Comparison of forward hockey skating kinetics and kinematics on ice and on a synthetic surface by means of a customized force measurement system and electrogoniometry

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STATEMENT OF ORIGINALITY

All material presented in this thesis contains original work completed by the author, except where noted via references indicating outside contributions. It is the belief of the author of this thesis that the material presented significantly contributes to the large void pertaining to the kinetic analysis of ice hockey skating, as well providing insights into the discrepancies and similarities of skating on a yet unstudied synthetic ice surface.

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First and foremost I would like to thank my supervisor Dr. René Turcotte for his guidance throughout my Master's studies. René always made himself available for my many questions, allowing me to gain insights from his vast experience. Lastly, and quite possibly most importantly, René always provided an outlet to get away from the rigours of work, whether it be talking about last night's hockey game, or providing a formidable challenge on the ice each and every Monday afternoon.

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Thirdly, Phil Dixon was an invaluable resource in completing this project. His unconditional support, constant optimism, technical knowledge, and willingness to teach his many skills were priceless. Thanks for all your help Phil.

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Lastly, and most importantly, I want to thank my family for supporting me throughout this process. Collectively, your endless encouragement has helped me get through the last two years.

CONTRIBUTION OF AUTHORS

The following thesis has been presented in manuscript form, the main body (chapters 3 and 4) of which will be submitted as two separate publications. The first paper (Chapter 3 – Force Transducer System for Measurement of Ice Hockey Skating Force) will be co-authored, in order, by Dr. David Pearsall, Phil Dixon, and Dr. René Turcotte. For this paper I was responsible for manufacturing of the force transducer system, collection, processing, and statistical analysis of all validation and reliability data, as well as writing of the chapter and generation of the figures. Dr. Pearsall came up with the idea for the system, was influential in its design, provided insights into the results obtained, and provided comments on drafts of the chapter. Phil Dixon was an invaluable source of information and technical knowledge when designing the force transducer system, trouble shooting, and validating the system. Dr. Turcotte provided insights regarding the statistical analyses, and comments on drafts of the chapter.

The second paper (Chapter 4 – Comparison of Skating Kinetics and Kinematics on Ice and on a Synthetic Surface) will be co-authored, in order, by Dr. René Turcotte and Dr. David Pearsall. The contributions of each author for this paper are as follows; I was responsible for data collection, data processing, writing of the chapter, generating figures (except where noted), statistical analysis, experimental design and protocol, and subject recruitment. Dr. Turcotte provided invaluable experience regarding the experimental design and the statistical analysis for the project, as well as comments on the initial drafts of the chapter. Dr. Pearsall provided insights regarding results obtained in the analysis, as well as comments on chapter drafts.

I will be the primary author for both papers.

ABSTRACT

Given the technical challenges of measuring force during ice skating, little is known of the dynamics involved with this unique form of locomotion. Hence, the purpose of this study was first to develop a portable force measurement system, and second to compare kinetic and kinematic parameters of synthetic ice (SI) and traditional ice (ICE) surfaces during forward skating. The force measurement system allowed for simultaneous, accurate determination of the vertical and medial-lateral force components experienced by the blade holder. In general, the kinetic and kinematic variables investigated in this study showed minimal differences between the two surfaces ($p > 0.06$), and no individual differences were identified between the two surfaces ($p \geq 0.1$) with the exception of greater knee extension on SI than ICE (15.2° to 11.0 °; $p \leq 0.05$). The combination of the current force measurement system and the SI surface will allow for new insights to further our understanding of the biomechanics of ice hockey by allowing researchers to overcome many of the technological limitations of on-ice testing.

ABRÉGÉ

Étant donné les défis techniques de mesure de la force au cours du patinage sur glace, peu de choses sont connues quant à la dynamique de cette unique forme de locomotion. Par conséquent, le premier objectif de cette étude a été de développer un système portable de mesure de la force, et le second objectif à comparer les paramètres cinétiques et cinématiques de la glace synthétique (SI) et de la glace traditionnelle (ICE) durant le patinage vers l'avant. Le système de mesure de la force a permis en même temps, la détermination exacte des composantes verticales et medio-laterales de la force sur le porte-lame. En général, aucune différence entre les paramètres cinématiques ou cinétiques ont été identifiées entre les deux surfaces ($p > 0.06$), et aucune différence individuelle a été à identifiées ($p \geq 0.1$) avec l'exception d'une plus grande extension du genou sur la glace synthétique par rapport à la glace traditionnelle (15,2 ° à 11,0 °, $p \leq 0{,}05$). La combinaison du système de mesure de la force actuelle et de la surface SI permettra de nouvelles idées afin d'approfondir notre compréhension de la biomécanique du hockey sur glace en permettant aux chercheurs de faire face à bon nombre de limitations technologiques lors de l'essai sur glace.

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CHAPTER 1 – INTRODUCTION

1.1 THESIS OUTLINE

The following thesis will focus on the development of a system for determining on-ice skating kinetics, and the comparison of a previously unstudied synthetic ice surface by way of kinetic and kinematic analyses.

This thesis is presented in manuscript format containing six sections. Chapter 1 presents the rationale for the study, purpose and hypotheses, limitations and delimitations of the research, a summary of the variables investigated in each separate study along with the statistical methods used to analyze them. In addition, a nomenclature section summarizes the main terms and definitions used throughout this thesis. Chapter 2 provides an extensive literature review related to the topic of kinetic and kinematic ice hockey analyses, including a review of ice hockey, skating kinematics and kinetics, and a review of kinetic and kinematic analysis techniques. Chapters 3 and 4 are individual research papers, including a technical note related to the development and validation of a force transducer system for the measurement of ice hockey skating force, and a comparison of skating kinetics and kinematics on ice and on a synthetic ice surface. Chapter 5 serves as a summary of the main conclusions of the individual research projects, while chapter 6 lists the references used in this thesis.

1.2 NOMENCLATURE, OPERATIONAL DEFINITIONS, AND ABBREVIATIONS

The following are nomenclature, operational definitions, and abbreviations used throughout this thesis.

Blade holder: The plastic part of the hockey skate which holds the skate blade.

Contact Time (Ct): The time, in seconds, in which the skate is in contact with the ice surface.

Electrogoniometers (elgon): The instrument with which joint angle measures will be captured (Biometrics Ltd. Gwent, UK).

Force Transducer: A device used to predict forces based on strains exerted by an external load (Winter, 2005).

Goniometry: The objective measurement of angles. In the case of this study, the angles of concern will be joint angles.

Impulse: The change in momentum produced by an external force, defined as the integral of force with respect to time (Winter, 2005).

Kinematics: The area of biomechanics which describes movement without consideration of the forces leading to that motion (Winter, 2005).

Kinetics: The area of biomechanics concerned with the forces that produce given movements (Winter, 2005).

Medial-Lateral Force (ML): A force applied by a subject or skater perpendicular to the orientation of the caused by the deformation of the skate blade holder; medial force is shown as the action force in the Figure 1.

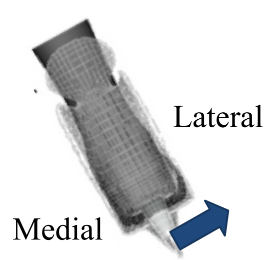

Figure 1 – Representation of medial force, shown in blue

Skating Stride: The biphasic motion of skating, which begins when the foot contacts the ice with the blade and progresses through glide, push-off, and recovery of the ipsilateral limb (Upjohn, 2008).

Strain Gauges: The equipment used to convert the mechanical deformations of the hockey skate into an electrical signal (Nigg and Herzog, 1999).

Stride Phases:

1) Initial Contact (Ic): Initial blade to skating surface contact.
2) Glide (Gl): Following initial contact, the phase of the stride in which no propulsion is occurring. The orientation of the blade of the skate on the ice is steering the body movement.
3) Push-Off (Po): Following the glide, the phase in which the blade turns outward (external), creating propulsion from extension of the hip, knee, and ankle.
4) Swing (Sw): Flexion of the non-weight bearing limb, allowing it to swing forward to begin the next stride.

Stride Time (St): The time required to complete one full gait cycle (one stride), initial contact to subsequent ice contact of the same skate.

Synthetic Ice (SI): 0.25" polyethylene sheets used to mimic a traditional ice surface.

Total Force (Tf): The summation of vertical and medial-lateral force components.

Traditional Ice (ICE): Water frozen in a solid state.

Vertical Force (V): A force applied by a subject or skater parallel to the orientation of the skate caused by the deformation of the skate blade holder, shown as the action force in the Figure 2.

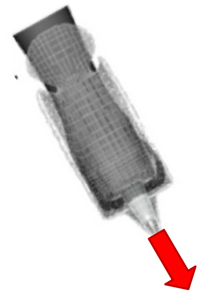

Figure 2 – Representation of vertical force, shown in red

1.3 RATIONALE

1.3.1 Study 1 – Force transducer system

Research investigating the mechanics of ice skating has focused primarily on the kinematic variables most influential in successful skating performance (de Koning et al., 1995; Lafontaine, 2007; Marino, 1977; Marino, 1979; Marino, 1983; Marino and Weese, 1979; Upjohn, 2008) and has primarily been restricted to forward skating. The combined measurement of kinetic parameters together with joint and segment kinematics would provide for the best understanding of the biomechanics of ice skating. However, due to the nature of the environment and other technical obstacles, the measurement of force during ice skating has not often been attempted. The group of Lamontagne, Gagnon, and Doré completed the only known studies attempting to directly determine forces specifically for ice hockey skating (Gagnon, 1983; Lamontagne, 1983). Though the study showed the feasibility of accurately collecting force measures on ice, practical application has not been possible until electrical components to power, condition, and record these signals became smaller and more durable for portable use. Technological developments in electronics have since been realized. Thus, the aim of this study was to build an accurate and practical instrumented system to enable the measurement of forces during ice hockey skating while maintaining the integrity of the hockey skate.

1.3.2 Study 2 – Surface comparison

The combined obstacles of the nature of the surface (ice; < 0°C), highly variable skill execution patterns, and large displacements have made it difficult to complete detailed studies of the kinematics and kinetics of ice hockey skating. Due to the dynamics of ice skating, systems used to measure kinematic data through active markering, such as Optotrak® and MotionStar®, are impractical because they require the subjects to be tethered to a computer for data logging. Passive marker systems such as Vicon® are not viable for field testing due to the large distances covered on-ice and the associated difficulties in observing skills over these large areas, as well as the inability to control ambient lighting (Upjohn et al., 2008). For these reasons, only a few published studies, and these with little success, have attempted to analyze full body kinematics of ice hockey skating (McPherson et al., 2004). An alternative methodology is to simulate the surface conditions in an in-lab setting large enough to allow unconstrained movement of the skater.

A synthetic ice surface (Viking Ice®, Wilsonville, OR) such as the one in the McGill biomechanics laboratory, may provide a suitable alternative to traditional ice surfaces. The synthetic ice surface is made of 0.25" polyethylene sheets, which when treated with a thin film of silicone based lubricant combine to yield a low friction surface with sufficient scoring capabilities (i.e. cutting) into the polymer surface to simulate gliding and push-offs. However, it is not known whether the artificial ice surface provides a valid representation of skating on ice.

1.4 PURPOSE

1.4.1 Study 1 – Force transducer system

The purpose of this first study was to build an accurate and practical instrumented system to enable the measurement of forces during ice hockey skating while maintaining the integrity of the hockey skate, thus allowing for effective and accurate analysis of the kinetics of ice hockey skating.

1.4.2 Study 2 – Surface comparison

The purpose of this second study was to determine the kinetics and lower body kinematics of hockey skating on a conventional arena ice surface, and to compare on-ice results with those obtained on a synthetic ice surface using force transducer strain gauge technology and electrogoniometry, thus establishing whether skating on the artificial ice surface is a valid representation of on ice skating.

1.5 HYPOTHESES

1.5.1 Study 1 – Force transducer system

It is expected that strain gauge technology will be able to reliably and accurately determine the compressive and tensile deformations of the skate blade holder between the skate boot and skate blade, and that these deformations will be highly correlated to known ground reaction forces measured on a force plate.

1.5.2 Study 2 – Surface comparison

It is anticipated that there will be no differences in the kinetics and the kinematics whether skating on the real ice surface or skating on the synthetic ice surface.

Considering the inherent complications with studying skating on a frozen ice surface, it is anticipated that the controllable in-lab conditions afforded by the artificial ice surface will allow for successful capture of information on the gross movement patterns of skating and other hockey skills.

1.6 Limitations

There are some inherent limitations with respect to these studies; both studies will be discussed together.

1) The force transducer (strain gauge) system does not produce a linear strain-force relationship below approximately 75 N in the medial-lateral orientation, and similarly does not produce a linear strain-force relationship below approximately 300 N in the vertical direction.
2) The subjects will not be wearing their own personal hockey skates, which may have an effect on their skating pattern.
3) The current configuration of the strain gauges renders the system insensitive to loads produced through the extreme front or extreme back of the skate blade holder.
4) The accuracy of the elgon can only be applied within the specific context of forward skating within the tested range of motion at the ankle and knee. As well, the elgons provide local angles; they do not provide the angles in a global reference frame.

1.7 Delimitations

The researchers have consciously decided to include the following delimitations; both studies will be discussed together.

1) While ice hockey skating is dynamic in nature, the current study will only be evaluating the front start, forward acceleration, and forward constant velocity skating strides.
2) The subjects will not be wearing full ice hockey equipment, thus possibly affecting the kinetics and kinematics of the skating stride.
3) Only male subjects will be studied.
4) The subject pool will include only forwards and defenseman.
5) The subjects will be asked to skate at their maximum velocity during all skating trials.

1.8 Independent (IV) and dependent (DV) variables

1.8.1 Study 1 – Force transducer system

The variables to be analyzed in this study can be found in table 1.

Table 1 – Variables to be investigated: force transducer system

Variable	Type	Scale	Definition
Force	Independent Variable	Continuous	Force reading as determined via force plate in vertical and medial-lateral orientations
Strain	Dependent Variable	Continuous	Micro strain reading as determined via deformations of the skate blade holder caused by loads in the vertical and medial-lateral orientations

The independent variables to be manipulated by the investigator are the force readings from the force plate and the micro strain readings from the force transducer system in the vertical, medial, and lateral orientations. Pearson product moment correlation coefficients will be calculated between the strain and force readings for all loading directions of each respective trial to establish the validity of the force measurement system.

1.8.2 Study 2 – Surface comparison

The variables to be analyzed in this study can be found in table 2.

Table 2 – Variables to be investigated: surface comparison

Variable	Type	Scale	Definition
Skating Surfaces	Independent Variable	Categorical	(1) Refrigerated Frozen Ice Surface (2) Synthetic Ice Surface
Task	Independent Variable	Categorical	- Start - Acceleration - Constant Velocity
Force	Dependent Variable	Continuous	Force as determined by the overall micro strain reading from the force transducers in the vertical and medial-lateral orientations
Stride Properties	Dependent Variable	Continuous	Stride properties of skating on both surfaces, including impulse, contact time, and stride time
Joint Kinematics	Dependent Variable	Continuous	Measurement of joint angles as recorded by the elgons at the ankle and knee

The independent variables to be manipulated by the investigator are the type of skating surface; a refrigerated frozen ice surface and a synthetic ice surface, and the tasks; start, and acceleration strides. The dependent variables of interest include the force produced by the skaters as recorded from the strain gauges. Finally, the lower body joint kinematics at the ankle and knee as recorded by the elgons will be recorded as dependent variables. All dependent variables will be compared within subjects across ice surfaces.

1.9 STATISTICAL METHODS

1.9.1 Study 1 – Force transducer system

Linear regression functions were derived using the strain gauge measures as the dependent variables to predict V and ML forces. In order to establish the validity and the reliability of the measurement technique, statistical comparisons between strain and force measures involved calculation of RMS error, coefficient of variation, as well as Pearson product correlation coefficients for all loading directions. All statistical analyses were performed using Matlab® (R200b, MathWorks, Inc. Natick, MA, USA).

1.9.2 Study 2 – Surface comparison

1.9.2.1 Sample size

A power analysis was performed using a freely available sample size calculator (Dupont and Plummer, 1997) to estimate the required sample size to obtain a power value of 0.85 or greater at an alpha level of 0.05. Using a detectible difference of 2 degrees, based on literature ±2° error of the elgon (Biometrics Ltd. DataLOG operating manual, 2004; Ouckama, 2007), and a predicted standard deviation of 2° (pilot data with one McGill varsity hockey player and one QMJHL hockey player), 10 subjects was deemed necessary for an adequate kinematic evaluation (see Figure 3).

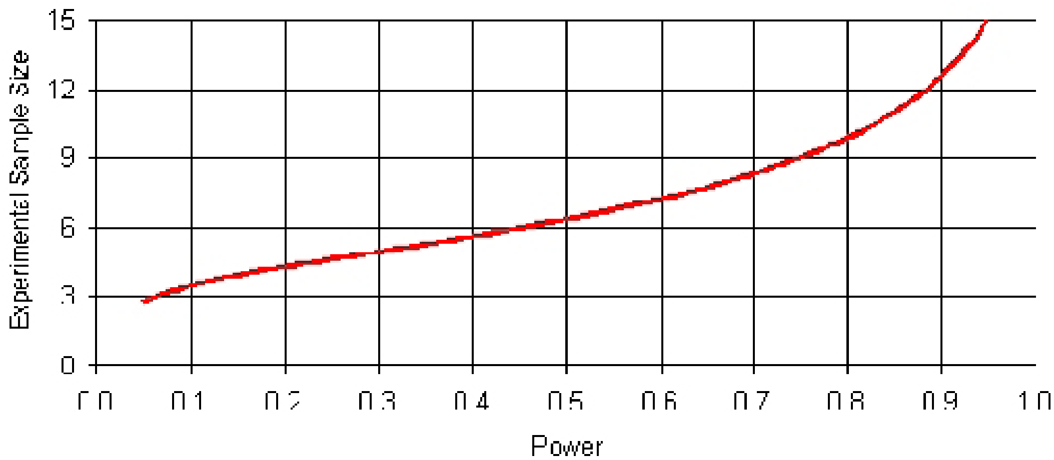

Figure 3 – Power analysis for kinematics

Likewise, it is probable that significantly different findings will be found for all expected kinetic outcome measures with a sample size of n = 10 based on in-lab pilot work, in which standard deviations for the force values were less than five percent.

A total of thirteen (13) subjects were recruited for participation in this study, although only 11 finished both testing protocols.

1.9.2.2 Statistical methods

The statistical analysis addressed the main objective of this study; to compare the kinetics and kinematics generated when skating on the two skating surfaces. A 2 way MANOVA was used to compare all kinetic and kinematic variables across three skating strides by the two skating surfaces. A univariate F-test was performed on each of the dependent variables to interpret the results of the MANOVA (George, 2006). Statistical significance was set at $\alpha = 0.05$. All statistical analyses were performed using SPSS (v.17, Chicago, IL, USA).

CHAPTER 2 – REVIEW OF LITERATURE

2.1 Origins of skating and hockey

Efficiency of locomotion is a constant obstacle for animals. The connection between the energy intake through food and energy used to stay alive is a delicate balance. Formenti and Minetti (2008) hypothesised that ice skating, developed in Scandinavian countries as early as two millennium BC, was originally an energy efficient alternative method of locomotion compared to walking. In order to survive in these ancient northern countries humans needed to hunt and fish during long winters. The development of ice skates may have helped humans to limit the necessary energy expenditure during a time when ground conditions would have significantly raised the energy cost of travel, thus increasing their chances for survival. The oldest known ice skates were made of animal bones in Scandinavian countries such as Finland, the Netherlands, Sweden, and Norway, however, no clear evidence supports this hypothesis with respect to where and why bone skating started. Archaeological findings show that these skates date back to approximately the second millennium BC (Formenti and Minetti, 2008).

During the 16th and 17th century's ice skating developed into a competitive sport. These skates consisted of a wooden boot with an iron runner strapped under the shoe. It was not until the middle of the 19th century that an all-steel skate was constructed, which would become the basis for the modern speed skate, called 'long blades' or 'Norwegian skates' (de Koning et al., 2000).

Unlike skating which originated in northern Europe, ice hockey owes its roots to Windsor, Nova Scotia (Diamond et al., 1998). Origins of ice hockey date back to the

1800's. Students at King's College School in Windsor, Nova Scotia have been credited with originating the game of ice hockey, adapting their favourite summer sport of hurley to the local skating ponds thus creating a new winter sport called ice hurley. During these times, cultural influences of English, Scottish, Irish, and French immigrants led to the organization of the play and rules of ice hockey (Pearsall et al., 2000). Ice hurley evolved from stick-ball games played on the ground, and attributes many of its aspects to early stick games such as hurley, bandy, shinny, cricket, and lacrosse (Diamond et al., 1998; Pearsall et al., 2000).

The evolution of the game of ice hockey has proceeded at a fast pace. The game is currently played world-wide, including on surfaces other than natural ice. In conjunction with the increasing popularity, the game of ice hockey has developed, becoming more sophisticated and expensive due to constant innovations in equipment design and facilities, as well as improvements in coaching, training, and game strategies (Pearsall et al., 2000).

2.2 Classification of hockey skills

Because of the specialized environment which is required to play the game of ice hockey, including a low surface friction and sub-zero temperatures, a unique set of skills distinct from other sports is required to play the game (Pearsall and Turcotte, 2007). The skills of the sport of ice hockey are principally result oriented, with the movement patterns secondary to the outcome of the task (Pearsall et al., 2000).

Certain hockey skills may be considered 'closed', in that specific features of the environment remain unchanged, such as rink dimensions and equipment. However, the majority of skills are 'open', varying with the changing surroundings of the athlete, such as position of team members, opponents, the puck, as well as current movement status (skating or stationary) (Latash, 1998). Given the ever changing conditions, specific skills are not always performed in a consistent manner (Pearsall et al., 2000). The athlete must choose between a multitude of visual and verbal cues to determine the best strategic response to a given situation, and this response must be executed in a very short time interval (Latash, 1998). Because of the generally 'open' and ever-changing environment in which the game of ice hockey is played, several factors aid in defining the efficiency and effectiveness of a movement, including timing, anticipation, speed, agility, balance, and reaction time, which generally combine to lead to unpredictable outcomes (Pearsall et al., 2000).

The fundamental skills of ice hockey include skating, stick handling, and checking, with each of these groupings containing several variations or subsets of the movement pattern, and can be found in Figure 4 (Pearsall et al., 2000).

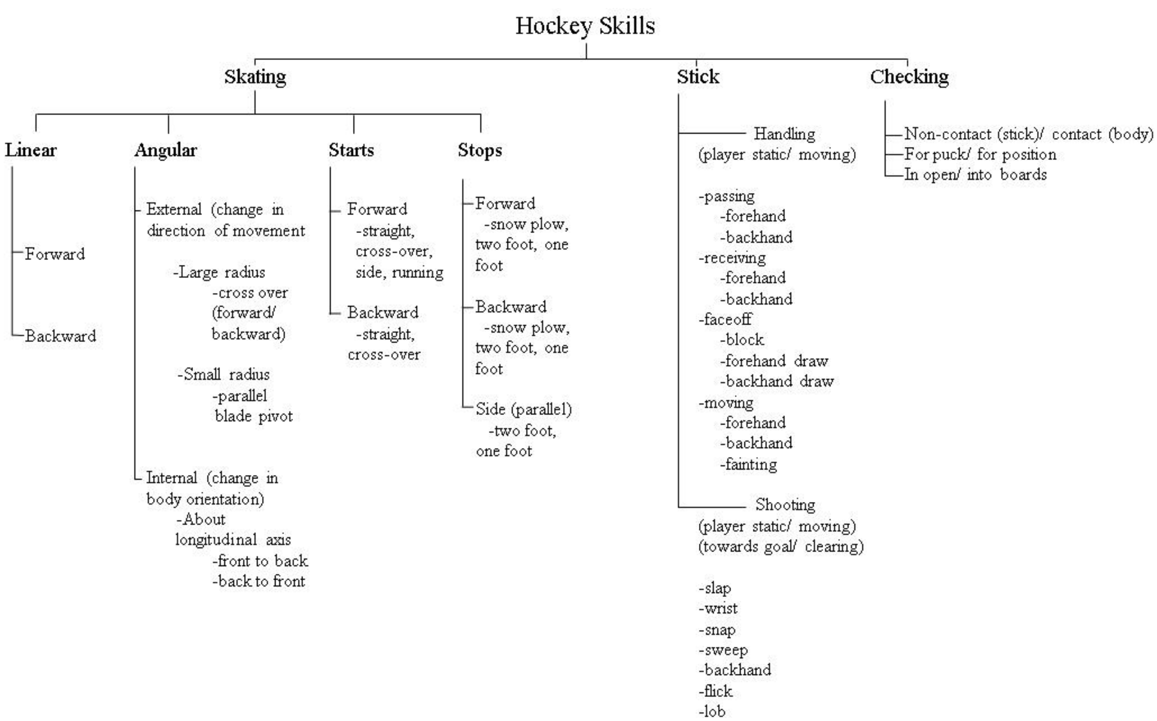

Figure 4 – Hockey's fundamental skills (adapted from Pearsall et al., 2000)

2.3 Skating

Skating is the most important, fundamental skill required for successful participation in the game of ice hockey; the equivalent to running in basketball or football. Ice skating is defined as the ability to travel on ice (Formenti and Minetti, 2008). It is the unique combination of an ice surface and the ice hockey skate that allows hockey players to move at high speeds while being extremely agile. The ice surface must have a low enough coefficient of friction to allow the skater to glide with ease, yet also provide sufficient friction at specific points in the stride to allow the player to push off in the desired direction of travel. Unlike running however, the reactive push-off force when skating cannot be elicited in the backward direction due to the low coefficient of friction between the ice surface and the skate blade. Instead, skaters rely on the reactive force that is produced perpendicular to the direction of travel, thus making ice skating a novel form of locomotion for humans (de Koning et al., 1995; Pearsall et al., 2000; Upjohn et al., 2008). The coordination patterns of skating, particularly the synchronous hip extension, hip abduction, knee extension, and plantar flexion, is a unique adaptation to the low friction ice surface of more natural movements, including walking and running (Pearsall et al, 2000; Upjohn, 2008; van Ingen Schenau et al., 1989).

Simply put, skating is what a hockey player does most. It is the foundation upon which every other skill depends. When playing a full length hockey game, an average player skates between three and five kilometres, with a forward skating movement pattern consisting of between ninety-five and eighty percent of all skating manoeuvres (Percival, 1970; Montgomery et al., 2004). There are a variety of skating skills associated with ice hockey. However forward skating is the fundamental movement pattern for most skating tasks (Upjohn et al., 2008). Other skating skills include skating backwards, turns, starts, and stops, with each of these containing skill subsets.

The forward skating stride is a biphasic motion which begins when the foot contacts the ice with the blade and progresses through glide, push-off, and recovery of the ipsilateral limb (de Boer et al., 1987; de Boer et al., 1986; de Koning et al., 1991; de Koning et al., 1995, de Koning et al., 2000; Marino and Weese, 1979; Upjohn, 2008). The glide phase of the stride follows initial contact of the skate to ice, and is the phase of the stride in which no propulsion is occurring (Pearsall et al., 2000). During the glide phase the orientation of the blade of the skate on the ice is steering the movement of the body (Pearsall et al., 2000). Following the glide, the push-off is the phase in which the blade externally rotates, and propulsion is created through the rapid extension of the hip and knee, as well as plantar flexion of the ankle (Pearsall et al., 2000). The push-off phase ends when the extending leg reaches full extension and the blade is lifted off the ice (de Boer et al., 1986). Lastly, the recovery phase begins as push-off is completed. The recovery consists of the flexion of the non-weight bearing limb, allowing it to swing forward to begin the next stride (Pearsall et al., 2000).

2.3.1 Skating kinematics

Due to the complexities of determining skating kinematics, including unique conditions of the task, large movement areas, and the difficulties associated with adequate motion capture on ice, kinematic measures of ice skating have not been extensively examined (Upjohn, 2008). There have however, been several pioneering studies investigating the kinematics of ice skating, generally using video analysis as the method of evaluation. No reported study has evaluated whole body kinematics of ice skating.

The following section will examine previous research relating to the lower body kinematics of ice skating.

Using video analysis, Marino (1977) found a relationship between selected kinematic variables and skating speed in ten subjects, whose ability level ranged from highly skilled to moderately low skilled. Particularly, the results from the study showed that skating velocity is determined by stride rate, as well as the ratio of single and double support time. Marino (1977; 1979) suggested that skating velocity is primarily derived from stride rate; when velocity is high so is stride rate. Similarly, velocity decreases as with decreasing stride rate. These results indicate that fast skating speed is more dependent on the frequency of force application than on the amount of the propulsive force of each stride as indicated by the length of each stride, a variable that was found not to be significantly correlated to skating speed (Marino, 1977). In subsequent studies, Marino (1979; 1983) has shown that stride length was not correlated to skating velocity. Likewise, Turcotte et al. (2001) noted that blade contact time with the ice surface decreased with increasing velocity, meaning impulse decreased with increasing speed, and thus the increase in propulsion was due to an increase in stride rate. The study by Marino (1977) also noted that when skating at slow and medium speeds, subjects skated in a more upright position and incorporated a long, leisurely glide phase into their movement patterns, whereas during fast skating the propulsion phase appeared to be much shorter and subjects brought the recovery leg forward much more rapidly so that a subsequent stride could begin.

In a 2-Dimensional analysis of the ice skating stride Marino and Weese (1979) discerned that the ice hockey skating stride is biphasic in nature, consisting of alternating periods of double support involving 18 percent of each stride, while 82 percent of each stride was spent in single support. The study also showed that highly skilled skaters were able to generate propulsive forces during periods of both single and double support. Marino and Weese (1979) concluded that acceleration begins approximately halfway through the single support phase and continues until early double support, and that acceleration is associated with the outward rotation of the thigh and extension of the hip and knee. Following ice contact of the non-support foot, the force generating leg completes its propulsion through full extension of the knee, hyperextension and abduction of the hip and plantar flexion of the ankle. This sequence results in a weight shift weight to the contra-lateral limb. This progression also suggests that the force generated by muscle contraction causing propulsion originates during single support and ends with the release of the skate from the ice surface following double support (Marino and Weese, 1979).

de Koning et al. (1995) analysed maximum effort skating starts in five elite speed skaters, calculating 3-Dimensional coordinates of body markers from three high-speed cameras. The study found substantial differences in the push-off mechanics of the second through eighth strides. The results from de Koning et al. (1995) showed little displacement of the skate during the second stroke, meaning that the athlete was pushing off against a fixed point similar to a running stride. During the first strides the external rotation of the leg caused the skate to be perpendicular to the intended direction of travel, extension of the hip and knee pushing directly backwards thus creating horizontal velocity. Throughout the eighth stride the skate was gliding during the push-off, creating more of a sideward push, while the outward rotation of the leg was minimal, instead creating horizontal velocity through a laterally directed push-off.

Pearsall et al. (2001) examined the kinematics of the foot and ankle during forward power skating through the use of biaxial electrogoniometers attached to the rear foot along the Achilles tendon inside the skate boot. The study demonstrated that during single support of the glide phase, the ankle was in 7.1 degrees of dorsi flexion with respect to the subjects' on-ice neutral standing position. During the period of double support the skate increased dorsi flexion, reaching a maximum dorsi flexion angle of 11.8 degrees. As the skate came off the ice at the end of the push-off, the skaters rapidly plantar flexed to minimum of angle 1.9 degrees of dorsi flexion. The foot was dorsi flexed throughout the entire skating cycle, likely an effect of the subjects skating position. van Ingen Schenau et al. (1989) revealed that speed skaters use a sitting position when skating and lean their trunks forward to minimize the effect of air resistance, thus causing the dorsi flexed state of the ankle throughout the skating stride.

Pearsall et al. (2001) also noted that during the glide phase the foot was slightly everted, with relatively little change at the ankle throughout the contact phase. A maximum eversion at the ankle of 7.1 degrees was seen as the skaters approached the double support phase, preparing for push-off. The maximum eversion was likely caused by the need to generate a laterally directed resultant force on the ice. During the swing phase the ankle inverted, slightly exceeding neutral position. The study by Pearsall et al. (2001) showed the effectiveness of electrogoniometers in examining the foot and ankle kinematics of ice hockey skating.

In an extension of Pearsall's study (2001), Chang (2002) investigated the changes in ankle, knee, and hip joint displacements and angular velocities during increasing forward skating velocities through the use of biaxial electrogoniometers. Chang (2002) found that skating velocity had very little effect on the gross motor movement patterns of the lower limb, and that stride rate was the singular kinematic variable to be significantly related to skating velocity. These results are in accordance with Marino (1977) and van Ingen Schenau (1985), who both suggested that stride rate is the primary controller for horizontal skating velocity.

In an innovative study, Lafontaine (2007) used two moving high-speed cameras attached to a guide rail to describe the three dimensional lower body kinematics of one leg for three consecutive push-offs of seven skaters, showing differences in knee and ankle kinematics across the three push-offs as the skaters gained speed. During the first push-off the skaters flexed for the first part of the push-off, followed by an extension during the last 30% of the phase, while during push-offs two and three the subjects initiated ice contact on a flexed leg and extended it throughout the observed push-offs. It was these knee flexion angles that Lafontaine (2007) found to be most effective for increasing skating velocity. The ankle profiles recorded were similar to those found by Pearsall et al. (2001).

As with de Koning (1995), Lafontaine (2007) noticed that the first push-off could best be described as ‘pushing against a fixed point’, while the third stride could be described as ‘pure glide’, unlike in speed skating where the transition between running (pushing against a fixed point) and gliding occurs about the eighth push-off (de Koning et al., 1995).

McPherson (2004) and Wrigley (2000) focused their research on developmental aged hockey players, investigating the relationship between age and body size with skating technique. Their research showed that as age increases, there is a coupled increase in maximal velocity and stride length. These changes were caused in part because the elder skaters were able to create a much greater plantar flexion angle at push-off than their developmental counterparts. Associated differences may be in part due to the lack of muscular force generated by the younger aged players (McPherson, 2004; Wrigley, 2000).

Upjohn et al. (2008) and Lockwood et al. (2007) are among the only published studies found to involve ice skating on a non-traditional surface. Upjohn et al. (2008) examined the kinematic variables that discriminate high-calibre hockey players from lower calibre hockey players when skating on a skating treadmill using the 3-dimensional reconstruction of four video camcorders.

The study revealed that high-calibre skaters achieved faster skating velocities than their low-calibre counterparts, even though stride rate was similar. Instead, Upjohn et al. (2008) noted that skating speed is likely attributed to stride width and kinematic differences in the recovery phase of the stride, particularly a greater hip flexion at weight acceptance and greater knee and ankle ranges of motion. The greater amplitude of hip flexion at weight acceptance is indicative of greater eccentric contraction of thigh and hip extension muscles before contraction during the push-off phase (muscle activation will be discussed in depth in following sections of this literature review). This increased transfer of elastic energy likely caused higher skating velocities through increased force production during the propulsive phase (Upjohn et al., 2008). The study also revealed that high-calibre skaters had a greater knee extension and plantar flexion during propulsion, which is consistent with the previous rationalization regarding the relationship between skating velocities and force production during the propulsive phase of ice skating. These results differ from Marino (1977; 1979) who suggested that skating speed is most highly correlated to stride frequency. Although Marino (1979) suggested this, it is likely that both kinematic characteristics coupled with stride frequency contribute to skating speed.

While Upjohn et al. (2007) investigated kinematic variables which discriminate high and low-calibre skaters, Lockwood et al. (2007) investigated the habituation of 10-year-old hockey players to a skating treadmill using a sagittal plane video of the skaters. The results showed that stride rate and stride length increased, while rating of perceived exertion and heart rate decreased, insinuating habituation to the new skating surface over a six week period. Of importance, Lockwood et al. (2007) found that changes in stride rate and stride length contributed to what appeared to be a more efficient skating style, and not kinematic variables such as knee and hip flexion, although no physiological parameters other than heart rate were recorded.

To compare physiological and kinematic factors of skating on-ice and on a skating treadmill, Nobes et al. (2003) investigated submaximal oxygen uptake (VO_2), heart rate, stride rate, and stride length of 15 male varsity hockey players when skating at velocities of 18, 20, and 22 km/h on both a skating treadmill and on-ice. Also investigated was maximal oxygen uptake on both surfaces (VO_2max). Results revealed that VO_2 was significantly lower at speeds of 18, 20, and 22 km/h on-ice, while VO_2max was similar on both surfaces. Stride rate and heart rate were found to be significantly higher on the skating treadmill, while stride length was significantly longer at the same skating velocities. Differences in physiological and kinematic factors were attributed to the increased co-efficient of friction on the skating treadmill; when skating on-ice at high velocities opposing forces are primarily due to air resistance (de Koning et al., 1992), while surface friction on the skating treadmill is much greater, effectively reducing the glide phase of the stride, whereas air resistance is minimal.

2.3.2 Skating kinetics

Because of the liquid medium between the ice surface and the skate blade, direct kinetic measures of ice skating traditionally used in biomechanics such as force plates have been elusive. As a result, research investigating the mechanics of both speed skating and hockey skating have focused primarily on the kinematic variables most influential in successful skating performance. Because of this, the following section will focus on the studies exploring muscle activation patterns and the few studies investigating the force profiles of skating.

2.3.2.1 Muscle activation

As the skater reaches constant velocity, the skating stride is characterized by a specific biphasic pattern, which can be broken down into glide, push-off, and recovery phases (Pearsall et al., 2000). This basic pattern can be seen in Figure 5.

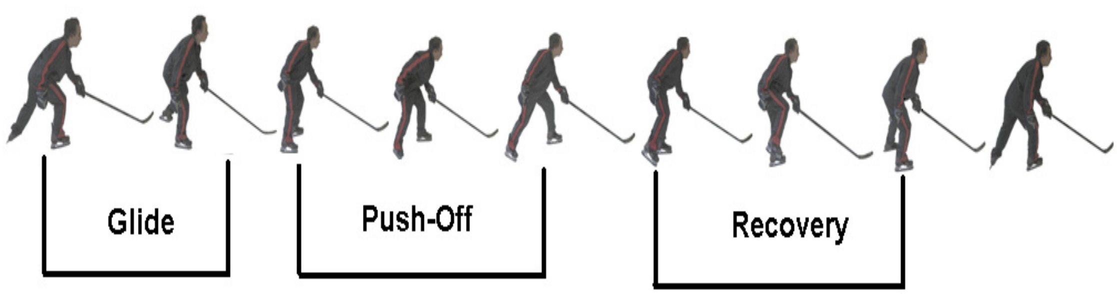

Figure 5 – Phases of the skating stride (from Pearsall et al., 2000).

Each of these phases is characterized by specific muscle patterns (de Boer et al., 1987; Goudreault, 2002). As a result, each phase will be discussed independently.

2.3.2.1.1 Glide

During the glide phase, characterized by single support, the hamstrings muscles are most active, specifically the biceps femoris (BF) and the semitendinosus (SM), as well as the hip extensor gluteus maximus (GM). These muscles do not contribute to power generation during the glide phase, but instead contract eccentrically to stabilize the knee during periods of single support (de Boer, 1997; Goudreault, 2002). For all of these muscles, activity increases from the moment of initial ice contact until approximately the point of push-off initiation (Goudreault, 2002). Quadriceps muscles, particularly the rectus femois (RF) and vastus lateralis (VL) are active during the glide phase, but like the hamstrings muscles are primarily used to support the knee (de Boer, 1987). At the same time, the tibialis anterior (TA) is working isometrically to stabilize the ankle (Goudreault, 2002). During the gliding phase, the knee extensors and flexors are coordinated to optimize leg position prior to the push-off (Pearsall et al., 2000). When comparing muscle activation patterns of ice skating and treadmill skating, Hinrichs (1982) found similar activation patterns as Goudreault (2002) and de Boer (1997). However, when on the treadmill the Adductor Longus (AL) showed activation at different times than on-ice, occurring earlier on-ice than on the treadmill surface. Differences observed were likely a result of a slight incline of the treadmill surface and the fact that the surface is moving under the skate, in turn causing a longer neutral glide position in which the foot is placed toward the midline of the body for support, a position which requires little if any activation in the AL (Hinrichs, 1982). As the foot moves laterally from the midline at the onset of push-off, AL activation is needed for stabilization (Hinrich, 1982).

2.3.2.1.2 Push-off

Concentric contraction of the GM is primarily responsible for the generation of power during push-off (de Boer, 1987). At about 200ms before the end of push-off a burst of activity of the quadriceps results in the explosive power generation at the knee joint, these muscles primarily include the vastus medialis (VM) and RF. This explosion of the quadriceps muscles coincides with a decrease of activity in the knee flexors, including the gastrocnemius (GAS) and BF (Goudreault, 2002). Following hip and knee extension, BF, GAS, and peroneus longus (PL) contracted to extend the ankle, suggesting a proximal-distal sequencing in speed skating, similar to that found in jumping (de Boer, 1987; de Koning, 1991). To support this phenomenon in ice hockey skating, Goudreault (2002) found that hip and knee extensions were essentially simultaneous, while ankle extension followed. Similar muscle activation patterns were found by Hinrich (1982).

2.3.2.1.3 Recovery

During the swing phase, activity naturally decreases in extensor muscles, particularly VM, GM, GAS, and PL. The primary hip flexor is the illiopsoas, which while as of yet not studied during ice skating, is thought to be the primary contributor to hip flexion during the swing phase of skating. The BF and TA are also active during this phase of the skating stride, contributing to knee flexion and ankle dorsiflexion respectively (Goudreault, 2002; Hinrich, 1982).

2.3.2.2 Forces

Because of the liquid medium between the ice surface and the skate blade, direct kinetic measures traditionally used in biomechanics (i.e. force plates) of ice skating have been, for the most part, elusive. One method used in speed skating to measure force on an ice surface is with the use of strain gauge transducers. Several studies investigating the kinetics of skating have used temperature compensated strain gauges as force transducers attached to an interconnected block assembly between the shoe and the blade of speed skates (de Boer et al., 1987; de Koning et al., 1992; Jobse et al., 1990).

While de Boer et al. (1987) were the first to publish a study reporting on-ice force values, the apparatus utilized was not fully described until done so by Jobse et al. (1990). The instrumentation system used by de Boer et al. (1987), de Koning et al. (1992), and Jobse et al. (1990) consisted of three subsystems, the instrumented skates, a microcomputer, and computer software.

The instrumented skates used consisted of a temperature compensated strain gauge block assembly inserted between the blade and boot of the speed skate. Exerting a load on this insert caused a transformation in the measuring unit, to which the Wheatstone bridges of the strain gauges produced an electrical signal proportional to the load. A transducer capable of determining frictional force was positioned in the middle of the unit, designed to be highly sensitive to horizontal force caused by frictional resistances, while normal force transducers were positioned in the front and back of the unit.

The system used in these studies was capable of measuring normal forces up to 1,400 N, and frictional forces up to a maximum of 40 N. With the insertion of the force transducer assembly, the weight of the normal speed skate increased by 55%. The instrumented skates were wired to a microcomputer, whose purpose was to amplify, digitize, and store force values of multiple strokes. At a frequency of 200Hz, the system could measure for a maximum of 40 seconds. The system software calculated mean coefficient of friction from the collected data, and outputted force and friction results on a hand-held display. Calibration of the system was performed via a combination of loads; linear regression models between the recorded signals from the transducers and the known force placed on the system were calculated.

Jobse et al. (1990) determined force-time curves during skating along the straightaway. Normal force values were determined via the summation of the front and back transducers. The normal force curves showed two peaks, the first due to the need to counteract body weight during the transfer of the body from the push-off leg, and the second due to the powerful push-off. These two peaks were intersected by a normal force equal to one body weight, recognized as the gliding phase. The primary purpose of the system described by Jobse et al. (1990) was to determine ice frictional properties during speed skating; these results will be discussed more in depth in following sections.

Using the same system, de Boer et al. (1987) recognized that the force pattern was increasing on the front connection towards the end of the stroke, while the force pattern on the back connection was decreasing, meaning that during the stroke the point of application of the total force vector was moving forward with respect to the ankle joint. Like Jobse et al. (1990), de Koning et al. (1992) used the instrumentation system to determine ice frictional properties when speed skating.

In an attempt to determine push-off forces in ice hockey for injury prevention purposes, Sim and Chao (1978) measured vertical reaction forces during push-off using a force plate. The experiment, conducted on two subjects, was performed by placing the subject with their thrusting leg on a force plate; the driving leg wore a regular hockey skate with the blade covered by a rubber protector to gain additional friction. The forward leg wore a roller skate to mimic on-ice mechanics as closely as possible. Vertical reaction forces were measured between 1.5 and 2.5 times the player's body weight, the posterior push-off force was approximately 688 N, and the lateral force was approximately 353 N, depending on the skating style of the subject (Sim and Chao, 1978). Though this study provided insights into the kinetics of ice-hockey skating, information on true on-ice dynamics were not available until Gagnon, Lamontagne, and Doré attempted to derive on-ice forces via strain gauge technology.

The group of Lamontagne, Gagnon, and Doré completed the only known studies attempting to directly determine forces specifically for ice hockey skating (Gagnon et al., 1983; Lamontagne et al., 1983). Lamontange et al. (1983) attempted to configure two separate instrumentation systems for transducing ice skating force; one using a plastic blade holder with little success, and a second with a more customary style metal blade and blade holder. By attaching pairs of 120Ω strain gauges to the anterior and posterior posts of a plastic blade holder to determine compressive forces (B in Figure 6) and a pair of strain gauges adhered to the front of the anterior post and back of the posterior post to determine medial-lateral (flexion) forces (A in Figure 6), Lamontange et al. (1983) attempted to discern skating forces. The plastic blade holder utilized in this study was found to be inadequate; this plastic structure was far too flexible and did not produce linear correlations in both the compressive and flexile orientations, likely a cause of the visco-elasticity of the plastic material. When strained, the material did not return to its initial form in a repeatable manner, resulting in inconsistent force readings (Lamontagne et al., 1983).

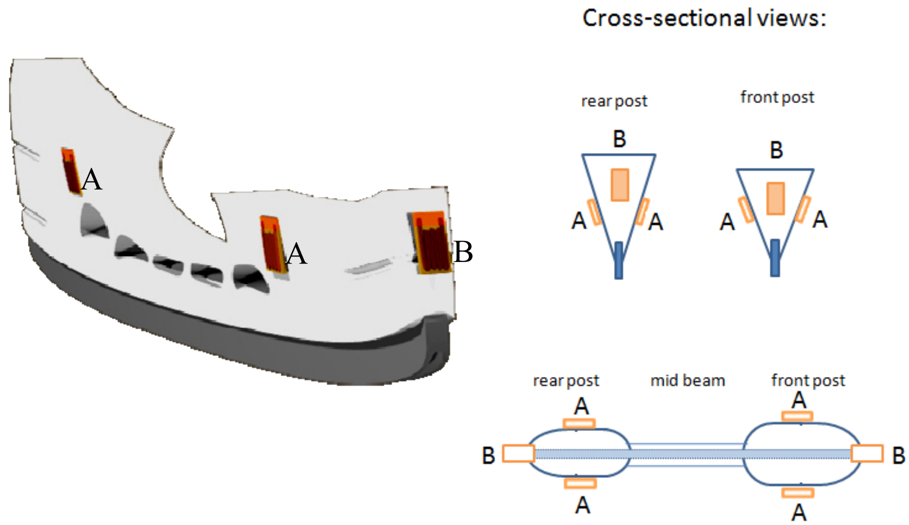

Figure 6 – Depiction of gauge placement used by Lamontagne et al. (1983) on plastic blade holder (adapted from Lamontagne et al., 1983). A denotes gauges used to determine compressive (normal) forces, B denotes gauges used to determine flexile (medial-lateral) forces.

A second instrumentation system utilized a metal skate blade and blade holder. However, for satisfactory deformations to occur in the blade holder, allowing for appropriate signals, modifications to the blade holder were required. First, holes of 1.3 and 1.5 cm^2 were punctured into both the anterior and posterior columns of the blade holder, denoted by A in Figure 7. Second, the front blade-boot connection had to be shaved down, denoted by B in Figure 7. These modifications to the blade/blade holder system allowed for an increased deformation in the blade holder system, allowing for sufficient signal strength.

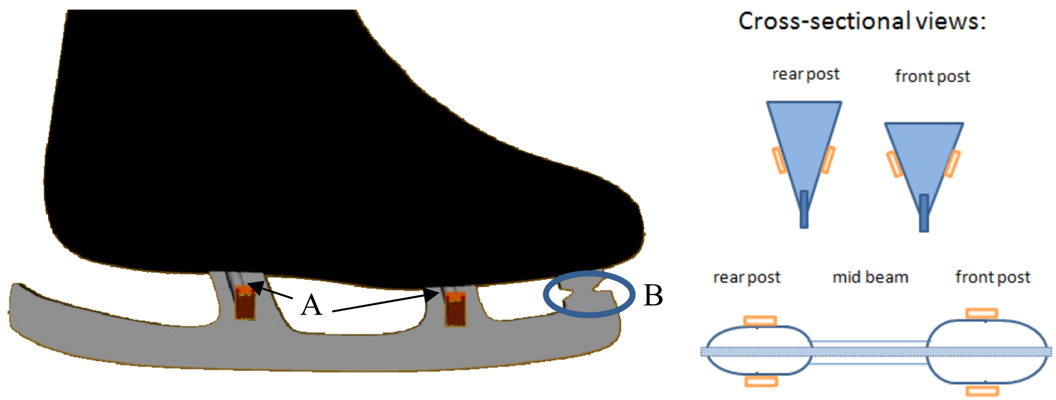

Figure 7 – Depiction of gauge placement used by Lamontagne et al. (1983) on metal bladeholder (adapted from Lamontagne et al., 1983).

Configuration of these gauges in a Wheatstone bridge allowed for measurements of compressive (normal) and flexile (medial-lateral) deformations. Calibration of this system was performed by riveting (locking) the skate upside-down on a specially constructed mount. A pulley system was manufactured, in which a loading device connected to a weight was placed on the skate blade. When the weight was released, known loads were placed on the blade. Linear regression equations were determined to verify the relationship between the load and the deformations determined by the strain gauges. The system used in these studies was calibrated up to a maximum vertical load of 450 N, and 270 N in the medial-lateral direction. These procedures showed a reliability of strain-force signals to within 14% (coefficient of variation) with limited hysteresis (Lamontagne et al., 1983). From the publication by Lamontagne et al. (1983), it is unclear how the strain signals were collected (i.e. connected to a computer), or sampling rate of the signal. It is also unknown if the subjects were tethered to the system, thus creating an encumbrance when performing skating skills. From interpretation of the published article it can be assumed that the length of connecting wires and portability of the system was an unresolved issue.

In addition to sophisticated 3D measures to determine skate orientation, the strain gauge force transducers determined forces while performing a parallel stop (Gagnon et al., 1983; Lamontagne et al., 1983). Two subjects were tested, demonstrating peak forces upwards of 900 N. The studies by Gagnon (1983) and Lamontagne et al. (1983) have shown the feasibility of collecting force measures on ice through the use of strain gauges, however practical application to skating tasks in a more widespread fashion has had to wait until the electrical components used to power and record signals have become smaller, more durable and portable. Lamontagne et al. (1983) recommended that future studies manufacture a smaller, more portable instrumentation system while maintaining the integrity of the hockey skate. The authors also mentioned that a new system would be improved by increasing signal precision.

2.4 ICE SURFACES

Recreational ice hockey is commonly played on outdoor ponds, rivers, or rinks in the winter when sub-zero Celsius temperatures allow for frozen ice. In recent years however, hockey is being played primarily on indoor rinks. These rinks take advantage of refrigeration systems to control the ambient temperature of the arena and the ice surface, as well as to control humidity in the arena. Indoor rinks and arenas also allow for an increased capability to repair cracks, unevenness, and other irregularities in the ice surface (Pearsall et al., 2000).

Skating can occur on ice due to the low coefficient of friction surface, which has been found to range between a μ of 0.003 and 0.007 when speed skating forwards (Kobayashi, 1973; de Koning et al., 1992; Jobse et al, 1990).

Using the previously described instrumented speed skates, Jobse et al. (1990) determined ice friction when skating at a constant velocity of 8m/s on an outdoor ice rink with ambient temperatures ranging from 4 to 5 °C, and ice temperatures between -3 and -4 °C. Using the same instrumented skates, de Koning et al. (1992) measured the ice frictional properties on the straightaways as well as the curves. Ice surface temperatures varied between -1.8 and 11°C during the testing sessions. In both studies the mean coefficients of friction ranged between 0.003 and 0.007 when skating the straight, with minimum values when the ice surface temperature was between -6 and -9°C, translating to frictional resistance forces of between 3.8 N and 4.9 N. Ice friction was found to have a linear relation to skating speed when measured on the straightaways, and a comparable relation on the curves with values between 28% and 35% higher (de Koning et al., 1992; Jobse et al., 1990). Similar ice frictional properties were found by Federolf et al. (2008) when investigating deceleration of a sled due to ice friction with four different skate blades.

Interestingly, frictional forces were found to increase as the subject increased horizontal velocity (de Koning et al., 1992). de Koning et al. (1992) also noticed that the value of μ is higher at the beginning of the stroke phase as compared to the mid-phase. This can be attributed to the rotation of the skate during the stroke; as the skate contacts the ice surface the outer edge of the blade makes a groove through the surface, while during push-off the inner edge creates a groove within which to slide, whereas during the mid-phase both edges are on the ice surface, creating less of a channel in the ice. It is these penetrations in the ice that cause the increase of the frictional force, and while only one edge of the blade is in contact with the ice surface the amplitude of this incursion is highest (de Koning et al., 1992).

There are two prevailing theories regarding how the low surface friction of ice occurs. One is the formation of water due to pressure-melting, and the other is melting due to frictional heating, with the latter being more supported (de Koning et al., 1992). The physics creating this decrease in ice surface friction are as follows; if a low-viscosity fluid acting as a lubricant is present between two rubbing surfaces, the two surfaces will become more or less separated, leading to a reduction in friction. It has been suggested that the low friction in skiing and skating is due to a thin film of water between the surface and the ski or skate blade (Bowden, 1953; Bowden and Hughes, 1939; Tabor and Walker, 1970).

Recently, the advent of synthetic ice surfaces has allowed for a more cost efficient alternative to refrigerated ice rinks. Synthetic ice surfaces are made of interconnected polyethylene panels, which when covered by a silicone lubricant acting as a medium between the surface and the skate blade, combine to create a low friction surface with sufficient cutting by the blade into the polymer surface, which can simulate glide and push-off when skating while using the same blades used for ice skating. Several companies manufacture synthetic ice surfaces, including KwikRink Synthetic Ice®, Super-Glide, and Viking Ice ®. It is unknown however, if skating mechanics on these synthetic ice surfaces are similar to those on frozen ice.

2.5 SKATES

As previously described, ice skates were first developed at least 3000 years ago as a method of locomotion (Formenti and Minetti, 2007). The modern skate design, used most commonly for sport, art, and leisure, has evolved primarily as a result of trial and error (Pearsall and Turcotte, 2007). The basic features, structural components, and appearance of the modern hockey skate are depicted in Figure 8.

Figure 8 – Structural components of a modern hockey skate (adapted from Pearsall and Turcotte, 2007).

The skate is the tool by which the player may harness the frictional properties of the ice to control their movement patterns (Minetti, 2004). The blade is the interface between the skate and the ice surface. The skate blade is curved along its length, with radii of curvature varying from 2m to 3m, and in cross-section consists of a medial and a lateral edge formed by an intermediate shallow hollow. During the gliding phase of skating, either one or both of the edges may be in contact with the ice surface, compressing and/or breaking into the ice surface creating a shallow channel on the ice surface. During the forward push-off phase, the blade is angled obliquely so as to momentarily gain leverage to enable an action-reaction force interface. The backwardly directed leg extension creates an equal and opposite reactive force from the ice (ground) to propel the body forward, which can be seen in Figure 9 (Pearsall et al., 2007).

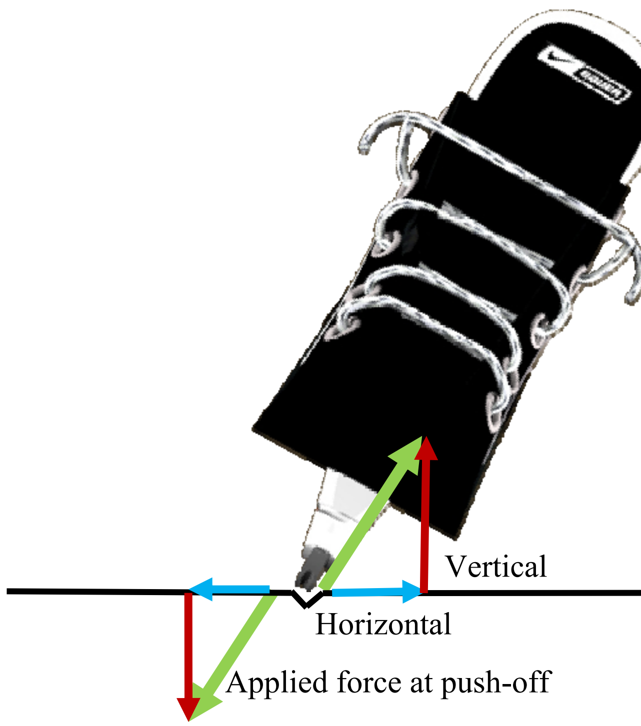

Figure 9 – Orientation of skate to ice surface at push-off (adapted from Pearsall et al., 2007).

Pearsall et al. (2000) noted that boot construction may have an impact on skating performance. As an example, the materials and construction techniques used in creating the skate boot can alter its stiffness characteristics, which may affect medial-lateral and/or anterior-posterior mobility. The boot of the hockey skate is cut high above the medial malleolus, providing medial and lateral support to the ankle when turning, but to a variable degree restricts plantar flexion and dorsi flexion during push-off, depending in part on the extent of lacing tightness and eyelet height.

When reverse engineering the hockey skate, Pearsall (2004) recognized that considerable force must be applied over a sufficient area in the skate's boot wall and insole to generate propulsion while maintaining optimal stability. Pearsall (2004) suggested that several factors should be considered in skate construction to obtain the most advantageous function of the hockey skate, including a kinaesthetic sense of joint position and limb orientation, accommodation for geometric anthropometrics and dynamic changes of the foot and ankle structures, and provision for effective anterior-posterior and medial-lateral alignment. Turcotte et al. (2001) have shown the validity of a system for the measurement of stiffness properties of ice hockey skates, an aid to manufacturers in evaluating the effects of specific designs, constructions, and materials on the mechanical responses of skate boots to various stresses. While the hockey skate still requires performance and comfort improvements, tools such as electrogoniometers, pressure sensors, and EMG sensors are now available to provide a framework for systematic evaluation of products regarding mechanical theories and skate function (Pearsall, 2004). Thus, manipulation of skate design characteristics is a possible avenue for the modification of a skate's functional characteristics.

Recently, a study by Federolf et al. (2008) investigated ice frictional properties of three types of flared ice hockey blades as compared to the frictional properties of standard ice hockey blades. Friction coefficients were determined by measurement of the deceleration from 1.8 m/s of a 53kg aluminum test sled equipped with blades angled at 4°, 6°, and 8°. Blade angles decreased ice friction by 13, 21, and 22% respectively when compared to standard ice hockey blades. This study illustrates that still, significant improvements in skate boot and components are possible, and that scientific studies investigating the relationship of each subsystem can yet improve skating performance.

2.6 Kinematics

Kinematics, a branch of mechanics, is the study and description of both linear and angular movements of anatomical landmarks or rigid body segments from a spatial and temporal perspective without reference to the forces which created the motions (Robertson and Caldwell, 2004; Winter, 2005). Kinematic analyses can be used to determine gait abnormalities, muscular dystrophies, as well as defining factors in sports performance. The following section will outline some of the developments leading to the current methods of capturing kinematic information.

All kinematic displacements and rotational variables are vectors, but in any direction or rotation, are considered as scalar signals and can be processed as such. Kinematic variables can be analysed in two co-ordinate systems; absolute or relative. An absolute co-ordinate system means that the coordinates of anatomical landmarks are referred to an external spatial reference system, while the relative system means that all coordinates are reported relative to an anatomical coordinate system. Basic kinematics are taught in 2-D in one plane, while in three-dimensional analyses an additional vector is added so as to have three planes to analyze (Winter, 2005).

2.6.1 History of kinematics

Interest in the movement patterns by both humans and animals goes back to prehistoric times; depictions of movements were created in cave drawings, statues, and paintings (Winter, 2005). It was not until the 1800s when the first motion picture cameras recorded locomotion patterns. By the late 1800s, Braun and Fisher recognized that the measurement of individual joint angles, as well as the displacements of limb segments and whole body mass are essential measurement when describing the kinematics of the human body (Sutherland, 2002). Using a clever approach, Braun and Fisher applied Geissler (glow) tubes to limb segments and interrupted the illumination process at regular intervals. The subjects were photographed walking in total darkness with four cameras, one in front of the subject, one behind, and one on each side, allowing for tri-dimensional measurements. Data collection required 8-10 hours per subject, while data reduction and kinematic calculations took months, rendering the process near obsolete (Sutherland, 2002).

In 1885, Marey, a French physiologist, used a photographic gun to record displacements in human gait analysis, using chronographic equipment to get a stick diagram of a runner. About the same time, Muybridge triggered 24 cameras to photograph at the same time to record the patterns of a running man (Winter, 2005).

In the 1940s Eberhardt and Inman expanded upon the idea presented by Braun and Fisher, again using an interrupted light. The researchers attached a small light to the subject's hip, knee, ankle, and foot. Photographs could be used to connect images captured at equal time intervals, but like the method used by Braun and Fisher, this method was very labour intensive in data collection and processing. Later, Inman replaced the lights with pins drilled into a subject's pelvis, femur, and tibia to record lower body movement. Needless to say, this method did not gain a large following as it was extremely painful for the subjects (Sutherland, 2002).

Later, in the 1960s, Murray pioneered the use of reflective markers in the measurement of kinematic variables. By attaching reflective markers to specific anatomical landmarks, Murray was able to photograph subjects in the illumination of a strobe light. These methods are similar to those currently used today by motion capture systems such as Vicon® (Sutherland, 2002).

2.6.2 Electrogoniometers

A goniometer is defined as a device that can measure angles, originating from the Greek words gonia meaning angle and metron meaning measure (Ouckama, 2002). There are many forms of goniometers, from basic protractors to sophisticated electrogoniometers, also referred to as 'elgons' (Ouckama, 2007). Electrogoniometers are advantageous when compared to manual goniometers because they can measure in both spatial and temporal domains, and are often used in kinematic analyses of human movement for several reasons; small dimensions, light weight, simple calibration and use, high sampling rate, and insensitivity to external factors such as light, temperature, and noise (Boocock et al., 1994; Legani et al., 2000).

There are two types of widely used electrogoniometers, planar electrogoniometers which measure angular movements in a single axis, and biplanar electrogoniometers, which measure angular movements in two orthogonal axes. Both of these types of goniometers consist of two bases which must be fixed to rigid bodies and a measuring cable. This measuring cable must be rigidly fixed to one end block, while the other is connected by means of a sliding device, allowing for translation of the spring within the block to adapt for changes if length of the block occurs during movement (Boocock et al., 1994; Legani et al., 2000; Ouckama, 2007).

The measuring cable for the planar electrogoniometer consists of a core made of a thin sheet of an isotropic material, while two strain gauges lie on the opposite faces of the sheet constituting two branches of a Wheatstone bridge. The biplanar electrogoniometer's measuring cable consists of a cylindrical core made of an isotropic material, with four strain gauges fixed to the external surface of the cable along the cylinder. Each pair of opposing strain gauges constitutes two branches of a Wheatstone bridge (Legani et al., 2000).

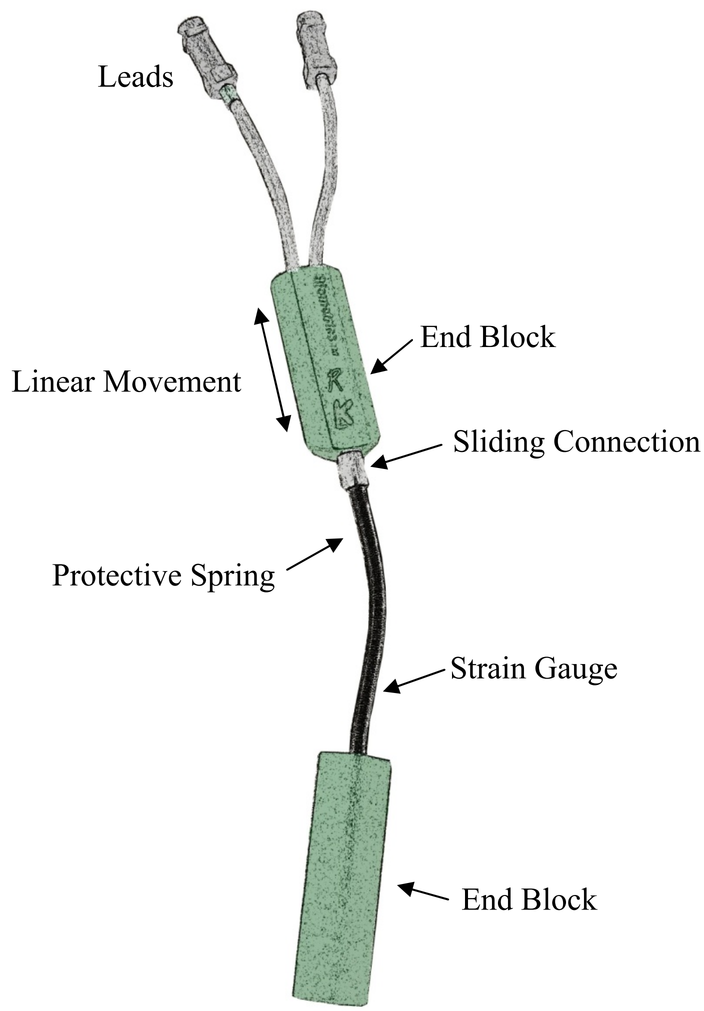

Figure 10 – Electrogonimeter (adapted from Goniometer and Torsinometer operating manual, 2002).

These types of electrogoniometers must be calibrated to a 'zero' reference frame from which all subsequent data will be evaluated. Mechanically, the reference frame means that the two opposing strain gauges will be parallel to one another, and that the measuring cable will follow a straight path from one end block to the other. As well, when collecting kinematic data with electrogoniometers the measuring cable must not be twisted, which likely will cause faulty distance measurements between the two pairs of gauges, resulting in incorrect angle measurements (Legani et al., 2000).

Ouckama (2007) found that electrogoniometers have a significantly high correlation ($r^2 = 0.78\text{-}0.97$) ($p \leq 0.0001$) to optical tracking systems at the ankle joint complex when mounted vertically along the posterior of the subjects' ankle when walking and running. Using the biplanar electrogoniometers as those explained above, Ouckama (2007) found that the root mean squared error (RMSE) was below the manufacturer's stated error of ±2° within the specified context of walking and running, and had a relatively small degree of error (<2.5°) at walking speeds. These goniometers have limited cross talk. If the goniometer is moved through 60° from the neutral position in one plane without movement in the orthogonal plane, then the sensor output in the orthogonal plane may change by a maximum of ±5° (Biometrics Ltd, 2002).

2.7 Kinetics

Kinetics refers to the general term given to forces, both internal and external, which cause movement (Winter, 2005). Internal forces come from muscular activity, tendons, and/or friction within muscles or joints, while external forces come from the ground or external loads, from active bodies such as the forces exerted by a tackler in football, or passive sources such as wind resistance. Kinetic analyses also incorporate the moments of force produced by muscles crossing a joint, the mechanical power both to and from the active muscles, and the energy changes caused by the muscular activity. Akin to kinematics, kinetics analyses can be performed in 2D or 3D (Winter, 2005).

2.7.1 History of kinetics

Newton stated "for every force applied there is an equal and opposite reaction" (Sutherland, 2005). Even early man understood this, making deductions about the movements of animals or humans from their paw or foot prints, they could determine the identity of animals or humans based on the shape, depth, alignment, and spacing of the prints (Sutherland, 2005).

Essential to understanding gait, in the search for a means to scientifically record the magnitude of heel/foot contact began when Carlet developed a system reliant on air reservoirs to measure the force applied to the heel and forefoot in the 19^{th} century. Although this system was limited to a one-dimensional analysis, Carlet was able to produce an "m" shaped curve with a fair resemblance to the vertical force pattern produced by a modern force plate (Sutherland, 2005). From this work, Demeny and Marey went on to produce the world's first force plate, which measured the vertical component of the ground reaction using a pneumatic system similar to the in-shoe air compressive system developed by Carlet (Sutherland, 2005).

Elftman pioneered measuring forces in more than one plane, describing a force plate system that could determine forces in three directions, using calibrated springs to measure ground reaction forces and separate them into components. Despite lacking in sophistication, the system described by Elftman was highly creative. It was not until Cunningham and Brown in the early 1950s that the force plate developed features that lend themselves to clinical use, in which they developed a platform that would divide the ground reaction forces into four components using strain gauge technology (Sutherland, 2005). The first commercially available force platform was developed by Wartenweiler and Sonderegger in 1969, building a force plate and charge amplifiers for the biomechanics laboratory of the ETH in Zurich, Switzerland for gait analysis of humans and animals (Nigg and Herzog, 1999). The currently commercially available and widely used force platforms are based on this system, now incorporating technologies such as piezoelectric and piezoeresistive crystals, and strain gauges (Nigg and Herzog, 1999; Sutherland, 2003; Winter, 2005).

2.7.2 Force transducer technologies

A suitable force measuring device, called a force transducer, is required to measure the force exerted by an external load (Winter, 2005), the most common of which is the force plate. The two most commonly used force plate sensors are strain gauge and piezoelectric, while piezoresistive, capacitive, air balloon, and spring transducers are also available (Nigg and Herzog, 1999; Winter, 2005). These force transducers function on the principle that a change in electrical signal is proportional to the applied force (Winter, 2005).

Strain gauge systems function due to a calibrated metal plate or beam within the transducer. When this beam undergoes a very small change in one of its dimensions, the mechanical deflection causes a change in resistances of the strain gauges connected to a bridge circuit. The resulting change in voltage is proportional to the applied force (Murray, 1992; Window, 1992; Winter, 2005). Strain gauge transducers may also easily, although painfully, be placed on human or animal bone or tendons, allowing for in-vivo force measurements (Nigg and Herzog, 1999). The same concept can apply to external surfaces, such as a skate blade holder's beam and post elements, or in measurement of other material deformations such as ski deflection, as Yoneyama (2008) showed.

Piezoelectric and piezoresistive force plates, on the other hand, require minute deformations of an atomic structure within a block of specialized crystals (Winter, 2005). For example, Quartz is a naturally found piezoelectrical material; deformations of its crystalline structure cause changes to its electrical properties such that the electrical charge across the surface of the block is altered and can be calibrated via suitable electronic devices to a signal proportional to an applied force (Nigg and Herzog, 1999; Winter, 2005).

2.8 Ground reaction force profiles of other exercise paradigms

While the kinetic profile of ice skating remains fairly obscure (de Boer et al., 1987; de Koning et al., 1992; Gagnon et al., 1983; Jobse et al., 1990; Lamontagne et al., 1983), kinetic evaluations of other locomotive paradigms, such as walking and running, have been extensively examined, largely due to simple data collection processes and advanced technologies such as force plates. Kinetic profiles of walking, running, and elliptical ergometer training will be discussed, and later used as comparative information when interpreting the kinetic profile ice hockey skating.

2.8.1 Walking

A number of clinical centers use information gathered from quantitative gait analyses in the evaluation and treatment of gait abnormalities (Rose and Gamble, 2006). For the purposes of this review, only ground reaction forces (GRF) of normal gait patterns will be examined. The GRF vector during walking has three components; vertical, anterior-posterior, and medial-lateral (Rose and Gamble, 2006; Winter, 2005).

Like skating, normal gait patterns are characterized by bimodal periods of single and double support. Vertical GRF show a cursive 'm' shaped curve during normal heel-toe contact patterns when walking (Sutherland, 2005), which can be seen in Figures 11 and 12g. When in double support, following initial heel contact, vertical GRF rapidly increases in magnitude as the external load is transferred from one limb to the other. Following this is a period of single support, in which the contralateral limb is in swing phase. The GRF during single support oscillates above and below the subjects' weight, due to the upward and downward acceleration of the body center of mass (COM). During the first part of single support, the COM translates from lowest to highest elevation; this upward acceleration coincides with a vertical GRF which is higher than body weight; the push-off. Subsequently, the upward velocity of the COM begins to decrease, resulting in a vertical GRF that is less than one body weight, followed by toe-off (Rose and Gamble, 2006).

In addition to these vertical GRF's, friction between the foot and ground produce anterior-posterior GRF's. During the initial heel strike, the ground pushes backward on the lower limb, essentially a braking action, which decelerates the body and controls forward movement. During mid-stance, relatively small force values reflect limited forward-backward accelerations of the body. During the second double support, muscular force propels the body forwards, accelerating the limb into swing (Rose and Gamble, 2006).

The third component, medial-lateral force, increases at heel strike to remain at a relatively constant value for single support, producing a small medial acceleration throughout the gait cycle (Rose and Gamble, 2006).

2.8.2 Running

While walking mechanics are characterized by a classic double peak formation, running GRF's are characterized by a slight peak formation during the initial loading phase followed by single large peak during push-off, located at about 40-50% of the total stance time (Keller et al., 1996; Munro et al., 1987). Average forces have been found to be upwards of 2.5 times body weight (Keller et al., 1996). Like walking, running mechanics consist of three distinct GRF vectors (Munro et al., 1987).

During running at speeds between 4 and 5 m/s vertical GRF patterns are characteristic of a limited heel-strike, followed by a relative minimum force and a subsequent rise to peak, described as the thrust maximum (Keller et al., 1996; Munro et al., 1987).

Anterior-posterior GRF patterns, also considered breaking forces, peak at approximately 25% of the total stance time, characterized by a heel strike (Munro et al., 1987). This breaking pattern is not as evident in higher speeds (Keller et al., 1996). Like walking, medial-lateral GRF patterns are minimal throughout the contact phase (Munro et al., 1987).

GRF patterns as a function of running speed as found by Keller et al. (1996) can be seen in Figure 11. In this study, 13 male subjects exhibited a double peak pattern below 2.5 m/s. At these speeds the thrust maximum was generally the first peak, occurring between 15 and 25% of the total stance time. At higher speeds the GRF patterns consisted of a single peak, averaging between 1.3 and 2.5 times body weight, with loading rates increasing from 8 to 29 body weights per second at speeds ranging from 1.5 to 6 m/s.

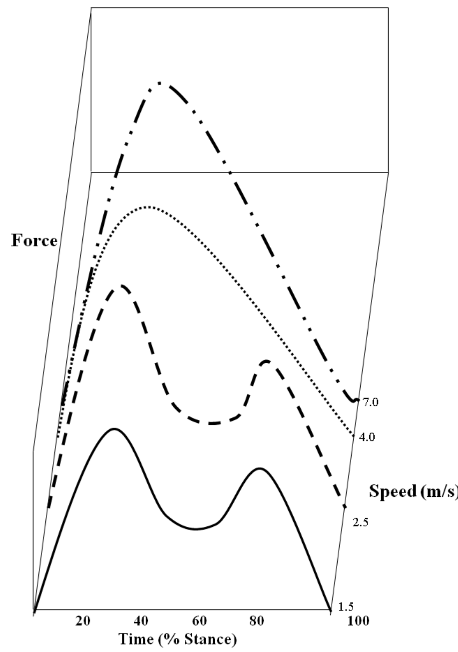

Figure 11 – GRF-time patterns when transitioning from walking to running (adapted from Keller et al., 1996).

2.8.3 Elliptical ergometer

Elliptical ergometers (EE) have become an increasingly popular exercise modality, whose GRF's have recently been documented by Lu et al. (2007) and Chien et al. (2007). The anterior-posterior GRF component during EE exercise is similar to those when walking; however the other two components are different. In walking, GRF is present throughout only the stance phase, whereas during EE the GRF is present during the entire cycle. Unlike both running and walking, when performing EE exercise a single peak is found in the vertical and medial-lateral orientations, total forces ranging up to 1 body weight. Compared with walking, these values along with loading patterns show EE to be a method of exercise more forgiving on joint loading due to significantly smaller maximum loading rates than both walking and running, while still providing an exercise which improves physiological parameters (Chien et al., 2007; Lu et al., 2007). Comparative EE and walking GRF's can be seen in Figure 12.

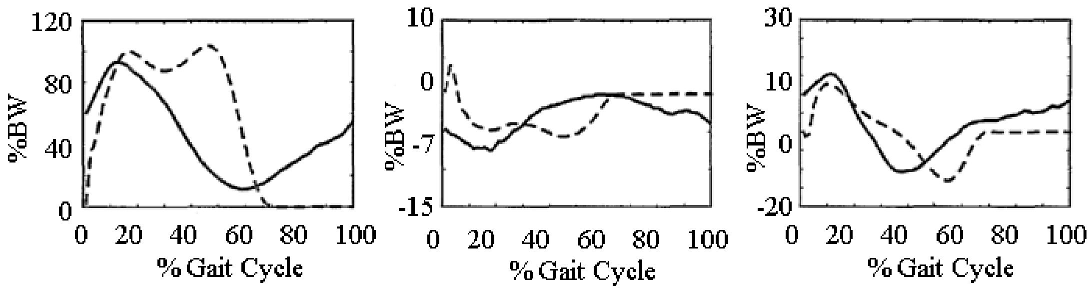

Figure 12 – GRF profiles for walking (dashed line) and EE (solid line) (adapted from Lu et al., 2007)

CHAPTER 3 - FORCE TRANSDUCER SYSTEM FOR MEASUREMENT OF ICE HOCKEY SKATING FORCE

3.1 Abstract

Given the technical challenges of measuring force during ice skating, not much is known of the dynamics involved with this unique form of locomotion. Hence, the purpose of this study was to develop a portable force measurement system. Specifically, this system consisted of three strain gauge pairs affixed to an ice hockey skate's blade holder with wire leads connected to a microprocessor controlled data acquisition device carried in a backpack worn by the skater. The configuration of the strain gauges simultaneously determined the vertical and medial-lateral force components experienced by the blade holder, up to a theoretical maximum of 7440 N, with a resolution accuracy of 1.9 N and an RMS error of ± 68 N (coefficient of variation = 9.2%). On-ice testing of this system with subjects performing forward start, acceleration, and constant velocity skating permitted unencumbered, natural movement and demonstrated clear, unambiguous signal responses, high trial-to-trial repeatability, and easy data retrieval. The practicality and accuracy of this testing approach has many applications, such as a quantitative tool for skating power assessment to aid athletes and coaches, as well as providing the means to examine other skill specific dynamics such as stops, pivot, etc., and the effect of ice conditions on blade thrust and glide friction.

3.2 Introduction

Research investigating the mechanics of ice skating have focused primarily on the kinematic variables most influential in successful skating performance (de Koning et al., 1995; Lafontaine, 2007; Marino, 1977; Marino, 1979; Marino, 1983; Marino and Weese, 1979; Upjohn, 2008) and mainly has been restricted to forward skating. The combined measurement of kinetic parameters together with joint and segment kinematics would provide for the best understanding of the biomechanics of ice skating. However, due to the nature of the environment and other technical obstacles, the measurement of force during ice skating has not often been attempted. Thus the challenge is to develop a suitable and accurate approach to measure the force between the ice and skater in-situ.

One method used in speed skating to measure force on an ice surface is with the use of strain gauge transducers. Several studies investigating the kinetics of skating have used temperature compensated strain gauges as force transducers attached to an interconnected block assembly between the shoe and the blade of speed skates (de Boer et al., 1987; de Koning, 1992; Jobse, 1990). These studies have primarily investigated ice frictional properties during speed skating, but demonstrated strain gauge transducers to be an effective tool in determining on-ice skating forces. However, given the orientation of the transducers, these studies were unable to measure medial-lateral forces. Further limitations included the small sample sizes assessed and disruption of original skate construction. Finally, the sensor fragility and limited capacity to record and display force information excluded this approach as a practical tool for wider public use.

Sim and Chao (1978) measured vertical reaction forces during push-off using a force plate. The experiment, conducted on two subjects, was performed by placing the subject with their thrusting leg on a force plate; the driving leg wore a regular hockey skate with the blade covered by a rubber protector to gain additional friction. The forward leg wore a roller skate to mimic on-ice mechanics as closely as possible. Vertical reaction forces were measured between 1.5 and 2.5 times the player's body weight, the posterior push-off force was approximately 688 N, and the lateral force was approximately 353 N depending on the skating style of the subject (Sim and Chao, 1978). Though this study provided insights into the kinetics of ice-hockey skating, information on true on-ice dynamics were not available until Gagnon, Lamontagne, and Doré attempted to derive on-ice forces via strain gauge technology.

The group of Lamontagne, Gagnon, and Doré completed the only known studies attempting to directly determine forces on-ice specifically for ice hockey skating (Gagnon, 1983; Lamontagne, 1983). In addition to sophisticated 3D measures to determine skate orientation, strain gauge transducers were attached to the blade to determine forces while performing a parallel stop. Three pairs of gauges were used to measure forces in the vertical, horizontal (parallel to blade orientation) and lateral directions. Two subjects were tested, demonstrating peak forces upwards of 900 N; however modifications were required to the skate blade to increase signal strength, thus facilitating data collection. Though the study showed the feasibility of accurately collecting force measures on ice, similar to the prior speed skating studies, practical application has not been possible until electrical components to power, condition, and record these signals became smaller and more durable for portable use. Technological developments in electronic components have since been realized. Thus, the aim of this study was to build an accurate and practical instrumented system to enable the measurement of forces during ice hockey skating while maintaining the integrity of the hockey skate.

3.3 Methods

3.3.1 Apparatus

The instrumentation system consisted of three main components: a hockey skate with strain gauges bonded to the blade holder, a portable data acquisition system, and post-processing of data to convert microstrain signals to force estimates. The following sections provide more specific details on these components.

3.3.1.1 Instrumented hockey skate

To determine the vertical and medial-lateral forces exerted on the ice hockey skate (right side only; model Nike-Bauer Supreme One95), 0.125” (0.3175 cm) strain gauges (350 Ω, Vishay, Malvern, PA, USA) were adhered to the skate blade holder at specific locations (Figure 13). The recorded signals indicated the compressive or tensile deformation of the skate blade holder between the skate boot and skate blade (Figure 14). Half-active Wheatstone bridge circuits were used to convert the resistances provided by the strain gauges into voltage signals, which corresponded to microstrains. One gauge was used to measure the vertical strain (V), and was oriented along the longitudinal axis (transverse plane) of the blade holder’s beam element. The V gauge was referenced to a static gauge, essentially making the V gauge a quarter-active Wheatstone bridge. Two pairs of gauges (Anterior Medial-Lateral, AML, and Posterior Medial-Lateral, PML) were used to measure medial-lateral strain and were oriented parallel to the vertical axis of the blade holder along the front and back posts. These gauges were referenced to their corresponding partner on the opposite side of the blade holder, and in effect measured the strain difference on the medial and lateral posts' walls due to torsion in the blade holder. The wires were glued to the outer surface of the blade holder, and were directed towards the back of the skate. Sufficient length and slack remained to extend the bundled wires upwards to connect with the bridge connections and data acquisition device housed within the backpack worn by the subject (< 1 kg).

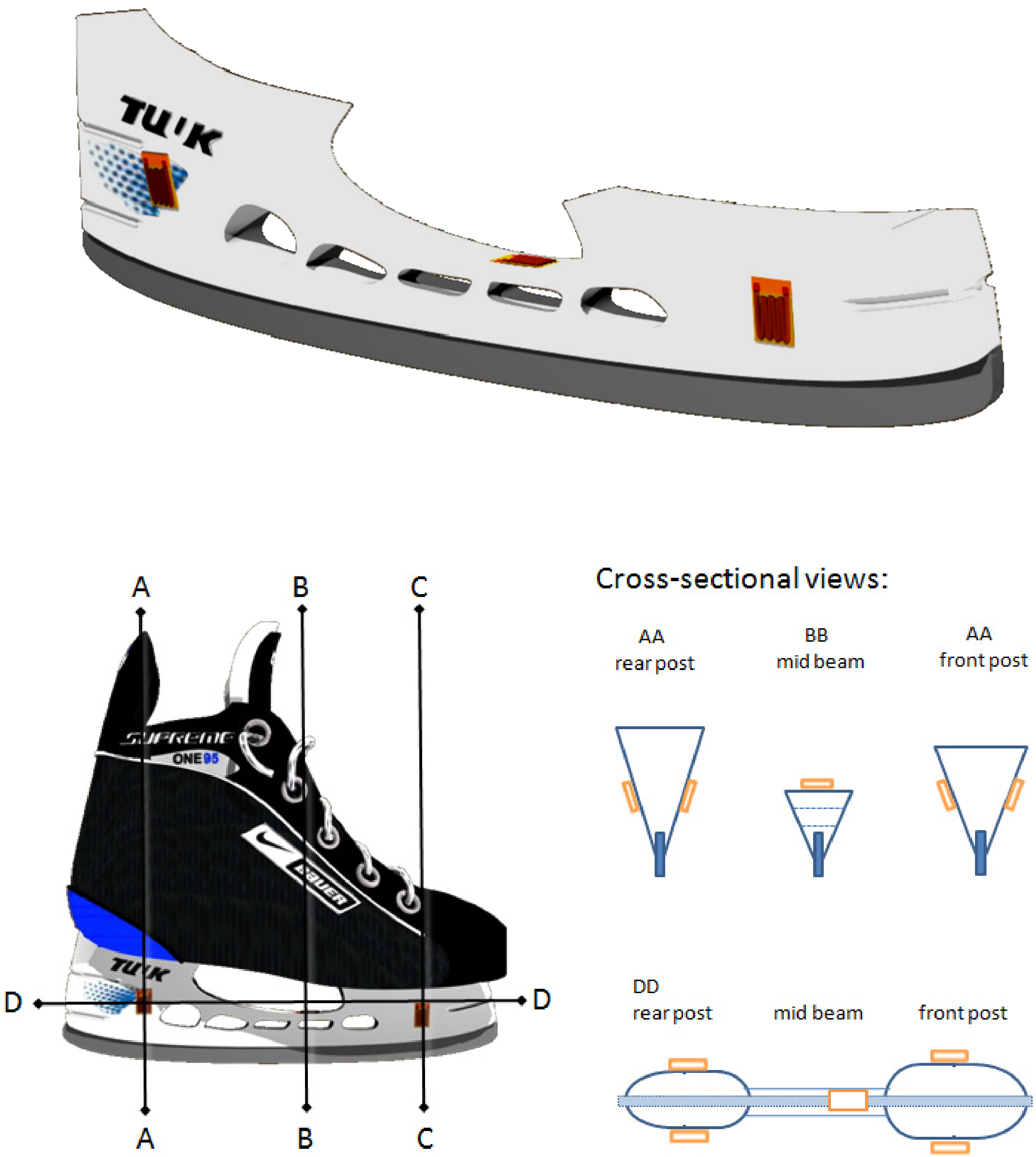

Figure 13 – Representation of instrumented skate blade holder (top), and cross-sectional views of gauge locations (bottom). Gauges AML and PML are oriented vertically along each post, while gauge V is oriented longitudinally along the beam element of the blade holder.

Figure 14 – Exaggeration of deformation caused by vertical loading (left) and deformation caused by lateral loading (right).

3.3.1.2 Measurement system

A portable 13 bit analog to digital converter (DataLOG model P3X8, Biometrics Ltd., Gwent, UK) was used to both power the three bridge circuits and record their signal during testing (Figure 15). A 2V ± 2% excitation voltage was supplied to the strain gauges. The DataLOG's microprocessor controlled digital acquisition unit stored data files to a Multi Media Card (MMC) flash memory card onboard the DataLOG in a proprietary .RWX format. The DataLOG's measurement scale was set to 10mV with a resolution of 0.0025mV. All signals were collected at a 100Hz frequency.

3.3.1.3 Post-processing software

DataLOG software (v.3.0; Biometrics Ltd., Gwent, UK) was used to import the .RWX files and save them as binary .LOG files. All subsequent processing was performed using customized Matlab® (R200b, MathWorks, Inc. Natick, MA, USA) routines. These functions incorporated a 4th order Butterworth filter with a 14Hz cut-off frequency. All statistical correlations were performed in Matlab®.

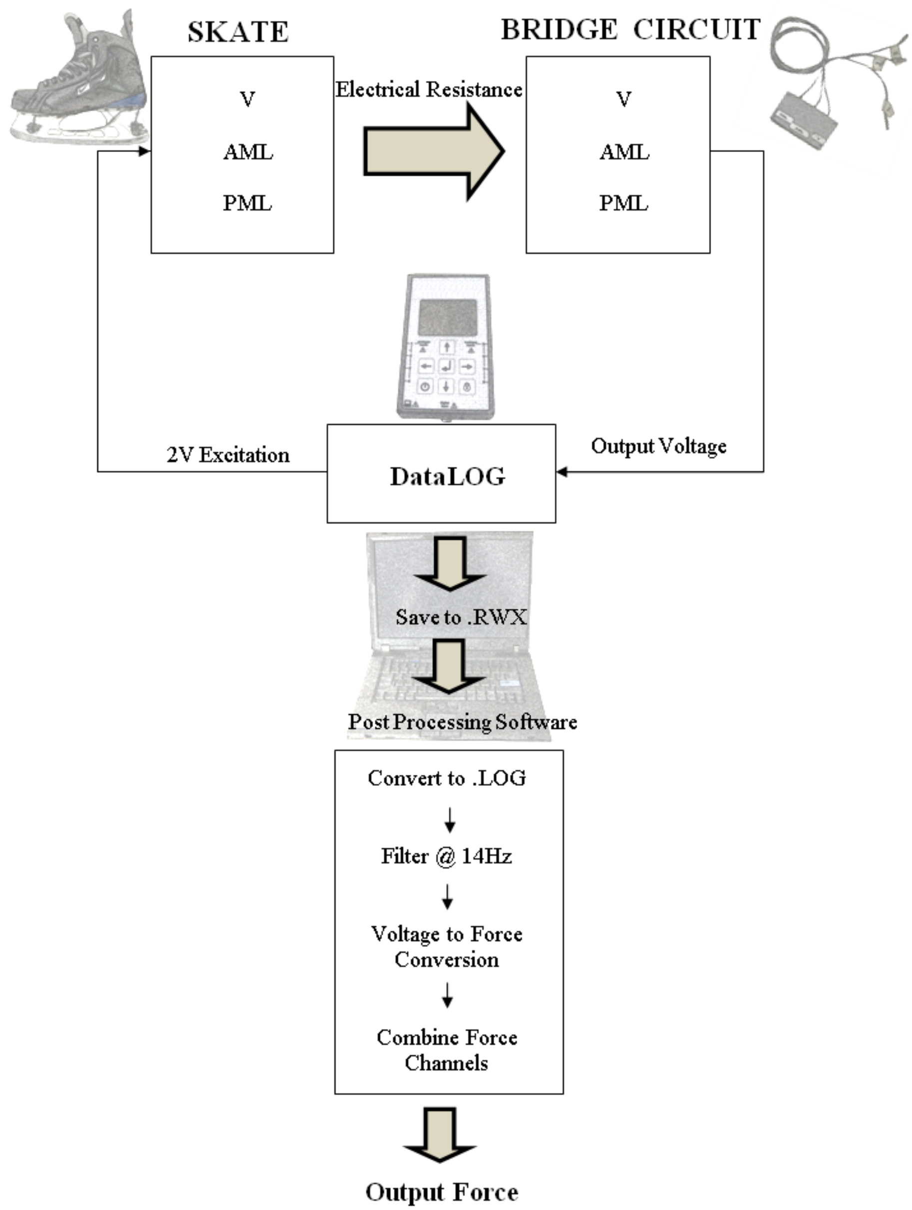

Figure 15 – Data acquisition and processing sequence.

3.3.2 Validation of force transducer system

Strain gauges, when bonded to linearly elastic materials, have been shown to be valid sensors to estimate (or "transduce") forces (Winter, 2005); however, each placement of gauges required custom calibration against a known reference for it to be an accurate means of determining force estimates. Given the complex geometric configuration of the Nylon 6 blade holder as well as varied junctions with different materials (i.e. metal blade below, thermo set epoxy with carbon fibre reinforcement foot plate above), an extensive dynamic validation process was conducted of both the vertical and medial-lateral strain to force relationships by loading in two orthogonal directions (vertical and medial-lateral) against a force plate (AMTI, model OR-6).

Vertical force calibration was performed by having a subject wearing an instrumented hockey skate step onto the force plate with varied loads and rates (Figure 16). Simultaneous force and strain data were recorded. Three vertical loading rates were assessed: 280 N/s, 850 N/s, and 3000 N/s, with 30 separate trials of loads ranging from 0 to 850 N (the equivalent of one body weight). These trial conditions were chosen to identify the dynamic behaviour of the strain gauge system so as to determine both magnitude (force) and temporal accuracy. Synchronization of the signals was performed manually based on predetermined criteria; force reading above 15N, voltage signal above 0.1 mV. These values were chosen based on inspection of the system's responsiveness to increasing loads (i.e. sufficient signal strength at loads of 15N or greater and voltages of 0.1mV or greater).

Figure 16 – Vertical validation viewed from side. The red arrow represents uniform loading throughout the skate, while the blue arrow represents the reaction strain signal.

The testing of strain gauge response to forces in the medial-lateral plane was performed by placing the skate blade longitudinally along the force plate with the medial side of the skate facing downwards, followed by downward loads ranging from 0 to 400 N (approximately one half body weight; Figure 17). The lateral loading was performed similarly by reversing the skate orientation such that the lateral side of the skate was facing downwards.

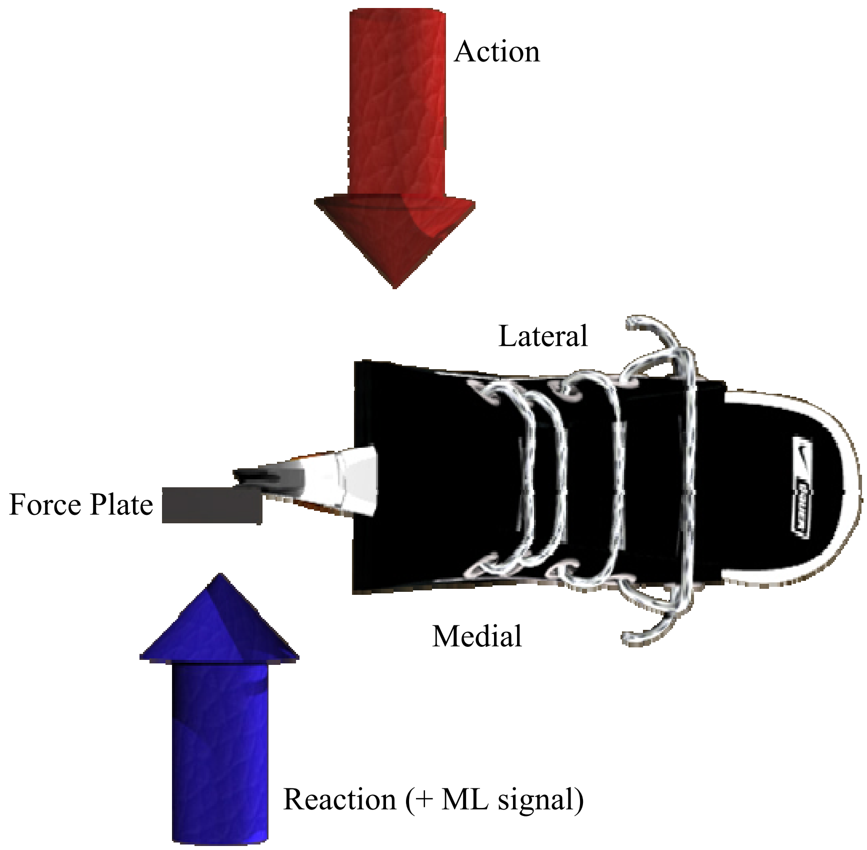

Figure 17 – Medial validation viewed from front. The red arrow represents uniform loading, while the blue arrow represents the reaction force produced by the force plate.

From these tests, linear regression functions were derived using the strain gauge measures as the dependent variables to predict V and ML forces. To express the accuracy for the measurement technique, statistical comparisons between strain and force measures involved calculation of RMS errors, coefficient of variation (COV), as well as Pearson product correlation coefficients for all loading directions.

Finally, to demonstrate the practical feasibility of using the above system in the cold environment of an ice arena, an experienced skater performed several trials of forward skating on ice. To permit natural and unencumbered movement of the skater, the wire bundle was given sufficient slack and secured with tape at a few locations along its path to avoid unwanted sway or entanglement. To account for possible signal response variation due to temperature, V and ML measures were collected both at two ambient air temperatures; in the locker room (18 °C) during subject preparation and on the ice rink (5 °C) after a 10 minute interval for acclimatization. After general skating manoeuvres to warm up, the subject was asked to perform a forward skating start, accelerate and then hold maximal speed from near goal line to far blue line (~35 m). Several trials were collected with continuous data recorded at 100 Hz. Subsequently, these data were segmented to evaluate the consistency of step-to-step dynamics patterns. The skater carried a hockey stick to mimic in-game skating patterns as closely as possible.

Due to the varying responsiveness of the strain gauges and the Nylon 6 plastic materials of the skate blade holder in cold climate situations, a temperature compensation of the system is required for on-ice testing. It was determined that by performing the same calibration procedure on-ice (ambient temperature ~ 5°C) as in-lab (18 to 22 °C), a compensation factor for on-ice estimates of 1.2 was required (i.e. force estimates were increased by a factor of 1.2 to maintain on-ice accuracy).

3.4 RESULTS

The vertical loading tests yielded correlations of the voltage reading (strain gauge) to force (measured on the force plate) for slow, medium and fast loading rates ranging from r = 0.94 to 0.99 (Figure 18). RMS error was ± 68 N (COV = 9.2). Vertical loadings showed a negligible (less than 40 N) response in the medial-lateral gauges (i.e. minimal false or cross-talk signals). The vertical loading conditions were ± 5° from vertical; if the skate is not perfectly vertical some ML force may be induced which would increase RMS error and COV values. Correlations for medial loading tests ranged from r = 0.98 to 0.99 and from r = 0.98 to 0.99 and correlations ranging from r = 0.95 to 0.99 and r = 0.96 to

0.99 in the lateral orientation for AML and PML gauges respectively (Figure 19; 20). RMS error was ± 39.5 N for ML signals (COV = 10.0). ML loading tests showed a small response in the vertical gauge (less than 40 N).

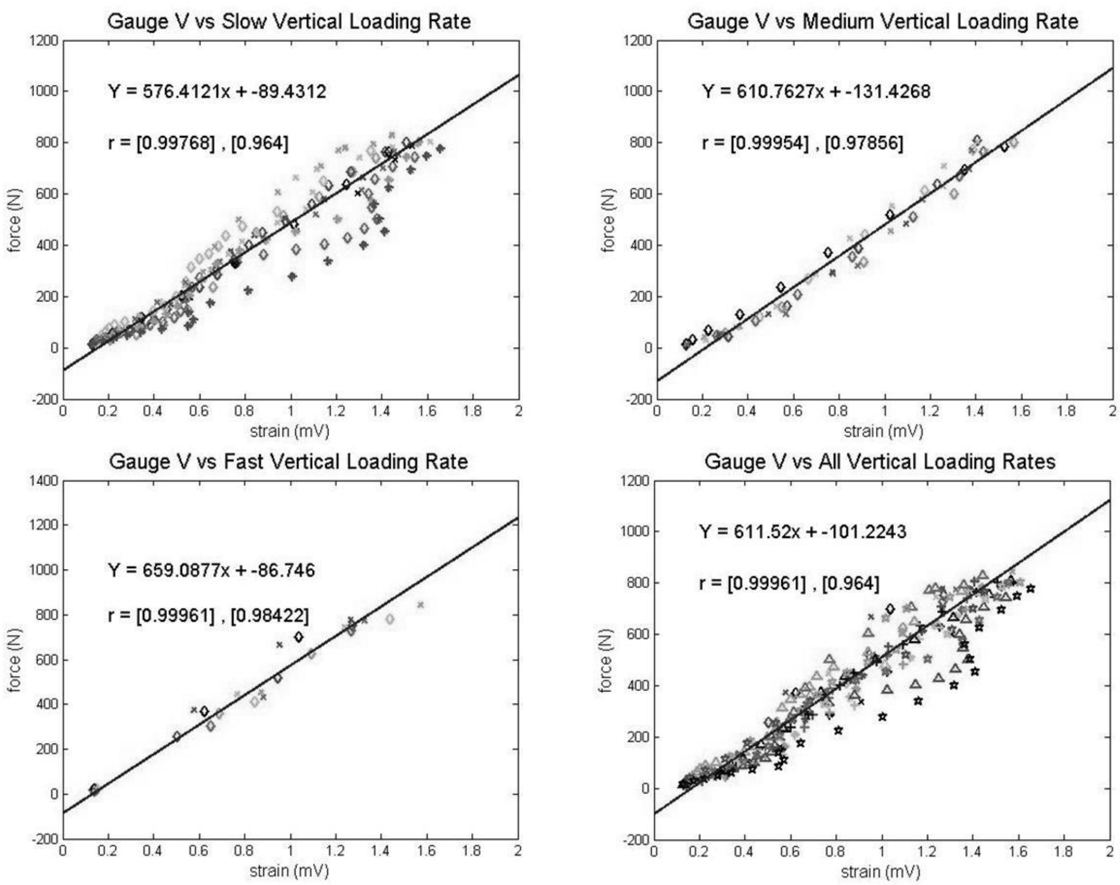

Figure 18 – (1) Gauge V versus slow vertical loading rate, (2) Gauge V versus medium vertical loading rate, (3) Gauge V versus fast vertical loading rate, and (4) Gauge V versus all vertical loading rates.

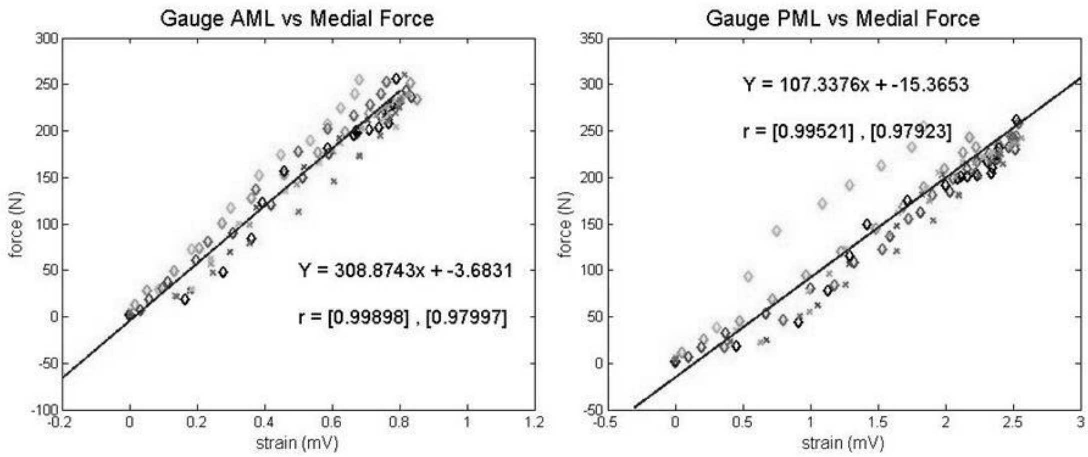

Figure 19 – (1) Gauge AML versus medial force, and (2) gauge PML versus medial force.

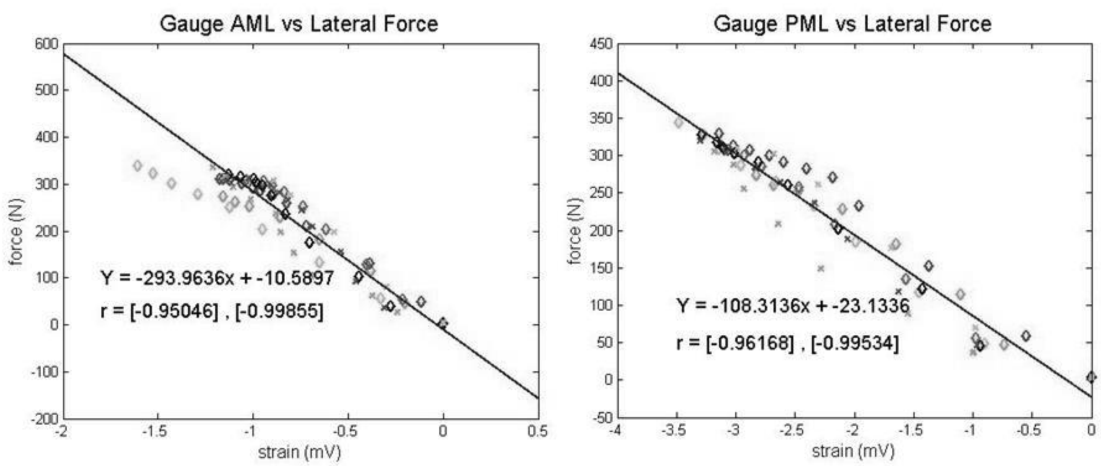

Figure 20 – (1) Gauge AML versus lateral force, and (2) gauge PML versus lateral force.

The strain gauge configuration was also found to be highly responsive when a subject shifted weight from a pure vertical load, to one comprising a medial or lateral component, and back again to a pure vertical load. In short, the current configuration of strain gauges can determine simultaneously and independently the vertical and/or medial-lateral force components experienced by the blade holder. While the results summarized above are for a single skate, a separate calibration is required for each instrumented hockey skate, as subtle differences in gauge location and orientation will affect force-strain relationships. As well, a temperature compensation of the strain gauges is required for on-ice testing.

In order to demonstrate the functional usefulness of the measurement system, a subject performed a forward skating task on ice with the right skate instrumented. During the skating task forces were measured for 6 consecutive strides. Total force values are represented by the averaged summation of the V and ML force readings (ML equals average of AML and PML force readings). Figure 21 shows force-time curves of the total force, as well as ML and V component forces for a representative skating trial on-ice of the right skate (note: for conceptual display the left skate forces were approximated by replicating the right skate's data, offset temporally by 50%). Descriptive parameters from these force-time patterns can be obtained; for examples, contact time (from initial contact to the end of final push-off), stride time (one full gait cycle), and force maximums (peaks). In this sample trial shown, clear dynamic differences are evident between step order, with a transition from short duration (0.31 s), single force peaks (200 % BW) in the 3^{rd} step to longer duration (0.38 s), and bimodal force peaks (120 and 180 % BW) by the 6^{th} step. This pattern was consistently recorded, with trial-to-trial coefficient of variation ranging between 3.9 and 12.5 for steps 2 through 6 in peak force and coefficient of variation ranging between 2.8 and 10.0 in contact time estimates for each respective step.

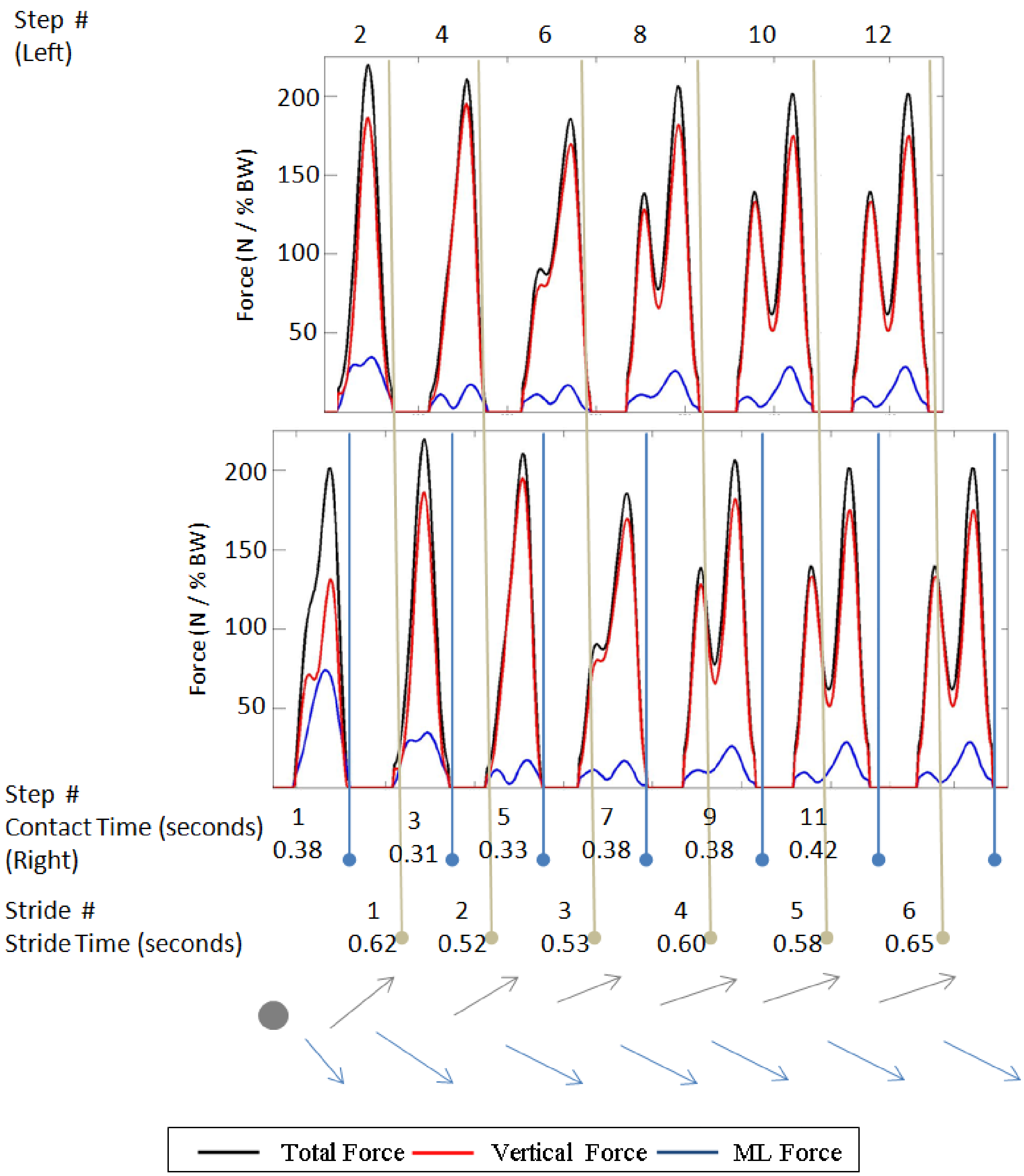

Figure 21 – Kinetics of a representative subject for the right and superimposed for the left skate, including contact time and stride time information. V force values are oriented along the frontal plane of the skate, while the ML forces are orthogonal to the V force. Short, single force peaks can be found in the initial steps, while a distinct bimodal force-time pattern can be seen in the latter steps.

3.5 Discussion

The aim of this study was to build an accurate and practical instrumented system to enable the measurement of forces during ice hockey skating. All validation results were consistent and reproducible. A high linear relationship of the force data obtained from the force plate and the voltage signals obtained from the strain gauge system showed that current configuration of strain gauge placement on the ice hockey skate blade holder accurately estimates ground reaction forces (r = 0.94 to 0.99). The recorded strain signals were independent of loading rate, as determined via trials of three distinct loading rates, which produced similar correlation and calibration equations. Based on the linear functions derived from the strain-force relationship, the strain signals can be used as dependent variables to estimate forces within an error of 10%. These resultant force magnitudes are calculated via the summation of V and ML signals, which may also be independently estimated. Minimal cross-talk or false signals between V and ML were found. Both component force estimates and resultant force estimates were shown to be sufficiently reliable.

Testing on-ice in the arena permitted for natural skating behaviour, rapid data collection, and meaningful force-time curves. Consistent force estimates were found trial-to-trial with an experienced ice hockey player (McGill University varsity at the time of testing) for several ice hockey strides (COV = 3.9 to 12.5).

The system's sensitivity is capable of discerning differences in voltages of 0.0025 mV, corresponding to 1.9 N up to a theoretical maximum load of 7440 N (Winter, 2005; Biometrics Ltd. DataLOG operating manual, 2004). Linear strain-force relationships were found in the medial-lateral orientations above 75 N, and above 300 N in the vertical orientation. Non-linear relationships may be more suitable to predict lower force values, particularly for slow loading rates (Figure 18). The current configuration of the strain gauges renders the system insensitive to loads produced through the extreme front or extreme back of the skate blade holder (i.e. when a subject stands on their toes). Based on the current set-up, the ML strain gauge pairs were referenced medial to lateral in a half-active Wheatstone bridge. Common vertical deformation signals were subtracted to yield only the ML deformation estimates. Adjustment of the strain gauge reference configurations to quarter-active bridges in future studies could yield anterior and posterior post vertical loads through post-processing techniques, while maintaining ML response. This configuration may also increase the systems signal reliability at given loads. This would be valuable information to determine in future studies, particularly in the examination of backwards skating, stopping, and turning manoeuvres.

It is important to recognize that the readings produced by the force transducer system are not ground/ice reaction forces, but rather are an estimation of the ground/ice reaction force based on the tensile strain at strategic locations on the skate blade holder. An exaggerated representation of these deformations occurring on the skate blade holder used to estimate force values can be seen in Figure 14. Because these forces are estimates based on the blade holder deformations it is difficult to obtain exact measures of force, thus a certain amount of error is inevitable.

Dynamic testing of the system was accomplished by having a subject skate forward on-ice from a standing start to maximum forward speed. In this experiment, evident differences in step mechanics are found, with a transition from short, single force peaks in the initial steps, evident of acceleration, to a distinct bimodal force-time pattern in the latter steps. The force-time curves of the first three steps show force-time patterns similar to those found when sprinting (Rose et al., 2006), which is consistent with a "running" motion observed during the first few steps in acceleration, wherein the athlete pushes off against a fixed point in the ice (de Koning et al., 1995; Lafontaine, 2007; Marino, 1983).

During stride four, the subject begins what can be considered a gliding push-off, and maintains that skating motion through stride six. The force patterns observed during the final strides during which constant velocity is achieved are similar to those presented in speed skating by de Koning et al. (1995) and Jobse et al. (1990). Vertical and total force values are in accordance with those found by Sim and Chao (1978).

This study has shown skating, already known to be a unique form of locomotion (Lafontaine, 2007), to have a distinct kinetic pattern at constant velocity, much like running, walking, and exercising on an elliptical trainer each have a distinct ground reaction force (GRF) pattern. Once constant velocity is reached, the subject initiates the previously mentioned bimodal skating pattern. Total GRF has an initial peak at approximately 15% of the stride, coinciding with initial blade-ice contact. Subsequently, a trough occurs, followed by a second peak. The second peak is caused by the intensive push-off of the ipsilateral limb. The trough in the middle of the two peaks of the force-time pattern is caused by the rigorous push-off of the contralateral limb, accelerating the body center of mass forward and upward, causing the total GRF of the ipsilateral limb to fall between 50 and 70% of body weight. The V GRF pattern closely follows the total GRF pattern, while the ML GRF pattern deviates from this mould. The ML GRF is relatively low during initial contact through contralateral push-off as the ipsilateral skate is gliding in a straight direction to guide the skater, thus not generating a ML force on the blade holder. Subsequently, as the ipsilateral limb externally rotates and extends through push-off, the skate boot collapses medially, generating a ML force acting on the blade holder.

Local forces with respect to the skates' local axis during push-off can be seen in Figure 22. From Upjohn et al. (2007) it is known that the skate is oriented approximately 30° from vertical during the push-off. Based on this, interpretation of the action-reaction force dynamics with respect to the skate can be assumed. The V reaction force is oriented along the frontal plane of the skate, approximately 30° from vertical, while the reaction ML force is oriented orthogonal to the V force, directed laterally with respect to the skate. The action force vectors can subsequently be described as the opposite of the reaction forces. From this, the resultant total force vector can be assumed to be approximately 8 to 14° back to vertical from the V reaction force, or approximately 16 to 22° off-center from vertical.

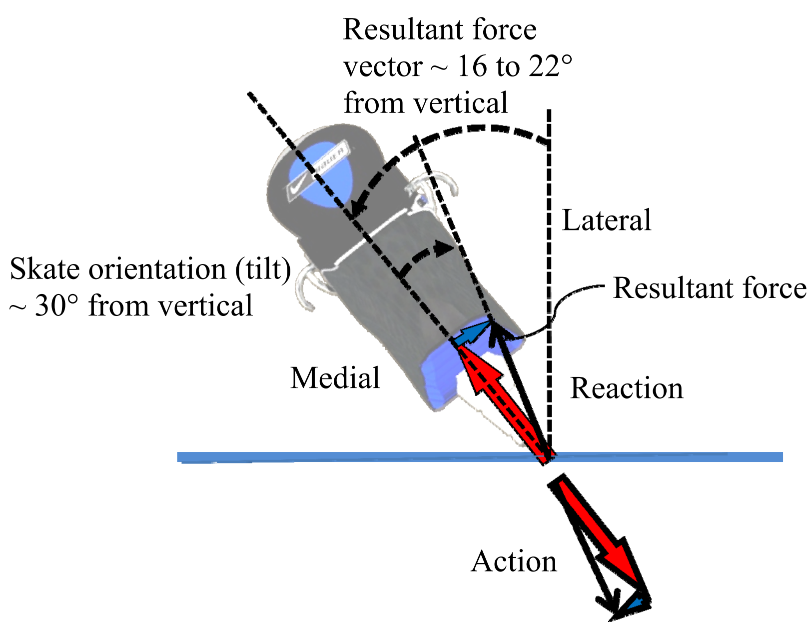

Figure 22 – Local forces with respect to the skate's local axis. Vertical forces are shown in red, while medial-lateral forces are shown in blue.

Based on studies by Dewan et al. (2004; 2004) and Upjohn et al. (2007) the orientation of the skate in the frontal plane along with approximate ankle joint eversion alignment during push-off are known. When combining the bone geometry and forces determined in the present study, the mechanics of the ankle joint complex during push-off are discernable. The resultant force vector off-center to the calcaneous creates a counter clockwise moment (as seen from the rear view of the right skate, red arrow in Figure 23), thus accentuating the eversion moment at the subtalar joint; an equal and opposite moment on the talus-tibia-fibula complex pivots these bones laterally, seen as orange arrow in Figure 23. This lateral movement in turn pushes the medial malleolus (distal tibia) into the medial wall of the upper boot collar as well as forces the lateral malleolus (distal fibula) into the lateral wall of the skate boot, both denoted by the red explosions in Figure 23. The pressure patterns within the skate boot while skating measured by Dewan (2004) are congruent with this scenario.

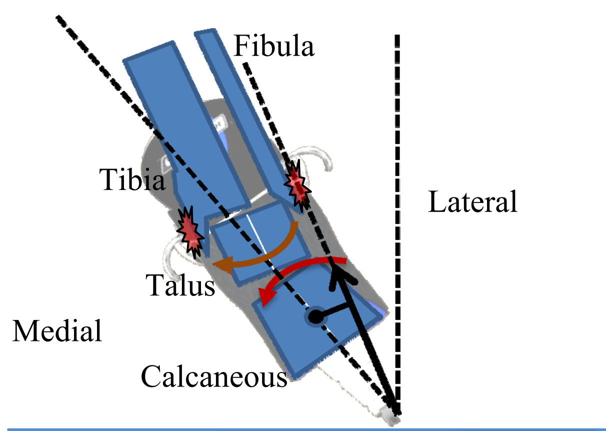

Figure 23 – Moments at the ankle joint complex when pushing-off.

Gagnon et al. (1983) and Lamontagne et al. (1983) have shown the feasibility of determining estimates of ground reaction forces through the use of strain gauge technologies adhered to the skate blade. Though these were innovative studies, because of the sensitivity of the gauges and minute deformations of the metal skate blade, modifications of the skate blade were required to ascertain sufficient strain readings. The system utilized by Gagnon et al. (1983) and Lamontagne et al. (1983) required holes of 1.3 and 1.5 cm^2 to be punctured into both the anterior and posterior columns of the blade holder, and sections of the front blade-boot connection had to be removed, thus allowing for increased deformations in the blade holder system resulting in sufficient signal strength. Through advancements in the technologies of plastic materials, the current system has been successfully used to determine V and ML force estimates without modification to the skate or any of its components (i.e. skate blade holder). Future developments of this system may allow for a technology which is transferable between skates without permanent adherence of the force transducer structure. Such a system would likely become a valuable coaching and training tool.

Wherein de Koning et al (1995), Jobse et al. (1990), Gagnon et al. (1983), and Lamontagne et al. (1983) have conceptually shown the feasibility of using strain gauge technology to estimate force profiles, with technological advances, particularly in strain gauge bonding adhesives, plastics, more robust electronics, as well as sufficiently small and portable data acquisition devices, the ability to discern on-ice skating kinetics in a valid, reliable, and time efficient manner is now practical in execution.

To the authors' knowledge, this is the first time that force-time patterns during acceleration, on-ice constant velocity hockey skating, and the transition from acceleration to constant velocity skating have been documented.

3.6 Conclusion

The results from this study demonstrate that the current system can be used on-ice to capture relevant kinetic data during the performance of ice hockey skating skills. Strain gauge signals produced a high linear relationship to known force values, independent of loading rate within an acceptable error. These force estimates were consistent trial-to-trial. Along with rapid data collection and meaningful force-time records, the use of this system permitted for natural, unencumbered skating during an on-ice situation. This is the first known system successfully designed specifically for testing ice hockey skating kinetics. The use of this system, along with the measurement of joint kinematics through the use of goniometry or motion capture systems such as Vicon® will allow for successful kinetic and kinematic analysis of ice hockey skating. Results obtained with the use of this system could also be used to provide insight for training and coaching purposes.

3.7 Acknowledgement

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CHAPTER 4 – COMPARISON OF SKATING KINETICS AND KINEMATICS ON ICE AND ON A SYNTHETIC SURFACE

4.1 ABSTRACT

The measurement of biomechanical parameters during skating on-ice has proven challenging; for instance previous attempts with optical measurement systems have been hampered by poor ambient lighting conditions and the difficulty in capturing an optimal field of view (i.e. movement over several meters) and spatial resolution (i.e. < 0.5 cm). Similarly, the standard technique to quantify ground reaction forces (i.e. force plates) cannot be used. Consequently, precise characterisation of on-ice skating mechanics in ice hockey remains elusive. The recent development of synthetic or artificial ice surfaces provide an alternative to true ice in venues where ice is impractical or impossible to install. Synthetic ice may be installed in controlled laboratory settings, thereby offering the possibility of detailed biomechanical analysis. Unknown, however, is the extent to which skating on synthetic ice (SI) replicates skating on traditional ice (ICE), particularly due to increased friction on SI. Hence, the purpose of this study was to compare kinetic and kinematic parameters of SI and ICE surfaces during forward skating. With eleven male hockey players, a portable strain gauge system was used to measure skate propulsive force synchronized with electrogoniometers for tracking dynamic knee and ankle angular movements during forward skating acceleration. In general, the kinetic and kinematic variables investigated in this study showed minimal differences between the two surfaces ($p > 0.06$), and no individual differences were identified between the two surfaces ($p \geq 0.1$) with the exception of greater knee extension on SI than ICE (15.2° to 11.0 °; $p \leq 0.05$). Overall, SI surfaces permit comparable mechanics for on-ice forward skating, and thus offer the potential for valid analogous conditions for in-lab testing and training.

4.2 Introduction

Despite appeal of the sport, little is known about the mechanics of ice hockey skating (Lafontaine, 2007). The reasons for this lack of knowledge include the unique surface upon which skating occurs, methodological difficulties of using motion capture systems due to the large field of view required to observe skills as they are executed, difficulties controlling ambient lighting of arenas, as well as the large diversity of skills characterizing the sport of ice hockey (Upjohn et al., 2008). However, there have been several pioneering studies investigating the kinematics of ice skating, generally using video analysis as the method of evaluation.

In a series of studies Marino (1977; 1979; 1979; 1983) concluded that skating is biphasic in nature consisting of periods of double support involving 15-18 percent of each stride, and single support periods ranging from 82-85 percent of each stride. Marino also found that when skating at maximal velocity, each skating stride consists of periods of acceleration and deceleration, with high calibre skaters able to generate propulsive forces during periods of both single and double support.

In an analysis of the acceleration strides of ice hockey skating, Marino (1983) discerned that a consistent movement pattern was noticeable after the third or fourth stride in 69 male hockey players. Similar to ice hockey, in the sport of speed skating de Koning et al. (1995) found substantial differences in the push-off mechanics of the second through eighth strides in five elite level speed skaters. The results from de Koning et al. (1995) showed little displacement of the skate during the second stride, signifying that the athlete was pushing off against a fixed point, similar to a running stride. During the eighth stride the skate was gliding during the push-off, creating more of a lateral push.

Similar results have been found by Lafontaine (2007) when investigating the ice hockey start.

Upjohn et al. (2008) and Lockwood et al. (2007) have published studies that used a non-traditional surface (i.e. skating treadmill) to evaluate the kinematics of skating. Upjohn et al. (2008) examined the kinematic variables that discriminate high-calibre hockey players from lower calibre hockey players when skating on a skating treadmill using four video camcorders. The study revealed that high-calibre skaters had a greater hip flexion at weight acceptance, greater knee extension and plantar flexion at the propulsion phase, and greater knee and ankle ranges of motion than their low-calibre counterparts.

Lockwood et al. (2007) investigated the habituation of 10-year-old hockey players to a skating treadmill using a sagittal plane video of the skaters. The results showed that stride rate and stride length increased, while rating of perceived exertion decreased, insinuating habituation to the new skating surface throughout 24 minutes of skating over a six week period.

Skating treadmills, however, are subject to several inherent limitations. First, players are restricted to forward skating. Second, tall skaters may have trouble fully extending their hips and knees due to the width of the treadmill. Researchers involved in the study by Upjohn (2008) noticed that some taller athletes had to restrict their leg extension to avoid hitting the side of the treadmill. Finally, with skating treadmills, skating speeds are not adaptable from stride to stride, and athletes are forced to skate at a steady state. As a result the subject does not accelerate and/or decelerate as would normally occur when a subject skates on-ice. For these reasons skating on a skating treadmill is not an optimal ergometer to represent on-ice, game-like conditions of ice hockey skating.

As an example of the differences in surface conditions between on-ice and skating treadmill, Nobes et al. (2003) investigated physiological and kinematic factors of 15 male varsity hockey players when skating at three different velocities on both surfaces. Results revealed that oxygen uptake (VO_2) was significantly lower at speeds of 18, 20, and 22 km/h on-ice, while maximal oxygen uptake (VO_2max) was similar on both surfaces. Stride rate and heart rate were found to be significantly higher on the skating treadmill, while stride length was significantly longer at the same skating velocities. Differences in physiological and kinematic factors were attributed to the increased co-efficient of friction on the skating treadmill. When skating on-ice at high velocities, air resistance is the primary cause of drag (de Koning et al., 1992), whereas when on the skating treadmill surface friction is much greater. Unlike on-ice, air resistance on the skating treadmill is minimal.

It may be possible to manage some of the difficulties associated with on-ice (ICE) kinematic analyses through the use of a synthetic ice (SI) surface. Several manufacturers produce SI surfaces, some of which consist of interconnected polyethylene panels. When these surfaces are covered with a silicone based lubricant the friction of the artificial surface is diminished, creating ice-like glide properties. With sufficient scoring of the polymer surface it is also possible for skaters to simulate glide and push-off carving when skating with the same skates as those used for ice skating. Furthermore, the SI surface offers the possibility for use within a lab environment, making it possible to overcome some of the aforementioned difficulties associated with on-ice studies. However, studies are needed to confirm whether SI surfaces are a valid representation of ICE skating.

Thus, the purpose of this study is to determine the kinetics and lower body kinematics of forward skating on ICE, and to compare these results with those obtained on a SI surface using a force transducer strain gauge technology to measure kinetics and electrogoniometry to measure kinematics.

4.3 Methods

4.3.1 Subjects

Thirteen adult male hockey players were recruited to voluntarily participate in the study, although only eleven completed both protocols. Ten of the subjects were playing for the McGill University varsity hockey team, while one subject was a former 'AAA' level hockey player (7 forwards, 4 defensemen, 21.45 years ± 1.86, 83.5 kg ± 4.3). The subjects were competent, high calibre skaters, and were able to easily complete the required skating protocol. The subjects were recruited by verbal communication, and completed an informed consent document prior to participation in the study. The study was approved by the McGill University Research Ethics Board (REB # 336-0508).

4.3.2 Experimental protocol

4.3.2.1 Ice surfaces

Testing comprised of two parts: an in-lab collection session on a SI surface (Viking Ice®) and an ICE data collection session within an ice arena. The in-lab testing occurred on a specially constructed SI surface in the McGill University Biomechanics Laboratory (see Figure 24), while the ICE testing took place at McGill's McConnell arena.

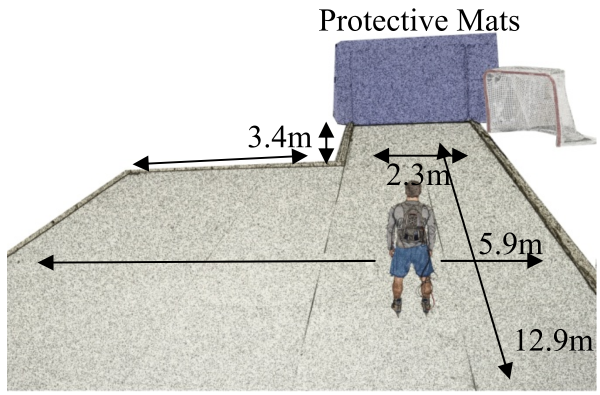


Figure 24 – View of skater on artificial ice surface.

4.3.2.2 Subject preparation

During testing the subjects wore a pair of appropriately sized ice hockey skates (model Nike-Bauer Supreme One95). The right skate was instrumented with force transducer strain gauges. The force measurement system utilized in the study was described in detail in Chapter 3 (force transducer system for measurement of ice hockey skating force). Each instrumented hockey skate had 3 half-active Wheatstone bridges composed of 350Ω, 0.125" long strain gauges provided with an excitation voltage of 2V ± 2% (5 gauges attached to skate) connected to a 13 bit analog to digital converter (DataLOG model P3X8, Biometrics Ltd., Gwent, UK). Each gauge was located at strategic locations on the blade holder so as to capture the amount of vertical and medial-lateral strain produced on the blade holder (see Figure 25 for a representation of the strain gauge placement). Each subject also carried a hockey stick to mimic game situation skating patterns as closely as possible. Kinetic information was captured at a frequency of 100Hz.

The subjects were also fitted with electrogoniometers (elgons) about the ankle and knee of the right leg. The elgons allowed for successful capture of the subjects' lower body joint kinematics. A Biometrics Ltd. DataLOG was used to record the data (100Hz) from the elgons (see Figure 26 for elgon placement). Once the subject was properly fitted with the elgons, the signals were set to zero with respect to the subject's neutral standing position while barefoot. All of the data collected was normalized to this 'zeroed' neutral standing position. The logger was placed in a small backpack worn by each subject during testing.

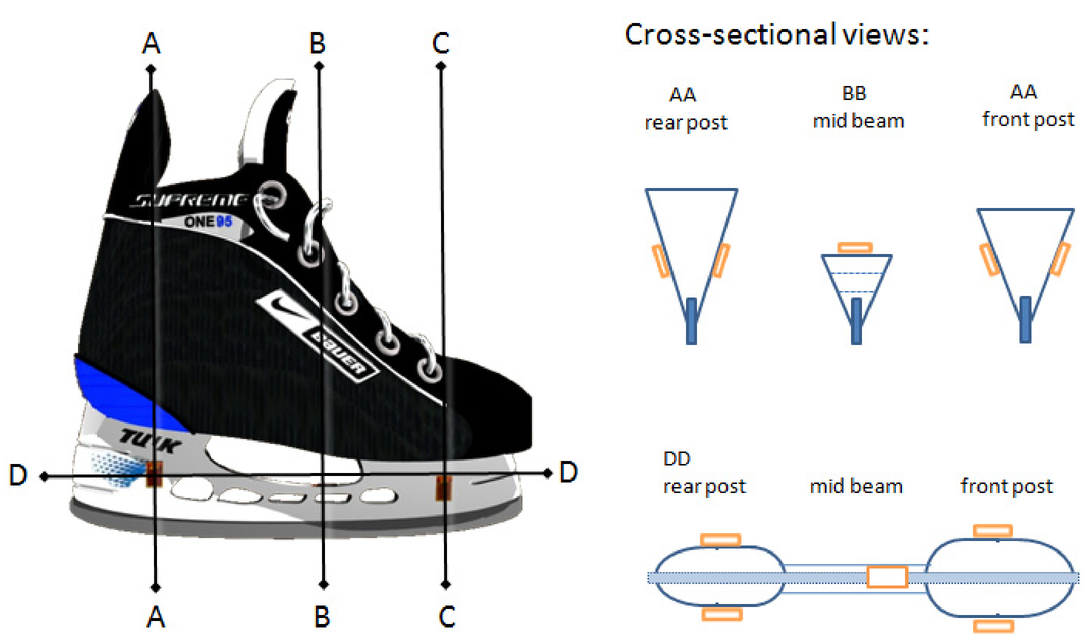
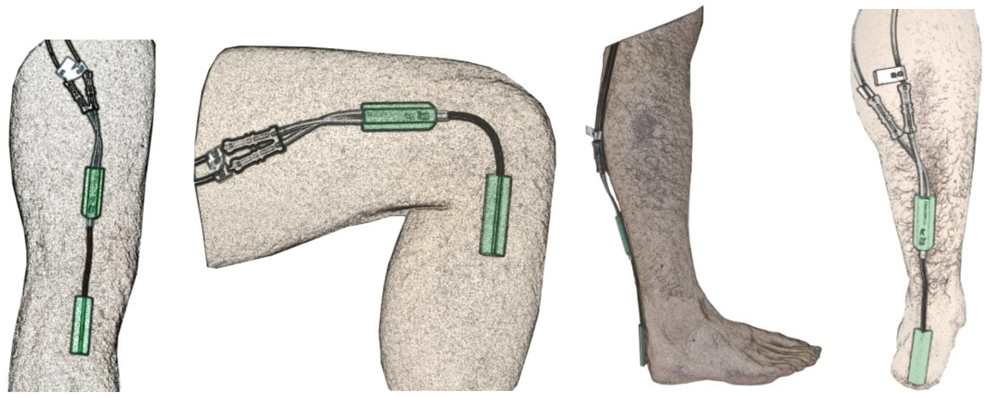


Figure 25 – Representation of cross-sectional views of gauge locations



a) b) c) d)

Figure 26 – Placement of the Elgons about the subject's knee(a, extended, b, flexed) and ankle (c,side view, d, rear view)

4.3.2.3 Tasks

The subjects were asked to perform five maximum effort skating starts on both surfaces (SI and ICE). The SI surface was treated with a thin film of a silicone based lubricant, while the ice rink surface was resurfaced with a Zamboni™ prior to each testing session to create optimal and consistent ice conditions.

Each trial consisted of the subject beginning from a standing position, starting with a front start, and accelerating as quickly as possible up to maximum velocity. A front start is a typical hockey skill in which the athlete begins facing their intended direction of travel. The athletes began by initially pushing with their right leg, and swinging their left leg first. Each trial consisted of a minimum of three full push-offs of the right leg.

The subjects were instructed to skate as fast as possible for a distance of approximately 13 meters, and were given ample recovery time between trials to avoid fatigue (approximately one minute) (Beachle and Earle, 2000). Crash mats were placed at the end of the runway for the in-lab testing condition to increase subject safety.

The initial sensation of skating on the SI surface is not the same as on a frozen ice surface. For this reason the subjects were asked to perform a ten to fifteen minute self selected skating warm-up routine prior to the beginning of the in-lab testing session to become familiar with skating on the SI surface.

During the on-ice testing, the subjects were again asked to perform a ten to fifteen minute self selected warm-up routine. Following the warm-ups, the subjects were asked to perform the skating protocol two or three times to become familiar with the testing procedure.

4.3.2.4 Statistical analysis

Analysis of kinetic variables included maximum total force (N/% body weight) as determined by the summation of vertical and medial-lateral force components, maximum vertical force (N/% body weight), maximum medial-lateral force (N/% body weight), impulse (Ns), and contact time (ms). Kinematic variables analyzed included maximum and minimum knee and ankle flexion amplitudes (degrees), knee and ankle flexion amplitude at the point of maximum force production (degrees), as well as knee and ankle maximum angular velocities during push-off (degrees). A 2 way MANOVA was used to compare all kinetic and kinematic variables across three skating strides by the two skating surfaces. A univariate F-test was performed on each of the dependent variables to interpret the results of the MANOVA (George, 2006).

Stride time (ms) was analysed independently from the MANOVA. Given that not all subjects were able to finish the recovery phase of their third stride during the in-lab scenario, it was not possible to compare the third stride on both surfaces with all other variables via the combined MANOVA. Thus, a two way ANOVA was performed on stride time for the first two strides across surface conditions. All statistical analyses were performed using SPSS (v.17, Chicago, IL, USA).

4.4 Results

In general, the kinetic and kinematic variables investigated in this study showed minimal differences between the two surfaces ($p > 0.06$). Presentation of each variable in turn follows.

4.4.1 Kinetics

Post-hoc analysis showed that none of the kinetic variables were significantly different across skating surfaces. Total force production was found to be similar between ICE and SI surfaces (163 N/%BW versus 160 N/%BW; $p \geq 0.67$). Similarly, average peak vertical forces were found to be equivalent in both conditions (141 N/%BW versus 134 N/%BW; $p \geq 0.31$). Average peak medial-lateral forces were found to be slightly higher on SI as compared with ICE approaching but not reaching significance (30 N/%BW versus 24 N/%BW; $p \geq 0.11$).

Similarly, contact time and impulse were not different during forward skating when the two surfaces were compared ($p \geq 0.61$; $p \geq 0.93$). Stride time for the first two strides was also not found to be different across the two surfaces ($p \geq 0.75$). The results of the kinetic analysis can be found in Table 3, and Figure 27.

Table 3 – Kinetic values across surface conditions averaged across all subjects, trials, and strides. Force variables are represented in Newton's per percent body weight, time variables are represented in milliseconds, and impulse variables are represented in Newton seconds.

Condition	Total Force	Vertical Force	Medial-Lateral Force	Contact Time	Impulse	Stride Time
ICE	163.7 (28.6)	141.8 (28.8)	24.0 (16.6)	354 (47)	203.6 (48.4)	585 (56)
SI	160.5 (33.3)	134.1 (31.1)	30.0 (18.4)	358 (56)	203.1 (60.2)	581 (72)

Group means and standard deviations (SD)

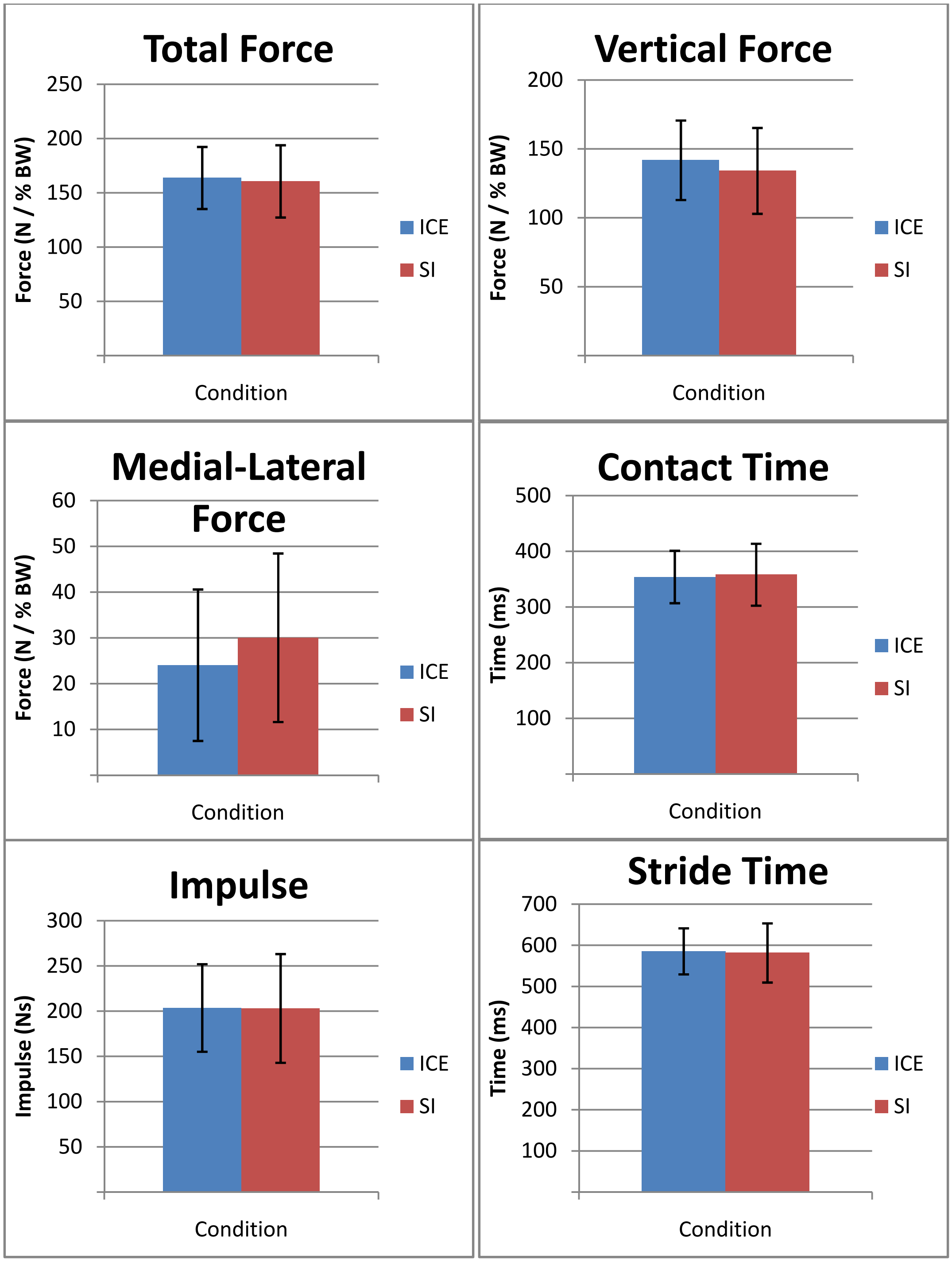


Figure 27 – Average kinetic variables (± SD bars) across surface conditions averaged across all subjects, trials, and strides

4.4.2 Kinematics

4.4.2.1 Knee

Mean maximum knee extension amplitude was found to be significantly different between conditions, with more extension occurring on SI than ICE (11° versus 15.2°; $p \leq 0.05$). Mean knee maximum flexion and knee flexion angle at the point of maximum force production ICE as compared with the SI condition were not significantly different ($p \geq 0.11$; $p \geq 0.14$). There was no difference found with respect to maximum knee angular velocity of extension during push-off across surface conditions ($p \geq 0.89$). Results can be found in Table 4 and Figure 28.

Table 4 – Averaged knee kinematic variables across surface conditions across all subjects, trials, and strides. Angular amplitudes are represented in degrees, while angular velocities are represented in degrees/second.

Condition	Knee Extension	Knee Flexion	Knee Flexion @ Maximum Force	Knee Angular Velocity
ICE	15.2 * (3.9)	86.9 (8.6)	39.1 (6.5)	334.4 (58.1)
SI	11.0 * (7.1)	81.0 (18.9)	35.5 (11.8)	336.9 (85.3)

Group means and standard deviations (SD)
*** Indicates significant difference at $\alpha \leq 0.05$ for the univariate F-test.**

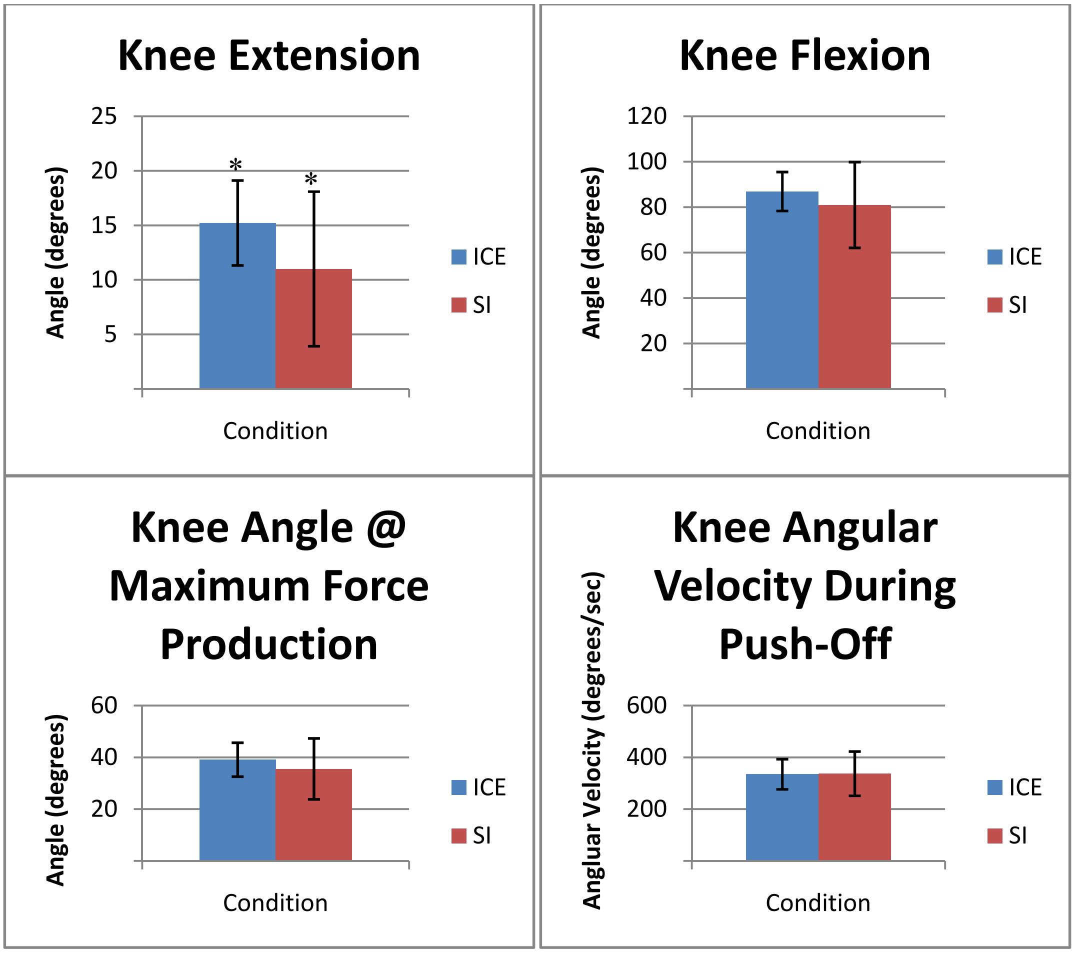


Figure 28 – Knee kinematic variables across surface conditions averaged across all subjects, all trials, and all strides. * indicates significant difference at $\alpha \leq 0.05$ for the univariate F-test

4.4. 2.2 Ankle

Due to equipment failure, data for only four subjects on both surfaces was available for analysis. The following results summarize findings from those four subjects.

Amplitude of maximum plantar flexion, maximum dorsi flexion, ankle flexion at the point of maximum force production, and angular velocity at the point of push-off were found to be similar when surface conditions were compared ($p \geq 0.66$; $p \geq 0.26$; $p \geq$

0.20; p ≥ 0.19). Results of the analysis of the ankle data can be found in Table 5 and Figure 29.

Table 5 – Ankle kinematic variables across surface conditions averaged across all subjects, trials, and strides. Angular amplitudes are represented in degrees, while angular velocities are represented in degrees/second.

Condition	Ankle Plantar Flexion	Ankle Dorsi Flexion	Ankle Flexion at Maximum Force Production	Ankle Angular Velocity
ICE	-12.9 (6.5)	18.6 (6.1)	17.4 (7.7)	353.1 (38.8)
SI	-11.8 (4.5)	15.1 (7.2)	11.4 (12.2)	277.9 (174.0)

Group means and standard deviations (SD)

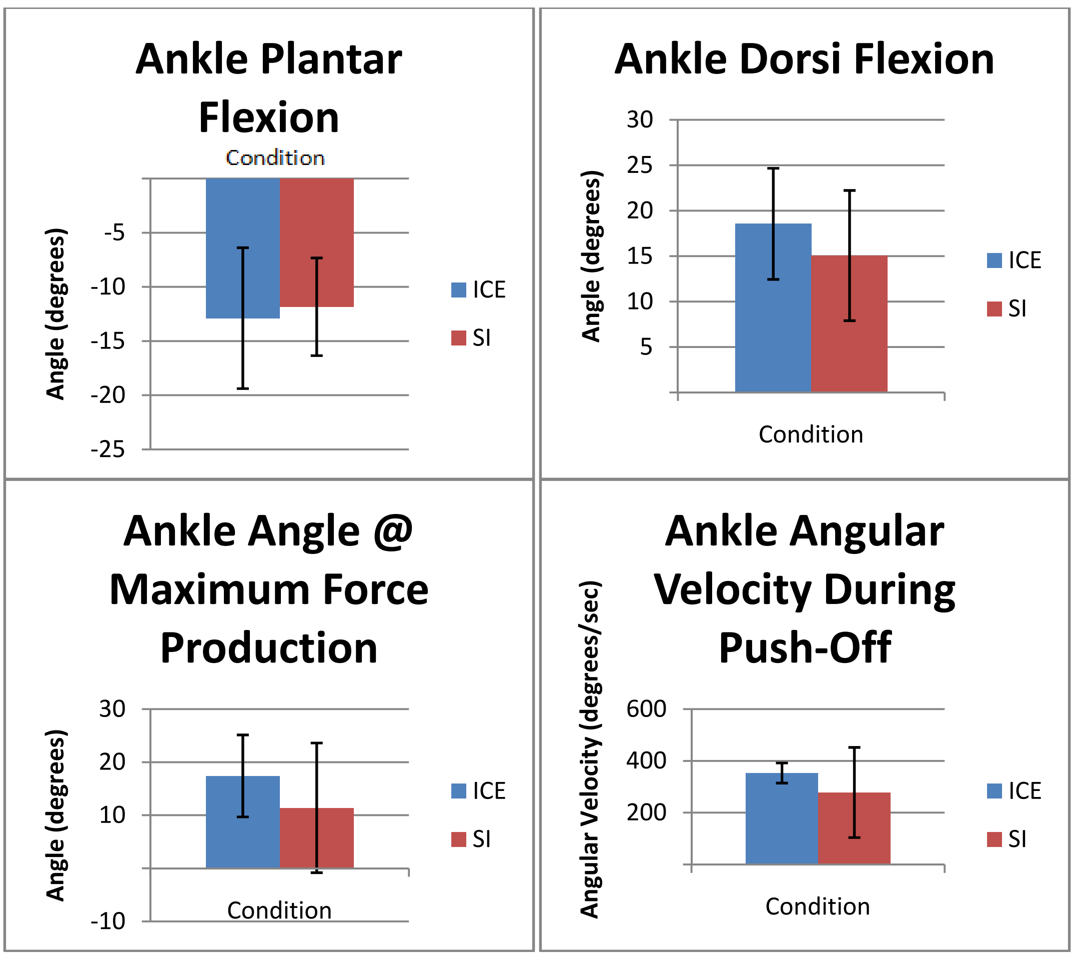


Figure 29 – Ankle kinematic variables across surface conditions averaged across all subjects, all trials, and all strides.

4.5 Discussion

The objective of this study was to determine kinetics and lower body kinematics of skating on a synthetic ice surface and to compare these results with those obtained on a traditional ice surface. Results of the present study have shown that, overall, the two surfaces are similar, although the main analysis approached statistical significance ($p \leq 0.06$). Knee extension was the only variable found to be different across surface conditions.

Subjects extended their knees by an average of four degrees greater on the SI compared to the ICE surface. From a qualitative inspection of the videos of each subject's trials, some distinct differences in skating style are present in approximately half of the subjects when skating on the two surfaces.

The acceleration phase of skating is characterised by pushing against a fixed point, where little to no gliding occurs in the stride (de Koning, 1995; Lafontaine, 2007). Through the qualitative analysis of the video records, several of the subjects did not begin bimodal constant velocity gliding mechanics when skating on the SI surface, whereas on ICE the subjects were beginning to show a gliding phase by stride three.

Another explanation for the extra extension seen on ICE is due to the extra friction created by the synthetic surface. The coefficient of friction of ice when skating has been reported to vary between a μ of 0.003 and 0.007 (Kobayashi, 1973; de Koning, 1992; Jobse, 1990), while the reported coefficient of friction of the synthetic surface used in this study is around 0.27 (Viking Ice, 2009). This creates a condition of higher resistance and may cause the skater to feel as if they are skating more slowly, and to compensate for this added resistance the subjects may push longer, causing the observed increase in knee extension. However, force production and contact time of the push-off were similar on both surfaces, making it difficult to attribute the observed differences to a harder or longer push-off. It is possible that the subjects would have needed to overcome the increased resistance, the direct response to which would have been an increase in knee extension.

The investigation of physiological and kinematic factors of skating on-ice and on a skating treadmill performed by Nobes et al. (2003) revealed differences in surface conditions. Reasons for this were attributed to the increased co-efficient of friction on the skating treadmill. While the surface friction of the skating treadmill used by Nobes et al. (2003) was not identified, the coefficient of friction of the surface used in this study is reported to be 0.27. This difference in friction between the current SI surface and ICE was not enough to produce significant differences in skating mechanics on the two surfaces.

Although not significant, knee flexion was slightly higher on ICE compared to the SI surface. Contact time, and subsequently stride time were similar on both surfaces resulting in a total push-recovery time that occurred in the same time frame on both surfaces. Thus, the increased knee extension seen on SI would have meant that the recovery phase would have to be either shortened, or that the recovering leg would not have been able to recover to the same flexion amplitude to accommodate the increased extension. The latter is more probable, owing to the fact that contact times and stride times on both surfaces were similar. The increased knee extension seen on SI accompanied by the decreased knee flexion would have combined to produce the similar force patterns seen on both surfaces.

Ankle plantar flexion and dorsi flexion were similar on both ice surfaces. Given the coupled motor pattern of the knee and ankle, minimal differences at the knee across surface conditions would likely result in minimal differences at the ankle across surfaces. The lack of differences at the ankle may also be attributed to the stiffness of the skate boot, which does not allow for large amplitudes of ankle motion (Pearsall et al., 2000).

Representative data for a single subject skating in-lab on SI surface and on ICE can be found in Figure 30. From the data it is noticeable that the three strides are characterized by running style mechanics (Rose and Gamble, 2006). Distinct changes in skating mechanics from strides three through five have been reported in published literature (de Koning, 1995; Lafontaine, 2007) as well as in Chapter 3 (force transducer system for measurement of ice hockey skating force). These changes in stride mechanics may have been more noticeable during the in-lab SI testing scenario had there been a longer surface allowing for more strides. It is noticeable that the kinetic and kinematic profiles of skating on both surfaces were very similar, both in magnitude and structure, further confirming the results of the statistical analysis.

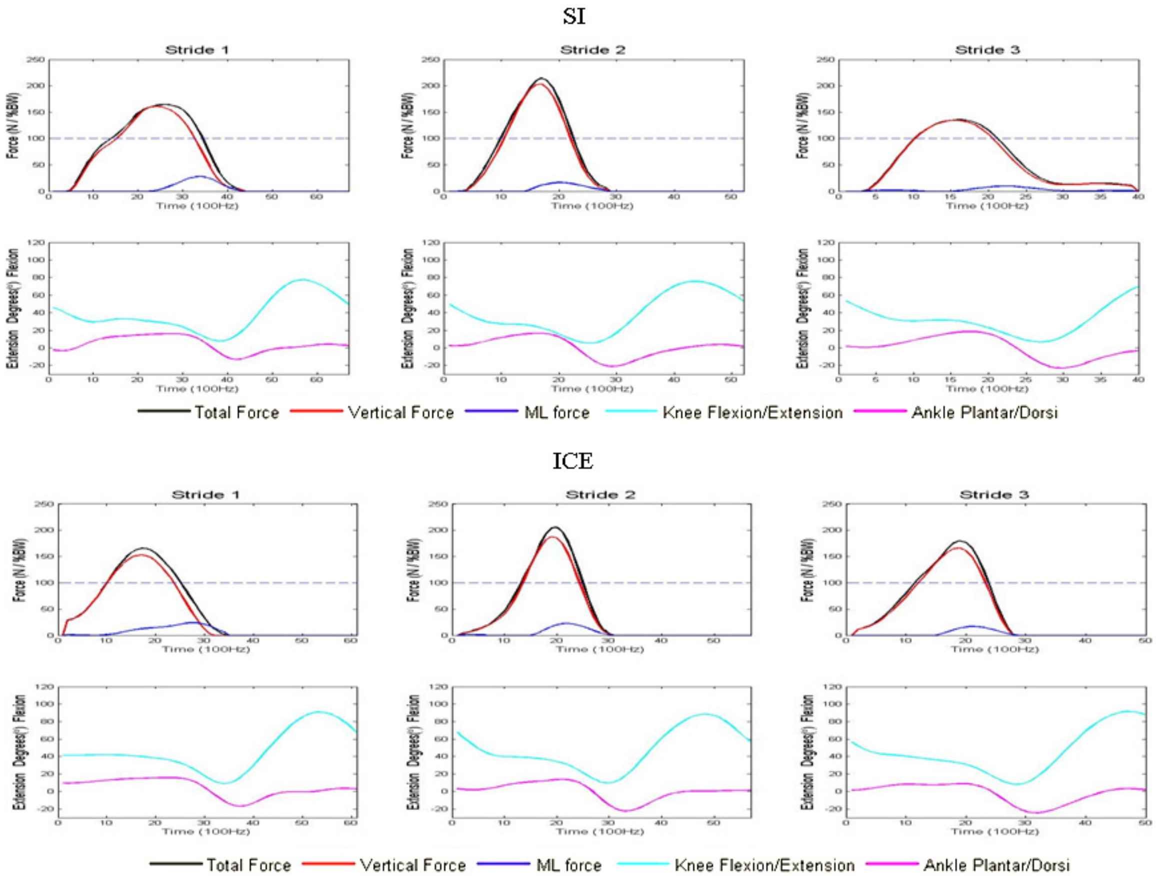


Figure 30 – Representative kinetic and kinematic data for a subject skating in-lab on SI surface (top) and ICE (bottom)

Component force profiles were not significantly different across surfaces. Similar knee movements, with the exception of a 4° offset, is likely the cause of the similar kinetic profiles, as are the similar angular velocities at the point of push-off seen at the knee across the two surfaces.

The subjects were required to perform a ten to fifteen minute familiarization period on the synthetic ice surface, though Lockwood et al. (2007) has shown that familiarization to a foreign surface can occur as quickly as twelve minutes, but may take up to twenty-four minutes or longer of skating time over the course of a six week period. Due to practicality issues, a longer familiarization protocol in this study was not possible.

The athletes tested in this study were high calibre level hockey players, conditioned through many years to skate using a consistent skating style. As such, the different surface conditions did not cause the skaters to perform forward skating tasks in a measurably different manner on the two surfaces.

4.6 Conclusion

Skating is ice hockey's most important skill, yet very little is known about the fundamental mechanics of skating with regard to gross movement patterns (Lafontaine, 2007). The present study using kinetic and kinematic analyses of forward skating has shown that the SI surface used in the current study permits a valid representation of ICE skating. Future comparative studies are needed to determine if the similarity of the synthetic surface extends to other skills, particularly agility skills requiring substantial carving into the surface and quick changes of direction. The synthetic ice surface provides an opportunity to conduct experiments in a controlled in-lab condition, and will allow for new insights to further our understanding of the biomechanics of ice hockey. Testing in this well controlled environment allows researchers to overcome many of the technological limitations of on-ice testing.

4.7 Acknowledgement

The authors would like to thank Bauer Hockey Inc. for their significant financial and in-kind contributions to the study, as well as NSERC for their financial support.

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CHAPTER 5 – SUMMARY AND CONCLUSIONS

5.1 FORCE TRANSDUCER SYSTEM

While previous studies have shown strain gauges to be a valuable tool in the determination of on-ice skating kinetics (de Boer et al., 1987; de Koning, 1992; Gagnon, 1983; Jobse, 1990; Lamontagne, 1983), the current study has shown the feasibility of manufacturing a strain gauge based system for the measurement of on-ice hockey skating forces without modification to the hockey skate's construction. To the author's knowledge, this is the first such system.

The recorded strain signals, based on tensile and compressive deformations of the skate blade holder, produced a highly linear relationship to known force values measured on a force plate, independent of loading rate with a low measurement error. The force estimates obtained with the strain gauges were consistent trial-to-trial, demonstrating the reliability of the system.

5.2 SYNTHETIC ICE SURFACE

The present study has shown the synthetic ice surface used (Viking Ice®) to provide a valid representation of forward ice skating through comparative kinetic and kinematic measures. The synthetic ice surface offers an opportunity to conduct experiments within controllable laboratory conditions, and will allow for new insights to further our understanding of the biomechanics of ice hockey skills. Testing in this well controlled environment allows researchers to overcome many of the technological limitations of on-ice testing with a reasonable replication of the unique surface upon which skating occurs. The controllable in-lab conditions also aid in overcoming methodological difficulties of using motion capture systems due to the large field of view required to observe skills as they are executed, and allows for better control of ambient lighting of arenas. The resulting studies using this synthetic surface will allow for better characterization of the large diversity of skills characterizing the sport of ice hockey (Upjohn et al., 2008).

5.3 Future directions

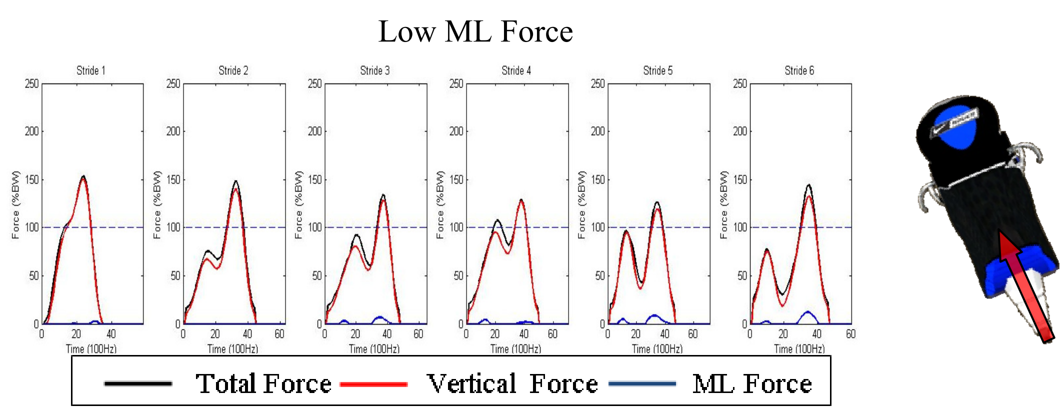
5.3.1 Force transducer system

5.3.1.1 System development

It would be desirable for future development of the current system to simplify strain gauge use and application. Such a system could become a valuable coaching and training tool and could simplify the conduct of research investigations.

5.3.1.2 Skating kinetics

In the present study, analysis of the on-ice forward skating kinetics has shown differences in the medial-lateral force profiles between skaters. Specifically, preliminary results suggest that skaters can be placed into one of three groupings; little to no medial-lateral force, moderate medial-lateral force, and high medial-lateral force profiles, reflecting possible differences in skating styles between skaters (Figure 31).



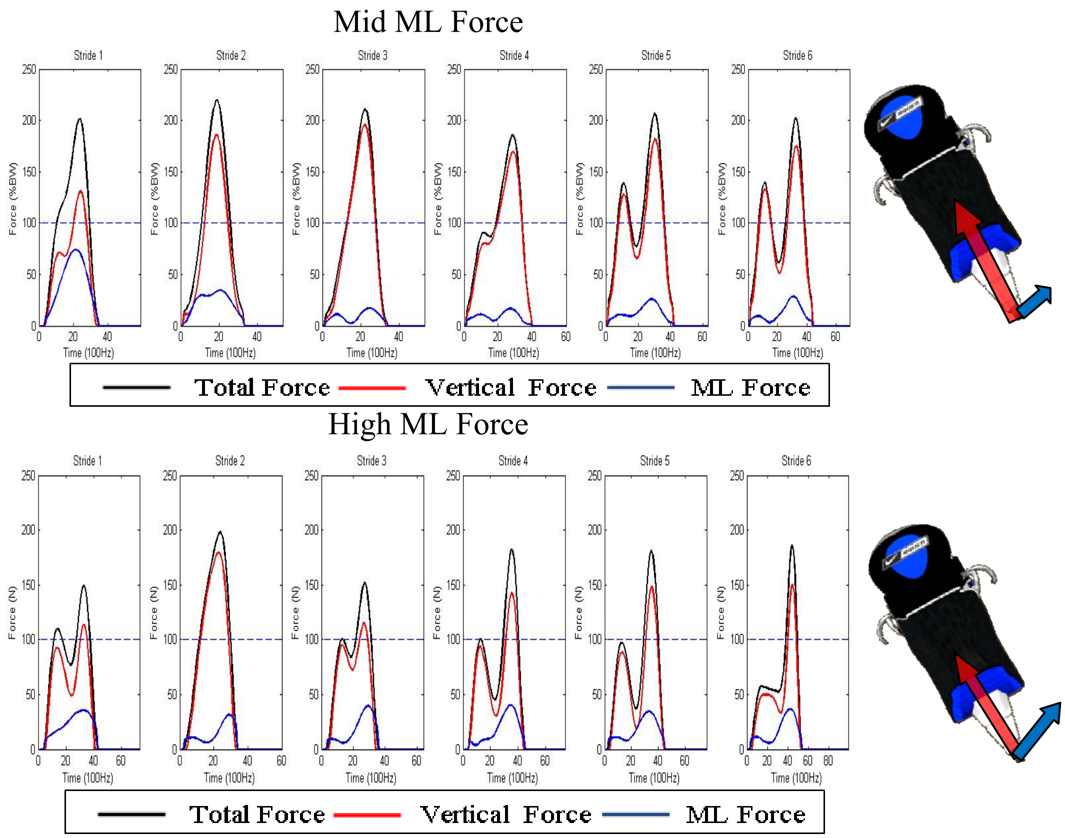


Figure 31 – Medial-lateral force groups: little to no medial-lateral force (top), moderate medial-lateral force (middle), and high medial-lateral force (bottom).

Based on inspection of the visual records of each subject's skating trials, it is hypothesized that the groups with little to no medial-lateral force readings generate a higher forward velocity, as well as higher power and work outputs than their counterparts in the other two groups. These preliminary results are insufficient to confirm or reject such a hypothesis. Future studies are needed to further investigate these notions.

The current study has also provided significant information regarding the deformation of the skate blade holder when subjected to varying loads. This may be an initial step in creating a finite element model of the hockey skate and it's components to predict responses to varying stresses.

5.3.2 Synthetic ice surface

The validity of the synthetic ice surface used in this study is presently limited to forward skating. As such, future comparative studies are needed to determine if the similarity of the synthetic surface extends to other skills, particularly agility skills requiring substantial carving into the surface and change of direction. The use of such a surface if deemed valid via supplementary comparative studies would also allow for precise kinematic description of a variety of skating and shooting skills that have been difficult to interpret when conducting research on-ice.

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APPENDIX A – CONSENT FORM

INFORMATION AND CONSENT DOCUMENT

Investigator: Tyler J. Stidwill M.Sc. candidate
René A. Turcotte Ph.D.
David J. Pearsall Ph.D.
Biomechanics Laboratory, Department of Kinesiology and Physical Education, McGill University

Statement of Invitation
You are invited to participate in a research project conducted by the above named investigator. This research project will be performed in the Biomechanics Laboratory of the Department of Kinesiology and Physical Education, McGill University, located at 475 Pine Ave. West, Montréal, Québec, H2W 1S4, as well as at McConnell Arena, located at 3883 University Ave., Montreal, Québec, H2W 1S4. You are asked to come to two experimental sessions that will each last up to 1 hour. We greatly appreciate your interest in our work.

Purpose of the Study
The purpose of this study is to compare the kinetics and lower body kinematics of hockey skating on frozen ice with those produced on a synthetic ice surface. This study will add some valuable insights into the underlying mechanics of ice hockey skating, as well as to help validate the synthetic ice surface as a valuable alternative to a traditional ice rink.

If the results of this study validate the synthetic ice surface as a reasonable facsimile of a frozen ice surface, showing that the synthetic ice surface allows the skater to skate with similar kinetic and kinematic parameters, synthetic ice surfaces may become a low cost, low maintenance method of providing year round, high quality ice surfaces both in a commercial and residential setting.

The synthetic ice surface will also hopefully allow for a useful setting within which to perform realistic, in-lab ice hockey testing in a controlled environment, where technological limitations may not allow for on-ice field testing.

Your participation in this study involves:

1. Providing informed consent prior to the experimental session,
2. Performing three to five forward skating tasks using a pair of Nike-Bauer One95 hockey skates. The procedure listed below are common to the experimental session:
    a. You will be outfitted with a hockey helmet (Nike-Bauer 8500, sized accordingly) hockey skates (Nike-Bauer One95, sized accordingly)
    b. You will be outfitted with electrogoniometers about your ankle, knee, and hip
    c. You will be asked to wear compression fitted Under Armour pants
    d. You will perform three to five skating tasks, performing common ice hockey skating maneuvers

e. You will be asked to conduct up to 5 trials per task

Risks and Discomforts

It is envisioned that you will encounter no significant discomfort during these experiments. It is anticipated that a 10-15 minute learning curve is associated when first skating on the artificial skating surface; however, after this learning period you will feel as though you are skating on an actual ice surface. There is a slight risk that you could fall on the artificial ice surface; however the danger is no greater than found in regular hockey and you will be wearing a helmet in case this does occur.

Benefits

There are no personal benefits to be derived from participating in this study. The results of this study may however, lead to a greater understanding of the underlying mechanics of ice hockey skating, as well as to provide a realistic alternative to skating on frozen ice surfaces.

Confidentiality

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

Inquiries Concerning this Study

If you require information concerning the study (experimental procedures or other details), please do not hesitate to contact *TJ Stidwill or René Turcotte*, at the numbers or addresses listed below.

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Responsibility clause

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

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

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

CONSENT

I, ______________________________________, AGREE TO VOLUNTARILY PARTICIPATE IN THE STUDY DESCRIBED ABOVE ABOUT THE KINEMATICS AND KINETICS OF ICE HOCKEY SKATING

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

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

Signatures

SUBJECT

____________________________________ ____________________________________
(signature) (print name)

RESEARCHER

____________________________________ ____________________________________

(signature) (print name)

Date: ___________________________

APPENDIX B – ETHICS CERTIFICATE

McGill

Research Ethics Board Office
McGill University
1555 Peel Street, 11th floor
Montreal, QC H3A 3L8

Tel: (514) 398-6831
Fax: (514) 398-4644
Ethics website: www.mcgill.ca/researchoffice/compliance/human/

Research Ethics Board II
Certificate of Ethical Acceptability of Research Involving Humans

REB File #: 336-0508

Project Title: Kinematic and kinetic analysis of ice hockey skating

Principal Investigator: Prof. David Pearsall **Department:** Kinesiology&Physical Education

Co- Investigators: R. Turcotte, T.J. Stidwell, P. Magee

Funding Agency and Title (if applicable): NSERC CRD CRDPJ 363586-07

This project was reviewed on May 24, 2008 by

Expedited Review ✓
Full Review ____

Mark Baldwin, Ph.D.
Chair, REB II

Approval Period: May 26, 2008 **to** May 25, 2009

This project was reviewed and approved in accordance with the requirements of the McGill University Policy on the Ethical Conduct of Research Involving Human Subjects and with the Tri-Council Policy Statement: Ethical Conduct For Research Involving Humans.

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* All research involving human subjects requires review on an annual basis. A Request for Renewal form should be submitted at least one month before the above expiry date.
* When a project has been completed or terminated a Final Report form must be submitted.
* Should any modification or other unanticipated development occur before the next required review, the REB must be informed and any modification can't be initiated until approval is received.

APPENDIX C – SKATE AND SUBJECT CALIBRATIONS

Table 6 – Skate calibrations

SKATE	V slope	V intercept	AML medial slope	AML medial intercept	AML lateral slope	AML lateral intercept	PML medial slope	PML medial intercept	PML lateral slope	PML lateral intercept
7.5	933	-42	308	-3	293	-10	107	-15	108	-23
8	1393	-36	318	47	296	42	94	59	92	53
8.5	1800	-7	350	29	258	41	86	25	104	39
9	983	-17	363	-35	315	-22	172	-20	179	-49
9.5	2242	-93	326	-15	259	-16	115	-36	111	-36

Table 7 – Subject calibrations

SUBJECT	SKATE	Weight (N)
subject1	8.0	756
subject2	8.0	822
subject3	9.0	749
subject4	8.5	858
subject5	8.5	845
subject6	9.0	853
subject7	9.0	794
subject8	7.5	806
subject9	9.0	845
subject10	9.0	883
subject11	7.5	794
subject12	8	822
subject13	8.5	761

APPENDIX D – SKATER SET-UP

Figure 32 – Skater set-up as viewed from (1) back, (2) side, and (3) during push-off.