Three-Dimensional Kinematics of the Lower Limbs during Forward Hockey Skating

Tegan Upjohn

Department of Kinesiology and Physical Education

McGill University, Montreal

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I am so very fortunate to have such a wonderful group of loving, supportive family and friends with which to share my challenges and successes. One person in particular has recently shared many of life’s challenges with me; I have given him my heart and he has given me his.
Abstract

Objectives: The purpose of this study was to determine whether there were significant kinematic differences between recreational and elite hockey players and between contra-lateral lower limbs during forward hockey skating.

Methods: While skating on a hockey treadmill subjects were filmed with four synchronized digital video cameras while wearing reflective marker triads on the thighs, shanks and skates. Subjects skated within a calibrated volume at a self selected speed that they could maintain comfortably for one minute. Each subject completed three trials separated by 5 minutes of rest. Data was reduced and analyzed using programs written in MATLAB. Two-way ANOVA and Tukey Post Hoc tests were used to determine statistic significance.

Results: Elite and recreational subjects were significantly different (p<0.05) during knee abduction and knee rotation at push off, as well as during knee abduction and knee flexion at blade contact. Contra lateral lower limbs were significantly different (p<0.05) during ankle abduction and hip rotation at blade contact as well as during knee abduction at push off.

Conclusion: Some aspects of the skating stride are similar in elite and recreational hockey skaters but there were several kinematic differences between skill levels and contra-lateral legs. The skating kinematics of elite hockey players may serve as a model for young hockey players and recreational hockey players, helping them develop a more efficient and effective stride.
Résumé

Objectifs : Déterminer s’il y a des différences cinématiques en patinant entre les joueurs de hockey élites et les joueurs de hockey récréatifs, et entre la jambe droite et la jambe gauche.

Méthodes : Les participants de l’étude ont patinés sur un tapis roulant et leurs mouvements étaient capturés par quatre caméras (vidéo digitale) synchronisés. Les participants ont patinés dans un volume calibré pour une période d’une minute. Chaque participant a accompli trois essais, séparés par cinq minutes de repos.

Résultats : Il y avait des différences significatives \((p<0.05)\) entre les participants élites et les participants récréatifs durant l’abduction du genou et la rotation du genou au moment du soulèvement du pied ainsi que durant l’abduction du genou et la flexion du genou au contacte de la lame. Il y avait des différences significatives entre la jambe gauche et la jambe droite durant l’abduction de la cheville et la rotation de la hanche au contacte de la lame, aussi que durant l’abduction du genou à au moment du soulèvement du pied.

Conclusion : Malgré les similarités durant la patinage des joueurs élites et les joueurs récréatifs, il existe plusieurs différences cinématiques entre les niveaux de compétence et entre les jambes gauche et droite. En essayant d’adapter les cinématiques de patinage des joueurs élites, les joueurs récréatifs et les jeunes joueurs pourraient peut-être développer leur abilité de patinage.
1.0 Introduction

Ice Hockey is a fast paced sport which requires players to have an excellent degree of physical conditioning, as well as precision and control in technical aspects of the game, such as shooting, passing, tight turns and forward skating. Forward hockey skating is arguably the most important skill that a hockey player possesses. Well developed hockey skating kinematics allow players to move efficiently on the ice, permitting more energy to be dedicated to skill-specific tasks.

The kinematics of forward ice hockey skating describe the motion of the body during the skating stride without reference to the forces that cause that motion. A kinematically efficient hockey skating stride is biphasic and is broken down into the support phase and the swing phase. The support phase can be further broken down into single support (18% of support phase) and double support (82% of support phase) (Pearsall et al, 2000; Marino et al, 1983). Propulsion takes place during both double and single support after the outward rotation of the thigh, coinciding with initial extension of the hip and knee (Pearsall et al, 2000).

Skating kinematics of recreational players are, by observation, markedly different than those of elite or professional players. The pace of the game and the speed at which the players skate suggests that elite players are kinematically more efficient than recreational players. McCaw and Hoshizaki (1987) evaluated skating kinematics and found that there were marked differences between elite and recreational players. Their
results show that elite players exhibit an increased stride rate and a decreased amount of
time spent in both single and double support, compared to recreational players. Elite
players also show a deceleration of hip and knee extension as the centre of gravity
comes ahead of the support foot, whereas there was no such noticeable deceleration in
the novice skater (McCaw and Hoshizaki, 1987). Their work suggests that kinematics
plays an important role in describing the proficiency of the skating stride.

Past kinematic research of forward hockey skating has investigated individual joint
angles during stride. However, there are very few studies that have adequately recorded
all three joint angles simultaneously during stride. Pearsall et al (2002) examined the
angular motion of the ankle during the skating stride using bilateral twin axis
electrogoniometers placed on the rear foot along the longitudinal axis of the Achilles
tendon, thus allowing simultaneous measurement of angles in two planes. By using this
technique, they discovered that, during single support of the glide phase in forward
hockey skating, the ankle was in 7.1 degrees of dorsiflexion. They also showed that the
ankle was slightly everted, with relatively little change as the glide phase progresses
towards push off. These investigators found that, during push off the ankle was everted
to a maximum of 6.8 degrees and dorsiflexed to a maximum of 11.5 degrees. At this
point in the stride, the ankle reached a point of maximum dorsiflexion and eversion in
order to generate a maximum propulsive force. During recovery, the ankle began to
plantar flex and went from being in 11.5 degrees of dorsiflexion to 1.9 degrees of
dorsiflexion (Pearsall et al, 2002). Although this research has provided invaluable
insight into the kinematics of forward hockey skating, the techniques that were used
allow analysis of only the local joint coordinate system (LCS) without reference to the
global coordinate system (GCS) and global kinematics (A more in-depth explanation of
LCS and GCS follows on page 5). There are still several unanswered questions with
regard to whole body kinematics during forward skating, specifically the internal and
external rotation of the hip during blade contact and push off. In an attempt to record
whole body kinematics during forward skating, McPherson et al (2004) studied the
whole body kinematics of developmental age hockey players. McPherson established a
set of kinematic data, including joint angles for the hip, knee and ankle at various points
during stride. Although the study was the first of its kind to be done in the sport of ice
hockey, it had several limitations. The study was conducted on ice over a distance of
6m. Two digital cameras with a recording rate of 30 frames per second (fps) were
placed in the sagittal plane 30m apart, each at a distance of 22m from the subjects
(MacPherson et al, 2004). Skating kinematics were recorded as subjects skated in a
straight line, 6m in length, perpendicular to the cameras. Although the experimental set
up was an accurate representation of actual skating conditions, the accuracy of
kinematic data is questionable due to a lack of precision of marker placement over joint
centres and type of marker used. McPherson et al (2004) opted to use flat reflective
tape strips instead of spherical reflective markers. Cappozzo et al 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 state that ‘sufficient
measurements (three-image coordinates) should be available on the markers from
available cameras at any given time’ (Cappozzo et al, 1995). Since the reflective tape
that McPherson used was flat, not spherical, it is doubtful that it met both of the above-
mentioned criteria. The flat nature of the reflective markers also makes it difficult, if not impossible, to determine the barycentre of the marker which may be confounded by the number of pixels used in the digitization process which is used in data reduction. Third, in order for the cameras to record the reflective tape, and to be able to digitize the data, the reflective tape placed on the joint centres must have been fairly large. An increased marker size increases error in estimating anatomical joint centres, and reduces the accuracy of joint angle calculations.

In order to accurately record forward hockey skating kinematics, data must be collected in a controlled environment that accurately simulates on-ice skating conditions. Not only is it important to record skating kinematics of elite players, but it is also important to record skating kinematics of recreational players in order to determine which specific characteristics of the skating stride undergo significant changes as skating proficiency improves. The present study proposes to determine the three dimensional kinematics of the lower limbs during forward hockey skating, specifically the angular kinematics of the hip, knee and ankle during blade contact and push off of contra-lateral lower limbs. This study will also determine whether there are differences in the skating kinematics of elite and recreational hockey players. It is hypothesized here that there will be significant kinematic differences between elite and recreational hockey players as has been suggested by related studies (McCaw, 1987, Boer, 1986). Such differences would apparent through joint angles and/or segment orientation with respect to adjoining segments or a global coordinate system. It is also hypothesized that there will be kinematic differences between contra-lateral lower limbs in both recreational and elite
hockey skaters. The present study should help researchers and practitioners achieve a better understanding of the mechanics of the skating stride. This knowledge may be used in turn to improve the kinematics of forward ice hockey skating and improve overall performance of the hockey player during the game.

Definition of Terms

Direct Linear Translation (DLT) – Method by which several sets of two-dimensional spatial coordinates (as filmed by a digital video camera) are transformed into a set of three-dimensional spatial coordinates. The DLT method provides a linear relationship between the two-dimensional coordinates of a marker on the film and its three-dimensional location in space (Nigg, 1999).

Forward Hockey Skating - Forward hockey skating is characterized by its specific application to the sport of ice hockey.

Global Coordinate System – Fixed coordinate system in the laboratory from which all positions are derived (Robertson et al, 2004). The GCS is an orthogonal system.

Kinematics - Kinematics allows determination of position, velocity and acceleration by examining an object’s speed and spatial position (Hamill and Knutzen, 1995).

Local Coordinate System – reference system that is fixed within a body or a segment and moves with the body or segment (Robertson et al, 2004). The LCS is an orthogonal system.
**Stride** – Biphasic motion of skating, which begins when the foot contacts the ice with the heel of the blade and progresses through glide, push off and recovery of the ipsilateral limb (Pearsall et al, 2000).
2.0 Methods

2.1 Subjects

Sixteen hockey players from the general public and the McGill University Men’s Varsity Ice Hockey team (age 37 ±18 years, height 182 ±12 cm, weight 89.4 ±18 kg) volunteered to participate in this study. Subjects were classified as either elite or recreational based on their league of play and years of experience. All subjects were informed of the experimental procedures and subsequently signed an informed consent form approved by the McGill University Board of Ethics stating their understanding of the risks and benefits associated with the study.

2.2 Instrumentation and Experimental Setup

All data were collected in a controlled indoor laboratory environment in the Seagram Sport Science Centre at McGill University. A skating treadmill (Frappier Acceleration Sport Training) was set at an inclination of 2 degrees to simulate on-ice skating conditions. Four 1.33 mega pixel digital video camcorders (Cannon Optra 200 MC) were used to film the subjects at 30 frames per second. (Appendix B, Figure B-1). Cameras were placed in the four corners of the laboratory at a diagonal distance of between 1.5 and 3 metres from the centre of the treadmill. (Appendix B, Figure B-2). In order to calibrate the skating volume, four high intensity lights were used to illuminate 27 spherical reflective markers (25mm in diameter) placed in a random pattern throughout the skating space above the treadmill. This calibration grid was
filmed for five seconds prior to and subsequent to data collection for each subject.
Camera placement was predicated by the ability to capture the calibrated skating space in each camera’s field of view. (Appendix B, figure B-4) Camera placement was limited by dimensional constraints of the laboratory space.

2.3 Experimental Procedure

Subjects’ height, weight and age were recorded, as well as anthropometric measurements of the right and left thigh, shank, foot and leg. Age was measured in years; height was measured in cm using a wall mounted measuring tape; weight was recorded to the nearest pound then converted to kilograms. All anthropometric measurements were taken using a tape measure (H.A. Kidd and Company Limited) and recorded to the nearest 0.5 cm. Subjects performed a standing vertical jump and right and left leg standing long jumps as a measure of leg strength and dominance. Subjects were instructed to perform all jumps from a stationary position and there were otherwise no restrictions.

Prior to kinematic data collection, subjects underwent an acclimation period, during which they were introduced to the skating treadmill, given an explanation of its operation and safety features and practiced skating on the treadmill. During the acclimation period, subjects were instructed to choose the maximum speed that they could comfortably maintain for a period of one minute during data collection.
Lightweight wooden spheres 5mm in diameter were covered in reflective tape and placed on bony landmarks of the lower limbs in accordance with the kinematic principles outlined by Grood and Suntay (1983) and Cappozzo et al (1995). Single reflective spheres were placed on the left and right anterior posterior iliac spine (ASIS), lateral and medial epicondyles, lateral and medial malleolus, and approximation of the distal end of the fifth metatarsal. (Appendix B, Figures 5-6) Rigid clusters consisting of three spherical reflective markers (5mm diameter) in equilateral triangular formation (Appendix B, figure B-5) were attached with double-sided Velcro to the right and left thigh, shank foot, and the pelvis. Markers within the rigid clusters on the thigh and pelvis were 13cm apart; markers within the rigid clusters on the shank and foot were 10cm apart.

Subjects were filmed standing stationary on the treadmill within the calibrated space for a period of 5 seconds. Single reflective spheres were removed from the subject, leaving only the rigid clusters. Subjects wore a safety harness attached to the overhead crossbar of the treadmill and held a hockey stick in one hand as they would while skating on ice during a hockey game. They held on to the treadmill safety bar in front of them with the other hand as the treadmill reached the predetermined subject-selected speed. Once the treadmill had reached its predetermined speed, subjects let go of the crossbar and began skating. Cameras began filming and were synchronized with a light emitting diode (LED), which was triggered at the beginning of each trial. (Appendix B, figure B-4) Subjects performed three trials of one minute in duration with five minutes of rest between trials (Appendix B, figure B-7).
2.4 Data Analysis

2.4.1 Video Capture and 3-D Image Reconstruction

Digital Video data were transferred to a personal computer and captured using Pinnacle Studio 8 software. Captured calibration data and standing trials from each of the four DV cameras were cut into segments of 5 frames each and saved as individual .avi files. Skating trials from each DV camera were cut into segments of 11 strides, beginning 1 frame prior to the LED synch light and ending on push off of the 11th stride. Each of these trials was also saved as an individual .avi file. This procedure was repeated for all 16 subjects. Following data capture, all .avi files were de-laced using a program written in MATLAB to double the sampling rate from 30 frames per second to 60 frames per second. The delacing program may have introduced a miniscule amount of error, but any error introduced would be less than one pixel, hence miniscule in comparison to any error occurring during the digitizing process (explanation of digitizing process follows). All .avi files were then digitized using a MATLAB program. All subject trials were rebuilt to form a three-dimensional image using the Direct Linear Translation method (Kwon, 2005).

2.4.2 Joint Angle Calculations

Joint angles were calculated using the joint coordinate system for clinical description of three dimensional motions proposed by Grood and Suntay (1983). Mechanical axes were defined during standing trials using reflective marker triads placed on adjacent
segments (pelvis/thigh/shank/foot). Here the z axis was positive in the proximal
direction, the x axis was positive in the lateral direction and the y axis was anteriorly.

Figure 1 - Calculation of mechanical axes (right leg) using data from standing trials.
Figure adapted from Grood and Suntay (1983) Pp-proximal pelvis Ap-anterior pelvis
Lp-lateral pelvis Pt-proximal thigh At-anterior thigh Ll-lateral thigh F-vector cross
product of Pt and Lp α-flexion β-abduction γ-twist/rotation.
Figure 1 shows the proximal, anterior and lateral axes of the pelvis and the right thigh, as defined by the orientation of the segmental triads. A floating axis (vector F) was defined by the cross product of the proximal thigh vector (Pt) with the Lateral pelvis vector (Lp) according to the right hand rule. Vector F is orthogonal to both Pt and Lp. Angle $\alpha$ is formed between the proximal pelvis vector (Pp) and the floating axis (vector F) and is representative of flexion. Angle $\beta$ is formed between the proximal thigh vector (Pt) and the floating axis (vector F) and is representative of abduction. Angle $\gamma$ is formed between the proximal thigh vector (Pt) and the lateral pelvis vector (Lp) and is representative of twist or rotation. Mechanical axes were calculated according to the same method for the left leg, however, the floating axis (vector F) was inverted so that it is pointing anteriorly, the same direction as the floating axis of the right leg (Appendix B, Figure B-8). This adjustment was necessary in order to calculate flexion angles correctly. $90^\circ$ was subtracted from all angles so that $\alpha$, $\beta$, and $\gamma$ are $0^\circ$ in the neutral standing position.

2.6 Statistics

All angles were calculated on a per-stride basis. Angles of the skate leg and the recovery leg were calculated at blade contact and push off. A two-way ANOVA was performed between skill levels and contra-lateral limbs followed by a Tukey post hoc test.
3.0 Results

3.1 Subject Characteristics

Mean subject characteristics are listed in table 1. Note that although there were statistical differences between groups in treadmill speed, stride rate was not significantly different. Right and left leg long jumps were significantly greater in elite players than recreational players, and although elite players did not exhibit a significantly higher vertical jump, the value did approach significance (p≤0.075). There were no significant differences in age, height, or weight between groups and all subjects declared their right leg to be dominant.

Table 1 – Mean subject characteristics of recreational and elite subjects. * indicates significant differences (p≤0.05) between recreational and elite subjects as determined by a t-test.

<table>
<thead>
<tr>
<th></th>
<th>Recreational mean (±SEM)</th>
<th>Elite mean (±SEM)</th>
<th>Statistical Significance <em>(p≤0.05)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>31 (±4.2)</td>
<td>25.5 (±2.0)</td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>180.6 (±2.8)</td>
<td>179 (±1.3)</td>
<td></td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>86.2 (±4.0)</td>
<td>87.5 (±2.4)</td>
<td></td>
</tr>
<tr>
<td>Treadmill Grade (%)</td>
<td>2.0 (±0.0)</td>
<td>2.0 (±0.0)</td>
<td></td>
</tr>
<tr>
<td>Treadmill Speed (km/h)</td>
<td>13.6 (±0.7)</td>
<td>17.6 (±0.3)</td>
<td></td>
</tr>
<tr>
<td>Stride Rate (Strides/min)</td>
<td>55.1 (±1.2)</td>
<td>59.9 (±1.5)</td>
<td></td>
</tr>
<tr>
<td>Vertical Jump (%height)</td>
<td>21.4 (±3.9)</td>
<td>29 (±1.0)</td>
<td></td>
</tr>
<tr>
<td>Left Leg Long Jump (%height)</td>
<td>94.8 (±4.1)</td>
<td>115.6 (±2.6)</td>
<td></td>
</tr>
<tr>
<td>Right Leg Long Jump (%height)</td>
<td>84.8 (±12.4)</td>
<td>115.1 (±2.2)</td>
<td></td>
</tr>
</tbody>
</table>
3.2 Angular Kinematics

Mean push off and contact angles for elite and recreational players are presented in tables 2-3. Note that an angle of 0 is representative of the subject’s neutral/anatomical position as determined by their posture in the still trials. External rotation, flexion, plantar flexion, eversion and abduction angles are denoted as positive, while internal rotation, extension, dorsi flexion, inversion and adduction are denoted as negative.

Table 2 – Mean push off angles for the left and right lower limbs of elite and recreational hockey players. *indicates significant differences between legs **indicates significant differences between recreational and elite levels. (p<0.05)

<table>
<thead>
<tr>
<th>Angle</th>
<th>Rec Left</th>
<th>Rec Right</th>
<th>Elite Left</th>
<th>Elite Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle abduction</td>
<td>12.8 (±1.6)</td>
<td>7.5 (±1.6)</td>
<td>8.0 (±1.3)</td>
<td>6.2 (±1.4)</td>
</tr>
<tr>
<td>Ankle flexion</td>
<td>7.6 (±2.0)</td>
<td>12.3 (±1.4)</td>
<td>10.8 (±2.4)</td>
<td>11.1 (±1.9)</td>
</tr>
<tr>
<td>Ankle rotation</td>
<td>6.3 (±1.8)</td>
<td>10.0 (±0.7)</td>
<td>5.2 (±2.8)</td>
<td>6.9 (±0.9)</td>
</tr>
<tr>
<td>Knee abduction</td>
<td>-3.7 (±0.8)</td>
<td>**-0.5 (±0.9)</td>
<td>*-1.0 (±2.0)</td>
<td><em>/</em>/**4.7(±1.1)</td>
</tr>
<tr>
<td>Knee flexion</td>
<td>12.5 (±2.5)</td>
<td>8.0 (±1.9)</td>
<td>18.4 (±2.6)</td>
<td>13.4(±2.6)</td>
</tr>
<tr>
<td>Knee rotation</td>
<td>**6.6 (±1.8)</td>
<td>2.1 (±2.0)</td>
<td>**0.1 (±0.9)</td>
<td>1.0 (±0.8)</td>
</tr>
<tr>
<td>Hip abduction</td>
<td>10.8 (±2.9)</td>
<td>9.2 (±0.6)</td>
<td>12.5 (±3.3)</td>
<td>6.6 (±2.4)</td>
</tr>
<tr>
<td>Hip flexion</td>
<td>-3.8 (±3.4)</td>
<td>-2.2 (±1.3)</td>
<td>-5.6 (±2.4)</td>
<td>-2.5 (±2.4)</td>
</tr>
<tr>
<td>Hip rotation</td>
<td>7.8 (±1.2)</td>
<td>7.8 (±1.9)</td>
<td>4.5 (±1.8)</td>
<td>5.5 (±1.4)</td>
</tr>
</tbody>
</table>

Table 3 – Mean blade contact angles of the left and right lower limbs of recreational and elite hockey players. *indicates significant differences between legs **indicates significant differences between recreational and elite levels. (p<0.05)

<table>
<thead>
<tr>
<th>Angle</th>
<th>Rec Left</th>
<th>Rec Right</th>
<th>Elite Left</th>
<th>Elite Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle abduction</td>
<td>10.8 (±1.2)</td>
<td>6.7 (±1.4)</td>
<td>10.8 (±1.1)</td>
<td>5.2 (±1.2)</td>
</tr>
<tr>
<td>Ankle flexion</td>
<td>-4.2 (±1.1)</td>
<td>-1.2 (±1.9)</td>
<td>-2.7 (±1.6)</td>
<td>-3.0 (±1.5)</td>
</tr>
<tr>
<td>Ankle rotation</td>
<td>-1.1 (±0.8)</td>
<td>2.6 (±0.7)</td>
<td>-0.3 (±1.9)</td>
<td>1.0 (±0.6)</td>
</tr>
<tr>
<td>Knee abduction</td>
<td>-10.1 (±0.9)</td>
<td>**-9.2 (±1.7)</td>
<td>-8.0 (±2.1)</td>
<td>**-1.9 (±1.7)</td>
</tr>
<tr>
<td>Knee flexion</td>
<td>**34.3 (±1.9)</td>
<td>*29.1 (±1.9)</td>
<td>*51.1 (±1.3)</td>
<td>**48.2 (±1.7)</td>
</tr>
<tr>
<td>Knee rotation</td>
<td>-2.4 (±1.4)</td>
<td>-5.2 (±0.9)</td>
<td>-2.3 (±1.9)</td>
<td>-0.4 (±1.4)</td>
</tr>
<tr>
<td>Hip abduction</td>
<td>5.6 (±1.9)</td>
<td>0.7 (±1.2)</td>
<td>6.3 (±2.0)</td>
<td>0.2 (±2.1)</td>
</tr>
<tr>
<td>Hip flexion</td>
<td>-42.8 (±2.5)</td>
<td>-41.6 (±2.4)</td>
<td>-50.3 (±2.1)</td>
<td>-42.8 (±1.5)</td>
</tr>
<tr>
<td>Hip rotation</td>
<td>*-3.4 (±1.5)</td>
<td>*3.0 (±1.6)</td>
<td>1.0 (±1.8)</td>
<td>1.4 (±1.3)</td>
</tr>
</tbody>
</table>
Angles at Blade Contact

The statistical analysis performed determined that there were significant differences (p≤0.05) between the left and right legs at blade contact during ankle abduction, ankle rotation, hip abduction, hip flexion, hip rotation, knee abduction, and knee flexion. The two-way ANOVA also revealed significant differences between skill level at blade contact during hip flexion, knee abduction and knee flexion. Post hoc test (Tukey HSD) showed that significant differences (p≤0.05) occurred specifically as follows: At blade contact significant differences (p≤0.05) occurred between legs in elite players during ankle abduction; between legs of recreational players during hip internal, external rotation; between skill levels during right knee abduction; and between skill levels during right and left knee flexion.

Angles at Push-off

At push off, the ANOVA revealed significant differences between legs during ankle abduction, knee abduction and knee flexion, as well as significant differences between skill levels at ankle abduction, knee abduction, knee flexion and knee rotation. Post hoc test (Tukey HSD) showed that significant differences occurred specifically as follows: At push off there were significant differences between legs in elite players at knee abduction; between skill levels at right knee abduction; and between skill levels during left knee internal/external rotation. Significant differences are depicted graphically in figures 2-6. All figures are normalized to one stride from blade contact to blade contact.
**Figure 2** – Mean knee abduction and adduction angles in the right and left legs of elite subjects. BC - Blade Contact; PO - Push Off. Significant differences (p≤0.05) occur between the right and left legs at push off and are indicated by Standard Errors of the Mean (SEM): BC left knee (±2.1); BC right knee (±1.7); PO left knee (±2.0); PO right knee (±1.1).

Figure 2 depicts the mean right and left knee abduction pattern of elite subjects during stride from blade contact to blade contact. Left and right legs generally follow the same kinematic pattern starting in adduction at blade contact and abducting throughout the support phase until push off. Following push off the knee begins to adduct in preparation for blade contact. It is important to note that although contra-lateral knees follow similar patterns of ab/adduction throughout stride, there was a significant difference (p≤0.05) between right and left knees at push off with angles of 4.7° and -1.0° respectively. Note that negative angles are representative of adduction, while positive angles are representative of abduction.
Figure 3 – Mean right knee abduction and adduction angles in elite and recreational subjects. BC – Blade Contact PO – Push Off. Significant differences (p≤0.05) occur at contact and push off and are indicated by †. Standard Errors of the Mean (SEM): BC elite (±1.7); BC rec (±1.7); PO elite (±1.1); PO rec (±0.9).

Figure 3 depicts the right knee ab/adduction patterns of elite and recreational subjects. As noted in figure 2 above, the knee is adducted at blade contact then begins to abduct through the support phase until push off where it is at peak abduction. Following push off the knee begins to adduct again preparing for blade contact. In this figure it is important to note that although elite and recreational subject follow very similar abduction/adduction patterns throughout stride, recreational players are constantly adducted, with peak abduction angles barely reaching neutral at push off, while elite players begin in adduction, then become abducted near mid support through push off reaching peak abduction of approximately 5° just following push off. Significant differences (p≤0.05) occur between elite and rec subject’s right knees at both blade contact (elite -1.9° ±1.7, rec -9.2° ±1.7) and push off (elite 4.7° ±1.1, rec -0.5° ±0.9).
Figure 4 – Mean knee flexion angles in recreational and elite subjects. BC – Blade Contact PO – Push Off. Significant differences \((p \leq 0.05)\) occur at blade contact between skill levels in the left and right legs and are indicated by \(\uparrow\). Standard Errors of the Mean (SEM) at BC: rec left ±1.9; elite left ±1.3; rec right ±1.9; elite right ±1.7.

Figure 4 shows the mean knee flexion angles of the left and right legs in elite and recreational subjects. Contra-lateral lower limbs of both elite and recreational subjects follow the same angular kinematic pattern throughout stride from blade contact to blade contact. Then knee begins in flexion at blade contact and gradually extends through the support phase until push off where it reaches maximal extension at an angle of approximately 20° of flexion. There is a rapid flexion of the knee after push off through mid recovery phase, at which point it begins to extend again in preparation for blade contact. It is important to note that although elite and recreational subjects exhibit very similar knee flexion patterns throughout stride, elite players are approximately 20° more flexed than recreational players at blade contact and through most of the support phase.
until just prior to push off where both elite and recreational players exhibit no significant differences (p≥0.05) in knee flexion angle. Following push off the angular difference again begins to increase between recreational and elite players until it reaches a significant difference of about 20° at push off.

Figure 5 – Mean knee internal and external rotation angles in recreational and elite subjects. BC – Blade Contact PO – Push Off. Significant differences (p≤0.05) occur between skill levels in the left leg at push off and are indicated by * . Standard Errors of the Mean (SEM) at BC: rec left ± 1.4; elite left ± 1.9; rec right ± 0.9; elite right ± 1.4. SEM at PO: rec left ± 1.8; elite left ± 0.9; rec right ± 2.0; elite right ± 0.8.

Figure 5 depicts the mean knee internal and external rotation of recreational and elite players during stride from blade contact to blade contact. Contra-lateral knees of elite subjects follow the same general kinematic pattern with no significant differences (p≥0.05) at either blade contact or push off, while the kinematic pattern exhibited by the contra-lateral knees of recreational subjects is more sporadic, with a large peak in external rotation occurring in the left knee at push off. Results show that there are
significant kinematic differences (p<0.05) between the elite left knee (-0.1° ± 0.9) and the recreational left knee (6.6° ±1.8) at push off. Again, it should be noted that negative angles indicate internal rotation, while positive angles indicate external rotation, therefore, while the left knee of elite subjects is slightly internally rotated at push off, the left knee of recreational subjects is substantially externally rotated at push off. Contra-lateral knees of both elite and recreational subjects are internally rotated at blade contact with no significant differences (p>0.05) between angles.

Figure 6 – Mean hip internal and external rotation angles in recreational and elite subjects. BC – Blade Contact PO – Push Off. Significant differences (p<0.05) occur between contra-lateral hips of recreational subjects at blade contact and are indicated by . Standard Errors of the Mean (SEM) at BC: rec left ±1.5; elite left ±1.8; rec right ±1.6; elite right ±1.3. SEM at PO: rec left ±1.2; elite left ±1.8; rec right ±1.9; elite right ±1.4.

After blade contact, the hip begins to externally rotate, reaching peak external rotation just prior to push off. Following peak external rotation, the hip begins to internally rotate until about 70% of stride where it is maximally internally rotated. Mid-recovery
(85% stride) there is a second external rotation peak, followed by internal rotation in preparation for blade contact. The internal and external rotation patterns of the contra-lateral hips of elite subjects are almost identical throughout the stride with no significant differences in angular kinematics at either blade contact of push off (figure 6). Unlike the elite subjects, recreational subjects show significant differences ($p<0.05$) between contra-lateral hips at blade contact with differences of up to $6^\circ$. At blade contact, the left hip of recreational subjects is internally rotated at an angle of $-3.4^\circ \pm 1.5$, while the right hip is externally rotated with an angle of $3.0^\circ \pm 1.6$.

![Figure 7](image)

Figure 7 – Mean ankle eversion angles in elite subjects. **BC** – Blade Contact **PO** – Push Off. Significant differences ($p<0.05$) occur between contra-lateral legs at blade contact and are indicated by $\Delta$. Standard Errors of the Mean (SEM): BC right ± 1.2; BC left ± 1.1; PO right ± 1.4; PO left ± 1.3.

Figure 7 depicts the mean ankle eversion angles in the left and right legs of elite subjects. Contra-lateral limbs follow a similar pattern throughout the stride. There is an increasing eversion from blade contact until just prior to push off, followed by a rapid inversion at push off continuing through recovery phase until just prior to blade contact.
when the ankle begins to evert again. Although the kinematic pattern of the contra-
lateral ankles in elite players is relatively similar, there is a significant difference
($p<0.05$) in angle at blade contact between the right ankle ($5.2^\circ \pm 1.2$) and left ankle
($10.8^\circ \pm 1.1$). There are no significant differences at push off.

4.0 Discussion

The current study was conducted in order to determine whether there are significant
kinematic differences ($p<0.05$) between recreational and elite hockey players and
between contra-lateral lower limbs during the hockey skating stride. Our results
indicate that most of the angular kinematics of the hip, knee and ankle of the right and
left legs of recreational and elite subjects follow similar angular kinematic patterns
throughout the stride with statistically significant differences occurring at blade contact
and push off.

4.1 Kinematic differences between skill levels (elite vs. recreational)

Figure 3 shows elite and recreational subjects follow a similar knee abduction pattern
during stride; however, recreational subjects are consistently between 5 and $7^\circ$ more
adducted than elite subjects. By looking at figure 2, it is apparent that although the right
knee of recreational subjects abducts increasingly throughout the support phase, its
maximal angle at push off never exceeds neutral, whereas elite subjects cross into
abduction earlier on in the stance phase (approximately 25% of stance) and reach a
maximal abduction angle of $5^\circ$ just after push off. The hockey stride could be
considered a form of gait, and as such, may be compared to the kinematics of other forms of gait such as walking and running to attempt to explain the kinematic differences found here. Novacheck (1998) reviewed the biomechanics of the running gait and suggests that motion in the frontal or coronal plane, such as knee abduction, is important in minimizing upper body movement. To that extent, perhaps a greater knee abduction during stride allows maximal lower body movement and propulsion while keeping the upper body relatively stable, thereby increasing efficiency of the stride.

Figure 4 shows mean flexion angles in recreational and elite subjects. The data shows that at blade contact, the knee is flexed but begins to extend throughout stride until push off when it is maximally extended at an angle of between 15 and 20° of flexion depending on level of skill. Although there is little literature describing angular kinematics of knee flexion during hockey skating, one study investigating the kinematics of speed skating found that at push off the knee is in 10.4° of flexion (Boer et al, 1986) while another study which investigated push off mechanics in speed skating with conventional skates (Houdijk et al, 2000) found that the knee was in 9.2° of flexion at push off. These angular differences may be attributable to the use of different types of skates as well differing postures due to the use of a hockey stick in hockey skating as well as having to maintain a more upright posture to adjust to the fast paced nature of the game. While our results show no significant differences at push off, there are significant differences between skill levels at blade contact in both the left and the right legs (elite left 51.1°, rec left 34.3°; elite right 48.2°, rec right 29.1°). These findings support our hypothesis that kinematic differences exist between recreational and elite
subjects. Elite players show significantly greater knee flexion at blade contact in both the left and the right legs. In the current study elite subject skated at a mean speed of 17.6 km/h, while recreational subjects skated at a mean speed of 13.6 km/h. Yet, in spite of similarities in stride rate between recreational and elite subjects, we still see differences in knee flexion angles, which suggest that perhaps increased flexion in elite subjects leads to a greater generation of power. It has also been suggested in the literature that an increase in speed such as is seen in elite subjects in the present study, may account for an increased knee angle in elite players during stride (Novacheck, 1998, Boer, 1987).

Figure 5 shows mean knee internal and external rotation angles during stride in recreational and elite subjects. The contra-lateral knees of elite players have a fairly similar rotational pattern beginning with slight internal rotation at blade contact and exhibiting external rotation peaks during mid support phase then again at push off and for a third time in mid recovery. The most prominent external rotation occurs during mid support (3° externally rotated, as seen in figure 4). Contra-lateral knees of recreational subjects are less similar to each other, beginning with internal rotation at blade contact and slowly externally rotating throughout the support phase peaking at push off, followed by internal rotation throughout the recovery phase. Although there are significant differences between skill levels in the left leg at push off, there are no such differences in the right leg; in fact, all knee angles at push off seem to be fairly similar except the left knee of recreational players, possibly caused by individual subject irregularities in skating pattern. The increased external rotation of the elite
subjects during the support phase may allow them to generate more power than recreational subjects. It has been noted in other gait literature that transverse plane motions such as internal and external rotation are important for energy efficiency (Novacheck, 1998), and so the large external rotation peak exhibited by the left leg of recreational subjects may be less energy efficient than the near neutral position of the contra-lateral limbs of the elite subjects.

In discussing differences in skill levels, it should be noted that although the vertical jump height of elite subjects was not significantly different than that of the recreational subjects, the mean vertical jump height of the elite subjects was much greater than that of recreational subjects (29% height and 21.4% height respectively) and did approach significance at $p \leq 0.075$. It has been suggested that during push-off the leg muscles show a proximo-distal temporal order which is comparable to that of a vertical jump (Koning et al, 1991). These findings suggest that since elite players demonstrated results indicative of a greater power during vertical jump, that they would also demonstrate greater power than recreational subjects during push-off. This power may be due to a more efficient proximo-distal temporal order of activation producing propulsive forces and joint rotations in the present study as has been found in previously in speed skating studies (Koning, 1991).

4.2 Asymmetry

Figure 2 shows knee abduction/adduction angles of the left and right leg of elite subjects. The data shows that at blade contact, the knee is adducted and begins to
abduct through the support phase until just after push off when it is maximally abducted. There is a fairly rapid adduction of the knee through recovery phase until just prior to blade contact. By looking at Figure 2, we see that there is a marked difference between the left and right knees at blade contact and throughout the stride, becoming statistically significant at push off (0.97° adducted left leg and 4.74° abducted right leg). As mentioned previously, motions in the frontal plane are instrumental in minimizing the motion of the upper body during stride (Novacheck, 1998). Here we see differences in the right and left legs throughout the stride, but specifically at push off. Unlike other forms of gait such as speed skating and running where there is equal movement in the contra-lateral arms, upper limb and trunk movement in hockey is generally skewed by the grasping and control of a hockey stick with one hand. In the case of the elite subjects in this study, 88% held the hockey stick in their right hand while they skated. Perhaps the increased abduction in the right legs of the subjects is a compensatory kinematic adjustment in order to maximize the efficiency of trunk movement during stride.

Figure 6 shows that hip internal/external rotation patterns of recreational and elite subjects are fairly similar throughout stride. At blade contact, the hip is slightly externally rotated and continues to externally rotate until just prior to push off, reaching a maximum external rotation of between 7° and 8°. After peak external rotation, the hip begins to internally rotate prior to push off, and continues to rotate internally during the beginning of the recovery phase, reaching an internal rotation of between 3° and 0° (designated here as neutral). After peak internal rotation, the hip begins once again to
externally rotate, reaching a second peak at 80% stride in the recovery phase, after which it then begins to internally rotate again in preparation for blade contact (figure 6). Results from the current study show significant differences between contra-lateral hips of recreational subjects at blade contact. The internal and external rotations of the hip are due in part to the transverse rotations of the pelvis, which are particularly important for energy efficiency during gait (Novacheck, 1998). Novacheck (1998) notes that during walking, pelvic rotation is an important method of lengthening the stride and that during running, maximum internal rotation occurs in mid-swing to lengthen the stride. We see here that there are similarities in the hockey stride and the running gait in that the hip is maximally internally rotated during mid recovery phase, similar to the pelvic rotations occurring during the running gait.

Figure 7 illustrates the mean ankle eversion angles in elite hockey players, indicating that there are significant differences in contra-lateral ankles at blade contact. Results of the current study indicate that although both the left and the right ankles are everted at blade contact, the right ankle (mean 5.2°) is significantly less everted than the left ankle (mean 10.8°). Following blade contact, left and right ankle eversion increases to angles of approximately 17° and 13° respectively until approximately 50 percent of stride. Just prior to push off, there is a rapid inversion of the ankle, reaching 5° of eversion just after push off. Both ankles remain constant at this angle until just prior to blade contact when eversion begins once again. The results of this study are slightly different than those found by Pearsall et al (2002). Pearsall et al (2002) found that from blade contact until approximately 22% of stride, the ankle was slightly everted. As the skater
approached double support phase, the ankle reached a maximum eversion of 7.1° (as compared to 17° in the current study). As the skater progressed through swing phase, the ankle was inverted beyond neutral and then regained a neutral position in preparation for blade contact. The current study shows no inversion at all, and a much higher angle of eversion throughout the support phase leading to push off. These differences may be due to the use of different data acquisition techniques. Pearsall et al (2002) used bi-lateral twin-axis goniometers placed on the Achilles tendon of the skater inside the skate to measure ankle angle during stride. This technique may have produced a more accurate representation of the kinematics of the ankle during stride since they were able to bypass the constraints of the rigid skate boot; something this study was not able to accomplish.

There were no significant differences ($p \geq 0.05$) between skill levels or between contralateral limbs during either ankle plantar/dorsi flexion, or ankle internal and internal rotation. Both recreational and elite players follow similar patterns of plantar/dorsi flexion.

4.3 Limitations

Although the current study has many advantages over previous studies which have described the kinematics of the hockey skating stride, it does have a few limitations. The most important limitation is that subjects skated on a skating treadmill, not on an ice rink on which they would normally skate during a game. As previously noted, the skating surface of the treadmill used in this study (Frappier Acceleration) is made of polyethylene slats which are sprayed with silicone to mimic the ice surface. There have
been very few studies quantifying the skating treadmill as a good representation of ice skating, however a study by Hinrichs (1982) suggests that there are no significant differences in the muscle activation patterns of the right leg while skating on a skating treadmill as compared to skating on ice. Hinrichs (1982) concluded that treadmill skating simulates the leg muscles during the skating stride closer than many other types of dryland training devices (Hinrichs, 1982). Since muscle activation patterns were similar, presumably, there will be relatively few kinematic differences while skating on the treadmill as compared to skating on-ice. When comparing other methods of gait such as running, one author suggests that 'there is no difference between treadmill walking or running when the mechanical variables are described with respect to the surface on which the subject locomotes' (IngenSchenau, 1980). Although there may be few kinematic differences between treadmill skating and on-ice skating, several subjects noted that there is an increased amount of friction between the treadmill surface and the skate as compared to the ice surface, and that there is no opportunity to glide while skating on the treadmill. These two factors may combine to make it more difficult to skate on the treadmill due to an increased energy expenditure required to overcome friction and to compensate for a shortened glide phase.

As previously mentioned, the majority of subjects were right handed and all subjects declared that their right leg was their dominant leg. A propensity for holding the hockey stick in the right hand while skating may affect upper body mechanics and in turn influence lower limb mechanics and kinematics. Further studies in this area may wish to recruit an equal number of right-hand and left-hand dominant subjects in order
to account for any upper body influence on the lower limbs, which could in turn cause lower limb asymmetry.

Another limitation to the current study was the size of the laboratory where the treadmill was housed. Due to dimensional restraints, it was not possible to capture the entire body of the subjects while skating on the treadmill, and so this study examined only lower body kinematics. It would also have been useful to have placed a 5th and 6th camera in front of the subject to capture frontal plane movements, and above the subject to capture transverse plane movements.

5.0 Conclusions

While there are some aspects of the skating stride which are similar in elite and recreational hockey skaters, there exist several kinematic differences between skill levels and contra-lateral legs. Elite and recreational subjects show significant differences during knee abduction, knee flexion and knee internal/external rotation. Contra-lateral limbs show significant differences during knee abduction, hip internal/external rotation and ankle eversion. By striving to adopt the skating kinematics of elite hockey skaters, developmental age hockey skaters and recreational hockey skaters may develop a more efficient and effective stride thereby improving their overall performance during the hockey game. In order to more completely understand the kinematics of forward hockey skating, a whole body, three-dimensional analysis of the skating stride should be conducted.
References


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Appendix A – Literature Review
1.0 Historical Origins of Skating: Speed Skating and Hockey Skating

Ice skating has been in existence since the early 14th century when it was used as a common form of transportation in northern parts of Europe (Koning et al., 2000). It was not until the late 16th and early 17th centuries that ice skating developed a competitive facet. (Koning et al., 2000). The first skates are thought to have been constructed from the rib or shank of an elk or ox attached to a walking boot (Montgomery, 1988). As skating progressed from a form of transportation to a recreational sport in the 16th century, a wooden boot with an iron runner had replaced the earlier models (Koning et al., 2000). By the 19th century the skate was constructed from a single mold and was made entirely of steel. It was this model that would eventually serve as the template for the modern speed skate (Koning et al., 2000). Although the origin of the speed skate and the hockey skate are the same, their construction varies greatly in order to accommodate the sport-specific tasks associated with speed skating and power skating in hockey.

Although speed skating has experienced many advances in equipment and technique, the most notable, and most recent, may be the introduction of the Klapskate (Koning et al., 2000). (Figure A-1). The Klapskate was introduced by scientists Gerrit Jan Ingen Schenau and Groot in 1985. This new skate was constructed with a hinge between the blade and the boot under the ball of the foot to allow greater plantar flexion during push off (skating phases are to be discussed in greater detail in following sections), while allowing the blade to remain on the ice for a greater amount of time.
than traditional skates (Houdjik et al, 2000, IngenSchenau et al, 1996). Traditionally, due to required maintenance of a horizontal trunk position in order to reduce air friction, the skater has been forced to suppress plantar flexion during push off to avoid the front of the blade scratching through the ice and causing additional ice friction (Houdjik et al, 2000, Koning et al, 2000). Frictional force loss during push off with conventional skates is 10N. With the hinged Klapskate, frictional force losses are reduced to 3-4N during the last 50ms of push off (approximately equal to the friction loss).

![Figure A-1](image)

**Figure A-1**
Model of the Klapskate (from Houdjik et al, 2000)

during the glide phase). (Koning et al, 2000). This reduction in friction is thought to save the skater 3J of energy (Koning et al, 2000). Despite these findings, elite speed skaters were initially skeptical of the new skate design. It was not until 1994-1995 when 11 male junior skaters of the regional team of Zurich-Holland consented to switch to klapskates and consequently improved their best times by 6.2% that the Klapskate began to gain credibility. Finally, during the 1998 winter Olympic Games in Nagano Japan, both male and female members of the Dutch national speed skating team donned Klapskates and shattered world records (Koning et al, 2000; Allinger, 1998). The Klapskate is now used worldwide in the speed skating circuit.
Although skating has its origins in northern Europe, the first game of ice hockey
is believed to have been played in Eastern Canada in the mid 1800s. (Minkoff et al,
1982). The origin of hockey is thought to be in Huronia, Ontario, Canada, where
curved sticks were used to push a wooden ball along the ice. The name of the game
stems from the French word “hoquet”, which refers to a shepherd’s staff, possibly used
as the first hockey stick. (Minkoff et al, 1982). The game was played in the winter
months where the cold winter climate provided ice for the playing surface (Pearsall et
al, 2000). Scottish, English and Irish immigrants in the predominantly French eastern
Canada contributed to the founding rules of the game (Pearsall et al, 2000). Since the
1800s, hockey has evolved into a fast paced, structured sport played worldwide. The
constant improvement in equipment, technology and training strategy has led to a game
that requires players to be skilled in countless areas, including timing, anticipation,
direction, balance, accuracy, rhythm, speed, versatility, agility, and reaction time
(Pearsall et al, 2000). Although there are many skills pertinent to ice hockey, forward
skating is arguably the most important.

2.0 Skating Mechanics

2.1 Speed Skating

Speed Skating is a sport historically dominated by the Dutch due to its northern
European and Scandinavian heritage. As such, much of the published research today
involves subjects from various levels of Dutch speed skating, from the national team to
the junior national team (Boer et al, 1984,1985,1986,1987; Koning et al, 1991; Ingen
Schenau et al, 1980; Ingen Schenau, 1996). The speed skating stride has three phases:
glide, push off, and recovery (Akileswar et al, 1997; Boer et al, 1987; Boer et al, 1986; Koning et al, 1991; Koning et al, 1995; Koning et al, 2000). Glide is defined as the point in the stride where the body is supported over one leg, which remains at a constant length from hip to ankle (Boer et al, 1986). Glide phase begins once the contra-lateral skate is lifted from the ice and ends at the onset of push off (Boer et al, 1986). Push off begins with ipsilateral knee extension and ends as the leg reaches near full extension and the blade is lifted off the ice (Akileswar, et al, 1997, Boer et al, 1986). Finally, recovery phase begins as push off is completed, and ends when the skate is returned to the initial position under the body and contacts the ice (Akileswar et al, 1997). The glide phase begins again, and the cycle repeats itself. The skating stride is biphasic, including a support phase (glide and push off), and a swing phase (recovery). During the support phase of the speed skating stride, there is a period of single support and a period of double support. Double support is said to be the time during the stride when one leg is in the push off phase, while the other leg is in the gliding phase. During this period, body weight is transferred from the push off skate to the glide skate (Akileswar et al, 1997). Each phase (glide, push off and recovery) is characterized by specific muscle activation patterns and joint angles. The skater follows a specific sequence of muscle activation ensuring that his body segments are in the optimal angular position during each phase of the stride in order to maximize acceleration and power output when maximum performance is desired. In order to achieve translational velocities in the forward direction, the skater must transfer joint rotations into translations of body segments (Koning et al, 1991).
2.2 Hockey Skating

Forward hockey skating is characterized by its specific application to the sport of ice hockey. Hockey skating is said to involve several complex skills, including skating starts, stops, full speed striding, tight turns, pivots and cross-over strides, both forward and backwards (Marino et al, 1983).

It should be noted that, in both speed skating and power skating, the first four strides from stand-still are considerably different than the strides following push off. It is during the first four strides where there is considerable acceleration. Both kinetics and kinematics change drastically from the first stride to the fourth stride (representative of “speed striding”, or the constant pattern exhibited over an extended distance) (Marino et al, 1983; Naud et al, 1979; Koning et al, 1991). Specific differences in muscle activation pattern and kinematics will be discussed in greater detail in later sections of this paper.

3.0 Active Muscles During the Skating Stride

Once the skater has achieved a constant speed, the skating stride is characterized by a specific biomechanical pattern. The biomechanical pattern exhibited by the skater is biphasic and is broken down into the support phase and the swing phase. The support phase can be further broken down into single support (18% of support phase) and double support (82% of support phase) (Pearsall et al, 2000; Marino et al, 1983). Propulsion takes place during both double and single support after the outward rotation of the thigh, coinciding with initial extension of the hip and knee (Pearsall et al, 2000) (Figure A-2).
Each phase is characterized by specific muscle activation patterns in order to generate power. During the single support phase the hamstrings, specifically the
semitendinosus and biceps femoris, are active. These muscles are not used to generate power, they are used instead for stabilization of the knee joint (Boer et al, 1987). Active muscles may be seen in Figure A-3. During double support, approximately 200ms before push off, there is an explosive generation of power at the knee joint caused by the quadriceps, specifically the vastus medialis and rectus femoris (Pearsall et al, 2000). Power during push off is generated by concentric contraction of the gluteus maximus. Final power generation comes from the gastrocnemius, active during the end of the push off phase, causing flexion of the ankle (Humble, 1988) (Figure A-3).

An unpublished thesis from McGill University (Gaudreault, 1998), which studied the muscle activity patterns of the lower limbs during forward hockey skating on a skating treadmill, determined that the muscle activities of the vastus medialis (VM), adductor magnus (AM) biceps femoris (BF), gluteus maximus (GM) and peroneus longus (PL) are instrumental in propelling the skater forward during each phase of the forward hockey skating stride. (Please refer to muscle anatomy in Appendix A). From initial blade contact, there was an increasing activity in the VM, AM, BF, GM and PL, peaking between 60-80% maximal dynamic contraction (MDC) at approximately 10-15% of the normalized stride. Following this initial peak, muscular activity of the VM, AM, and GM decreased to 20-40% MDC, while BF and PL activity continued at a more elevated (20-40%) percentage of MDC until push off. The lateral gastrocnemius (GL) showed no activity during glide. From push off to swing phase, there was an increased activity of the VM and GM, peaking for the second time at 70-100% MDC. This second peak occurred at 52% of the normalized stride. The BF, GL and PL followed, with peaks at 58% of the normalized stride. The AM and TA peaked
during the swing phase at 68% and 91% respectively, while the BF, GL and PL showed minimal activity during this phase.

It should also be noted that the same study (Goudreault, 1998) showed that an increase in stride rate corresponded with an increase in speed, and that although participants were asked to perform maximum voluntary contractions (MVC) of all muscles studied, the maximum dynamic contractions (MDC) during the skating stride were much higher than the recorded MVC’s in all muscles, with the exception of the BF and TA. Also of note were the significant differences observed in the amplitude of muscle activation recorded at different speeds. There was a significant increase in the peak amplitude at 24km/h as opposed to 12km/h.

Although there have been a few studies documenting muscle activation patterns during hockey skating, muscle activity during speed skating is somewhat better documented. The instrumental muscles that propel the speed skater forward are quite similar to those that propel the hockey skater forward. Boer et al (1987) conducted a study in which the moments of force, power and muscle contraction were investigated during speed skating. They concluded that “the power in the knee joint is mainly generated by the quadriceps”. They monitored the vastus medialis and rectus femoris and noted that the quadriceps antagonists (biceps femoris and gastrocnemius) counteracted the action of the vastus medialis and the rectus femoris until approximately 200ms before the end of the stride (Boer et al, 1987). Although the study took place on a standard 400m ice rink under “fair ice and weather conditions”,

and subjects consisted of well trained male speed skaters, it should be noted that there
were only two subjects tested, and only one trial per subject was recorded. Koning et al
(1991) conducted a similar study involving elite male speed skaters, in which
coordination of leg muscles was investigated. In this particular study, muscle activation
patterns of the skating stride of eleven elite male members of the national Dutch speed
skating team were analyzed. It was determined that the activity of the vastus lateralis
and vastus medialis was fairly constant during the support phase of the stride when
skaters were gliding in a flexed hip and knee position (Koning et al, 1991).

The hamstrings, specifically the semitendinosus and biceps femoris are active
during the gliding phase of the hockey skating stride. However, they do not contribute
to generation of power due to eccentric contraction (Pearsall et al, 2000). Boer et al
support these findings in their study of muscle coordination during speed skating. As
previously mentioned, the study involving two elite speed skaters stated that “the
hamstring muscles (BF and ST) are active during the gliding phase, but due to the
eccentric contraction they cannot contribute to the generation of power.” (Boer et al,
1987). In their study, Boer et al (1987) assumed that the biceps femoris and
semitendinosus show the same pattern of muscle contraction velocity as the gluteus
maximus. However, it was not measured, and they did not indicate during which phase
of the stride the muscles are concentrically and eccentrically contracting. In their
discussion, they stated that “for the generation of power, it should be kept in mind that
only concentric contracting muscles can contribute to a positive power output in a joint”
and that the biceps femoris and semitendinosus are probably responsible for knee
flexion in the swing phase preceding the support/glide phase. Koning et al (1991) suggested that the semitendinosus and biceps femoris reach peak activity (though not at the same instant in time) during the glide phase. They also noted that there was a pronounced decrease in activity of the semitendinosus and simultaneous increase in activity of the biceps femoris during the final 200ms of the stroke (Koning et al, 1991). Humble (1988) suggested that the activity in the hamstrings serves to stabilize the knee joint as the skater shifts weight to the support leg prior to propulsion.

The gastrocnemius exerts a small force to plantar flex the ankle for the final push off of the stride (Humble, 1988). Traditionally, due to the maintenance of a horizontal trunk position in order to reduce air friction, the skater has been forced to suppress plantar flexion during push off to avoid the front of the blade scratching through the ice and causing additional ice friction (Houdjik et al, 2000, Koning et al, 2000). However, with the fairly recent development of the klapskate, skaters are able to plantar flex their ankles while the skate blade remains on the ice surface, thereby reducing frictional losses. It is possible that the gastrocnemius now plays a greater role in the generation of force in the final stages of the speed skating stride. Although speed skates have changed drastically in design during the past couple of decades, the hockey skate remains relatively unchanged, with a rigid tendon guard in place, preventing a great degree of plantar flexion. In their study, Koning et al (1991) report that the gastrocnemius lateralis is most active immediately prior and post push off, confirming its role as a plantar flexor. This particular study was conducted using traditional speed skates. Results may have been different had the study been conducted with klapskates.
However, Houdijk et al (2000) studied the push off mechanics in speed skating with conventional skates and klapskates and determined that although the effectiveness of plantar flexion during the final 50ms of the push off was increased with klapskates, "no differences in muscle coordination were observed from EMG". Although the paper clearly states that no differences in muscle coordination were observed, comparative data was presented for stride frequency, joint angles, peak angular velocity and work. No comparative data were presented for EMG activity of the muscles studied. It would be useful to express muscle coordination in terms of EMG activation pattern as well as joint angles and peak angular velocities. Its activity seems to be constant throughout the stride with no exaggerated peaks at any point during the stride.

The Gluteus maximus is generally active throughout the skating stride, reaching peak muscular activity just prior to toe off in order to propel the skater forward (Boer et al, 1987, Boer et al, 1991, Houdijk et al, 2000). Although the activity of the gluteus maximus is generally well documented during experimental studies on speed and power skating, there is little information on its contribution as a concentrically or eccentrically contracting muscle. It has been noted that muscles may only contribute to power generation if they are contracting concentrically and then can be assumed that the gluteus maximus is concentrically contracting during toe off to generate power and propel the skater forward.
4.0 Skating Kinematics

The following section will examine the three main joint angles of the lower limb – Hip, Knee, and Ankle – during start of the stride, glide, push off and recovery. Several papers have investigated individual joint angles during stride. However, there are very few which have adequately recorded all three joint angles simultaneously during stride.

4.1 Glide

Pearsall et al (2002) examined the angular motion of the ankle during the skating stride using bilateral twin axis electrogoniometers placed on the rear foot along the longitudinal axis of the Achilles tendon, thus allowing for simultaneous measurement of angles in two planes. (Figure A-4). By using this technique, they discovered that during single support of the glide phase in forward power skating, the ankle was in 7.1 degrees of dorsiflexion. They also documented that the ankle was slightly everted with relatively little change as the glide phase progressed towards push off.
Boer et al (1987) studied the moments of force, power and muscle coordination in speed skating, and used film analysis and a motion analyzer to determine the angles of the knee and hip/trunk during speed skating. They determined that the knee angle during glide decreases from approximately 150 degrees to approximately 115 degrees as glide progresses into push off. Boer et al (1987) used internal timing lights and timing light generators pulsing at a frequency of 2 Hz to quantify film speeds, which were approximately 67 Hz. They then obtained coordinates of the positions of the neck, hip, knee and ankle from the cinefilm plane Y-Z, which they converted into hip, knee and ankle angles. It is possible that there may be some error in the exact angle of the body positions, as all angles were derived from calculations, not exact measurement from anatomically placed markers. For a more accurate account of body segment angles, a more direct approach should be taken. Boer et al (1987) also noted that the trunk angle is relatively constant during glide, increasing slightly from about 10 degrees to 14 degrees flexion. It has been noted that during glide, the hip is at 45 degrees at onset and
progresses to 100 degrees and is externally rotated during middle support (Pearsall et al, 2000). It has also been noted that the ankle moves from a position of pronated dorsiflexion to pronated neutral (Pearsall et al, 2000).

4.2 Push Off

During push off Pearsall et al (2002) found that the ankle is everted to a maximum of 6.8 degrees and dorsiflexed to a maximum of 11.5 degrees. At this point in the stride the ankle has reached a point of maximum dorsiflexion and eversion in order to generate a maximum propulsive force. These findings are only reflective of hockey skating, not speed skating. Hockey skaters must suppress plantar flexion to avoid scraping the blade on the ice, whereas speed skaters need not suppress plantar flexion when wearing the klappskate. Boer et al (1987) state that the knee angle at push off in speed skating is 115 degrees, and the trunk angle is approximately 10 degrees. Pearsall et al (2000) note that, during push off in ice hockey skating, the hip is 180 degrees and externally rotated, the knee is at 180 degrees and the ankle and foot are plantar flexed and pronated. A representation of body position during speed skating may be seen in Figure A-5, produced by Boer et al (1986).
4.3 Recovery

During recovery, the ankle begins to plantar flex and goes from being in 11.5 degrees of dorsiflexion to 1.9 degrees of dorsiflexion (Pearsall et al, 2002). Later on, during recovery, the ankle begins to dorsiflex again in preparation for touch down and glide (Pearsall et al, 2000). The knee angle decreases from 180 degrees to 90 degrees and the hip angle decreases from 180 degrees to 40 degrees. The hip is also internally rotated (Pearsall et al, 2000). Angular kinematics during stride in speed skating can be seen in Table A-1.
Table A-1 – Mean values (standard deviation SD) of maximum joint angles (\(\varphi\) - max), maximum angular velocity (\(\varphi'\) - max), maximum net moment (M - max), time between the peak moment and the end of push-off (M-time), maximum net joint power (P-max), time between the peak power and the end of push-off power (P-time), maximum velocity difference between ankle and hip (\(V_{ah}\) -max) and between ankle and mass centre of the body (\(V_{a-mcb}\) -max). Significant differences between the groups are indicated by (*) in the last column (Koning, 1991).

<table>
<thead>
<tr>
<th></th>
<th>Elite mean ± SD</th>
<th>Trained mean±SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\varphi)-max (rad)</td>
<td>Hip 2.06±0.20</td>
<td>2.25±0.20</td>
</tr>
<tr>
<td></td>
<td>Knee 3.00±0.04</td>
<td>2.93±0.12</td>
</tr>
<tr>
<td></td>
<td>Ankle 1.77±0.13</td>
<td>1.73±0.07</td>
</tr>
<tr>
<td>(\varphi')-max (rad/s)</td>
<td>Hip 7.42±1.29</td>
<td>6.48±1.25</td>
</tr>
<tr>
<td></td>
<td>Knee 12.22±0.67</td>
<td>9.96±1.27</td>
</tr>
<tr>
<td></td>
<td>Ankle 5.29±1.10</td>
<td>4.22±0.86</td>
</tr>
<tr>
<td>M-max (Nm/kg)</td>
<td>Knee 1.66±0.20</td>
<td>1.60±0.20</td>
</tr>
<tr>
<td></td>
<td>Ankle 1.76±0.54</td>
<td>1.35±0.15</td>
</tr>
<tr>
<td>M-time (ms)</td>
<td>Knee 203±78</td>
<td>194±49</td>
</tr>
<tr>
<td></td>
<td>Ankle 116±20</td>
<td>138±66</td>
</tr>
<tr>
<td>P-max (W/kg)</td>
<td>Hip 6.30±1.52</td>
<td>4.76±1.05</td>
</tr>
<tr>
<td></td>
<td>Knee 5.59±1.59</td>
<td>5.64±2.03</td>
</tr>
<tr>
<td></td>
<td>Ankle 4.80±1.54</td>
<td>3.06±0.78</td>
</tr>
<tr>
<td>P-time (ms)</td>
<td>Hip 163±58</td>
<td>155±37</td>
</tr>
<tr>
<td></td>
<td>Knee 114±44</td>
<td>108±24</td>
</tr>
<tr>
<td></td>
<td>Ankle 52±11</td>
<td>54±22</td>
</tr>
<tr>
<td>(V_{ah})-max (m/s)</td>
<td>1.59±0.29</td>
<td>1.10±0.24</td>
</tr>
<tr>
<td>(V_{a-mcb})-max(m/s)</td>
<td>1.78±0.31</td>
<td>1.22±0.29</td>
</tr>
</tbody>
</table>

The literature seems to be fairly consistent in terms of joint angles during stride; however, there are still several unanswered questions in regards to whole body kinematics. There are few papers that address these questions in regards to speed skating, and fewer still which address these concerns with regards to hockey skating.
5.0 Novice vs. Elite Hockey Skaters

The literature suggests that there are several kinematic differences in hockey skating between a novice player and an elite player. Ability is generally evaluated based on stride. In their study of the kinematic comparison of novice, intermediate, and elite ice skaters, McCaw and Hoshizaki (1987) evaluated 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 showed that '(stride) length did not differ significantly among the levels, nor was it significantly correlated with skating velocity.' They also found that the stride rate was higher in elite skaters than novice skaters and was correlated with maximal skating velocity. There was also a decrease in single and double support time from novice to elite skaters. Elite skaters exhibited a deceleration of hip and knee extension as the centre of gravity came ahead of the support foot, whereas there was no such noticeable deceleration in novice skaters (McCaw and Hoshizaki, 1987).

McPherson (2004) focused her research on developmental age hockey players and determined that, as age increases, there is a concomitant increase in maximal velocity and in stride length. She also noted that elite players were able to create a much greater ankle angle at push off than developmental age players, as well as a greater amount of plantar flexion (McPherson et al, 2004). These differences may be due, in part, to the lack of muscular force being generated by the developmental age player, as their bodies are simply not as strong as the elite players. However, methods
used in data collection by McPherson et al (2004) have several limitations, which may impact the quality of data and results. Two digital cameras with a recording rate of 30fps were placed in the sagittal plane 30m apart, each at a distance of 22m from the subjects. (Figure A-6) Subjects wore dark, tight fitting clothing and reflective tape was placed over each anatomical joint centre. McPherson et al (2004) established a set of kinematic data, including joint angles for the hip, knee and ankle at various points during stride.

![Figure A-6](image)

*Figure A-6
Experimental setup used by McPherson et al (2004) to record acceleration and kinematics of developmental aged hockey players.*

Although the study was the first of its kind to be done in the sport of ice hockey, it has several limitations. The distance of the cameras may have reduced accuracy when digitizing the data. As well, reflective tape was used instead of spherical reflective markers. 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 state that ‘sufficient measurements (three-image coordinates) should be available on the markers from available cameras at any given time’ (Cappozzo et al, 1995). Since the reflective tape that McPherson et al (2004) used was flat, not spherical, it is doubtful that it met both of the above mentioned criteria. Thirdly, in order for the cameras to record the reflective tape, and to be able to digitize the data, the reflective tape placed on the joint centres must have been fairly large. An increased marker size increases error in estimating anatomical joint centres, and reduces the accuracy of joint angle calculations.

6.0 Kinematics

Kinematics is the study of the description of movement which examines motion from a spatial and temporal perspective without reference to the forces causing motion (Hamill et al, 1995). Position, velocity and acceleration are the key components in the study of kinematics. Kinematics can be used to identify the type of muscle contraction (isometric, concentric or eccentric), the phases of a movement and to distinguish between voluntary and involuntary reflex actions. High speed cameras (used for absolute space coordinates), goniometers (relative space coordinates), foot switches (measure contact events) and reflective markers are only a few of the tools used to study kinematics. Electromyography may be combined with kinematics to provide a more complete understanding of the motion of a specific sport.
6.1 History of Kinematics

Braun and Fischer discovered in the late 1800s that measurements of individual joint angle rotations, as well as translations of segments and whole body mass, are essential measurements when examining the kinematics of the human body (Sutherland, 2002). In the late 19th century, collecting kinematic data was a long and arduous process involving the attachment of Geissler tubes to the limb segments and interrupted illumination at regular intervals by using a large tuning fork. The subject would walk in complete darkness and be photographed with four cameras with open lenses (Sutherland, 2002). The data collection process alone took 8-10 hours per subject, followed by months of data analysis (Sutherland, 2002). Later on, in the mid 1900s, Eberhardt and Inman attached small light bulbs to their subjects' hip, knee and ankle joints and photographed them with the open lens of a camera using a slotted disc, which was rotated in front of the camera, producing a series of white dots at equal time intervals (Sutherland, 2002). Joint angles could be calculated by connecting the white dots and manually measuring them. Inman later replaced the light bulbs with pins drilled into the pelvis, femur and tibia and recorded the movement of the pins with a movie camera above the subject while the subject walked (Sutherland, 2002). In the 1960s, Mary Pat Murray pioneered the use of reflective markers for kinematic measurement. She attached reflective markers to specific anatomical landmarks and photographed her subjects as they walked in the illumination of a strobe light.
(Sutherland, 2002). Her methods are similar to those used today; however, all her measurements were done in the sagittal plane and lacked measurements of joint angles and joint rotations in the frontal and transverse planes (Sutherland, 2002).

6.2 Electrogoniometers

The electrogoniometer is often used to study the kinematics of human movement due to its small dimensions, diminutive weight, simple calibration and use, high sampling rate and insensitivity to external factors such as light, temperature and noise (Legani et al, 2000). The planar goniometer has a measuring cable core constructed of a thin sheet of isotropic material with two strain-gauges lying on the opposite faces of the sheet. The strain gauges constitute two contiguous branches of a Wheatstone’s bridge (Legani et al, 2000). The biplanar goniometer has a cylindrical measuring cable constructed of isotropic material with four strain gauges fixed to the external surface of the cable along four generating lines of the cylinder (Legani et al, 2000). Each couple of opposite gauges lies on orthogonal planes and constitutes two contiguous branches of a Wheatstone’s bridge (Legani et al, 2000). In order to achieve proper measurement, it is important to calibrate the goniometers in ‘zero configuration’ with the two bases parallel to each other and the measuring cable following a straight path from one base to the next. It is also important to note that, when using electrogoniometers to collect kinematic data, the measuring cable must not be twisted. A twisted cable will result in an incorrect distance between the gauges; hence, an incorrect angle measurement (Legani et al, 2000). Although the electrogoniometer is
widely used in biomechanical studies, investigators must take into consideration the difficulties that may arise with its use. It is not possible to obtain simultaneous measurements of all the moving segments of the subject and, therefore, difficult to obtain whole body kinematics with goniometers alone. The goniometer may, therefore, give an accurate measurement of angles within a local coordinate system, but they do not make reference to the global coordinate system. It is also important to note that the size of the individual must be taken into account when choosing the goniometers and the offset of the recording device must be matched to the size of the limb segments (Sutherland, 2002). It is also possible that the attachment of the goniometers to the subject could produce errors in measurement due to the movement of the underlying tissues (Sutherland, 2002). Goniometers are often used in a clinical setting to diagnose pathologies. Christenson recently investigated the accuracy and precision of the electrogoniometer (OSI CA 6000) and concluded that it “has a very high precision when range of motion measurements are made. However, the accuracy of the device is less than acceptable”. Here, accuracy is defined as ‘the closeness of a measured or computed value to its true value’ and precision is ‘the closeness of repeated measurements to the same quantity to each other’ (Christensen, 1999). Christensen measured the device against two precision protractors and found that the accuracy was up to 11.5% away from a preset value of one of the two protractors, and 9.6% away from the preset value of the other. The precision was +/- 0.1 degrees (Christensen, 1999). As such, he concluded that “the device was insufficiently validated”.

6.3 Film and reflective markers

One of the first photographic methods for capturing whole body kinematics in gait analysis was the Vanguard Motion Analyzer. After recording x and y coordinate measurements from cinefilm, a slide rule was used to perform trigonometric calculations (Sutherland, 2002). Later, an optical recorder replaced the manual measurement of x and y coordinates and a sonic digitizer was used to input data (Sutherland, 2002). In 1967 in the Netherlands, E.H. Furnee began to develop TV/motion analysis systems with automated recordings of reflective marker positions (Sutherland, 2002). Furnee used passive paper discs brightly visible in ultra violet light to measure multiple joint angles of a cat running on a treadmill (Sutherland, 2002). Later on, in 1973, the first VICON 3-D software system was developed by Graham Klyne and D. Sutherland. Most advances in motion and gait analysis took place in the Netherlands, England and Scotland, with the first gait laboratory appearing in Canada as part of the Shriners network in the early 1970s. There are now over 19 orthopedic Shriners Hospitals in the U.S., Canada and Mexico, 12 of which have a gait laboratory (Sutherland, 2002). Technologies continue to advance with new development in hardware and software in attempts to eliminate problems with marker identification and tracking. Future developments may include better methods of defining joint centres, and the ability to accurately analyze joints distal to the ankle.
6.4 Three-Dimensional Kinematics

Three-dimensional kinematics refer to motion that occurs in three-dimensional space without reference to the forces that cause the motion (Hamill et al., 2004). Three-dimensional space is defined by a global coordinate system that has three orthogonal axes: X, Y and Z. According to the convention set by the International Society of Biomechanics (ISB), Fx corresponds to the principal direction of horizontal motion, Fy is orthogonal to Fx, pointing vertically upwards, and Fz is right-perpendicular to the x-y plane (Hamill et al., 2004). (Figure A-7). In order to describe rigid body orientation in the global coordinate system, a local coordinate system (LCS) is used (Hamill et al., 2004; Nigg et al., 1999). In order to interpret body segment orientation in biomechanical analysis, a parametric representation of a rotation matrix is used (Nigg et al., 1999). The most common parametric representations used are Cardan/Euler angles and the Joint Coordinate System (JCS).¹

![Global Coordinate System as the adopted convention of the International Society of Biomechanics. Principal movement progresses along the X axis.](image)

¹ When discussing the Cardan/Euler and JCS, we assume that (a) each body segments have cartesian coordinate systems embedded in them and that the x-axis points anteriorly, the y-axis points vertically and the z-axis to the right when the subject is in anatomical position; and (b) joint orientation is specified by a rotation matrix (Nigg and Herzog, 1999).
6.5 Cardan/Euler Angles

In the Cardan/Euler angle representation of three-dimensional orientation, each vector forms three projection angles on each orthogonal plane of the Cartesian coordinate system. For example, vector ‘p’ forms Xp, Yp and Zp direction angles in each of the XY, XZ and ZY planes of the coordinate system, for a total of nine projection angles (Nigg and Herzog, 1999, Hamill et al, 2004). However, only three of these angles are independent of each other (Hamill et al, 2004). By rotating these three independent angles in an ordered sequence (first about an axis in a specified Cartesian coordinate system, second about a floating axis, and third about an axis in a second ‘determined’ coordinate system) the orientation of the LCS in space can be determined (Hamill et al, 2004; Nigg et al, 1999). Parametric rotation matrices for rotations about the x, y, and z axes of a Cartesian coordinate system are as in Figure A-8. “Once the rotational sequence has been determined, the parametric rotation matrix can be constructed in terms of the angles θx, θy, and θz” (Nigg et al, 1999). These three Cardan angles can then be used to represent the anatomical joint orientations and movements of flexion/extension, adduction/abduction, and internal/external rotation (Nigg et al, 1999). Although Cardan/Euler angles provide a similar representation of joint orientation to the anatomical representation used by clinicians and researchers they are sequence dependent and there is always the possibility of Gimble lock\(^2\) (Nigg et al, 1999).

\(^2\) Gimble lock occurs when the second rotation equals +/-π\(^2\).
6.6 Joint Coordinate System (JCS)

The JCS was proposed by Grood and Suntay (1983) in order to 'describe three dimensional joint motions in a way which facilitates the communication between biomechanician and physician' (Grood and Suntay, 1983). Grood and Suntay (1983) remind their readers that the purpose of a coordinate system is to allow the relative position between two bodies to be specified. Each body segment has its own LCS, and the JCS uses one coordinate axis from each segment that constitutes the joint. These axes are called fixed body axes and are embedded in the two bodies whose relative motion is to be described (Grood and Suntay, 1983). The third axis is a floating axis.
and is the common perpendicular axis to the body fixed axes (Grood and Suntay, 1983). Robertson et al (2004) noted that the vertical and lateral axes are not necessarily perpendicular; therefore, unlike the Cartesian coordinate system, the JCS is not an orthogonal system. Flexion/extension angles are denoted by $\alpha$, abduction/adduction angles are denoted by $\beta$, and axial rotation is denoted by $\gamma$ (Robertson et al, 2004; Nigg et al, 1999, Grood and Suntay, 1983). An example of right limb angle calculations can be seen in Figure A-9. Although the JCS may be conceptually easier to implement than Cardan/Euler angles, it has the same advantages and disadvantages as Cardan/Euler angles, with the exception that it can describe displacements along each of the three axes independently of one another (Nigg et al, 1999).

\begin{align*}
\alpha &= 90 - \cos^{-1} \left( \hat{k}_{\text{proximal}} \cdot \hat{F}_A \right) \\
\beta &= -90 - \cos^{-1} \left( \hat{k}_{\text{distal}} \cdot \hat{y}_{\text{proximal}} \right) \\
\gamma &= 90 - \cos^{-1} \left( \hat{r}_{\text{distal}} \cdot \hat{F}_A \right)
\end{align*}

Figure A-9
JCS angle calculations for the right limb (Robertson et al, 2004).
6.7 Cameras and Markers

There are several types of combinations of camera and marker systems that can be used to record kinematic movement in three-dimensional space. Combinations such as passive cameras and passive markers, passive cameras and active markers, or active cameras and passive markers are all used in biomechanics laboratories today.

Regardless of the optical system used to collect the data, each camera must provide a set of two-dimensional coordinates, and each digitized landmark must appear in at least two cameras (Robertson et al, 2004). Karamanidis et al (2003) studied lower extremity kinematic reproducibility by using two genlocked, high speed video cameras (250 Hz, Redlake Motionscope 250 C) to capture the lower extremity of subjects running on a treadmill (Karamanidis et al, 2003). Although high speed cameras provide the most accurate information, digital video cameras with a moderately high frequency and a high shutter speed can capture images with a fairly high degree of accuracy. In order to measure stride characteristics and lower extremity kinematics of the hip and knee as a function of increasing treadmill velocity, Kivi et al used an 8-mm Cannon video camera recording at 60 Hz which they placed in the sagittal plane such that the optical axis was perpendicular to the plane of movement (Kivi et al, 2002). By using the 8-mm video camera along with reflective markers and an Ariel Performance Analysis System (APAS) for data reduction and analysis, the experimenters were able to determine absolute hip joint angles with respect to the vertical and relative knee angles. They were also able to determine segmental angular velocity (Kivi et al, 2002).
Once each camera has captured the images in two-dimension, a linear relationship to three-dimensional spatial coordinates is generated by direct linear translation (DLT) (Robertson et al, 2004). Kwon3D (2004) describes the DLT method below:

6.8 Direct Linear Transformation (DLT)

Direct Linear Translation is essentially the process whereby an object point in the object space (generally a laboratory environment) is mapped to an image point within the film plane. Once all of the object points are mapped in the film plane, an image is formed. The recorded image will then be projected to yet another plane, here designated the image plane. However, for simplicity, it is possible to relate the object in the object space directly to the image in the image plane. There are two reference frames that define each of the object space and the image plane. The object space reference frame is defined by the XYZ coordinate system and the image plane reference frame is defined by the UV reference system. Point N (node) is the projection centre. Since the optical system of the camera maps point O in the object space to image I in the image plane, [x, y, z] are the object-space coordinates of Point O, while [u, v] are the image-plane coordinates of the image Point I. Thus, Points I, N and O are collinear. The DLT method is based on this collinearity condition. A vector A can be drawn from Point O to Point N, and exists in the object space. Once a third axis, W, is added to the image plane reference plane, it becomes three-dimensional. Another vector, B, can be drawn from Point I to Point N, and exists in the image plane. This vector is also called the principal axis. Since Points O, I and N are collinear, Vectors A
and B form a single straight line. This allows the use of a scaling scalar to be used to transform Vector A, existing currently in the object-space reference frame to the image plane reference frame. This transformation is accomplished by using a transformation matrix as seen in Figure A-10.

\[
A^{(l)} = T_{(l/O)} * A^{(O)} = \begin{pmatrix}
    r_{11} & r_{12} & r_{13} \\
    r_{21} & r_{22} & r_{23} \\
    r_{31} & r_{32} & r_{33}
\end{pmatrix} * A^{(O)}
\]

Figure A-10 – Transformation Matrix for DLT. Adapted from Kwon3D (www.kwon3d.com)

It should also be noted that the U, V coordinates in the image plane are generally in units such as cm, while the digitization system may use different length units such as pixels. In order to accommodate this, the conversion factor \( \lambda \) is used. Once the transformation matrix is complete, eleven DLT parameters (L$_1$-L$_{11}$) reflect the relationships between the object-space reference frame and the image-plane reference frame. The standard DLT equation is also slightly modified for optical errors such as de-centreing and distortion. Parameters L$_{12}$-L$_{14}$ are introduced to account for optical distortion, and L$_{15}$-L$_{16}$ are introduced to account for de-centreing distortion. In order to solve the basic DLT equation, a Least Squared Method (LSM) must be used to define the unknown parameters. In order to use the LSM, a group of control points whose coordinates are known must be used. These control points must not be co-planar; so must form a control volume. Generally these control points are fixed to, or form, a calibration grid. A Weight Matrix is applied to the points of the known volume of the
calibration grid to solve for the unknown using an iterative approach called the

*weighted least squares method* as follows:

\[
\begin{align*}
X_L &= Y \\
W X_L &= W Y \\
(X^t W X)L &= X^t W Y \\
(X^t W X)^{-1}(X^t W X)L &= (X^t W X)^{-1}(X^t W Y) \\
L &= (X^t W X)^{-1}(X^t W Y)
\end{align*}
\]

Where \( W \) = weight matrix, each of \( X, L, \) and \( Y \) are matrices in and of themselves. For further information, please see [www.kwon3d.com](http://www.kwon3d.com)

### 6.9 Marker Placement

Placement of reflective markers is extremely important when attempting to determine joint angles. When determining marker placement, Cappozzo et al (1995) suggest that there are several key points that must be taken into consideration. The marker must be placed in a location such that

- **a)** the light emitted or reflected from the marker is directly oriented towards the camera's field of view;
- **b)** "the distance between three markers associated with each body segment and the offset of any marker from the line joining the other two should be sufficiently large so that error propagation from reconstructed marker coordinates to the known orientation in space will be minimal";
- **c)** there should be minimal movement between the markers and the underlying bone; and
- **d)** subject preparation and marker mounting is a fast and simple procedure (Capozzo et al, 1995). Although marker placement has historically been done so that the markers overlie the bony prominence directly, there are differing opinions on strategies of optimal placement. Leardini et al (1999) used the Calibrated Anatomical System Technique (CAST) to study the kinematics of the foot during gait. Clusters of four
reflective markers mounted on plexiglass plates were “rigidly attached” to the subject using metallic clamps on previously determined anatomical landmarks. The markers were not attached directly to the skin; instead, the plexiglass plate with markers of a known distance from the tip was pointed in the direction of the anatomical landmark. Leardini (1999) contends that this method may be better than simply placing the markers on the skin overlying the anatomical landmark. He suggests that marker position accuracy is as good as 0.2 degrees and that the metallic clamps used to attach the plexiglass-mounted markers embrace the underlying bones better than skin-mounted markers. Although this method may be practical for the foot, it may not be as successful with larger landmarks, where the use of a metal clamp may be uncomfortable and may not adhere to the joint as well. Most experimenters still prefer to use skin-mounted markers to capture kinematic movement of joint segments. It is also questionable why Leardini (1999) chose to use a set of four markers instead of three markers forming a triad, which has been the acceptable number to create an orientation. Although much care is taken to place the markers in the anatomically correct position, there is still error that needs to be corrected for mathematically in order to quantify joint centres. Marker size varies, from small markers of 0.5 cm in diameter, to medium/large marker of 2 or more cm in diameter. Marker size is chosen based on the type of activity, the speed of activity and the cameras used to capture the activity and the markers. Generally, smaller markers are preferable during faster paced activities to reduce the amount of glare and increase accuracy when digitizing.
6.10 Data processing

After data are collected using video cameras, the data must then be processed by first cutting the film, then digitizing and filtering it before analysis may begin. Generally data are smoothed using a Butterworth fourth-order low pass filter. Filters act only in the time domain and modify the region of the power spectrum in which specific noise is thought to be located. There are several types of filters, each designed to cut specific regions of the signal. A low pass filter removes all frequencies above the "cutoff" frequency at which the filter is set. A high pass filter removes all frequencies below the cutoff frequency. A band pass filter removes all signals in one specific frequency. For example, a band pass filter might be set at 60 Hz to filter out all noise from power lines in North America. The most commonly used filter is a low pass Butterworth filter. It has no oscillation and a very gradual breaking slope at the cutoff frequency (DeLuca, 2002). Such a filter is best suited for applications requiring preservation of amplitude linearity in the pass band region (DeLuca, 2002). Filter parameters such as order (measure of the filter equation’s complexity), attenuation factor (used to specify steepness of slope) and phase delay (time delay after which each frequency is acquired) must also be taken into consideration when choosing a filter (DeLuca, 2002). After the data are filtered, they are then smoothed by filtering out the high frequency content of the signal using a low-pass filter to give a smooth pattern that represents the volume of the activity (De Luca, 2002).
Past research has focused mainly on speed skating and the associated biomechanics. Most authors agree on the established muscle activation patterns during stride. However, there is little research on body position and three-dimensional kinematics during hockey skating. Future research should focus on whole body kinematics of the hockey skater using newer technologies. Such technologies include 3-D high speed film, spherical reflective markers placed on joint centres and skating treadmills (Figure A-11). By using such technologies, the experimenter will be able to gain insight into the most favorable joint angles to produce optimal performance in the athlete. Future research should also focus on basic hockey skills, such as turns, cornering, cross-over stride, backwards skating, puck handling and shooting. By determining the kinetics and kinematics of these skills, opportunities for introducing vast improvements in the technical ability of athletes should emerge.
Figure A-11
Skating treadmill (Frappier Acceleration) located in the Seagrum Spots Science Centre at McGill University
Appendix B – Methodological Pictures
Figure B-1: Digital Video cameras used to collect all data: A) camera 1 B) camera 2 C) camera 3 D) camera 4
**Figure B-2:** Experimental set up. A) camera and lights 1 B) camera and lights 2 C) Light Emitting Diode (LED) trigger D) treadmill controls E) skating treadmill ‘belt’ F) frontal crossbar G) LED H) overhead crossbar. Global Coordinate System axes are shown to the left of the diagram.
Figure B-3: light emitting diode (A) and trigger for light emitting diode (B)
Figure B-4: Calibration grid captured by cameras 1-4 prior and subsequent to each subject. Skating space was calibrated by 27 spherical reflective markers suspended at known distances from the ceiling. Global coordinate system axes are shown for cameras 3 and 4.
Figure B-5: Marker placement on the right lower limb. A) right thigh triad B) right lateral epicondyle marker C) right shank triad D) left heel marker E) right heel marker F) right foot triad G) right 5th metatarsal marker H) right toe marker I) left toe marker. All markers were placed by palpation.
Figure B-6: Frontal view of marker placement. A) right anterior superior iliac spine (ASIS) marker B) left ASIS marker C) right thigh triad D) left thigh triad E) right lateral and medial epicondyle markers F) left medial and lateral epicondyle markers G) right shank triad H) left shank triad I) right foot triad J) left foot triad. All marker were placed by palpation.
Figure B-7: Skating trial of an elite subject. 1) camera 1 just prior to toe off of the left leg (subject’s left leg is in double support phase) 2) camera 2 just after blade contact of the left leg (subject’s left leg is in single support) 3) camera 3 just prior to blade contact of the right leg (subject’s right leg is in swing/recovery phase) 4) camera 4 (subject’s right leg is in swing/recovery phase).
Figure B-8 Calculation of mechanical axes (left leg) using data from standing trials.
Figure adapted from Grood and Suntay (1983) Pp-proximal pelvis Ap-anterior pelvis Lp-lateral pelvis Pt-proximal thigh At-anterior thigh Lt-lateral thigh F-vector cross product of Pt and Lp α-flexion β-abduction γ-twist/rotation.
Appendix C: Additional Tables and Figures
Figure C-1: Right hip flexion/extension

Figure C-2: Right Hip Ab/Adduction
Figure C-3: Ankle plantar/dorsi flexion in elite subjects.

Figure C-4: Ankle internal/external rotation in elite subjects
Table C-1: Mean blade contact angles of the left and right recovery legs of recreational and elite hockey players. * indicates significant differences between legs ** indicates significant differences between recreational and elite levels.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Rec Left</th>
<th>Rec Right</th>
<th>Elite Left</th>
<th>Elite Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle abduction</td>
<td>17.6 +/- 1.5</td>
<td>18.8 +/- 1.5</td>
<td>**12.2 +/- 0.8</td>
<td>17.2 +/- 0.9</td>
</tr>
<tr>
<td>Ankle flexion</td>
<td>-2.7 +/- 1.8</td>
<td>-2.2 +/- 1.9</td>
<td>-6.7 +/- 1.4</td>
<td>-6.5 +/- 1.7</td>
</tr>
<tr>
<td>Ankle rotation</td>
<td>8.0 +/- 0.9</td>
<td>5.2 +/- 1.5</td>
<td>6.4 +/- 0.6</td>
<td>6.7 +/- 1.7</td>
</tr>
<tr>
<td>Knee abduction</td>
<td>-2.9 +/- 1.3</td>
<td>-4.4 +/- 0.7</td>
<td>**4.3 +/- 1.4</td>
<td>0.7 +/- 2.5</td>
</tr>
<tr>
<td>Knee flexion</td>
<td>**17.7 +/- 2.8</td>
<td>**19.0 +/- 2.4</td>
<td>**31.1 +/- 2.6</td>
<td>**37.1 +/- 2.3</td>
</tr>
<tr>
<td>Knee rotation</td>
<td>-4.0 +/- 1.4</td>
<td>0.9 +/- 1.3</td>
<td>-0.7 +/- 1.6</td>
<td>-2.3 +/- 1.8</td>
</tr>
<tr>
<td>Hip abduction</td>
<td>3.0 +/- 1.2</td>
<td>8.4 +/- 1.2</td>
<td>0.8 +/- 2.3</td>
<td>7.4 +/- 2.2</td>
</tr>
<tr>
<td>Hip flexion</td>
<td>-18.0 +/- 3.0</td>
<td>-15.7 +/- 3.0</td>
<td>-20.4 +/- 1.9</td>
<td>-23.7 +/- 2.0</td>
</tr>
<tr>
<td>Hip rotation</td>
<td>7.3 +/- 1.6</td>
<td>6.3 +/- 1.8</td>
<td>7.9 +/- 1.9</td>
<td>6.6 +/- 2.1</td>
</tr>
</tbody>
</table>

Table C-2: Mean push-off angles of the left and right recovery legs of recreational and elite hockey players. * indicates significant differences between legs ** indicates significant differences between recreational and elite levels.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Rec Left</th>
<th>Rec Right</th>
<th>Elite Left</th>
<th>Elite Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle abduction</td>
<td>**59.7 ± (0.7)</td>
<td>58.2 (± 1.2)</td>
<td>**60.5 (± 0.6)</td>
<td>80.6 (± 0.8)</td>
</tr>
<tr>
<td>Ankle flexion</td>
<td>N/A</td>
<td>-2.8 (± 1.4)</td>
<td>-1.9 (± 1.5)</td>
<td>-2.2 (± 1.4)</td>
</tr>
<tr>
<td>Ankle rotation</td>
<td>N/A</td>
<td>0.7 (± 0.9)</td>
<td>4.4 (± 0.7)</td>
<td>1.4 (± 1.9)</td>
</tr>
<tr>
<td>Knee abduction</td>
<td>**-9.7 (± 1.6)</td>
<td>-10.4 (± 1.1)</td>
<td>**-3.0 (± 1.9)</td>
<td>-7.6 (± 1.9)</td>
</tr>
<tr>
<td>Knee flexion</td>
<td>**29.6 (± 2.2)</td>
<td>**33.4 (± 1.7)</td>
<td>**45.3 (± 2.2)</td>
<td>**50.0 (± 1.2)</td>
</tr>
<tr>
<td>Knee rotation</td>
<td>-5.7 (± 1.1)</td>
<td>-1.1 (± 1.6)</td>
<td>-0.6 (± 1.3)</td>
<td>-2.5 (± 1.9)</td>
</tr>
<tr>
<td>Hip abduction</td>
<td>5.5 (± 1.7)</td>
<td>8.1 (± 3.2)</td>
<td>6.4 (± 1.7)</td>
<td>14.3 (± 2.4)</td>
</tr>
<tr>
<td>Hip flexion</td>
<td>-38.8 (± 2.6)</td>
<td>**-42.9 (± 2.2)</td>
<td>-46.7 (± 1.6)</td>
<td>**-52.5 (± 2.3)</td>
</tr>
<tr>
<td>Hip rotation</td>
<td>5.6 (± 1.6)</td>
<td>0.1 (± 1.5)</td>
<td>1.7 (± 2.0)</td>
<td>1.6 (± 2.1)</td>
</tr>
</tbody>
</table>

Table C-1 illustrates the angles of the recovery leg occurring at the same moment in time as blade contact of the contra-lateral leg. For example, left leg recreational angles at blade contact (table C-1) occur at the same moment in time as right leg recreational angles at blade contact in table 5. The same holds true for angles in table C-2, which is to say that left leg recreational angles at push-off (table C-2) occur at the same moment in time as right leg recreational angles at blade contact in table 4. Note that there are
significant differences between skill levels occurring in the recovery legs at both blade contact of the contra-lateral leg (ankle abduction, knee abduction, knee flexion) and push-off of the contra-lateral leg (ankle abduction, knee abduction, knee flexion and hip flexion). There are also significant differences occurring between legs during ankle abduction at blade contact and push-off of the contra-lateral legs.
Appendix D: Ethics Approval Forms
The Faculty of Education Ethics Review Board consists of 6 faculty members appointed by the Faculty of Education, an appointed member from the community, and the Chair of the Ethics Review Board.

The undersigned considered the application for certification of the ethical acceptability of the project entitled: Three Dimensional Kinematics of the Lower Limb During Forward Power Skating as proposed by:

Applicant's Name: Tegan Uppjohn
Applicant's Signature/Date: [Signature] [Nov 1, 2004]
Degree/Program/Course: M.Sc

The application is considered to be:
A Full Review
A Renewal for an Approved Project

The review committee considers the research procedures and practices as explained by the applicant in this application, to be acceptable on ethical grounds.

1. Prof. René Turcotte
   Department of Kinesiology and Physical Education
   Signature/date

2. Prof. Ron Morris
   Department of Integrated Studies in Education
   Signature/date [Nov 16/04]

3. Prof. Ron Stringer
   Department of Educational and Counselling Psychology
   Signature/date

4. Prof. Joan Russell
   Department of Integrated Studies in Education
   Signature/date

5. Prof. Doreen Starke-Meyering
   Department of Integrated Studies in Education
   Signature/date [Nov 19/04]

6. Prof. Ada Sinacore
   Department of Educational and Counselling Psychology
   Signature/date [11/24/04]

7. Member of the Community
   Signature/date

Office of the Associate Dean (Research & Graduate Students)
Faculty of Education, Room 230
Tel: (514) 398-7039 Fax: (514) 398-1527

Office Use Only
REB #: 473-1104
APPROVAL PERIOD: Nov 1/04 to Dec 1/05
(Updated September 2003)
The items indicated below require your attention before the Ethical Review Board can process and approve your research project. Please make sure to include all of them and refer to the attached Ethical Research Procedures and Ethical Research Guidelines. Incomplete applications or applications with errors will be sent back to the applicant.

1. X. Indicate the Type of Review:
   - Full Review
   - Expedited Review __ X
   - Annual Renewal of Approved Project
   - Departmental Approval as Part of Undergraduate or Graduate Course Work

2. X. Two (2) copies of the Certificate of Ethical Acceptability for Funded and Non Funded Research Involving Humans.
   - It includes:
     - name of the applicant and signature
     - name of the supervisor and signature (if applicable)
     - title of the research project
     - degree program (if applicable)
     - granting agency (if applicable)

3. X. Two (2) copies of a clear, comprehensible Statement of Ethics of Proposed Research with both your signature and your supervisor's signature.
   (Refer to form - items 1 to 6):

4. X. Two (2) copies of an abstract or brief summary (1-2 pages) of the research proposal.

5. X. Submission requirements:
   A. For Expedited Review submit 2 copies of the certificate, statement forms, and summary (1-2 pages) or abstract of the research proposal.
   B. For Full Review submit 8 copies of the certificate, statement forms, and the entire proposal.
   C. For Departmental Review submit to the researcher's home department 2 copies of the completed statement form and the certificate signed by the Department Chair, or Designate.

6. X. Two (2) copies of informed consent form(s) and procedures for obtaining free and informed consent.
   The informed consent must be written in language that is appropriate for the participants.

7. N/A. If applicable, two (2) copies of the instrument to be used for collecting the data (e.g. questionnaire, interview, etc.) or, if using a commercial test, include two (2) copies of the test and a brief description of it.

8. N/A. Any other certificate of ethics which funding agencies may require.

9. N/A. For Review of Research in other jurisdictions or countries: Submit a copy of Ethics Review Approval from the relevant agency or institution for research to be performed outside the jurisdiction or country of the institute which employs the researcher.

IMPORTANT POLICY STATEMENTS:

- Approval of ethics acceptability must be obtained before data collection for a funded or non funded project.
- All funded and non funded research undertaken at McGill University must be verifiable where possible (McGill Research Policy).
- All researchers must be able to have respondents confirm that they gave specific data where possible.
- Confidentiality must be ensured. It can be generally achieved by establishing a system such as matching identification numbers with names and placing the names in a sealed envelope that is kept in a secure place.
- The exact procedures used should be clearly explained in (6.1) of the statement of ethics form.
- All researchers in the Faculty of Education must obtain the name and informed consent of all research participants 18 years of age or older. For populations under 18, in most circumstances, informed consent must be obtained from parents or guardians as well as children.
MC Gib UNIVERSITY FACULTY OF EDUCATION
STATEMENT OF ETHICS OF PROPOSED RESEARCH

It is assumed that the responses to the questions below reflect the author's (or authors') familiarity with the ethical guidelines for funded and non-funded research with human subjects that have been adopted by the Faculty of Education and that responses conform to and respect the Tri-council Policy Statement: Ethical Conduct for Research Involving Humans (1998).

Note: It is important to answer every question.

1. Informed Consent of Subjects

   Explain how you propose to seek informed consent from each of your subjects (or should they be minors, from their parents or guardian). Informed consent includes comprehension of the nature, procedures, purposes, risks, and benefits of the research in which subjects are participating. Please append to this statement a copy of the consent form that you intend to use.

   Each subject will receive an overview of the proposed project indicating the nature and objectives of the study and the methods and equipment that will be used. In addition, he will be informed, in writing, of the setting in which the study is to take place as well as any potential risks involved in his participation. Subjects will be asked to skate on a skating treadmill wearing ice skates and marked with reflective markers placed over their joint centers using adhesive tape. Subjects will be filmed from three angles using JVC camcorders.

2. Subject Population and Subject Recruitment

   2.1 Describe the subject population and how and from where they will be recruited and encouraged to participate. If applicable, attach a copy of any advertisement, letter, flyer, brochure or oral script used to solicit potential subjects (including information sent to third parties). Describe the setting in which the research will take place. Describe any compensation or inducement subjects may receive for participating.

   Subjects participating in this study will be highly skilled members of the McGill Men's Varsity Hockey team and members of the general public who qualify as recreational hockey players. All subjects will be volunteers.

   2.2 Indicate if the subjects are a captive population (e.g. prisoners, residents in a centre, students in a class) or are in any kind of conflict of interest relationship with the researcher such as being students, clients, patients or family members.

   Subjects will be volunteers who may withdraw from the study at any time with no penalty.

   2.3 Explain how you will ensure pressure to participate or perceived pressure will not penalize students for choosing not to participate. (Please take note that it is important to inform subjects, especially in Teacher Action Research or Participatory Action Research, that no grading or evaluation is involved).

   At the time of both recruitment and of data collection, subjects will be informed that their participation is purely voluntary, and that they are free to withdraw from the study at any time.
2.4 What is the nature of any inducement you intend to present to prospective subjects to persuade them to participate in your study?

Subjects will have access to their own results of the study upon completion. These results may help the skater improve his technique and become a better hockey player.

2.5 How will you help prospective participants understand that they may freely withdraw from the study at their own discretion and for any reason?

At the time informed consent is described and signed, subjects will also be explained that his participation is voluntary and that he may withdraw from the study at any time.

2.6 Comment on any other potential ethical concerns that may arise during the course of the research.

No other potential ethical concerns are expected to arise during the course of research. If such concerns should arise, they will be addressed swiftly and in the appropriate manner; by being brought to the attention of the REB.

3. Subject Risk and Well-being

What assurance can you provide this committee (as well as the subjects) that the risks, physical and/or psychological, that are inherent to this study are either minimal or fully justifiable given the benefits that these same subjects can reasonably expect to receive?

Subjects who participate in this study will be skating on a skating treadmill in a controlled environment with a skilled operator. Prior to the beginning of the trials, subjects will undergo a familiarization/training period on the treadmill in order to assure that the subject is comfortable on the treadmill. While skating on the treadmill, subjects will be wearing a harness over their shoulders and waist. The harness will be attached by a thick cable to a metal anchoring system suspended from an overhead cross bar. In the event of loss of balance of a fall, the harness will support the subject and prevent him from falling off of the treadmill.

4. Deception of Subjects

4.1 Will the research design necessitate any deception to the subjects?

No.

4.2 If so, what assurance can you provide this committee that no alternative methodology is adequate? If so, how do you intend to nullify any negative consequences of the deception?

Not Applicable.

5. Privacy of Subjects

Describe the degree to which the anonymity of subjects and the confidentiality of data will be assured and the specific methods to be used for this, both during the research and in the release of findings. This includes the use of data coding systems how and where data will be stored, who will have access to it, what will happen to the data after the study is finished, and the potential use of the data by others.

Indicate if there are any conditions under which privacy or confidentiality cannot be guaranteed (e.g. focus groups), or, if confidentiality is not an issue in this research, explain why.

No personal information will be required from the subject other than the physical characteristics of height, weight, age and extent of power skating experience. Subjects names will be recorded, but not published in
any form be it thesis or journal article publication. Only the researchers will have access to the data and will be informed to keep it under the strictest of confidentiality.

6. Confidentiality/Anonymity

6.1 How will this study ensure that (a) the identity of the subjects will be concealed and (b) the confidentiality of the information, which they will furnish to the researchers or their surrogates, will be safeguarded?

No information with regards to the subject will be divulged to any individual. Each subject will be referred to by number instead of name when data is presented in written or oral form.

6.2 If applicable, explain how data will be aggregated in such a way that even should the identity of the participants become known, no reasonable inference could be made about the performance, competence, or character of any one of these participants. If data will not be aggregated, provide a detailed explanation.

The only data presented will be kinematic data of the subject while he is skating on the treadmill.

If this project has been submitted to another ethics committee, please note the particulars:

Principal Investigator Statement: I will ensure that this project is conducted in accordance with the policies and procedures governing the ethical conduct of research involving human subjects at McGill University.

Principal Investigator Signature: ___________ Date: Nov 01, 04

Faculty Supervisor Statement: I have read and approved this project and affirm that it has received the appropriate academic approval. I will ensure that the student investigator is aware of the applicable policies and procedures governing the ethical conduct of human subject research at McGill University and I agree to provide all necessary supervision to the student.

Faculty Supervisor Signature: ___________ Date: Nov 01, 04

Submit this statement to:
Office of the Associate Dean
(Research & Graduate Students)
Faculty of Education, Room 230
Tel: (514) 398-7039
Fax: (514) 398-1527
Summary of Proposed Research

The sport of ice hockey is continually advancing. More emphasis is now being put on skating ability and skill and less on physical force. As such, if players hope to advance to elite levels of play, they must concentrate on skating stride, skating faster and more efficiently. By determining the kinematic differences between recreational and elite players, it may be possible for provincial and junior league players to improve their skating stride in a shorter period of time, advancing to higher levels of competition.

Pearsall et al (2002) recently studied the three-dimensional kinematics of the ankle during the forward power skating stride using electrogoniometers. Although this project provides insight into how the ankle moves during stride, it has several delimitations. By using electrogoniometers, the experimenters were only able to describe motion of the ankle as an individual joint, with no relation to other lower body movement in the knee and hip joints. McPherson et al (2004) attempted to capture three dimensional images of development age hockey players while they skated on a regulation size hockey rink. McPherson established a set of kinematic data including joint angles for the hip, knee and ankle at various points during stride (McPherson et al, 2004). Although the study was the first of its kind to be done in the sport of ice hockey, it has several delimitations. Cameras were relatively far away from the subjects in order to have a wide enough field of view to capture several strides. The distance of the cameras may have reduced accuracy when digitizing the data. As well, reflective tape was used instead of spherical reflective markers. Cappozzo et al 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 state that “Sufficient measurements (three-image coordinates) should be available on the markers from available cameras at any given time” (Cappozzo et al, 1995). Since the reflective tape that McPherson used was flat, not spherical, it is doubtful that it met both of the above mentioned criteria.

McCaw and Hoshizaki completed a kinematic comparison of novice, intermediate and elite ice skaters and suggest that identification of hip and knee angles at developmental stages may be a viable direction of future research (McCaw and Hoshizaki). This study proposes to investigate the three dimensional kinematics of the lower limb in recreational and elite ice hockey players. Joint centers of rotation will be used to aid in the determination of segmental angular position of the lower limb during each phase of the power skating stride. By determining the kinematic differences between recreational and elite players, it may be possible for provincial and junior league players to improve their skating stride in a shorter period of time, advancing to higher levels of competition.

Methods

2.1 Subjects

Subjects will consist of two groups of athletes. (1) five elite hockey players from the McGill men’s varsity hockey team (2) five male recreational players from the general public. Subjects will be healthy and active.
2.2 Kinematics

3 cannon 8 mm video cameras will be placed facing the subjects in the sagittal, frontal and transverse planes at a distance of between 1.5 and 3 meters. Camera angle and distance will be determined by the ability to capture the subject's entire lower limb as well as all of the reflective markers placed on the joint centers.

A skating treadmill (Frappier Acceleration model) will be used to simulate on-ice skating conditions while data is collected from the subjects. A 1.2 cubic meter calibration frame will be used to insure captured images are properly calibrated.

2.3 Experimental Protocol

Before data collection begins, subjects will undergo four 20 minute training periods on the skating treadmill (Broad and Trumper, 2004) where they will become familiarized with the equipment. Prior to the trials, reflective markers will be placed as close as possible to the centre of rotation of their hip joint (Posterior superior iliac spine, anterior posterior iliac spine and femoral head), knee joint (lateral epicondyle of the femur and apex of the head of the fibula, distal apex of the lateral malleolus of the tibia) and ankle joint (approximation of the lateral malleolus of the fibula and the calcaneus) and on an approximation of the distal fifth phalange. All marker placements will be done by palpation and were determined based on their designation as anatomical landmarks used to define anatomical frames. (Cappozzo et al, 1995) An image of the calibration frame will be filmed prior to each subject trial. A reference marker will be placed so that it is within the field of view of all three cameras throughout the trials and will be placed in the same spot for all subjects. Synchronization of the cameras will take place by placing an LED within the field of view of all three cameras and flashing it once per trial.

Once the calibration frame has been filmed, subjects will be asked to mount the treadmill and will be attached to the safety harness. Subjects will be instructed to hold on to the cross bar in front of them while the treadmill is turned on and reaches the predetermined speed of 18 km/hr. Once the treadmill has reached 18 km/hr, subjects will be instructed to begin skating and to let go of the crossbar. Each trial will last two minutes. There will be 5 minutes of rest in between each trial where the subject will be permitted to sit and re-hydrate if necessary.
Signed consent

- I understand the purpose of this study and know about the risks, benefits and inconveniences that this research project entails.
- I understand that I am free to withdraw at anytime from the study without any penalty or prejudice.
- I understand how confidentiality will be maintained during this research project.
- I understand the anticipated uses of data, especially with respect to publication, communication and dissemination of results.

I have carefully studied the above and understand my participation in this agreement. I freely consent and voluntarily agree to participate in this study.

Name (please print) ____________________________________________

Signature __________________________ Date __________________

If you would like to receive an electronic copy of the results of the study, please check the appropriate box below and provide your email address:

☐ I would like to receive an electronic copy of the results of the study

☐ I do not wish to receive an electronic copy of the results of the study

Email address: _______________________________________________