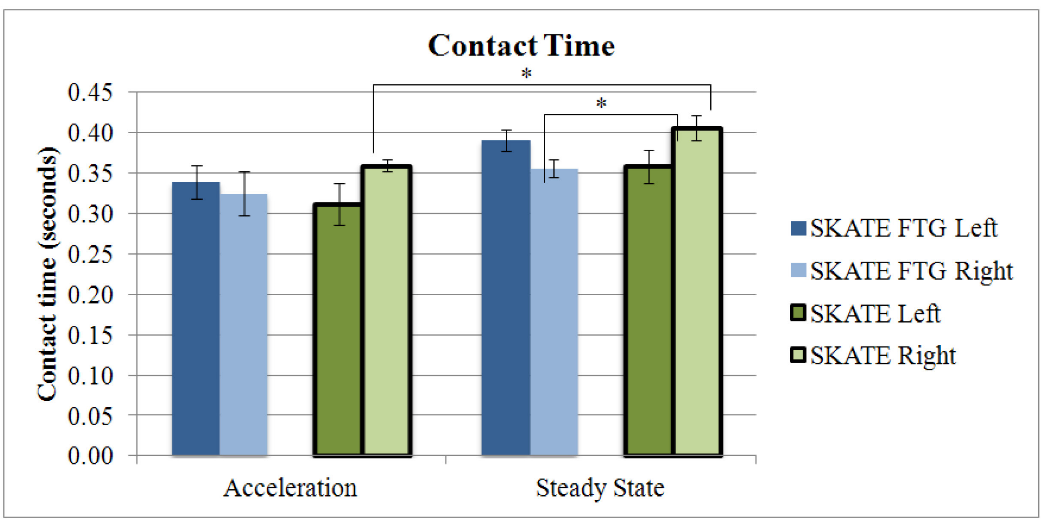

Figure e: Contact time (± SD) in the acceleration and steady state phases (* $p < 0.05$)

Table 2: Contact time (mean ± SD) identified in the Acceleration and Steady state phases

Skating Tasks	Acceleration				Steady State			
	Left Foot		Right Foot		Left Foot		Right Foot	
Skate Type	SKATE FTG	SKATE	SKATE FTG	SKATE	SKATE FTG	SKATE	SKATE FTG	SKATE
Contact time (sec)	0.34 (0.05)	0.31 (0.07)	0.33 (0.07)	0.36 (0.02)	0.39 (0.03)	0.36 (0.06)	0.36 (0.03)	0.41 (0.04)
	$p = 0.429$		$p = 0.251$		$p = 0.212$		**$p = 0.023$**	

In terms of single and double limb support times, these varied from 39.2 to 43.2% during single support and 7.8 to 12.4% during double support (Figure f; Table 3). These percentages were based on the strain force estimates obtained from each respective skate side. Hence the combined left and right stride estimates would approximate 80% and 20% of the skating stride in single and double support. There were no significant differences between skate models or skate sides. However, there was a trend indicating the double support times were slightly greater (2 to 5%) in the SKATE, while the single support times were slightly greater (2 to 3%) in the SKATE FTG.

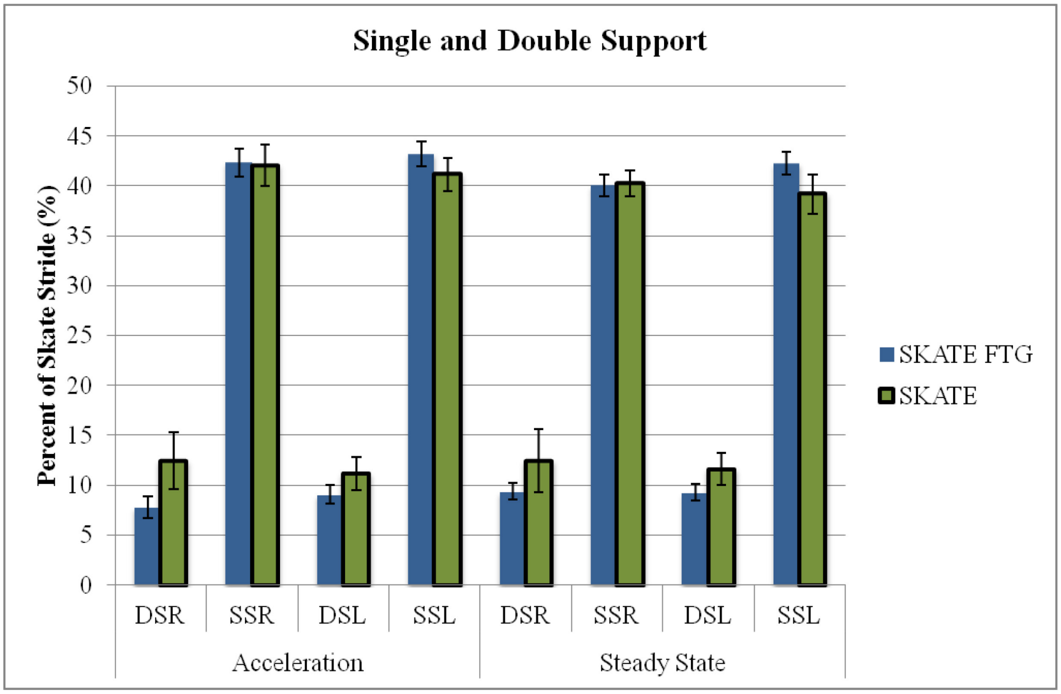

Figure f: Single and double support (± SD) in the acceleration and steady state phases. SSR represents the Single Support Right skate and SSL represents Single Support Left skate. Subsequently, DSR represents the Double Support while the Right skate is gliding and the DSL represents the Double Support while the Left skate is gliding.

Table 3: Single and Double Support results identified in the Acceleration and Steady State Phases (per limb side stride = 50% total; note: multiple these values by 2 for combined left and right estimates)

	Skate Task	Acceleration		Steady State	
	Skate Type	SKATE FTG	SKATE	SKATE FTG	SKATE
% Skate Stride	Double Support Right	7.8 (3.8)	12.4 (3.8)	9.4 (2.8)	12.4 (10.9)
		$p = 0.140$		$p = 0.353$	

	Single Support Right	42.3 (4.8)	42.1 (7.2)	40.0 (3.7)	40.3 (4.6)
		$p = 0.911$		$p = 0.890$	
	Double Support Left	9.1 (3.1)	11.2 (5.9)	9.3 (2.9)	11.6 (5.4)
		$p = 0.288$		$p = 0.200$	
	Single Support Left	43.2 (4.4)	41.1 (5.9)	42.3 (4.1)	39.2 (6.8)
		$p = 0.338$		$p = 0.192$	

In terms of bilateral skating dynamics and the corresponding body accelerations, it was possible to obtain discrete measure of stride by stride behavior. Figure g shows a typical data time series from which the various dependent variables were derived.

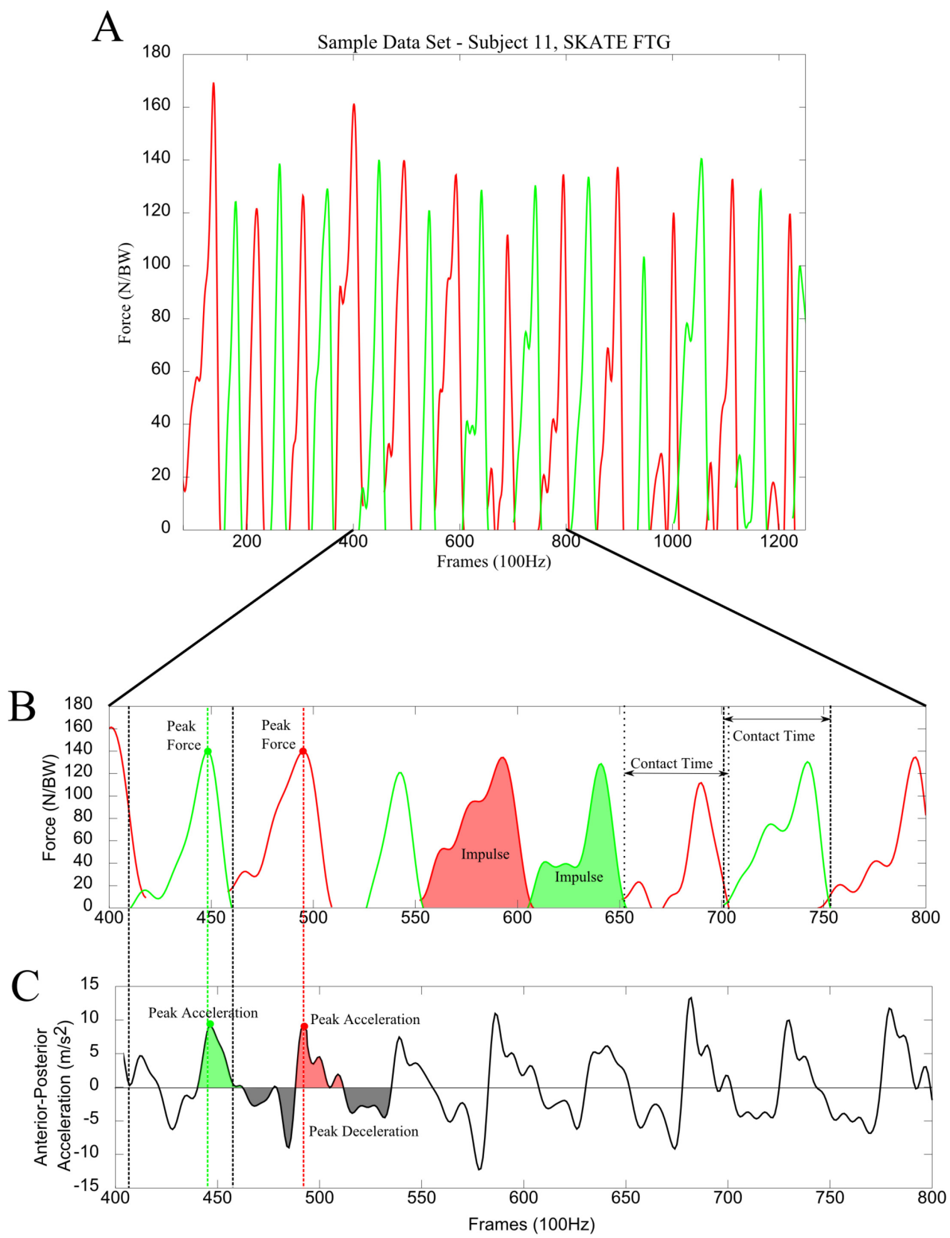

Figure g: A sample data set of vertical force and the anterior-posterior trunk acceleration during the steady state phase of the subject's forward acceleration trial. The upper panel (a) represents the skate force measures for the right (GREEN) and left (RED) skates during steady state skating. The mid panel (b) shows a closer view of a subset of skate force data with step to step dependant variables shown (e.g. contact time, peak force, impulse). The lower panel (c) shows the corresponding body anterior-posterior accelerations with dependant variables shown (e.g. peak acceleration and deceleration).

Force data were normalized as percentage of body weight (%BW). The forward skating task was analyzed in two parts: the acceleration phase (first 3 strides) and the steady state phase (the next 3-5 strides). All data were averaged by strides involved in each condition (i.e. acceleration, steady state). Peak force magnitudes ranged from 112 to 123%BW (Tab. 4). The SKATE FTG yielded slightly higher peak vertical force (7% of bodyweight) during the acceleration phase than the SKATE. Conversely, the SKATE yielded slightly higher vertical peak forces (8% of bodyweight) during the steady state phase. However, no significant differences were found between skate models or skate sides (left vs right) in either phase.

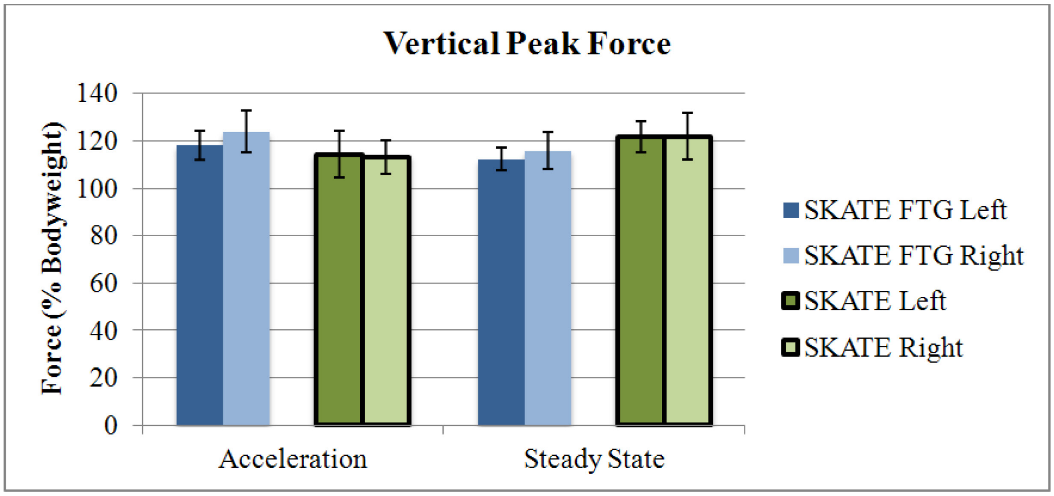

Figure h: Vertical Peak Force (± SD) in the acceleration and steady state phases

Table 4: Peak vertical force, Impulse, and Peak Acceleration and Deceleration (mean ± SD) identified in the Acceleration and Steady state phases

Skating Tasks	Acceleration				Steady State			
	Left Foot		Right Foot		Left Foot		Right Foot	
Skate Type	SKATE FTG	SKATE	SKATE FTG	SKATE	SKATE FTG	SKATE	SKATE FTG	SKATE
Vertical Peak Force (% BW)	118.2 (16.9)	114.3 (26.2)	123.7 (24.4)	113.4 (18.9)	112.3 (12.8)	121.8 (17.8)	115.9 (21.1)	122.0 (26.4)
	p = 0.748		*p* = 0.394		*p* = 0.272		*p* = 0.640	
Impulse (N*sec/kg)	17.3 (2.9)	18.9 (8.1)	17.1 (4.6)	21.8 (4.1)	18.8 (5.2)	25.3 (8.2)	18.0 (4.4)	26.4 (6.6)
	p = 0.639		*p* = 0.066		*p* = 0.104		***p* = 0.016**	
Peak Acceleration (m/s^2)	11.9 (3.6)	12.2 (3.9)	11.6 (3.6)	13.6 (3.8)	15.0 (4.5)	14.0 (3.3)	15.6 (4.5)	15.5 (4.2)
	p = 0.861		*p* = 0.331		*p* = 0.664		*p* = 0.991	
Peak	-7.4 (1.6)	-7.2 (1.4)	-6.6 (1.5)	-7.2 (1.2)	-9.3 (1.3)	-9.5 (0.8)	-9.2 (2.0)	-9.0 (1.9)

Deceleration (m/s^2)	$p = 0.784$	$p = 0.452$	$p = 0.682$	$p = 0.894$

Table 5: Average Work and Power throughout entire skating task

Skating Tasks	Forward Skating			
	Left Foot		Right Foot	
Skate Type	SKATE FTG	SKATE	SKATE FTG	SKATE
Power (watts/kg)	175.7 (30.3)	213.3 (79.3)	209.6 (64.3)	268.5 (46.0)
	$p = 0.263$		$p = 0.072$	
Work (Joules/kg)	1769.9 (217.7)	2131.4 (709.1)	2089.8 (514.4)	2697.6 (483.6)
	$p = 0.222$		**$p = 0.042$**	

With regards to skating impulse (Fig. i), in general, the SKATE showed greater impulse magnitudes than SKATE FTG during acceleration (1 to 3%) and steady state (6 to 7%). In particular, during steady state skating the right SKATE impulse was significantly greater than the right SKATE FTG ($p<0.05$). In terms of power, combining both left and right sides measures, power magnitudes were found to be significantly greater for the SKATEs than the SKATE FTGs (~190 vs 245 W). Lastly, in terms of work done, SKATE measures were greater than SKATE FTG (p<. Similarly the left SKATE was greater than the left SKATE FTG however they were not significantly different.

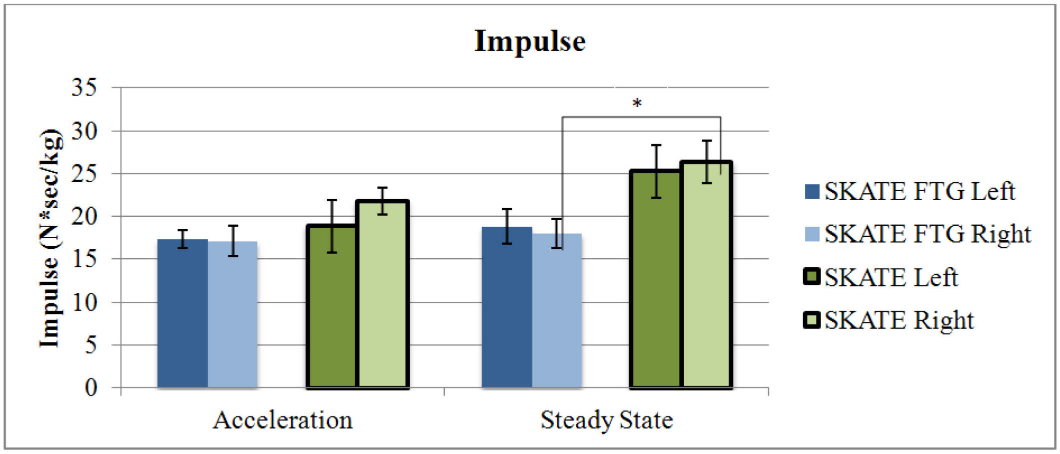

Figure i: Mean impulse (± SD; % bodyweight) in the acceleration and steady state phases (* $p < 0.05$)

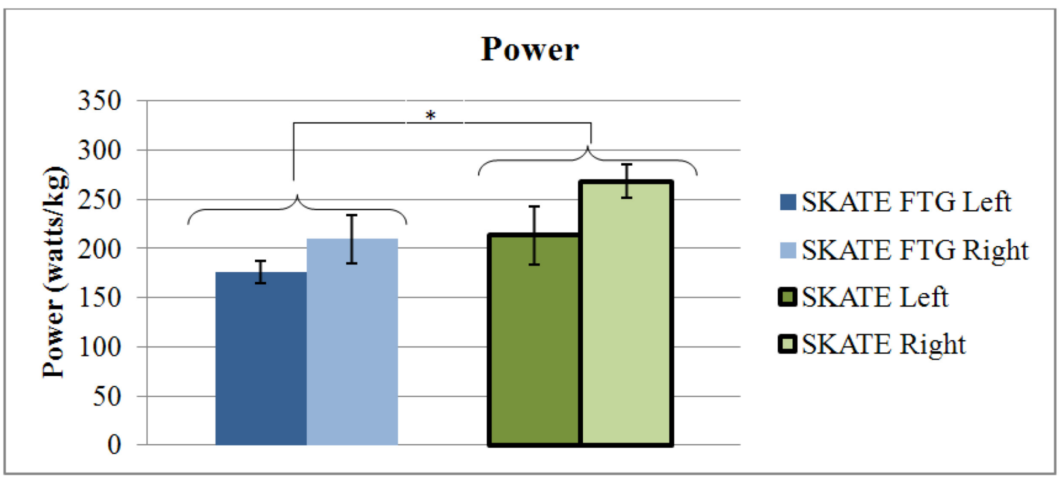

Figure j: Mean power (± SD normalized to bodyweight) in the forward skating task (* $p < 0.05$)

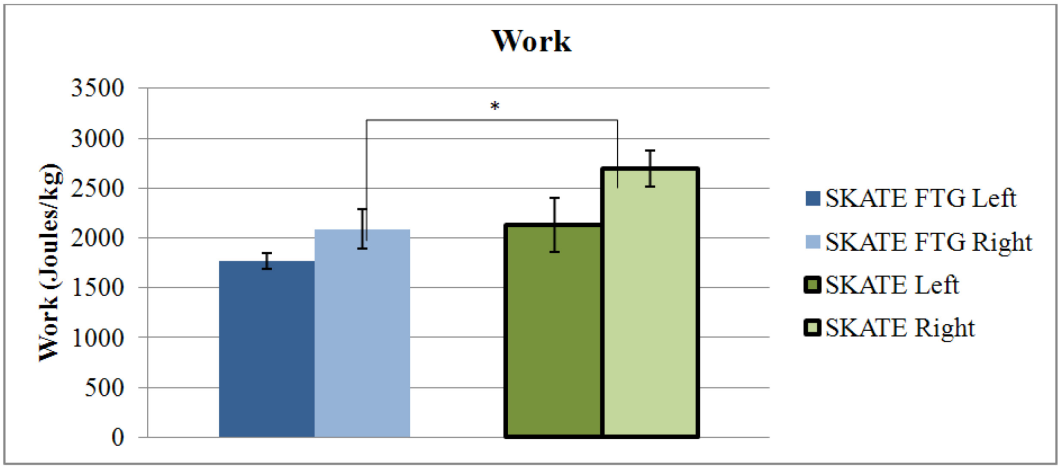

Figure k: Mean Work (± SD) in the forward skating task (* $p < 0.05$)

The peak forward accelerations of the body (Tab. 4, Fig. l, m) attained while on the SKATE FTG and the SKATE were quite comparable, ranging from 11.6 to 13.6 m/s/s during the skating start (acceleration phase) and from 14.0 to 15.6 m/s/s during steady state. Forward accelerations tended to be greater during right skate push off than on the left (ranging from -0.3 to 1.5 m/s/s difference), though not statistical differences were found. In terms of peak decelerations, these too were equivalent by skate model and skate side. These ranged from -6.6 to -7.4 m/s/s during acceleration skating phase and -9.0 to -9.2 m/s/s during steady state. No significant differences were found between skate model or body side.

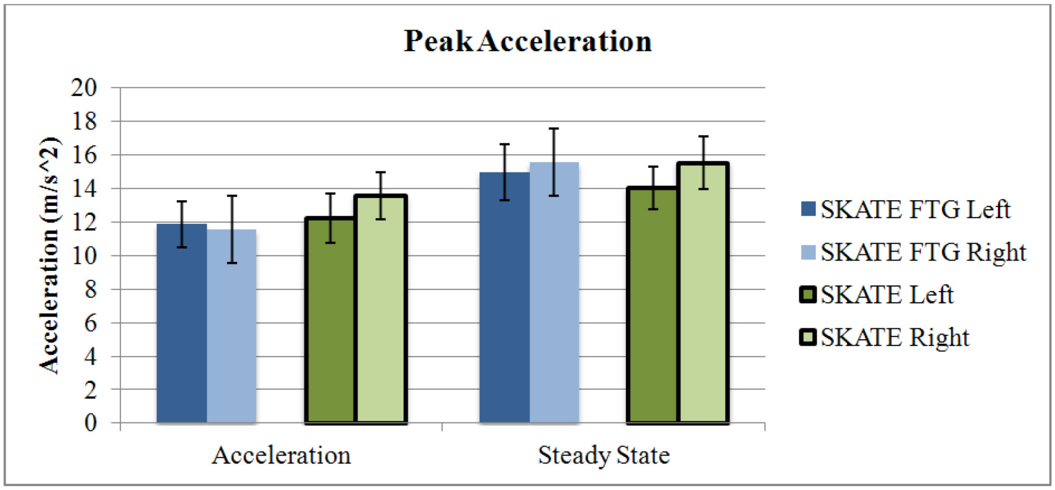

Figure l: Peak Acceleration (± SD) in the acceleration and steady state phases

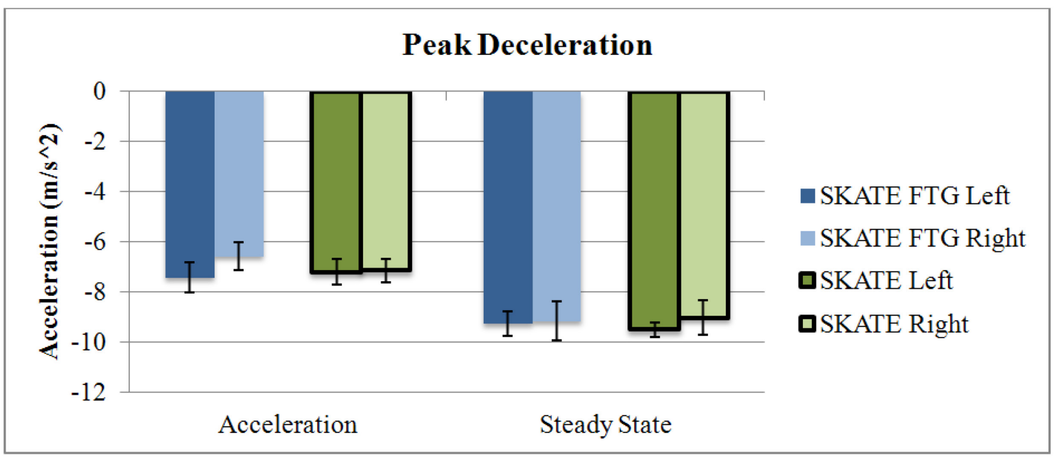

Figure m: Peak Deceleration (± SD) in the acceleration and steady state phases

Chapter 5: Discussion

This study successfully captured bilateral kinetic and kinematic skate measures during hockey forward skating tasks with simultaneous estimates of trunk anterior and posterior accelerations. This novel study provides a greater understanding of the skating locomotion mechanics.

Ice-skate contact times ranged from 0.31 to 0.36 s during acceleration and 0.36 to 0.41 during steady state skating. These are similar to the contact times of 0.25 to 0.4 s reported by Allinger et al (1997) during speed skating ice force measures. Skating forces were shown to begin as unimodal pulses during the first and second steps for the period of initial acceleration but rapidly transitioned to bimodal waveforms during subsequent skating strides. Forces peaked at around 112 to 124% of body weight. Double support intervals were quickly achieved even early in acceleration. The cyclical force patterns partially overlapped such that in initial support (weight acceptance) on one skate side corresponded to the end of push-off of the other skate. These finding are similar to other speed skating (Allinger et al, 1997; Ingen Schenau, 1996) and hockey skating studies (Stidwill et al, 2010; Lachaine 2010). Double support was limited to less than 16 to 24% of a stride duration while a majority of the time is in single support (84 to 76%). In many ways, these temporal stride and ice-skate forces patterns resemble that exhibited in walking gait.

Body accelerations closely corresponded to skate force patterns. Peak forward accelerations ranged from 14.0 to 15.6 m/s^2 coinciding with each push off (second peak of skate force) while peak decelerations (backward) ranged from 6.6 to 7.4 m/s^2 during the glide phase (first peak skate force). In general, average acceleration/decelerations ranged from ± 4 m/s^2 during the stride. The transition between acceleration and deceleration was quite abrupt, such that immediately after one skate's push-off the opposite skate's glide phase was in net deceleration due to air resistance and ice friction. The rate of deceleration increased rapidly during this glide phase presumably due to air resistance and the ever decreasing fluid film layer between the blade and ice as the blade glide's velocity slowed. Taken together, the net average velocity obtained over the skate distance of 54.25 m was 8.5 m/s or 30.5 kph.

With regards to the other skating variables, kinetic estimates of impulse, work and impulse per skate contact time were obtained. Impulse measures (force*contact time) ranged from 17.1 to 26.4 N*sec/kg. Given that the first half of skate contact was during the glide phase (weight support; blade's force perpendicular to ice surface) only the latter half of contact (push-off) actually contributed to forward propulsion (i.e. impulse contribution of 8.6 to 13.2 N*sec/kg). Similarly, the latter halves of work and power estimates are most relevant to propulsion effort. The push-off work done throughout the 54.25 m skating task ranged from 900 to 1300 J/kg and the corresponding rate of work done, or power ranged from 90 to 135 W/kg (or 1.7 to 2.6 W/(kg*m)). These power findings are similar to the 2.3 J/kg and 3.3 W/kg for long track speed skating (de Boer et al, 1987) and those reported by Lachaine (2010).

Though substantial, only a portion of these kinetic outputs contributed to forward propulsion. Given the skate moves at 35° to the intended direction of motion at the time of push-off (Denny 2011, pp 35-35; Upjohn et al 2008), only a portion equal 77% of these kinetic measures acts in the forward direction on the rink (the remaining portion of 13% pushes the body sideways). Further, there is a continual net deceleration acting on the skater: ice and air frictions account for about 20% and 80% respectively of the total resistance acting on the body (van Ingen Schenau, 1982). Hence, at steady state the average +4 m/s^2 acceleration due to push-off is checked by the average -4 m/s^2 deceleration due to ice and air resistance.

In terms of the performance comparison on the two skate models, no differences were seen for stride rates, single/double support times, acceleration/decelerations, nor in time to completion. Conversely, significant differences in contact times and related kinetic variables were observed such that 2 to 5% greater values were shown for the regular SKATE but only for the right side. This was counter to findings reported by Lachaine (2010) wherein a 14 to 20% increase in work and power output was found for the SKATE FTG. The reason for these contradictory results is not clear, though the lack of player familiarization with the SKATE FTG may be a factor. Nonetheless, in neither the current or past study did kinetic differences at the level of the skate-ice push-off translate into performance differences (i.e. faster speeds and shorter times to completion). This is probably attributed to air resistance; for example, de Koning et al (2000) reported that despite a 7 to 12% higher mean power output during skating on klapskates only a 3 to 5% higher speed was detected, and only over a distance of 2000 m. Hence, air resistance results in a power loss proportional to v^3, and any remain speed gain would not be detected over distances as short as 50 m.

So why did the SKATE FTG not show similar 7 to 12% higher power outputs? The greater plantar-dorsi flexion movement gained is quickly achieved, even by the skater not familiar with this skate design (Stidwill et al, 2010; Lachaine 2010). Unlike in speed skating where the klapskate augmented contact time at push-off by avoiding the conventional skate's toe-pick drag on the ice, this is not an issue in ice hockey skates. Stidwill's study suggested that the extra plantar flexion observed in the SKATE FTG occurs after push-off; no additional forward propulsion was generated. Hence, the potential benefits of the SKATE FTG design may not be observed in forward acceleration tasks but rather in other agility and change-of-direction skills such as cross-overs and pivots.

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Apendix I – Information and Consent Document

McGill

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INFORMATION AND CONSENT DOCUMENT

Investigator: Leo Culhane, M.Sc. candidate
Chau LeNgoc, M.Sc. candidate
David J. Pearsall, Associate Professor, Ph.D.
René Turcotte, Associate Professor, 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 investigators. This research project will be performed at McConnell Arena, located at 3883 University Street, Montreal, Québec, H2W 1S4. You are asked to come to one experimental session that will each last up to 1 hour. We greatly appreciate your interest in our work.

Purpose of the Study

The purpose of this study is to analyze and quantify kinetic and kinematic variables in ice hockey forward skating tasks. A comparison will be made between a Regular hockey skate (Bauer One95) and a prototype skate known as the DROM (highly modified Bauer One95 without a tendon guard leaving an opened space in the back of the skate). The study aims to measure the plantar center of pressure, the total force generated at the skate and the center of mass acceleration during on-ice skating tasks. The results of this study will lead to a better understanding of the movements and forces generated at the skate during ice hockey skating. Coaching ameliorations for technique, further development in hockey equipment for injury prevention as well as providing hockey players an alternative selection in terms of skate design depending on their skating style can be provided from the results we will gather in this study.

Your participation in this study involves:

1. Providing informed consent prior to the experimental session,
2. You will be asked to perform a skating acceleration task using two different pairs of Bauer One95 hockey skates. The procedure listed below explains the experimental session:
    a. You will be outfitted with a hockey helmet (Nike-Bauer 8500, sized accordingly), hockey skates (Nike-Bauer One95 and prototype model, sized accordingly) and hockey stick
    b. You will be asked to wear shorts or track pants and a backpack
    c. You will perform a series of skating acceleration tasks in both skate types.
    d. You will be asked to conduct up to 3 trials per task.

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CONSENT

I, ______________________________________, AGREE TO VOLUNTARILY PARTICIPATE IN THE STUDY ***KINEMATIC AND KINETIC DIFFERENCES BETWEEN TWO SKATE MODELS DURING FORWARD SKATING IN ICE HOCKEY***

I HAVE RECEIVED AND READ A DETAILED DESCRIPTION OF THE EXPERIMENTAL PROTOCOL. I AM FULLY SATISFIED WITH THE EXPLANATIONS THAT WERE GIVEN TO ME REGARDING THE NATURE OF THIS RESEARCH PROJECT, INCLUDING THE POTENTIAL RISKS AND DISCOMFORTS RELATED TO MY PARTICIPATION IN THIS STUDY.

I am aware that I have the right to withdraw my consent and discontinue my participation at any time without any prejudices.

Signatures

SUBJECT

________________________________ ________________________________
(signature) (print name)

RESEARCHER

________________________________ ________________________________

(signature) (print name)

Date: ________________________

Appendix II – Player Profile Form

PLAYER PROFILE FORM

Name ____

Age ________________

Height ________________

Weight ________________

Position played ________________

Hockey experience (years) ________________

Highest level of competition ____

Shooting side (circle) R L

Dominant leg (circle) R L

Skate size __________________

Skates usually worn ____

History of injuries ____

____

Health condition ____

____

____

Other information (by the investigator):

Laces width -Regular: Top_________ Middle_________ Bottom_________

-DROM: Top_________ Middle_________ Bottom_________

Ice Temperature _____________

Humidity _____________