Three-dimensional kinematics of the lower limbs
during ice hockey skating starts on the ice surface

Philippe J. Renaud

Master of Science

Department of Kinesiology and Physical Education

475 Pine Avenue West

Montreal, Quebec, Canada

H2W 1S4

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Abstract

The forward skating start is a fundamental skill for ice hockey players. The purpose of this study was to compare the movement patterns of high and low calibre skaters. Seven high and eight low calibre ice hockey players completed three ice hockey parallel starts on an ice hockey arena surface. A 10-camera motion capture system placed on the ice surface recorded lower body kinematics and centre of mass (CoM) motion during the first four steps. This is the first three-dimensional kinematic analysis of ice hockey skating using optical camera tracking conducted on ice. Though the gross movement patterns of the lower limbs were very similar between groups, high calibre skaters’ joint movements were substantially faster. This in turn, helped to achieve a higher CoM path and shorter double support times during these “running” start steps that may have contributed to their greater forward acceleration. From this study, in contrast to over ground sprint start kinematic technique, greater concurrent hip abduction, external rotation and extension is essential for optimal skate-to-ice push-off orientation needed for propulsion. Further direct on-ice kinematic analysis is feasible to examine other skating skills.
L’accélération depuis un départ-arrêté est une habileté fondamentale pour les joueurs de hockey sur glace. L’objectif de cette étude était de réaliser une analyse en trois-dimension du départ-arrêté de hockey sur glace et de comparer les mouvements entre les joueurs de haut et bas calibre. Sept joueurs de haut calibre et huit joueurs de bas calibre ont complété trois départ-arrêté sur une patinoire de hockey sur glace. Un système de capture de mouvement comprenant 10 caméras infrarouges a été placé sur la glace pour capturer la cinématique du bas du corps et du centre de masse durant les quatre premier coups de patin. En général, comme il fallait s’y attendre, les joueurs de haut calibre ont complété la tâche plus rapidement et à une plus grande vitesse que les joueurs de bas calibre. Malgré le fait que les mouvements des membres du bas du corps étaient très similaires entre les deux groupes, les mouvements des articulations des joueurs de haut calibre étaient considérablement plus rapides. De plus, les joueurs de haut calibre ont maintenu leur centre de masse plus haut et réduit à un minimum les instants où les deux patins étaient sur la glace durant les premiers coups de patin de style « sprint »; ceci a possiblement contribué à augmenter leur accélération vers l’avant. Grâce à ce projet, il a été mis en évidence que, en contraste avec les techniques cinématiques du sprint, la combinaison de l’abduction et de la rotation et extension externe de la hanche est essentielle pour optimiser l’orientation du patin par rapport à la glace de manière à obtenir une propulsion efficace. De plus amples études réalisées en patinoire et analysant la cinématique du patinage sont nécessaires pour examiner les diverses habiletés requises dans le sport de hockey sur glace.
Chapter 1: Introduction and Literature Review

1.1 Introduction

The popular international sport of ice hockey includes many different skills, such as stickhandling, shooting and, arguably the most important, skating and skating starts. Detailed analysis of the locomotion movement (kinematic) parameters of these latter skills using state-of-art motion capture technologies has been elusive. This is due to the environment of play (ice arenas), which are a barrier to the use of most electronic equipment. Some kinematic studies have been conducted on ice hockey (Chang et al., 2009; Upjohn et al., 2008) using electrogoniometers with synthetic skating surfaces. Other researchers have demonstrated the feasibility of conducting studies on or near the ice surface related to figure skating (Bruening & Richards, 2006) and ice hockey (Buckeridge et al., 2015; Lafontaine, 2007; McPherson et al., 2004). The purpose of this study is to compare the movement patterns of high and low calibre skaters during the ice hockey skating start; as well as capture high-resolution three-dimensional motion data for one of the first times on an arena ice surface.

1.2 The History of Skating: Speed Skating and Ice Hockey

Archeological evidence suggests that the first form of ice skates could date back to the Bronze Age (Formenti & Minetti, 2007). Using animal long bones as “blades” and leather straps to hold these against their feet in addition to a stick pole for propulsion and stability, early people developed a technology to take advantage of frozen winter lake and river surfaces as a means of transportation. Surprisingly, some bone skates were used until the 18th century in parts of Europe (Formenti & Minetti, 2007). As skating progressed from a means of transportation to recreation, so did the changes in skate design and materials. Between the 15th and 18th centuries, wood
blocks with metal runners attached to the bottom were introduced. By the 19th century, the skate was made from a single steel chassis clamped or anchored to the soles of boots. This template evolved into different modern skate families: the speed skate (Formenti & Minetti, 2007), figure skate and ice hockey skate, according to sport-specific task requirements.

During most of the 20th century, new manufacturing techniques and synthetic materials have been adopted, but skate design templates remained the same. However, more recently, some major design changes have come to fruition in order to affect the performance of high-level skaters. The most significant advance in speed skate design (the Klapskate) was introduced in 1985 by scientists Gerrit Jan Ingen Schenau and Groot (de Koning et al., 2000). This ergonomically inspired design was constructed with a hinge located between the blade and boot at the ball of the foot meant to allow greater plantar flexion of the ankle during the push off phase of the skating stride (skating phases will be discussed in greater detail in following sections), and also allowing the skate’s blade to remain in contact with the ice surface for a longer period of time (Houdijk et al., 2000). Prior to the Klapskate, and due to required preservation of a horizontal trunk position in order to reduce air friction, the speed skater had delimited ankle plantar flexion during push off in order to avoid the skate blade’s tip from dragging on the ice surface (de Koning et al., 2000; Houdijk et al., 2000). With a conventional skate, there is a frictional force loss of 10N during push off. In comparison, during the last 50ms of the push off, the Klapskate’s frictional losses are decreased to 3-4N (approximately equal to the friction during the glide phase) (de Koning et al., 2000). This decrease in friction has been shown to save the skater 3J of energy per stride (de Koning et al., 2000). Although these findings were significant, elite speed skaters remained skeptical of the new Klapskate’s design. It was not until 1994-1995 when 11 male junior speed skaters for the Zurich-Holland regional team...
wearing Klapskates achieved remarkable improvements in skating times of 6.2% (and
dominating the medal standings). A few years later, at the 1998 Nagano Japan winter Olympic
Games, both the male and female Dutch national speed skating teams competed with the
Klapskates and shattered world records (de Koning et al., 2000). After this watershed moment,
all long track speed skaters have adopted the Klapskate.

The first recreational games of ice hockey are believed to have been played in Eastern
Canada around the 1880’s (Pearsall et al., 2000). Influenced by earlier stick and ball games, such
as bandy, shinny, and hurley, the first games of ice hockey were played with curved sticks which
pushed a ball across the ice surface (Pearsall et al., 2000). The game was played during the long
and cold winter months which provided natural outdoor ice for a playing surface. Many
European immigrants in eastern Canada contributed to the founding rules of the game (Pearsall
et al., 2000). Since this time, ice hockey has evolved into a fast paced, competitive and popular
ingernational winter sport. This evolution has led to many improvements in all aspects of the
game, from equipment, training, and technology (Pearsall et al., 2000).

1.3 Skating Locomotion Patterns

1.3.1 Speed Skating

Due to its northern European and Scandinavian origins, speed skating is a sport that
historically has been dominated by the Dutch national teams. Consequently, most of the
published research on the sport involves subjects from various levels of Dutch teams, ranging
from the national to the junior national team (de Boer, Cabri, et al., 1987; de Boer, de Groot, et
al., 1986; de Boer, Ettema, et al., 1987; de Boer, Schermerhorn, et al., 1986; de Koning et al.,
1991; de Koning et al., 1995; van Ingen Schenau, 1982; van Ingen Schenau et al., 1985). The fundamental skill is forward skating. The stride in speed skating is comprised of three phases: glide, push off, and recovery (Akileswar & Baillieul, 1997; de Boer, Cabri, et al., 1987; de Boer, Schermerhorn, et al., 1986; de Koning et al., 1991; de Koning et al., 2000; de Koning et al., 1995). The glide phase is defined as the point in the stride when the body is supported over one leg, where the hip to ankle length remains constant (de Boer, Schermerhorn, et al., 1986). This phase begins when the contra-lateral skate is lifted from the ice surface and ends at the commencement of the push off (de Boer, Schermerhorn, et al., 1986). The push off starts with ipsilateral knee extension and ends just prior to full leg extension, where the blade is then lifted from the ice (Akileswar & Baillieul, 1997; de Boer, Schermerhorn, et al., 1986). The final phase, recovery, begins as the push off is completed, and ends as the skate is returned back to the initial position under the body and is in contact with the ice (Akileswar & Baillieul, 1997). The glide phase then begins again which re-starts the cycle. This skating stride cycle is biphasic, in that the glide and push off create the “support phase”, and the recovery creates the “swing phase” (Pearsall et al., 2013). The support phase is comprised of a period of single and double support. Double support is defined as when one leg is performing the push-off and the other is gliding, and as body weight is being transferred from the push off skate to the glide skate (Akileswar & Baillieul, 1997). Each of the glide, push off, and recovery phases are characterized by their own specific joint angles and muscle activation patterns. These patterns allow the skater to ensure that their body segments will be in optimal angular positions in order to elicit maximal acceleration and power outputs when needed during game situations. The combination of muscle activation and joint angles also let the skater achieve translational velocities during forward skating (de Koning et al., 1991).
1.3.2 Ice Hockey Skating

Forward skating in ice hockey is defined by its many applications to the sport’s context. Ice hockey skating in general involves many transitional tasks such as starts, stops, full speed strides, pivots, tight turns and cross-over strides (Marino, 1983). It is important to note that in both speed skating and hockey skating, the first four strides in a skating start are substantially different from the subsequent strides (steady state). For ice hockey starts, it has been shown that with each of the four starting strides, the ankle and knee range of motion angles increase with each stride until maximal speed is reached and the glide phase is then included (Lafontaine, 2007). Both a skaters’ kinetics and kinematics change drastically from the first to fourth stride; the stride goes from an acceleration phase into a “speed stride” phase indicative of the skating pattern performed over an extended distance (de Koning et al., 1991; Marino, 1983; Naud & Hold, 1979).

1.5 Kinematics of Ice Skating

In this following section, the three main joint angles of the lower limbs – Hip, Knee, and Ankle – will be examined during the start, glide, push off and recovery of the skating stride. There have been several papers that have investigated the individual joints, and only a few which have looked at all three joint angles simultaneously during the stride.
1.5.1 Start

Studying the ice hockey skating start over the first 20 feet with a Locam 16 mm camera, Marino (1979) found that from the first movement of a stationary position, the largest period of acceleration lasts approximately 1.25 seconds, and positive acceleration of a power skating start stops after 1.75 seconds. Visually, these 1.75 seconds relate to a minimum of three to four strides, which means that forward propulsion during the start is occurring during both single and double support (Marino, 1979). Marino (1975) also observed the optimal starting stride kinematics by use of multiple linear regression models. They noted that the ideal skating pattern should include a low takeoff angle, significant forward lean, a high stride rate, and the placement of the recovery foot directly under the body at the end of the single support phase. Marino (1983) confirmed these findings in a later study looking at which mechanical factors are associated with acceleration in ice skating. Two Locam 16 mm cameras were placed in the frontal and overhead views operating at 100 frames per seconds. Along with the aforementioned skating pattern characteristics, it was noted that short periods of single support helped reach high rates of acceleration during the start.

1.5.2 Glide

Pearsall et al. (2001) examined the angular motion of the ankle during the forward skating stride using bilateral twin axis electrogoniometers positioned on the rear foot along the longitudinal axis of the Achilles tendon. They were able to achieve simultaneous measurement of angles in two planes. From this technique, it was observed that the ankle, during single support of the glide phase, was dorsiflexed 7.1 degrees and will move from a pronated and dorsiflexed
position to pronated neutral throughout the glide. As well, they discovered that the ankle was slightly everted with moderately little change as the glide phase transferred to the push off.

de Boer, Cabri, et al. (1987) studied the moments of force, power and muscle coordination in speed skating. By using film analysis (67 frames per second) and a motion analyzer to determine the lower limb angle, they determined that the knee angle during the glide decreases from 150 to 115 degrees. Coordinates of the neck, hip, knee and ankle positions were then obtained from the cine film plane Y-Z, which were then converted into hip, knee and ankle angles. It is possible that some error was present in the exact angles, due to the fact that they were derived from calculations, and not from anatomically placed markers, which are much more precise. The study by Upjohn et al. (2008) used anatomical markers with a calibration grid, which allowed for a much more accurate documentation of the local and global joint angles. They used four digital cameras to record and compare elite vs. recreational skaters on a synthetic skating treadmill. Four high-intensity lights were also used to help illuminate the reflective markers on the subject and the calibration grid. They also observed, as did de Boer, Cabri, et al. (1987), a decrease in the total knee angle during the glide of approximately 30-35 degrees. The trunk segment angle was relatively constant during the glide, increasing slightly from 10 to 14 degrees flexion (de Boer, Cabri, et al., 1987). The hip is at 45 degrees at onset and progresses to 100 degrees, while being externally rotated during middle support (Pearsall et al., 2000). It has been shown to follow a similar flexion-extension pattern as does the knee, with a decrease of roughly 30-35 degrees of flexion (Upjohn et al., 2008).
1.5.3 Push Off

For ice hockey skating, Pearsall et al. (2001) used twin axis electrogoniometers fixed on both Achilles tendons, and found the ankle joint complex to evert to 6.8 degrees and dorsiflexed 11.5 degrees during push off. These motions were coupled with the extension of the hip and knee joints that in turn generates the necessary ground (ice) reaction force for forward propulsion. Speed skaters need not suppress plantar flexion while wearing Klapskates, while hockey skaters have delimited plantar flexion due to the prior conventional rigid tendon guard. However, the work by Robert-Lachaine et al. (2012) and their modified (i.e. flexible tendon guard) skate may allow the hockey skaters to utilize plantarflexion for propulsion.

The knee angle at push off in speed skating is at 115 degrees, with an approximate trunk angle of 10 degrees (de Boer, Cabri, et al., 1987). As for the hip in ice hockey skating, it has been observed to be at 180 degrees and externally rotated during the late stages of the push-off push off; while the knee is also at 180 degrees at the end of the push-off, with the ankle and foot plantar flexed and pronated (Pearsall et al., 2000). It has also been shown that the knee is rapidly extended during push off which creates the bulk of the skaters power and propulsion (Upjohn et al., 2008).

1.5.4 Recovery

In the recovery phase, the ankle plantarflexes from 11.5 dorsiflexion to 1.9 degrees dorsiflexion (Pearsall et al., 2001). In the later stages of recovery, the ankle dorsiflexes again in preparation for touchdown and glide (Pearsall et al., 2000). As for the knee, its angle decreases from 180 to 90 degrees, while the hip, as it internally rotates, also decreases from 180 to 40 degrees (Pearsall et al., 2000).
In summary, there is some consensus of the description of joint angles during the stride within the literature; however, the study of whole body characteristics of the skating stride has only been touched on lightly. There have been few studies that address whole body kinematics in speed skating, and even less for ice hockey skating. Some studies have looked at lower limb characteristics (Dewan et al., 2008; Upjohn et al., 2008), but on a skating treadmill. The value of a whole body characteristics study would present a definition of the coordination strategies necessary for skating locomotion, as well as provide insight on how different skate models and properties change skating locomotion and even ground reaction forces.

1.6 Low vs. High Calibre Hockey Skaters

Within the ice hockey literature, it has been shown that there are several kinematic differences in skating between high and low calibre players. One of the major differences between high and low calibre skaters is the quality of their skating stride. McCaw and Hoshizaki (1987) studied the kinematic comparison of novice, intermediate, and elite skaters: they documented stride length, stride rate, single and double support time, and kinematics of the left leg hip (thigh to vertical) and knee (thigh to shank). Their results stated that “(stride) length did not differ significantly among the levels, nor was it significantly correlated with skating velocity.” They did note, however, that stride rate was higher in elite skaters compared to novice skaters, and was correlated with maximal skating velocity. The elite skaters also had higher amounts of absolute single and double support, which decreased for intermediate skaters and even further for novice skaters. There was a deceleration of hip and knee extension by elite skaters as their centre of gravity came in front of their support foot; this was not observed in novice skaters (McCaw and Hoshizaki, 1987).
The research by McPherson et al. (2004) focused on developmental age hockey players. They found that there was an associated increase in stride length and maximal velocity as age increased. It was also noted that high calibre players (compared to developmental players) were able to greater ankle push off movement, as well as produce greater amounts of plantar flexion (McPherson et al., 2004). These findings were supported by the findings of Upjohn et al. (2008) who found that “high calibre participants showed a greater range and rate of joint motion in both the sagittal and frontal planes”. These differences may be attributed, in part, to the lack of muscular force generated by developmental age players, as they have not developed the same strength as high calibre players. The McPherson et al. (2004) study did have several limitations with regards to the data collection, which may have influenced the measurement resolution of the results. Only two digital cameras with recoding rates of 30fps were located 30m apart in the sagittal plane, each at a distance of 22m from the subjects. Subjects wore tight fitting, dark clothing and reflective tape was placed over each anatomical joint centre. From this, a set of kinematic data, comprised of joint angles for the hip, knee, and ankle were established at various points during the stride (McPherson et al., 2004).

Even though this was the first 3D study of its kind conducted for ice hockey, its limitations must be taken into consideration. The distance of the cameras from the subjects reduced the measurement accuracy when digitizing the data. Additionally, reflective tape, and not spherical markers, were used on the anatomical landmarks. Cappozzo et al. (1995) state that “for a given experiment, the light emitted or reflected from markers should be oriented within the field of view of a sufficient number of cameras”. They also suggest that “sufficient measurements (three-image coordinates) should be available on the markers from available cameras at any given time” (Cappozzo et al., 1995). Because the reflective tape bands used by
McPherson et al. (2004) were not spherical, but flat, it is questionable if they met both the above mentioned data collection criteria. Moreover, the reflective tape bands used must have been reasonable large in order for the cameras to capture them. As marker size increases, so does error in estimating anatomical joint centres, which in turn reduces the overall accuracy of joint angle calculations. The work by Upjohn et al. (2008) was much more advanced, in that they used four digital cameras with sufficient lighting on the spherical reflective markers. However, their study was conducted on a skating treadmill which potentially does not illicit the same movement patterns.

A more recent study conducted by Buckeridge et al. (2015) investigated the differences in joint kinematics and plantar foot pressures in nine high and nine low calibre ice hockey skaters during acceleration and steady state phases. Electrogoniometers were used to measure lower limb joint angles. They found that high calibre skaters were able to achieve a faster sprint start, as well as exhibited larger hip adduction angles at ice contact compared to low calibre skaters. They concluded that high calibre skaters brought their legs back towards the midline of their body faster than low calibre skaters; this allows them to use a greater hip ROM which leads to larger hip abduction velocities during the propulsion phase. Although this may be one of the more advanced ice hockey skating analysis conducted, a similar study, while using today’s motion capture technology in warranted to achieve high levels of kinematic precision.
1.8 Summary

Past kinematic research has been focused on speed skating, and ice hockey skating on synthetic surfaces. However, little three-dimensional kinematic research has been conducted on skating tasks, specifically hockey, on the actual ice surface. With the emergence and advances in motion capture technology, a study of hockey skating tasks is warranted on the actual ice surface. By conducting such a research project, the experimenter will be able to gain insight into the actual segmental and joint angles of the lower limbs during realistic ice hockey skating.
1.9 Operational Definitions

The following nomenclature, operational definitions, and abbreviations are used in this study.

**LCS**: Local Coordinate System of the lower limb joints

**GCS**: Global Coordinate System of the calibrated capture area

**Start/Ready position**: the point where the skater is in a stationary position with their knees bent and weight forward.

**Lead Leg (LD)**: the leg which first moved in the direction of the skating start

**Push Leg (PU)**: the leg which is used for propulsion initiation of the skating start and moves in the direction of the skating start after the Lead Leg has done so

**ON**: event at which the players skate touches the ice surface, example: LDON1 would be the first time the lead leg’s skate touches the ice surface.

**OFF**: event at which the players skate comes off the ice surface, example: PUOFF2 would be the second time the push leg’s skate comes off the ice surface.

**Step**: location of the skate at a specific ON events, example: LDON1, LDON2, PUON1, PUON2

**Stride**: distance travelled by the skate from an OFF to an ON event, example: LDOFF1 to LDON1, PUOFF1 to PUON1, LDOFF2 to LDON2, PUOFF2 to PUON2

**Start Phase** *(SP1 and SP2)*: the two full cycles of the skating start, SP1 goes from LDOFF1 to LDOFF2, SP2 goes from LDOFF2 to PUON2

**Push-Off**: point in the skating stride as the skate first contacts the ice and pushes the leg laterally until the skate is lifted back off the ice.

**Glide**: point in the skating stride where only one skate is in contact with the ice, and is stabilizing the leg it is supporting.
Recovery: point in the skating stride directly after the skate finished the push-off and is lifted from the ice until it contacts the ice once again for propulsion.

Single Support: point at which only one skate is in contact with the ice

Double Support: point at which both skates are in contact with the ice

High Calibre (HC): used to identify elite level skaters

Low Calibre (LC): used to identify recreational level skaters

ROM: Range of Motion of a lower limb during the skating start

CoM: Centre of Mass of the body
1.10 Rationale and Hypotheses

Despite the popularity of ice hockey and the emphasis on “power skate” training, limited quantitative information exists with regards to the optimal body movement pattern coordination for skating acceleration (Lafontaine, 2007; McPherson et al., 2004; Upjohn et al., 2008). Hence, the goal of this study was to conduct a three-dimensional kinematic analysis of the lower limbs during ice hockey forward skating starts for the first two strides (four steps), as well as to compare the kinematic movements of high and low calibre skaters on the actual ice surface. The predicted effect of player calibre on ice hockey starts are:

1. High calibre skaters will achieve greater top skating speeds associated with longer step lengths and widths than low calibre skaters.

2. Skating velocity will be positively correlated with leg strength test (standing double support long jump).

3. The peak angles and rate of lower joints’ motion will increase over the first four steps during the skating start, which will correspond to greater step-to-step acceleration as estimated by the body’s center mass movement.

4. High calibre skaters will show greater overall excursion and rate of lower joints’ motion throughout the skating start, in comparison to low calibre skaters.
1.11 Limitations

- With ten motion capture cameras, the skating calibrated capture area was limited to a volume of 3m wide x 5m long x 1.5 m high to track the first four skating steps of the start.

- Participants skated with the test skate models provided and were allowed two to three minutes familiarization prior to testing.

- Ice conditions varied between and within each testing trial and session (temperature -3 to 5°C; relative humidity ± 40%; ice surface scoring).

- Participants wore tight fitting compression clothing in order to secure the retro-reflective markers on anatomical landmarks; contrary to a real game situation where they would be wearing full hockey equipment.

1.12 Delimitations

- Only male skaters between the ages of 21-30 were observed (skate sizes of 7 to 10).

- Testing took place on the actual ice surface of an ice hockey rink arena.

- Participants were wearing hockey skates, helmet and gloves and carried an ice hockey stick while skating.
1.13 Participant Consent

Each participant was presented a consent form which was read and signed before testing. Participation in this study was voluntary and participants were not compensated for their time. Participants had the right to withdraw from the study at any point. The consent form outlined the risks associated with the study; rest times were included to avoid excessive fatigue that could endanger the participants and affect project results.

1.14 Contribution to the Field

In comparison to past studies, this research will provide higher quality kinematic measurement accuracy of ice hockey skating by the use of a gold standard motion capture system. It will also allow better understanding of the lower limb kinematic differences between high calibre skaters and low calibre skaters on the actual ice surface. These results could potentially allow coaches and trainers to identify the kinematic cues to teach beginner skaters, by referring to the kinematic patterns exhibited by high calibre skaters.
Chapter 2: Methods

2.1 Participants

Seven high calibre (HC) and eight low calibre (LC) skaters, aged 21 to 30, took part in this study (Table 1). High calibre participants were recruited from the McGill men’s varsity ice hockey team and played at a Junior hockey level or higher. Low calibre participants were recruited from McGill ice hockey intramural teams and local recreational players; they had to have played any level lower than Junior hockey. Participants who had major lower limb injuries were excluded from this study. Prior to testing, an ethics certificate (ID #132-0813) was obtained and participants were required to read and sign a consent form in accordance with the Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans.

Participant calibre groups were equivalent in leg strength as estimated from double support long jump distance, based on one-way ANOVA ($F(1,13) = 1.27, p = .280$).

Table 1 - Participants’ Descriptive Statistics.

<table>
<thead>
<tr>
<th></th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>Experience (years)</th>
<th>Long Jump (cm)</th>
<th>Max Skating Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Calibre (HC, n = 7)</td>
<td>24.7 (±3.1)</td>
<td>1.84 (±0.64)</td>
<td>87.1 (±6.0)</td>
<td>19.7 (±3.9)</td>
<td>219.1 (±17.0)</td>
<td>5.94 (±0.35)</td>
</tr>
<tr>
<td>Low Calibre (LC, n = 8)</td>
<td>23.9 (±3.1)</td>
<td>1.79 (±0.34)</td>
<td>81.3 (±8.4)</td>
<td>9.0 (±6.0)</td>
<td>208.5 (±18.8)</td>
<td>5.53 (±0.59)</td>
</tr>
</tbody>
</table>

Note: The average height and mass were similar between HC and LC groups (t-test p>0.05). Maximal skating speed was the average speed at the 7th skating step.2.2 Equipment
A ten-camera Vicon MX and T-Series motion capture system (Vicon®, Oxford, UK) was setup on the ice surface of the McGill McConnell arena. This includes two T40S cameras, eight MX3 cameras, camera cables, tripods, camera connection hubs (MX Ultranet and Giganet), and computer station. The system was calibrated prior to each testing session and captured at a rate of 240Hz. The calibrated capture area was approximately a volume of 3m wide x 5m long x 1.5 m high to track the first four skating steps of the start. Data collected was stored onto an external hard drive and was manually transferred to the laboratory computer network after the data collection process. Two digital cameras (GoPro Hero3+ Silver Edition) were setup in the sagittal and frontal planes with respect to the subject’s forward skating direction. These cameras collected a video log of each test trial.

Prior to on-ice data collection, subjects performed three standing long jump tests (taking the average of the three jumps as an estimate of functional leg strength). Subsequently, subjects wore tight fitting compression clothing to wear in addition to test skates, hockey gloves, helmet, and a hockey stick to carry while skating. Each subject had 24 passive retro-reflective markers placed on their lower limbs according to the Vicon™ Plug-in-Gait (Vicon Inc., (Oxford Metrics Ltd., 1999)) lower body setup, (Table 2 and Figure 1). This marker set was slightly modified by adding additional markers to the skates and knees of each subject, allowing for more precise analysis within the post-processing software.
Table 2 - Name and location of the 24 passive retro-reflective markers

<table>
<thead>
<tr>
<th>Marker Name</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>- LPSI</td>
<td>- Left Posterior Superior Iliac Spines</td>
</tr>
<tr>
<td>- RPSI</td>
<td>- Right Posterior Superior Iliac Spines</td>
</tr>
<tr>
<td>- LASI</td>
<td>- Left Anterior Superior Iliac Spines</td>
</tr>
<tr>
<td>- RASI</td>
<td>- Right Anterior Superior Iliac Spines</td>
</tr>
<tr>
<td>- LTHI</td>
<td>- Left Thigh</td>
</tr>
<tr>
<td>- RTHI</td>
<td>- Right Thigh</td>
</tr>
<tr>
<td>- LKNE</td>
<td>- Left Lateral Knee</td>
</tr>
<tr>
<td>- RKNE</td>
<td>- Right Lateral Knee</td>
</tr>
<tr>
<td>- LMKNE (calibration)</td>
<td>- Left Medial Knee</td>
</tr>
<tr>
<td>- RMKNE (calibration)</td>
<td>- Right Medial Knee</td>
</tr>
<tr>
<td>- LTIB</td>
<td>- Left Tibia</td>
</tr>
<tr>
<td>- RTIB</td>
<td>- Right Tibia</td>
</tr>
<tr>
<td>- LANK</td>
<td>- Left Lateral Ankle</td>
</tr>
<tr>
<td>- RANK</td>
<td>- Right Lateral Ankle</td>
</tr>
<tr>
<td>- LMANK (calibration)</td>
<td>- Left Medial Ankle</td>
</tr>
<tr>
<td>- RMANK (calibration)</td>
<td>- Right Medial Ankle</td>
</tr>
<tr>
<td>- LHEE</td>
<td>- Left Heel</td>
</tr>
<tr>
<td>- RHEE</td>
<td>- Right Heel</td>
</tr>
<tr>
<td>- LTOE</td>
<td>- Left Toe</td>
</tr>
<tr>
<td>- RTOE</td>
<td>- Right Toe</td>
</tr>
<tr>
<td>- LTOE1</td>
<td>- Left First Metatarsal</td>
</tr>
<tr>
<td>- RTOE1</td>
<td>- Right First Metatarsal</td>
</tr>
<tr>
<td>- LTOE5</td>
<td>- Left Fifth Metatarsal</td>
</tr>
<tr>
<td>- RTOE5</td>
<td>- Right Fifth Metatarsal</td>
</tr>
</tbody>
</table>
Of the four markers defining the knee, and the twelve defining the skates, four of them, the medial knee and medial ankle markers, were only present for subject calibration: they were then removed during the dynamic skating trials. The lateral knee and ankle markers remained during the dynamic trials. This allowed each knee joint’s center to be identified in the post-processing Visual3D software. In order to calculate centre of mass, the software also created a digital middle posterior superior iliac spine middle marker between the left and right posterior superior iliac spine markers (shown as red dot on (B) of Figure 1). The skates were provided to the participants, while fitting them for their proper size. The low and high calibre participants were provided with Bauer Supreme skates. A weight scale was used to measure the participants’ weight; while a measuring tape and calipers was used to measure the anatomical lengths of the
lower limbs and joints that were entered into the Vicon™ Nexus 1.8.5 software prior to starting the testing session. Prior to placing the retro-reflective markers, the participant’s body height and double support long jump distance were measured with the measuring tape. The ice surface quality (air temperature and relative humidity, extent of surface abrasion) was monitored during testing. To avoid the effect of excessive ice surface abrasion (due to repeated test trial’s skating exposure), the participant’s starting position was shifted laterally within the calibrated capture area between skating test blocks (Figure 2-A) allowing the prior ice test path to be reconditioned (wet mopped).
Figure 2 - Diagram of on ice experimental setup. Camera positions were standardized for all subjects. A) Fixed points in the rink (stars) were used as reference for camera positions. B) Reconstruction in Vicon software of camera positions and field of view (blue rectangle) for data collection.
2.3 Experimental Design

This study employed a research design with categorical factors. The independent variables included player calibre (high/low). Multiple mixed-ANOVA’s were employed to analyze within (Step) and between (Calibre) comparisons. The dependent variables were standing double support long jump, lead and push leg step length, step width, double support time, skating velocity and acceleration, CoM ROM, and lead and push hip, knee, and ankle joint kinematics. See Table 3 for a complete description of all dependent variables.

Discrete variables were extracted from the time series; specifically peak forward body CoM velocity and average acceleration, as well as joint and segment angle maximum and minimum during each of the four skate start step phases.
Table 3 - Description of dependent variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variable description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standing Double Support Long Jump&lt;sup&gt;A&lt;/sup&gt;</td>
<td>Average Max forward jump distance of three trials</td>
<td>Mean ±SD</td>
</tr>
<tr>
<td>Start Task Completion Time</td>
<td>Absolute time for participant to complete the start task, from LDOFF1 to PUON2</td>
<td>Mean ±SD</td>
</tr>
<tr>
<td>Lead Leg Step Length</td>
<td>x and y coordinates of right heel marker from LDOFF1-LDON1 for first step, LDON1-LDON2 for second step</td>
<td>Mean ±SD</td>
</tr>
<tr>
<td>Push Leg Step Length</td>
<td>x and y coordinates of right heel marker from PUOFF1-PUON1 for first step, PUON1-PUON2 for second step</td>
<td>Mean ±SD</td>
</tr>
<tr>
<td>Step Width</td>
<td>Cross-product of step vectors and mean of stride vectors</td>
<td>Mean ±SD</td>
</tr>
<tr>
<td>Double Support Time</td>
<td>Amount of time with both skates on the ice, calculated from the onset of an ON event to the end of the following OFF event</td>
<td>Mean ±SD</td>
</tr>
<tr>
<td>Skating velocity (CoMx,y,z)</td>
<td>Velocity of the digitized PSIS middle marker in the coronal, sagittal, and transverse planes (x, y, z)</td>
<td>Mean ±SD</td>
</tr>
<tr>
<td>CoM ROM (CoMx,z)</td>
<td>Range of Motion (max – min) of the digitized PSIS middle marker in the coronal and transverse planes (x, z)</td>
<td>Mean ±SD</td>
</tr>
<tr>
<td>CoM acceleration (CoMx,y,z)</td>
<td>Acceleration of the digitized PSIS middle marker in the coronal, sagittal, and transverse planes (x, y, z)</td>
<td>Mean ±SD</td>
</tr>
</tbody>
</table>
| Hip Angle<sup>B</sup> (x,y,z)   | **Flex**(+)/**Ext**(−): Angle between the projected sagittal thigh axis and sagittal pelvic axis  
|                                 | **Abd**(+)/**Add**(−): Angle between the long axis of the thigh and frontal axis of the pelvis projected  
|                                 | **Int**(+)/**Ext Rot**(−): Angle between sagittal axis of the thigh and sagittal axis the pelvis projected into plane perpendicular to long axis of thigh  | Mean ±SD     |
| Knee Angle<sup>B</sup> (x)      | **Flex**(+)/**Ext**(−): Angle between plane perpendicular to the knee flexion axis and sagittal thigh axis | Mean ±SD     |
| Ankle Angle<sup>B</sup> (x)     | **Dorsi**(+)/**Plantar**(−): Angle between foot vector and sagittal axis of the shank | Mean ±SD     |

<sup>A</sup> Off-ice measurement

<sup>B</sup> Description of joint angle definitions adapted from the Vicon™ Plug-in-Gait manual (Vicon Inc., manual)
2.4 Experimental Protocol

Prior to every testing session and participant arrival, all equipment was taken out of the storage locker at the arena and setup on the ice surface. Tripods, cameras, and cables were placed in predetermined positions (Figure 2-A); the cables were run to the Vicon MX Ultranet and Giganet connection hubs that were setup at the computer station. The Vicon™ Nexus 1.8.5 (Vicon®, Oxford, UK) software was turned on, as well as all of the cameras. Each camera was individually checked to make sure the field of view and video quality was optimal for testing. Once this was completed, the system was calibrated and ready for subject calibration and trial capture.

As the participant arrived, they read then signed the Subject Consent forms. After receiving participant consent, they changed into tight fitting compression clothing, followed by the collection of descriptive measures of body mass, height, and anatomical lengths of limbs and joints. This latter information was entered into the Vicon™ Nexus 1.8.5 software prior to subject calibration on the ice surface. Participants then performed three double support long jumps. This data was used as a strength co-variate to the skating kinematic data.

Subsequently, the participant put on the hockey equipment used for testing: skates, helmet, gloves, and stick. They then stepped onto the ice surface and were given a two to three minute warm-up period in a defined area of the ice surface, away from the previously calibrated area. Longer time was permitted until participants felt comfortable with the test skates provided. Once the warm-up period was over, the participant then had 24 retro-reflective markers placed on their lower limbs (see “Equipment” above). The participant then stood in the calibrated capture area on the ice and a five second static subject calibration file was recorded through the Vicon™ Nexus 1.8.5 software. The static calibration file, where the participant stood with his
knees as straight as possible, was used as the reference file while conducting analysis within the Visual3D software program. Upon completion, the medial knee and ankle markers were removed and a dynamic calibration file was then captured. This dynamic calibration file consisted of the participant performing simple limb lifts and rotations in order for the retro-reflective markers to be calibrated to the participant’s motion, as well as apply the marker labels to the actual active skating trials.

Each low and high calibre participant performed three skating start trials. Each trial started with the subject in a still “ready” position, with their knees slightly bent, and their weight leaning forward in order to start and skate as fast as they could forwards (Figure 3). The capture area allowed the recording of the first four push-offs (steps). All participants were given a one minute rest period in between trials in order to avoid fatigue. Data was stored onto an external hard drive and transferred to the laboratory’s computer network for processing and analysis.

**Figure 3** - Starting position in the (A) left sagittal (B) posterior (C) anterior and (D) right sagittal views (picture take in laboratory setting, emulating on ice position).
2.5 Data Acquisition, Processing, and Analysis

Vicon™ Nexus 1.8.5 (Vicon®, Oxford, UK) software was used to collect data from all ten infrared cameras through the MX Ultranet and Giganet connection hubs, which is then connected to the desktop computer. Data was transferred onto an external hard drive at the end of each testing session, in order to upload it to the laboratory’s internal network. Once the data was uploaded, the Vicon™ Nexus 1.8.5 software was also be used to label all retro-reflective markers for all trials in the modified Plug-in-Gait setup. The hip, knee, and ankle angles were calculated using their LCS. Each trial was then opened up in Vicon IQ (Ver 2.5, Vicon®, Oxford, UK) which allowed for gap filling of the retro-reflective markers. Visual3D (Ver 5.01.23, C-Motion, Germantown, Maryland, United States) and custom MATLAB scripts (MathWorks, Natick, Massachusetts, United States) were used to post-process and analyze the data. These software’s were also used to partition the data from LDOFF1 to PUON2 events (four steps of the acting start) for the whole data set, and to also create comparative graphs which help make the data more readable and “clean”. A fourth order Butterworth filter with a cutoff frequency of 6 Hz was used to smooth the data.
2.5.1 Event and Phase Definitions

Human locomotion analysis typically evaluates bilateral step/stride events and phases during steady state, repeating gait cycles. However, for the initiation of locomotion (in this case the skating start), stereotypical step sequence events are not present; hence, modified terms need to be defined. By observing the Vicon lower limb model animations of subject trials, the first and second foot steps defined the “LEAD” and “PUSH” step, respectively, to differentiate their observed functions. That is, the **LEAD side was the foot side that began the start movement**: either by sliding or stepping forward. This was followed by the **PUSH step** that demonstrated the first substantial forward propulsion of the whole body. For each step side, events of foot ON (Zeni et al., 2008) (velocity based method) and OFF (Hreljac & Marshall, 2000) were identified. The **event sequence began with the LDOFF1 event and ends with the PUON2 event**, see Figure 4 for Vicon events. In addition, **two start phases** (cycles) were identified: **Start Phase 1 (SP1)** goes from LDOFF1 to LDOFF2, which was all the data before the 50% point, and **Start Phase 2 (SP2)** goes from LDOFF2 to PUON2, which was all of the data after the 50% point. These events and phases thus defined the discrete dependent kinematic variables used for analysis.

Within the results section, waveform graphs have solid vertical lines which depict ON events (LDON1, PUON1, LDON2) and dashed vertical lines which depict OFF events (PUOFF1, LDOFF2, PUOFF2). Black vertical lines depict Lead leg (LD) events, and orange vertical lines depict Push leg (PU) events.
**Figure 4** - Sequence of Plug-in-Gait step events (left to right). These have been used to define the variables within the results section. Blue circles depict lead leg events, orange circles depict push leg events. Solid circles are ON events, dashed circles are OFF events. Green and red solid bars show when the lead and push legs were in contact with the ice surface.
2.5.2 Joint Angle Definitions

The Vicon™ Plug-in-Gait model was used to calculate the hip and knee local angles; the local ankle angles were calculated using the Joint Coordinate System (Grood & Suntay, 1983) (Figure 5), with a modified Plug-in-Gait marker placement on the testing skates (see Figure 1). The local hip and knee angles were adjusted using the Thigh-Offset technique as described by Baker et al. (1999). This technique allows for local hip and knee angle values to be adjusted in the case of thigh wand marker misalignment during data collection.

<table>
<thead>
<tr>
<th>Sagittal Plane Angles</th>
<th>Frontal Plane Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Sagittal Plane Angles Diagram" /></td>
<td><img src="image2.png" alt="Frontal Plane Angles Diagram" /></td>
</tr>
</tbody>
</table>

**Figure 5** - Joint angle definitions for the sagittal (left) and frontal/transverse (right) planes. Note: $\theta_1 =$ Hip flexion/extension, $\theta_2 =$ Hip abduction/adduction, $\theta_3 =$ Hip internal/external rotation, $\theta_4 =$ Knee flexion/extension, $\theta_5 =$ Ankle plantar/dorsi flexion.
2.5.3 Estimation of CoM Calculations

Within the Visual3D software, the body’s Centre of Mass (CoM) location was estimated by the mid PSIS markers position, an approximation technique of whole body CoM shown to be accurate during running tasks (Ernst et al., 2014) and ski skating tasks on a treadmill (Myklebust et al., 2015). CoM displacement, velocity and accelerations were calculated in the side-to-side, forward and vertical axes.

2.5.4 Trial Selection

A representative trial selection method (Dixon et al., 2013) was used for this study. Each subject performed three skating start trials. The root mean squared error between each curve and the mean curve for all dependent variables was calculated with a custom MATLAB script. From this calculation, the trial out of the three which had the overall average minimum root mean squared error was chosen as the representative trial. This technique was chosen in order for a true captured trial to be used for data analysis.
2.5.5 *Statistical Analysis*

This study used multiple mixed-ANOVA’s. The independent variable was player calibre (High/Low). Mixed-ANOVA’s were conducted on the nine spatiotemporal dependent variables as well as on the three kinematic dependent variables. SPSS Statistics (IBM Corporations, Somers, U.S.A., Version 19.0) was used to perform statistical analyses of dependent variables. Specific hypotheses were:

1. High calibre skaters will achieve greater top skating speeds associated with longer stride lengths and widths than low calibre skaters. Analyzed by a mixed-ANOVA test.

2. Skating velocity will be positively correlated with leg strength test (standing double support long jump). Analyzed by a Pearson’s r correlation test.

3. The peak angles and rate of lower joints’ motion will increase over the first four steps during the skating start, which will correspond to greater stride-to-stride accelerations. Analyzed by a mixed-ANOVA test.

4. High calibre skaters will show greater peak angles and rate of lower joints’ motion throughout the skating start, in comparison to low calibre skaters. Analyzed by a mixed-ANOVA test.
Chapter 3: Results

The following section presents the analysis of the kinematic parameters of the skating start. Skating calibre is the main factor of interest. The purpose of this study was to quantify the differences in skating velocity and acceleration, COM displacement, and lower limb joint angles between two different skater calibre conditions.

3.1 Skating Calibre and Start Acceleration Performance

High calibre skaters were able to complete the skating start task in significantly shorter time than low calibre skaters ($F(1,13) = 5.42, p = .037$). Leg strength as estimated from long jump distances did not correlate with forward skating velocity at the fourth skating start step (PUON2) ($r(13) = .489, p = .064$, Table 4).

Step length and step width measures were similar between groups ($F(1,13) = .008, p = .930$, and $F(1,13) = 1.62, p = .226$, respectively Table 5, Figure 6 and 7). Both groups demonstrated substantial increases in step length with each consecutive step ($F(3,39) = 4.44, p = .009$). The high calibre skaters showed smaller double support time on average over all three steps ($F(1,13) = 8.05, p = .014$, Table 6, Figure 8).

<table>
<thead>
<tr>
<th></th>
<th>Max Forward Velocity at 4th step (PUON2)</th>
<th>Task Completion Time (LDOFF1-PUON2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC</td>
<td>5.53 (±0.15)</td>
<td>1.03 (±0.08)*</td>
</tr>
<tr>
<td>LC</td>
<td>5.10 (±0.61)</td>
<td>1.20 (±0.18)*</td>
</tr>
</tbody>
</table>

Table 4 - Average forward velocity (m/s ±SD) and task completion time (s ±SD) for both HC and LC skaters *indicates significant difference between calibre (p<0.05).
Table 5 - Average skating step length and width (cm ± SD) for both HC and LC skaters at each step. **indicates significant step interaction for step length. (p<0.05).

<table>
<thead>
<tr>
<th>Step</th>
<th>Step Length</th>
<th>Step Width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
<td>LC</td>
</tr>
<tr>
<td>1</td>
<td>LDOFF1 to LDON1**</td>
<td>515.8 (±278.2)</td>
</tr>
<tr>
<td>2</td>
<td>PUOFF1 to PUON1**</td>
<td>1558.7 (±195.1)</td>
</tr>
<tr>
<td>3</td>
<td>LDOFF2 to LDON2**</td>
<td>2023.9 (±221.6)</td>
</tr>
<tr>
<td>4</td>
<td>PUOFF2 to PUON2**</td>
<td>2169.3 (±195.5)</td>
</tr>
</tbody>
</table>

Note: only the first three step widths could be calculated.

Figure 6 - Average step lengths for each respective step by skating calibre (±SD bars). Step lengths increased for each consecutive step * p<0.05
**Figure 7** - Average step width for each respective step by skater calibre (±SD bars).

**Table 6** - Average skating double support time (s ±SD) for both HC and LC skaters at each step *indicates significant difference between calibre (p<0.05).

<table>
<thead>
<tr>
<th>Step</th>
<th>HC</th>
<th>LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDON1</td>
<td>0.036 (±0.042)</td>
<td>0.098 (±0.063)*</td>
</tr>
<tr>
<td>PUON1</td>
<td>-0.015 (±0.029)</td>
<td>0.040 (±0.046)*</td>
</tr>
<tr>
<td>LDON2</td>
<td>0.003 (±0.029)</td>
<td>0.038 (±0.028)*</td>
</tr>
</tbody>
</table>

Note: a negative value denotes a flight phase (no double support)
Figure 8 - Average double support time for each respective step by skater calibre (+SD bars).

3.2 Estimation of Body Centre of Mass (CoM) movement during Skating Start

The subjects’ body CoM movements were estimated for the Side-to-Side, Forward and Vertical directions over the first two skating start phases: Start Phase 1 (SP1, LDOFF1 to LDOFF2) and Start Phase 2 (SP2, LDOFF2 to PUON2).

No difference in Side-to-Side or Vertical CoM range of motion (ROM) were found between calibre groups from the time normalized data ($F(1,13) = .000, p = .988$ and $F(1,13) = .124, p = .730$, respectively, Table 7, Figure 9). However, high calibre skaters had higher average CoM vertical position over the four start steps ($F(1,13) = 26.79, p = .000$, Table 8, Figure 9).
Table 7 - Average Centre of Mass range of motion (cm ±SD) for both HC and LC skaters for each start phase.

<table>
<thead>
<tr>
<th>Start Phase</th>
<th>Side-to-Side (x)</th>
<th>Vertical (z)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
<td>LC</td>
</tr>
<tr>
<td>SP1</td>
<td>13.8 (±3.6)</td>
<td>10.3 (±3.3)</td>
</tr>
<tr>
<td>SP2</td>
<td>12.7 (±3.4)</td>
<td>16.2 (±5.7)</td>
</tr>
</tbody>
</table>

Figure 9 - Average CoM position in the Side-to-Side, Forward, and Vertical directions during skate start strides. Yellow outlined rectangle is SP1, green outlined rectangle is SP2. Symbols correspond to Table 8.

Table 8 - Average Centre of Mass vertical (z) position (cm ±SD) for both HC and LC skaters at each step *indicates significant difference between calibre (p<0.05). Refer to Figure 21 for waveform specific data.

<table>
<thead>
<tr>
<th>Step</th>
<th>HC</th>
<th>LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDON1♦</td>
<td>-2.0 (±3.3)</td>
<td>-4.8 (±2.7)*</td>
</tr>
<tr>
<td>PUON1♦</td>
<td>3.3 (±2.7)</td>
<td>-4.3 (±4.3)*</td>
</tr>
<tr>
<td>LDON2♥</td>
<td>3.2 (±2.8)</td>
<td>-3.9 (±2.8)*</td>
</tr>
<tr>
<td>PUON2♦</td>
<td>1.1 (±2.7)</td>
<td>-4.8 (±3.2)*</td>
</tr>
</tbody>
</table>
From the primary displacement and time measures, corresponding skating CoM velocity and acceleration measures were calculated. High calibre skaters achieved larger average Forward velocity than low calibre skaters over the four start steps \((F(1,13) = 4.79, p = .048; \text{Table 6})\). No calibre differences in Side-to-Side or Vertical velocities were evident, \((F(1,13) = .929, p = .353\) and \(F(1,13) = 4.48, p = .054\), respectively, Table 9, Figure 10).

**Table 9** - Average skating velocity (m/s ±SD) for both HC and LC skaters in the Side-to-Side, Forward, and Vertical axes at each step *indicates significant difference between calibre **indicates significant step interaction. (p<0.05).

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Step} & \text{Side-to-Side axis (x)} & & \text{Forward axis (y)} & & \text{Vertical axis (z)} \\
& HC & LC & & HC & LC & \\
\hline
LDON1\& & -0.63 (±0.24) & -0.19 (±0.23)** & & 2.65 (±0.49) & 1.97 (±0.55)* & 0.25 (±0.16) & -0.09 (±0.20) \\
PUON1\& & 0.70 (±0.44) & 0.48 (±0.37) & & 3.89 (±0.27) & 3.58 (±0.60)* & 0.11 (±0.23) & 0.14 (±0.27) \\
LDON2\& & -0.58 (±0.40) & -0.50 (±0.49) & & 4.84 (±0.21) & 4.47 (±0.53)* & 0.19 (±0.19) & 0.01 (±0.29) \\
PUON2\& & 0.80 (±0.56) & 0.12 (±0.37)** & & 5.53 (±0.15) & 5.10 (±0.61)* & 0.10 (±0.14) & -0.04 (±0.29) \\
\hline
\end{array}
\]

**Figure 10** - Average skating velocities in the Side-to-Side, Forward, and Vertical axes (x, y, z). Symbols correspond to Table 9.
High calibre skaters achieved larger average forward acceleration than low calibre skaters \((F(1,13) = 5.50, p = .036, \text{Table 10, Figure 11})\). High calibre skaters showed larger accelerations at the first and forth steps in the Side-to-Side and Vertical directions, compared to low calibre skaters.

**Table 10** - Average skating acceleration \((\text{m/s}^2 \pm \text{SD})\) for both HC and LC skaters in the in the Side-to-Side, Forward, and Vertical axes at each step *indicates significant difference between calibre **indicates significant step interaction \((p<0.05)\).

<table>
<thead>
<tr>
<th>Step</th>
<th>Side-to-Side (x)</th>
<th>Forward (y)</th>
<th>Vertical (z)</th>
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<tbody>
<tr>
<td></td>
<td>HC</td>
<td>LC</td>
<td>HC</td>
</tr>
<tr>
<td>LDON1</td>
<td>-12.88 (±4.16)</td>
<td>-6.82 (±2.84)**</td>
<td>15.88 (±2.00)</td>
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<tr>
<td>PUON1</td>
<td>13.44 (±6.36)</td>
<td>10.31 (±2.89)</td>
<td>18.35 (±3.54)</td>
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<tr>
<td>LDON2</td>
<td>-13.73 (±4.97)</td>
<td>-11.26 (±1.86)</td>
<td>20.05 (±2.55)</td>
</tr>
<tr>
<td>PUON2</td>
<td>12.77 (±3.82)</td>
<td>8.85 (±2.15)**</td>
<td>18.20 (±3.22)</td>
</tr>
</tbody>
</table>

**Figure 11** - Average skating acceleration in the in the Side-to-Side, Forward, and Vertical axes \((x, y, z)\). Symbols correspond to Table 10.
3.4 Lower Limb Joint Angles

For both the lead and push limb, hip flexion / extension, abduction / adduction, and internal / external rotation were calculated. For the knee only flexion / extension and ankle dorsiflexion / plantar flexion are reported, as the values within the other two planes are prone to substantial kinematic cross-talk (Benoit et al., 2006; Collins et al., 2009). The solid green bars at the bottom of each waveform (Figure 12) denote the skate-ice contact support duration. These occur between corresponding ON and OFF events. The lower limb joint angles were split into the two start phases (cycles): Start Phase 1 (SP1) and Start Phase 2 (SP2).

3.4.1 Step 1 (Lead Leg) Kinematics

There was no statistically significant main calibre nor calibre-step interaction effects for the Lead leg kinematic joint angles (Table 11). See Figure 12 for waveform specific data.

Table 11 - Average Lead leg joint angles (degrees ±SD) for both HC and LC skaters at each start phase (+ angles were hip flexion, adduction, internal rotation; knee flexion; ankle dorsiflexion).

<table>
<thead>
<tr>
<th>Angle</th>
<th>SP1†</th>
<th></th>
<th>SP2†</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip flexion</td>
<td>64.5 (±13.9)</td>
<td>64.0 (±8.9)</td>
<td>75.3 (±7.2)</td>
<td>75.8 (±4.9)</td>
</tr>
<tr>
<td>Hip adduction</td>
<td>-32.7 (±8.9)</td>
<td>-28.1 (±9.4)</td>
<td>-22.3 (±6.8)</td>
<td>-17.4 (±6.9)</td>
</tr>
<tr>
<td>Hip int rotation</td>
<td>-15.7 (±22.2)</td>
<td>-8.5 (±7.4)</td>
<td>-4.9 (±7.6)</td>
<td>-5.8 (±5.5)</td>
</tr>
<tr>
<td>Knee flexion</td>
<td>101.4 (±6.2)</td>
<td>91.8 (±14.0)</td>
<td>119.4 (±9.3)</td>
<td>111.2 (±10.4)</td>
</tr>
<tr>
<td>Ankle dorsi flexion</td>
<td>23.6 (±8.9)</td>
<td>20.4 (±5.8)</td>
<td>21.7 (±8.0)</td>
<td>17.5 (±4.7)</td>
</tr>
</tbody>
</table>
Figure 12 - Average Lead (steps 1 and 3) and Push (steps 2 and 4) Leg kinematics during skating start. Symbols correspond to Tables 11 and 12.
3.4.2 Step 2 (Push Leg) Kinematics

There was no statistically significant main calibre nor calibre-step interaction effects for the push leg kinematic joint angles. However, there was a statistically significant step to step interaction for hip flexion-extension between both start phases, \( F(1,13) = 4.93, p = .045 \). There was also no main effects of calibre, except for knee flexion/extension, \( F(1,13) = 6.30, p = .026 \). High calibre skaters created larger knee flexion near the end of both start phases (Figure 12).

Table 12 shows the descriptive values of each of the lead leg joint angles.

Table 12 - Average push leg joint angles (degrees ±SD) for both HC and LC skaters at each start phase *indicates significant difference between calibre. (p<0.05) **indicates significant stride interaction (p<0.05) (+ angles were hip flexion, adduction, internal rotation; knee flexion; ankle dorsiflexion).

<table>
<thead>
<tr>
<th>Angle</th>
<th>SP1*_mean ±SD</th>
<th>SP2*_mean ±SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip flexion**</td>
<td>-4.9 (±6.7)</td>
<td>2.5 (±14.6)</td>
</tr>
<tr>
<td>Hip adduction</td>
<td>-33.4 (±12.6)</td>
<td>-29.5 (±10.0)</td>
</tr>
<tr>
<td>Hip int rotation</td>
<td>-31.3 (±7.1)</td>
<td>-30.3 (±11.2)</td>
</tr>
<tr>
<td>Knee flexion</td>
<td>114.6 (±9.1)</td>
<td>103.4 (±7.6)*</td>
</tr>
<tr>
<td>Ankle dorsi flexion</td>
<td>-2.5 (±4.7)</td>
<td>-4.8 (±8.5)</td>
</tr>
</tbody>
</table>
Chapter 4: Discussion

This study set out to demonstrate that a detailed three-dimensional kinematics analysis of ice hockey skating was possible on a real ice surface. This was achieved though participants were not able to wear typical ice hockey equipment, as this would have obscured tracking of the body segments’ movements; rather, participant wore tight fitting compression clothing. Having achieved this, the study sought to compare the kinematic movements of high and low calibre skaters during the first four steps of the skating start.

Quantitative measures of step events and phases, centre of mass displacement and lower limb kinematics were derived using, to our knowledge for the first time, a three-dimensional motion capture system on an actual arena ice surface. The left and right limbs were defined as LEAD and PUSH, as stated within the methods section. These were derived from manual inspection of the data to see which leg began the forward movement. This limb was then labelled as the LEAD leg side (i.e. that initiated the first step); with the PUSH leg (i.e. that followed with second step).

As was expected, the high calibre skaters achieved greater start acceleration than their low calibre counterparts. Both calibre groups showed grossly similar lower limb joint kinematic profiles during skate support in the sagittal plane, contrary to findings by (Buckeridge et al., 2015; Lafontaine, 2007; Upjohn et al., 2008), that high calibre skaters amplified their lower limb ROM to achieve greater forward propulsion. The functional difference was that high calibre skaters achieved a more rapid, running start relative to the lower calibre’s slower, stepping advancement. In addition, the high calibre skaters achieved a substantially higher body CoM “bounce” with shorter skate contact time and greater vertical and forward propulsion velocities.
Differences in skating start velocities could not be related to strength differences per se, as these were equivalent between calibre groups; rather, it was the rate of lower limb movement that was the defining difference technique between calibre groups, as observed by Upjohn et al. (2008).

Most of the original hypotheses were not confirmed; being that, in general the peak kinematics and rate of lower limb joints’ motion did not increase over the first for steps of the skating start. Nor was skating velocity positively correlated with leg strength. Furthermore, high calibre skaters did not show greater lower limb joint peak angles throughout the start task, nor longer step lengths or larger step widths compared to low calibre skaters. Given the rejection of the hypotheses, other factors must be considered.

With regards to the start time to end of the fourth step, high calibre skaters completed the skating start faster than low calibre skaters. This finding is similar with a recent study conducted by Buckeridge et al. (2015). So how were the high calibre skaters able to start faster than low calibre skaters given grossly similar leg joint movements, leg strengths, as well as step length or widths? The rate of joint movement was the main discriminating variable, that is, high calibre skaters generated faster hip, knee and ankle step cycles. This matches the findings of Upjohn et al. (2008), who found that high calibre skaters showed greater rate of joint motion during steady-state ice hockey skating.

The faster power stroke executed by the high calibre skaters also corresponded to significantly shorter double support time than low calibre skaters. Indeed, high calibre skaters actually achieved a flight phase between second and third steps. This short support time and flight phase behaviour is similar to running gait patterns (Lee & Farley, 1998). Likely, this more rapid step “turning over” during the start created a larger forward net propulsion, and thus faster
start time. This agrees with de Koning et al. (1995) observations that the start phase is speed skating is similar to a running start, where elite skaters displayed “running-like” initial push-offs to create their initial propulsion.

The net result of the limb movements may be interpreted by movement the body’s center of mass. Both groups showed similar CoM range of movement step oscillations in both the Side-to-Side or Vertical directions. However, notably the high calibre skaters attained a higher average CoM vertical position throughout the full skating start (Figure 9) by 5 to 7 cm higher than their initial starting position, much like the spring-mass system for running (Lee & Farley, 1998). In comparison, the lower calibre skaters kept a lower, more dampened CoM vertical start. The high calibre’s greater vertical accelerations helped to sustain this higher body CoM position during the full skating start. This further agrees with the findings of de Koning et al. (1995), where elite speed skaters showed a “running-like” start. Hence, the vertical CoM variable may well functionally relate skate start performance. Further research including body CoM tracking is warranted in order to validate these findings.

The high calibre skaters had greater overall forward velocity during the first and fourth steps in both the Forward and Side-to-Side directions. The study by de Koning et al. (1995) supports these findings. They showed that elite speed skaters create larger leg segment rotational velocities during the start phase, allowing them to achieve their large “running-like” propulsion. Similar findings in acceleration were seen; where the overall forward acceleration, as well as the first and fourth step in the Side-to-Side direction were larger for high calibre skaters than low calibre skaters. These concurrent findings reinforce the notion that high calibre skaters are creating more powerful and explosive first steps during the skating start. Buckeridge et al. (2015) also stated that the differences between high and low calibre skaters lie within the acceleration
phase, whereby the high calibre skaters use a sprint-like running start to achieve their higher skating velocities (Keller et al., 1996).

The differences in lower limb kinematics were minimal between the groups for both the lead and push leg during skate-ice contact during the skating start. This was counter the findings of Upjohn et al. (2008), who found that high calibre skaters had higher knee flexion at ice contact during steady-state skating. This disagreement may be due to the functional difference in body CoM movement; that is, the skate start being more similar to a running spring-mass model versus steady-state skating being equivalent to a walking inverted pendulum model of locomotion.

Although not many gross kinematic differences were found between the high and low calibre groups, some unique joint kinematic patterns were noted. For example, both leg sides showed synchronized hip abduction/adduction profiles that never passed into adduction (Figure 12). This finding of greater skate start step widths (20-11 cm) compared to walking (~10 cm) (Owings & Grabiner, 2004) and running (~4 cm) (Arellano & Kram, 2011) may be a result of the need to attain greater stability by means of a large base of support on the ice surface, as well as to permit sufficient blade-to-ice angles to catch (“bite”) into the ice for propulsion.

Similarly, greater hip external rotation values were found throughout the first four steps during the skate start. The range of internal (+) and external (-) hip rotation was from 0 to -35 degrees. These values are substantially higher than what was found by in steady-state skating by Upjohn et al. (2008). Our findings show that the hip were both substantially abducted and externally rotated during the start phase. This is counter to Buckeridge et al. (2015) postulation that the transition from the acceleration phase to steady skate skating was defined by the change
from hip extension to hip abduction. It is the combination of appreciable hip abduction, external rotation and extension that is essential for optimal skate-to-ice push-off orientation needed for propulsion. Future three-dimensional study of the acceleration to steady-state ice hockey skating transition is warranted.

Also of note are the ankle plantar / dorsi flexion profiles, where clear pattern differences (though not significant) were seen. The high calibre skaters attained approximately 10 degrees greater dorsiflexion while the skate was in contact with the ice. This greater pre-dorsiflex position of the ankle may in turn contribute to a greater “plantar coil reflex” action that, in turn, may contribute to the observed greater and faster vertical CoM flight. These findings are similar to those of Pearsall et al. (2001), who found that elite ice hockey skaters quickly plantarflexed their foot directly after push-off. Buckeridge et al. (2015) also states that the gastrocnemius at the ankle joint acts as an explosive plantar-flexor muscle, allowing for skaters to achieve the “running-like” start motion. They found that there was more force in the skate during the acceleration phase. This could potentially explain how the high calibre skaters showed, although not significant, larger amounts of dorsiflexion during ice contact, allowing them to create more force to push-off, thus leading to higher skating velocities. Closer examination of skate start ankle motions is warranted.

The implication of this study are many. Firstly, to our knowledge, this is the first study to demonstrate the feasibility of using start-of-the-art motion capture systems for a detailed three-dimensional kinematic analysis of ice hockey skating on an actual ice surface. This allowed for the capture of high resolution kinematic data. Future studies are conceivable with inclusion of more cameras to create a longer skating corridor to analyze the ice hockey skating start through
to steady-state transition, as well as other tasks such as backwards skating, turning, shooting, and stickhandling.

In terms of practical, coach implications, this study’s results indicate that kinematic tracking of the estimated body’s CoM was a discriminating variable for performance outcomes between the groups. To confirm this future studies should include analysis the full-body kinematics. Though muscle strength (as estimated from long jump trials) was not found as a predictor of skating start speed, future studies should focus on muscle power. This could be achieved by adding more off-ice measurements to the testing protocol. Vertical and lateral jump tests, as well as other explosive plyometric tests could perhaps elicit the difference in muscle power between high and low calibre skaters. Lastly, future on-ice analysis should include a broader range in subjects ranging in developmental age as well as by gender.
Chapter 5: Conclusion

This study was the first of its kind to use state-of-the-art three-dimensional camera systems directly within an ice arena and on the ice surface to record detailed lower body kinematics of ice hockey skating. This is a remarkable achievement and demonstrates the feasibility of this approach for further skating studies within the actual skating environment. Overall, as expected, high calibre skaters completed the task faster and with larger overall forward velocity than low calibre skaters. Though the gross movement patterns of the lower limbs were very similar between groups, high calibre skaters’ joint movements were substantially faster. In turn, the high calibre skaters achieved a higher upright CoM position and shorter double support times during these “running” start steps that may have contributed to their greater forward acceleration. The differences noted cannot be attributed to leg strength discrepancies, as both groups had similar leg strength profiles, but rather faster joint movement to elicit greater muscle power. Scrutiny of the results indicate that closer kinematic analysis of the ankle dorsi-plantar flexion in relation to power output is justified. From this study, in contrast to over ground sprint start kinematic technique, greater concurrent hip abduction, external rotation and extension is essential for optimal skate-to-ice push-off orientation needed to for propulsion. Further direct on-ice research is warranted to address other skating skills using detailed kinematic analysis.
References


de Boer, R., de Groot, G., & van Ingen Schenau, G. J. (1986). Specificity of training in speed skating. *Biomechanics XB.*


Ernst, M., Götte, M., Müller, R., & Blickhan, R. (2014). Vertical adaptation of the center of mass in human running on uneven ground. *Human Movement Science, 38*(0), 293-304. doi: [http://dx.doi.org/10.1016/j.humov.2014.05.012](http://dx.doi.org/10.1016/j.humov.2014.05.012)


Marino, G. (1975). *Multiple regression models of the mechanics of the acceleration phase of ice skating*. University of Illinois at Urbana-Champaign.


Appendix I – Participant Information and Consent Form

Subject:

ID:

Date:

Order:

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<th>√ After</th>
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**Required Subject Measurements for Plug-in-Gait**

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<td>Inter-ASIS Distance (cm)</td>
<td>Lower &amp; All</td>
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<td>Distance between the left ASIS and right ASIS. This measurement is only needed when markers cannot be placed directly on the ASIS, for example, in obese patients.</td>
</tr>
<tr>
<td>Leg Length (mm)</td>
<td>Lower &amp; All</td>
<td></td>
<td></td>
<td>measured between the ASIS and the medial malleolus, via the knee joint. If, for example, the subject is standing in crouch, this measurement is NOT the shortest distance between the ASIS and medial malleoli, but rather the measure of the skeletal leg length.</td>
</tr>
<tr>
<td>Knee Width (mm)</td>
<td>Lower &amp; All</td>
<td></td>
<td></td>
<td>The medio-lateral width of the knee across the line of the knee axis. Measure this distance with the subject standing if possible.</td>
</tr>
<tr>
<td>Ankle Width (mm)</td>
<td>Lower &amp; All</td>
<td></td>
<td></td>
<td>The medio-lateral distance across the malleoli. Measure this distance with the subject standing if possible.</td>
</tr>
<tr>
<td>Tibial Torsion (deg)</td>
<td>N/A</td>
<td>N/A</td>
<td>Lower &amp; All</td>
<td>(Optional) Not necessary when using the tibial marker to identify the ankle axis.</td>
</tr>
<tr>
<td>Thigh Rotation offset (deg)</td>
<td>CPIG</td>
<td>CPIG</td>
<td>Lower &amp; All</td>
<td>Calculated by the Plug-in-Gait model if you are using the Knee Alignment Device</td>
</tr>
<tr>
<td>Shank Rotation offset (deg)</td>
<td>CPIG</td>
<td>CPIG</td>
<td>Lower &amp; All</td>
<td>Calculated by the Plug-in-Gait model if you are using the Knee Alignment Device</td>
</tr>
<tr>
<td>Foot Plantar Flexion offset (deg)</td>
<td>CPIG</td>
<td>CPIG</td>
<td>Lower &amp; All</td>
<td>Calculated by the Plug-in-Gait model</td>
</tr>
<tr>
<td>Foot Rotation offset (deg)</td>
<td>CPIG</td>
<td>CPIG</td>
<td>Lower &amp; All</td>
<td>Calculated by the Plug-in-Gait model</td>
</tr>
<tr>
<td>Shoulder Offset (mm)</td>
<td>Upper &amp; All</td>
<td></td>
<td></td>
<td>vertical offset from the base of the acromion marker to shoulder joint center</td>
</tr>
<tr>
<td>Elbow Width (mm)</td>
<td>Upper &amp; All</td>
<td></td>
<td></td>
<td>Width of elbow along flexion axis (roughly between the distal epicondyles of the humerus)</td>
</tr>
<tr>
<td>Wrist Width (mm)</td>
<td>Upper &amp; All</td>
<td></td>
<td></td>
<td>Anterior/ Posterior thickness of wrist at position where wrist marker bar is attached.</td>
</tr>
<tr>
<td>Hand Thickness</td>
<td>Upper &amp; All</td>
<td></td>
<td></td>
<td>Anterior/ Posterior thickness between the dorsum and palmar surfaces of the hand.</td>
</tr>
<tr>
<td>Shoulder width (cm)</td>
<td></td>
<td></td>
<td></td>
<td>Distance b/w the 2 Acroclavicular joints. Take measurement from back of neck.</td>
</tr>
</tbody>
</table>

* CPIG are measurements that are calculated by the Plug-in-Gait mode
INFORMATION AND INFORMED CONSENT

Investigator: Philippe Renaud, M.Sc. candidate, philippe.renaud@mail.mcgill.ca
David J. Pearsall, PhD
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 the McGill McConnell Arena and the Biomechanics Laboratory (Room 400) of the Department of Kinesiology and Physical Education, McGill University, located at 475 Ave des Pins Ouest, Montreal, Quebec H2W 1S4. You are asked to come to one experimental session that will last up to two hours. To qualify for this study, participants must not presently have any lower limb injuries or any that have prevented them from playing within the past year.

Purpose of the Study
The purpose of this study is to conduct a three-dimensional kinematic motion analysis of ice hockey forward skating start and strides on the actual ice surface; and to compare the movement patterns of high and low calibre skaters. Specifically, we will be comparing the differences, if any, in velocity, lower limb (hip, knee, ankle) range of motions, and skate/ice orientations between the high and low calibre subjects.

Your participation in this study involves:
1. Providing informed consent prior to experimental participation.
2. Providing data concerning your physical attributes (weight, height, age, and different body segment measurements).
3. Perform three maximal long jumps
4. Skating through the motion capture area
5. The following is the general procedures for your experimental session
   a. Review of the experimental protocol and informed consent
   b. Recording of body segment dimensions, height and weight
   c. Perform three maximal long jumps
   d. The placement of 24 reflective and adhesive makers on various landmarks on both sides of your body
   e. The completion of three calibration files, followed by three skating start and three skating stride trials (high caliber subjects will perform these trial with both skate models)
Risks and Discomforts

It is anticipated that you will encounter no significant discomfort during these experiments. You will be required to wear tight fitting athletic clothing during the experiment. Redness and itchiness from the double-sided adhesive tape used to affix the reflective markers to your skin will be temporary and short lived if experienced at all.

Benefits

There is no financial compensation for participating in this study.

Confidentiality

All of the personal information collected during the study concerning you will be numerically encoded based on the order of testing in order to keep your identity confidential. These records will be maintained in a locked cabinet at the Biomechanics Laboratory by Dr. David Pearsall for five years after the completion of the project, and will be destroyed afterwards. Only members of the research team will have access to them. For presentation and publication purposes, you will remain entirely anonymous.

Inquiries Concerning this Study

If you require information concerning the study (experimental procedures or other details), please do not hesitate to contact Philippe Renaud <philippe.renaud@mail.mcgill.ca> or Dr. Pearsall <david.pearsall@mcgill.ca>.

Responsibility clause

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

Consent

Please be advised that your participation in this research undertaking is strictly on a voluntary basis, and you may withdraw at any time. A copy of this form will be given to you before the end of the experimental session.

If you have any questions or concerns regarding your rights or welfare as a participant in this research study, please contact the McGill Ethics Officer at 514-398-6831 or lynda.mcneil@mcgill.ca.

Signatures

I, ________________________________, AGREE TO VOLUNTARILY PARTICIPATE IN THE STUDY DESCRIBED ABOVE PERTAINING TO POSTURAL CONTROL ON SKATES.

Signature: ________________________________ Date: ________________________________
PRE-SCREENING QUESTIONNAIRE

Name: _____________________________

Age: _____________________________

Hockey Experience (years): _____________________________

Highest Level Played: _____________________________

Current Team: _____________________________

Skate Size: _____________________________

Skate Model: _____________________________

Shot Handedness: _____________________________

1. In the past year have you suffered any hip, knee, or ankle injuries? Has it prevented you from playing hockey? Please explain.

_____________________________________________________________________________
_____________________________________________________________________________

2. In the past year have you experienced any other lower body injuries? (E.g. broken bones, torn ligaments, etc.) Have they prevented you from playing hockey? Please explain.

_____________________________________________________________________________
_____________________________________________________________________________

3. In the past year have you suffered any nervous system injury? (E.g. Damage to a nerve, numbness or pins and needles, etc.) Has it prevented you from playing hockey? Please explain.

_____________________________________________________________________________
_____________________________________________________________________________

4. Is there any other reason why you believe you shouldn’t participate in this study? Please explain.

_____________________________________________________________________________
_____________________________________________________________________________