A Comparison Between Elite and Recreational Skaters' Foot Pressure Patterns During Backward Cross-Overs

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Abstract

The study examined the peak pressures and pressure patterns in the skate boot of hockey players during the backward cross-over stride. Fifteen flexible piezo-resistive pressure sensors (1.2 x 1.1 x 0.2cm thick) were placed on the plantar, dorsal, medial, and lateral surfaces of each foot for eight varsity level hockey players (mean ± SD: height (m) = 1.80 ± 0.07, weight (kg) = 87 ± 0.06) and eight recreational hockey players (mean ± SD: height = 1.76 (m) ± 0.06, weight (kg) = 82 ± 0.07). The strides were cut and the data was processed according to ability group and cross-over direction. The results demonstrated significant differences between groups in average speed, and in peak pressures on the medial and lateral surfaces of the foot ($p \leq 0.05$). The results also indicated a significant difference on the plantar surface of the foot when comparing cross-over directions ($p \leq 0.05$).

Résumé

Le but de cet article était d'examiner les pressions maximales et les profils de pressions dans le patin de hockey entre les joueurs élites et récréatifs pendant le pas croisé en arrière. Les données de huit joueurs de hockey de niveau élite (écart-type moyen de ± SD: taille (m) = 1.80 ± 0.07; poids (kg) = 87 ± 6.48) et huit joueurs de hockey récréatif (écart-type moyen de ± : la taille = 1.76 ± 0.06 poids = 82 ± 7.49) ont été mesurée à l'aide de quinze sondes piezo-resistive fixes sur chaque pied pendant le pas croisé en arrière. Pour chaque épreuve, les profils de pression de trois foulées ont été coupés et ramenés à une moyenne selon les groupes en fonction d'abilités et de la direction du pas croisé. Les résultats ont démontré des différences significatives dans la vitesse moyenne et dans les pressions maximales sur les surfaces médiales et latérales du pied entre les deux groupes ($p \leq 0.05$). Les résultats ont aussi démontré une différence significative sur la surface plantaire pendant un croisé en arrière quand la direction est comparée ($p \leq 0.05$).

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Chapter 1: Introduction

Chapter 1

Introduction

The sport of ice hockey has evolved greatly since its early beginnings as a recreational winter activity played on Canada's ponds and lakes in the 1880's (Pearsall et al. 2000). Ice hockey is practiced in organized leagues by males and females of all ages, and has evolved into a national passion for many Canadians (Robidoux 2002). Confirmation of its importance to Canadian culture is the fact that a picture of children playing hockey on a frozen pond appears on the Canadian five-dollar bill. Over the years, the sport of ice hockey has developed into a multi-million dollar business, with much research performed in order to improve or maximize athletic performance. The players are training harder and becoming bigger and stronger than ever. Also, there is a tremendous amount of research in the field of hockey equipment development, which is allowing for lighter and more sport-specific specialized gear, thus enabling the athletes to perform at even higher levels.

The earliest known forms of skates used animal bones as the blades and were used as a means for facilitating travel across icy regions during the 9th century (Montgomery1988; Vaughan 2001). During the 1850's steel skates with straps and clamps were used in order to attach the skate to the shoe (Vaughan 2001). By the late 1880's the metal blade was attached to the boot by means of a wooden support, which was later replaced by an all metal blade assembly. Since this time, skate design has continued to evolve in order to maximize athletic performance and comfort in ice hockey.

Surprisingly, little research has been conducted on the biomechanics of ice hockey in terms of skating skills, which were found to be the most important skills that can be attributed to hockey players of all positions according to a survey of 16 professional National Hockey League scouts (Renger 1994). Renger also notes that the results of his study indicate that coaches should focus on improving speed and acceleration in forward skating, while focusing on mobility and backward skating in defensemen. In fact, the majority of the ice hockey research that has taken place has focused primarily on the physiology of training and conditioning, skill development, and safety and injury prevention (Pearsall et al. 2000).

Due to the fast paced nature of the sport, it is technically difficult to evaluate ice-hockey skating skills from a biomechanical perspective (Humble, Gastwirth 1988; Pearsall et al. 2000). There has been limited research performed on the forward power skating stride which has focused on: ankle kinematics (Chang 2002; Dewan 2004; Hoshizaki 1989), lower limb EMG (Goudreault 2002; Dewan 2004), and foot pressures (Loh 2003; Dewan 2004; Turcotte et al. 2001; Turcotte et al. 2004). Often, in order to further understand the kinematics of the skating stride, inferences have been made from the movement patterns investigated during speed skating (De Koning et al. 1991). With regard to the many intricate skating skills, which are of great importance in order to excel at the sport of ice hockey limited biomechanical studies have been performed (Humble, Gastwirth 1988). Naud and Holt (1980) investigated specific hockey skating starts, and selected stop, reverse and start techniques. Marino (1993) performed the only known scientific study involving backward skating. Therefore, there is a limited amount of hockey skating research that describes the biomechanics of skating despite the importance of the ability to the sport of ice hockey.

Investigating sport biomechanics is valuable as it can be used as a tool to increase training efficacy, determine the causes of certain injuries and decrease their rates, and aid in the development of athletic products to improve performance. For example, there was a tremendous increase in the number of joggers in the 1970's, which led to a significant rise in running related injuries. An increase in biomechanic research regarding this phenomenon then occurred and many biomechanical issues were heavily investigated such as joint kinematics, ground reaction forces, heel flare, ankle pronation, and many others (Nigg et al. 1986). This new insight in running biomechanics led to a more thorough understanding of many injuries and led to an improvement in running shoe design and orthotics. The current knowledge base in sport biomechanics regarding skating in ice hockey is very limited, and many topics, such as the previously mentioned ones regarding running, need to be addressed for similar reasons. As the skate is the interface between the athlete and the ice, it is important to evaluate the mechanics of skating when making changes to the skate itself, whether by changing materials and construction, or altering other design features (Goudreault 2002). Cavanagh et al (1992) noted that athletic performance can be improved through the redesign and remodelling of sports equipment. Therefore, changes in the design of the skate will ultimately affect skating performance and comfort, hence a biomechanical evaluation of these skills is of great importance.

Nature and Scope of the Problem

Despite some previous work measuring the pressure magnitudes and distribution patterns between the foot and ankle within the skate boot during the forward ice hockey skating stride (Dewan 2004; Loh 2003; Turcotte et al. 2001; Turcotte et al. 2004), there is still much to be understood regarding the pressure exerted at these areas during other skating skill tasks. Turcotte et al (2001; 2004) examined the plantar pressure exerted by the foot during the forward skating stride, and also compared the plantar pressure profiles of skating on-ice versus those of skating on the treadmill. Dewan further examined the pressure pattern profile during the forward skating stride by placing 16 piezo-resistive sensors on the plantar, dorsal, medial, lateral, and posterior foot (2004). The more complete analysis performed by Dewan (2004) allowed for a description and understanding of the levering of the foot and ankle within the skate boot in an attempt to transfer forces from the skate to the ice surface.

Due to the lack of knowledge regarding pressure distribution patterns within the skate boot during any other fundamentally important skating task in the sport of ice hockey, it would be beneficial to measure the foot-to-skate boot pressures on the plantar, dorsal, medial, and lateral areas of the foot and ankle during backward cross-over skating in order to gain an understanding of the force generation patterns involved in the skill (Marino 1997).

Significance of the Problem

Increasing the knowledge base concerning pressure patterns within the skate boot during essential hockey skating tasks would be beneficial for various reasons, as was demonstrated with the tremendous increase in biomechanic running research. Researchers examined plantar forces, which led to the development of foot orthotics, hence decreasing injury prevalence and simultaneously increasing the comfort levels in footwear. Exclusive examination of plantar forces was sufficient for running as much of the impact and propulsive forces take place on the plantar surface of the foot (Dewan

2004). In skating however, due to the low friction of the ice surface, the skater must push off not only in a backward direction, but also in a lateral direction with the medial side of the skate boot angled toward the ice. This combined with the fact that the skate boot is very rigid leads to propulsive forces being generated from many areas of the foot and ankle during the forward skating stride (Dewan 2004). Therefore, only looking at the pressures on the plantar aspect of the foot during the other fundamental skating skills, and more specifically to this research, the backward cross-over stride, would not lead to a thorough understanding of the propulsive forces exerted by the foot within the skate boot.

Understanding the pressures within the skate boot during the other important skating skills may have implications regarding the proper fit of the skate, improving the skate boot design for increase of performance and comfort, and perhaps injury prevention. It has been demonstrated that 12% of male ice hockey injuries in the NCAA are related to the foot and ankle (Flick 2005). Also, the ankle has been shown to be the third most prevalent injury site behind concussions and adductor muscle strains in university level women ice-hockey players (Schick, Meeuwisse 2003). Foot and ankle injuries have also been demonstrated to account for 15% of inline skating injuries (Schieber et al. 1996). Also, there is a high prevalence of foot deformations, bunions, and callosities, known as "hockey feet" in hockey players, which can become uncomfortable and potentially very painful. A more thorough understanding of the pressures and forces exerted by the foot within the skate boot during the different skating skills could help in designing skates that decrease the occurrence of foot and ankle injuries.

Technique differences between elite and recreational athletes have also been shown in previous research (De Koning 1991; Williams 2000; Button 2003; McCaw, Hoshizaki 1985). A comparison between athletes of different skill levels during the task of backward cross-over skating would allow for the determination of technique differences. This could prove to be beneficial to both coaches and trainers, and athletes. This could also help young players to further the development of their skating skills with training, or aid in the creation of rehabilitation regimes during recovery from lower limb injuries.

Purpose

The primary purpose of this study was to identify and compare peak pressures and foot pressure patterns within the skate boot between elite and recreational level ice hockey players while performing the backward cross-over stride.

The secondary purpose was to compare the timing of peak pressures, in absolute time and as a percent of the stride, between the elite and recreational skaters during the backward cross-over stride.

The tertiary purpose was to determine the effect of backward cross-over direction on peak pressure, in both the elite and recreational groups.

The quaternary purpose was to compare the peak pressures exerted within the skate boot between the inside and outside feet during the backward cross-over stride.

Hypotheses

The following statistical hypotheses are stated:

(1) There will be no difference in peak pressures between the elite and recreational groups.

(2) No differences in terms of timing in absolute time or normalized as a percent of stride will be seen between the elite and recreational skaters.

(3) There will be no differences in peak pressures between right and left backward cross-overs.

(4) No differences in terms of timing in absolute or in percent of stride will be seen between the right and left backward cross-overs.

(5) There will be no difference in peak pressure between the inside and outside feet during the backward cross-over stride.

Operational Definitions

Cross-over stride: Movement pattern where one passes the outside foot (the outermost foot during a curve) over the toe of the inside foot.

Backward cross-over stride: Movement pattern in which the skater is skating backward and passes his outside foot over the toe of the inside foot, as the inside foot is crossing under the under the body in the process of thrusting.

Stride phases: *Stride-push*: The first thrust of a backward cross-over. It is performed by the outside foot as it performs a c-cut and then crosses-over in front of the inside foot.

Glide: The movement pattern performed by the inside foot as the outside is in the stride-push phase.

Crossunder push: The second thrust of a backward cross-over. It is executed by the inside foot as the outside foot prepares for blade contact with the ice.

Single-support: The part of a stride where only one skate is in contact with the ice.

Double-support: The part of a stride where both skates are in contact with the ice.

Pressure profile: A pressure versus percent of stride graph.

Percent of stride: The time of an event relative to the entire stride.

Plantar surface: The surface of the sole of the foot.

Dorsal surface: The surface of the dorsum of the foot.

Posterior surface: The surface of the posterior foot and ankle.

Medial surface: The surface of the medial foot and ankle.

Lateral surface: The surface of the lateral foot and ankle.

Hysterisis: The energy lost when loading or unloading a sensor.

Creep: The tendency for the pressure readings to steadily increase under a constant load.

Kinetics: The area of biomechanics concerned with the forces producing motion or maintaining equilibrium (Levangie, Norkin 2001).

Kinematics: The area of biomechanics concerned with describing motion without regard to the forces producing it (Levangie, Norkin, 2001).

Limitations

1. The piezo resistive sensors measured the pressure normal to the surface of the foot (i.e. shear forces were not measured).
2. Only pressure values were measured throughout the task.

Delimitations

1. Subjects wore their own skates.
2. All subjects were male.
3. Subjects included both forwards and defensemen.

4. Only high intensity backward cross-over skating was examined (maximal velocity).

Chapter 2: Literature Review

Chapter 2

Literature Review

2.1. Origins of ice hockey

The sport of ice hockey is a high impact, very physical sport in which the participants face shots of over 100 KPH. It has become a focal point of Canadian culture, and a sport in which Canada is known to be able to compete with any other country in the world. Interestingly, the sport which is known for its ferociousness, speed, and violence was born out of a period of social reform in Canada, where the popular pastimes that involved gambling, violence, and disorderliness were being replaced by more "civilized" leisure activities imported from Europe (Robidoux 2002). Internationally, Canadians are generally perceived as peacekeepers and often overly polite, and despite the repeated threats of national separation, the one thing that has remained constant is Canada's expression of nationalism through the aggressive sport of ice hockey (Robidoux 2002).

A picture of children playing hockey on a frozen pond appears on the Canadian five-dollar monetary bill demonstrating the impact the sport has on Canadian culture. It is currently practiced in organized leagues by males and females of all ages, and has evolved into a national passion for many Canadians. It is uncertain and controversial exactly when and where the sport originated. Some reports claim it originated around the year 1800, with students at Canada's King's College, when they adapted the existing field game of hurley to the ice of their favorite skating pond. This led to the creation of a new winter game called ice hurley, which gradually became ice hockey (http://www.sihrhockey.org/origins_report.cfm#intro 2005).

Others have claimed that the origins of the game date even farther back to the 17th century in Huronia, Ontario. It was played there with a shepherd's stick, known in French as a "hoquet", turned upside down and a wooden ball. The French term for the shepherd's stick is believed by many to have led to the naming of the sport "hockey" (Robidoux 2002). There have also been even earlier references of the origins of the sport by ancient painters, one of which, Romeyn de Hooghe who resided in Holland from 1645-1708, showing a man on skates with a ball and a stick, which may be interpreted as a precursor to ice hockey players. However, it is now believed that this painting was of a type of Golf or polo on ice, rather than a form of ice hockey. Another piece of evidence supporting that ice hokey may have originated in Europe comes from a German by the name of Franz Kreisel, who wrote an ice hockey textbook after World War II in which he claims that in the 15th century a game very similar to ice hockey was played with a ball on ice in Friesland (http://www.iihf.com/iihf/history/origins.htm 2005).

There is no doubt that the game of ice hockey was created with much European influence, as it attributes many of the aspects of early European stick games such as bandy, shinny, hurley, and lacrosse. Combined with the cold winters and abundant amounts of ice, the English, Scottish, Irish, and French settlers developed the rules which led to the creation of the sport of ice hockey (Pearsall et al. 2000). Many variations of the sport were played and experimented with before the definitive version of the game evolved and was enthusiastically embraced by Canadians from the east to the west coast. From the games played in Windsor in the early 1800's, hockey had spread to Quebec by 1875, and reached Victoria, British Columbia by 1890, becoming a coast to coast Canadian game (http://www.virtualmuseum.ca.html 2005).

The sport has continued to evolve at a rapid pace and is now played throughout the world, despite the lack of natural ice in certain areas (Pearsall et al. 2000). The National Hockey League was developed in 1917, and hockey was included in the 1920 Olympic Games (Davidson, Steinbreder 1997). The sport has since developed into a billion dollar business with the development of the National Hockey League (NHL), consisting of highly-skilled professional athletes skating better and faster than ever, capable of shooting a puck at velocities around 160 KPH, where the use of physical force such as full speed body checking is encouraged and loved by the game's fans. The tremendous popularity that the sport now has throughout the world has led to a desire to increase athletic performance. Much research has gone into the development of technologically advanced equipment in order to improve skating technique and speed, shooting strength and accuracy, and overall comfort and protection.

2.2. The Skate Boot

Skating can be defined as "the act of moving or gliding over ice while supported on steel runners attached to the boot or shoe" (Minkoff 1994). Skating is an integral part of three distinct sports; speed skating, figure skating, and power skating, each with their own distinct characteristics and goals. Power skating, also referred to as ice hokey skating, is unique among these three sports as one must combine many different skills in order to perform at an elevated level. It encompasses forward and backward power skating at ever changing velocities, starts and stops, and lateral movements (Humble, Gastwirth 1988; Marino 1997). As a result, the skate boot is a crucial part of ice hockey performance as it is the "moderating link between the power generator (lower extremity of the skater) and the ice surface" (Minkoff 1994). Thus, changes in skate design could affect skating efficiency and technique, leading to either an increase or a decrease in comfort and performance (Goudreault 2002). The skate boot is comprised of an outer covering of leather or composite material, the heel counter, the toe box, a rigid plastic sole, the skate blade housing, a metal blade, an achilles tendon guard, and a padded tongue (Pearsall et al. 2000).

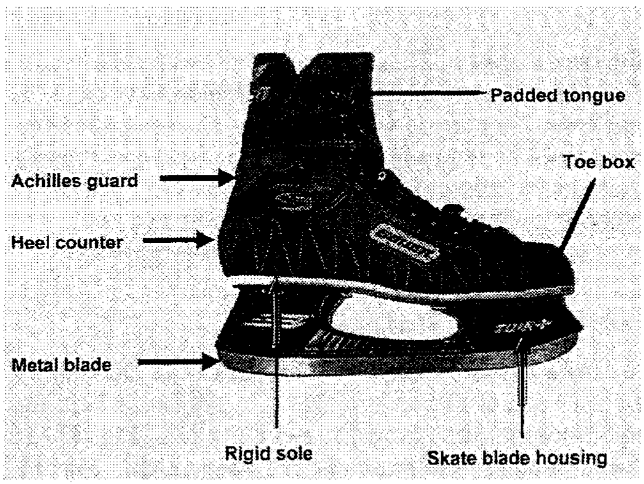


Figure 2.1: The modern skate boot (Pearsall et al. 2000).

The skate boot has evolved drastically from its early origins in Scandinavia, where animal bones were simply attached to a walking boot in order to facilitate travel across icy regions during approximately the 9th century (Montgomery 1988; Vaughn 2001). In the late 1880's, the metal blade was attached to the boot by means of a wooden support. This was later replaced by an all metal blade assembly, which added substantial weight to the skate boot thus reduced skating speeds, but increasing durability and maneuverability (Minkoff 1994; Pearsall et al. 2000). During the 1950's, in order to decrease the weight of the skate, tubular skate blades were developed. During the 1960's and 1970's several safety features such as covered blade ends, combined with the use of composite plastics such as polyethylene resins, carbonates, and fiber glass, led to further decreasing skate mass and increasing performance (Couture 1989; Pearsall et al. 2000).

Variables other than those involved in the manufacturing of skates exist which may also affect skating performance. For example, there has been much research performed by the Ice Skating Conditioning Equipment Corporation, which was supported by the International Olympic Committee, that looked at these other factors, which include; edge sharpness, blade geometry (including thickness and taper of the blade, and rocker radius), and the boot-to-blade angle (Minkoff 1994).

The skate blade consists of two sharpened edges separated by a groove called the hollow. The depth of the hollow can range from shallow to deep, each with its advantages and disadvantages. For instance, a deep hollow leads to a sharper blade edge, meaning that the blade penetrates deeper into the ice, thus improving start and push-off force, but compromising smooth starts. Conversely, a shallow hollow leads to less of the blade penetrating the ice, which diminishes agility and push-off power (Minkoff 1994). Players are constantly aware of their blade edges and modify them according to their personal preferences and position.

Both edges of the skate blade are crucial to skating performance during the game of ice-hockey. The inside edge of the skate blade is used primarily during the push-off and glide phases of the skating stride, while the outer edge is used mostly for stops and turns (Pearsall et al. 2000). The width of the skate blade itself has also been experimented with, with the notion that a narrower blade would increase the amount of force per unit area in contact with the ice. The increase in force would lead to a facilitated penetration of the blade into the ice, and increase the power of the stride while reducing the frictional resistance of the skate blade. In theory this seems sound, however the thinner blade makes sharpening the blade very complicated and the necessary blade hollows are difficult to create (Minkoff 1994).

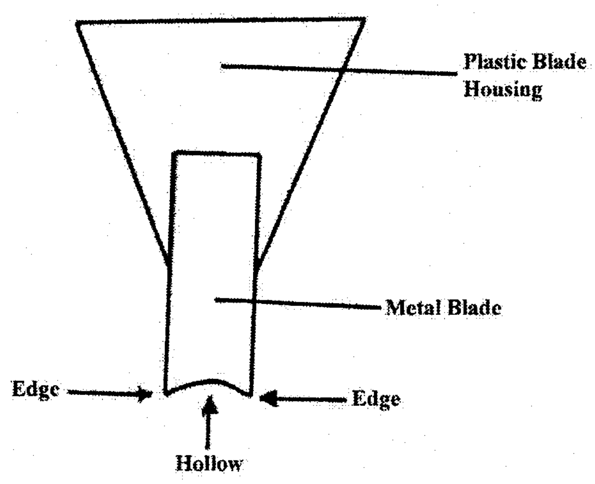


Figure 2.2: Frontal view of the skate blade and housing (Minkoff 1994).

The skate blade is also created with a degree of curvature along the blade which is called the rocker (figure 2.3). The rocker may also alter skating performance as professional players have reported an increase in agility when using a smaller rocker radius (increased curvature), such as 7 or 9 feet, while they have also stated an increase in stability with an increased rocker radius (flatter blade), such as 11-13 feet. It is also important to note that the centering of the rocker is also critical to performance. If it is too far anterior or posterior the skills of starting, turning, stopping, passing, and shooting can all be affected (Minkoff 1994).

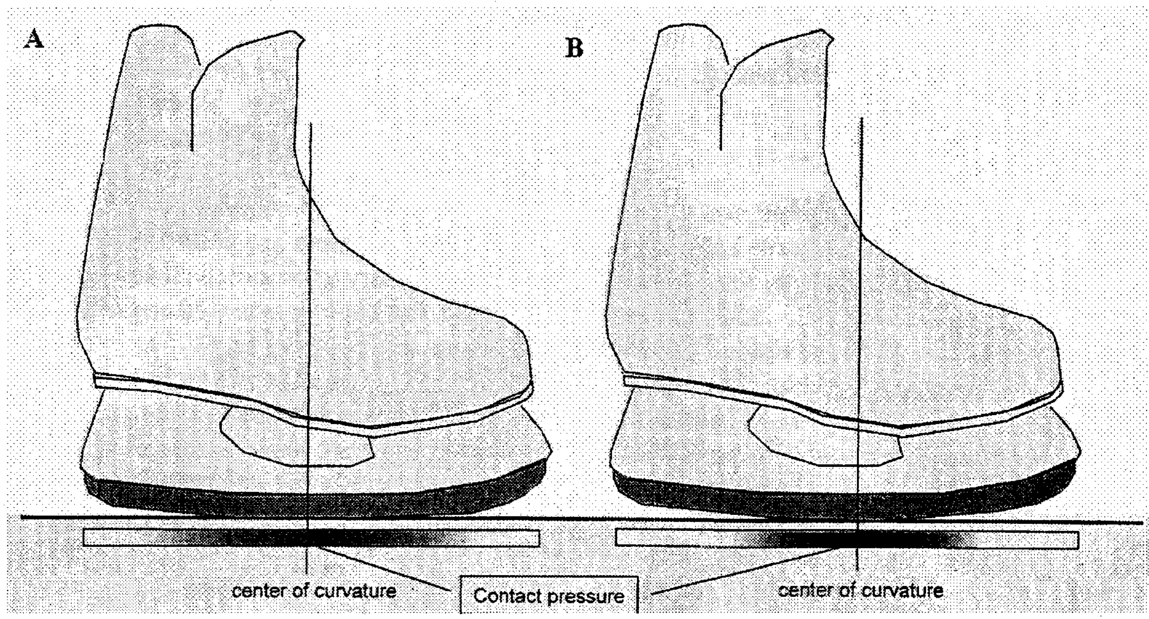


Figure 2.3: The blade rocker radius. A) A skate with a 2m rocker radius. B) A skate with a 3m rocker radius. (Pearsall et al. 2000)

Not only is the skate boot important for performance, but it also serves a crucial role for protection of the foot. It has been reported that amateur adult ice hockey players are capable of displacing the frozen, vulcanized, 6 ounce rubber puck at a velocity greater than 90mph, and professionals can reach over 120mph (Green, Dillman 1984). Puck impact forces have been estimated to exceed 1200 lbs (Haas 1990), which could potentially shatter the foot and ankle if left unprotected. It has also been shown that ice hockey players often suffer bursal enlargements over the malleoli due to repeated puck impacts (Minkoff 1994). Sim et al. (1989) compiled data on the mechanisms of ice hockey injuries, noting that the puck is responsible for 15-20% of total injuries. In a study comparing male and female ice hockey players injury rates it was shown that ankle injuries are the third most prevalent form of injury for female players, and is the sixth most common form of injury for the males (Schick et al. 2003). It has also been shown that 15% of inline skating injuries arise from the foot and ankle area (Schieber, Branche-Dorsey 1996).

In another study, the injury rates of eight NCAA division 1 level universities were analyzed and it was shown that the skates, sticks, and pucks were only directly responsible for 11.5% of the total injuries sustained by the players (Flick 2005). The study also notes that 12% of the total injuries are to the foot and ankle. Recovery times for syndesmotic ankle sprains (high ankle sprains) were the longest. This type of injury appears to be very common in ice hockey players due to the elevated skate blade combined with the high skating speeds and rapid direction changes. This places the ankle in a vulnerable position for torque injuries if one was to hit a rut or crack in the ice during this type of movement. Therefore it appears that the stiff skate boot may provide adequate support for the ankle itself, but may place the region directly proximal to the skate boot at high risk (Flik 2005). This seemingly almost sport-specific injury indicates that further biomechanical analysis of power skating skills is necessary in order to further ensure safety and decrease injury rates for the participants.

It has been stated that there are two important aspects with regards to skates. The first being the aforementioned importance of the skate boot with regards to protection against impacts and cuts, and the second consisting of proper fit, comfort, and support, allowing for the required range of motion necessary to play the sport of ice hockey (Hoshizaki et al. 1989). It has been demonstrated that power skating places specific aspects of the foot under tremendous pressure during the forward stride (Dewan 2004). Therefore, it seems highly likely that the other skills involved with performing the sport, such as tight-turns, stopping, and backward skating will place certain areas of the foot under periods of high pressure as well. This can be detrimental as Brand defines pressure as "the critical quantity that determines the harm done by force" (Brand 1988). It has been shown that skin disorders are among the most common overuse injuries for athletic individuals (Grouios 2004). Competitive athletes who engage in physically demanding, repetitive activities, or high-impact sports that place mechanical stress on pressure points between the skin and bones, are the most susceptible. Generally, the feet, which are considered the most overlooked and mechanically complicated part of the human body, succumb to all of the impacts, friction, and pressures, during the sport, leading to the formation of corns and calluses (Grouios 2004). They can severely affect an athletes' performance as they can lead to considerable discomfort and pain (King 1997).

Proper footwear fit can reduce the chances of developing skin disorders due to repetitive stress and pressures, and may also decrease the chances of developing other more serious injuries. For instance, recently there was a case reported where a hockey player wearing inflatable hockey skates developed tarsal tunnel syndrome. The skates caused the entrapment of the posterior tibial nerve due to an excessive amount of pressure in that region (Watson et al. 2002). There was also a case of a hockey player developing posterior ankle impingement syndrome. This is generally the result of repetitive or forced plantar flexion of the foot, and occurs due to the talus and surrounding soft tissues being compressed between the tibia and calcaneous (Bureau et al. 2000).

2.3. Skating in Hockey

Ice hockey is a physically intense, and rapid game where "skating is without a doubt the most important aspect" (Humble, Gastwirth 1988). The Central Scouting Bureau of the National Hockey League identified 10 task requirements which they believe define a hockey player. They consist of skating, shooting/scoring, position play, checking, puck control, passing, hockey sense, desire/attitude, and toughness/aggressiveness. In a survey of 16 professional scouts, skating was ranked the most important task requirement for both forwards and defensemen (Renger 1994). The study also demonstrated that acceleration and speed were the two most important aspects of skating for hockey players who play the forward position, and that backward skating and mobility tasks were most important for defensemen. Stamm (1989) also stressed the importance of the refinement of skating technique when she stated, "[a] player's skating ability must be honed so sharply that their reactions become second nature". The game evolves at such a rapid pace and is filled with unexpected events and situations that players do not have time to consciously think about skating technique (Stamm 1989). Despite the great importance of skating ability to the sport, there have been very little biomechanical studies analyzing skating technique. This is due mainly to the rapid flow of the game and the lack of repetitive cyclic movements, which are seen in other frequently studied sports (Humble, Gastwirth 1988).

2.4. Basic Kinematics of Skating and Ice Friction

Like most forms of human locomotion, the movement pattern for ice hockey skating is biphasic, with a support phase and a swing phase. The support phase can again be subdivided into two categories; a period of single support followed by a period of double support as can be seen in figure 2.4 (Humble, Gastwirth 1988; Pearsall et al. 2000). The skater is in each period for approximately 18% and 82% of the stride respectively (Minkoff 1994). The technique used for propulsion during ice skating is unique from other forms of human locomotion due to the ice surface's low coefficient of friction. In the walking and running gait cycles, a great amount of linear shear forces develop during the contact period by friction from the ground (Root 1977). In those tasks, the reactive push-off force is simply elicited in the backward direction, causing forward acceleration (Pearsall et al. 2000).

Forward propulsion is not as simple on ice due to its "slipperiness". Ice friction can be described by its relationship to surface friction; $\mathbf{F_{ice} = \mu N}$, where N equals the normal force (approximately equal to body weight) and μ represents the ice friction coefficient (Van Ingen Schenau et al. 1989). It has been reported that the coefficient of friction for properly treated ice rinks is approximately 0.004 (Minkoff 1994). Therefore, with skating, due to the low coefficient of friction between the skate blade and the ice surface, little force can be elicited by pushing off parallel to the long axis of the skate blade.

Therefore, in order to produce forward movement skaters use the reactive forces that are elicited perpendicular to the skate blade. In order to do so the skate must be angled in a different direction to the skater's direction of travel by an angle θ, which is known as the angle of propulsion (Hoshizaki et al. 1987). As a result, the component of the horizontal force (F) that propels the skater in a forward direction is given by F (sin θ) (Humble, Gastwirth 1988). Hence, for forward propulsion, the skater rotates externally at the hip and abducts the foot, which places the skate blade on its medial edge through ankle pronation, at a blade-to-ice angle of approximately 45 degrees to the ice plane, and pushes in a lateral direction, resulting in strides that are oblique to the intended line of direction as demonstrated in figure 2.4 (Pearsall et al. 2000; Humble, Gastwirth 1988; Stamm 1989). Consequently, the skate and the skater are moving in different directions, and the skater must conclude his stride before the skate extends too far laterally from his center of gravity. Thus, as the skater accelerates, either the angle of propulsion or the time period for which the leg is extended must decrease (Humble, Gastwirth 1988). A study by Lariviere (1968) demonstrated that it is in fact the angle of propulsion that decreases as a skater gains speed. During the thrust, the contralateral skate blade is placed in the line of progression because this position presents minimum resistance against forward movement (Humble, Gastwirth 1988). This phase, where both skates are in contact with the ice surface, is called the double support phase, and ends at which point it is called the single support phase when the thrusting leg loses contact with the ice. This leg then repositions itself in order to prepare for its own glide phase (Chang 2002).

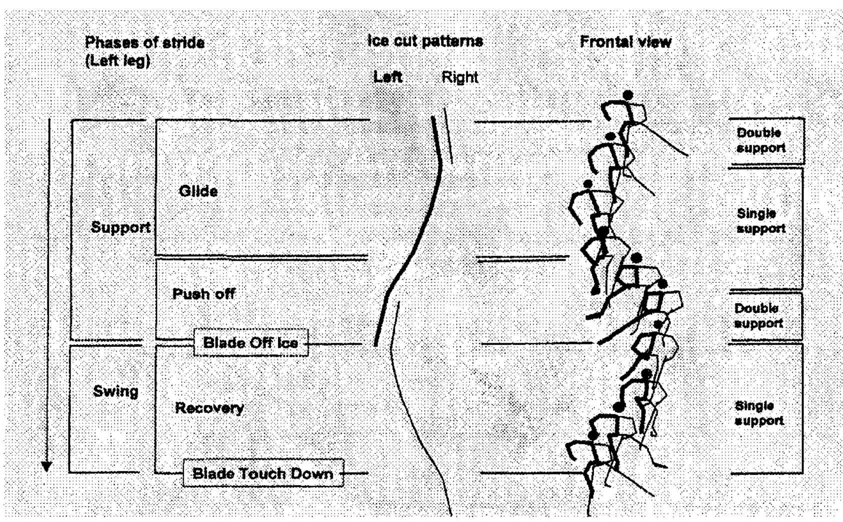


Figure 2.4: The various phases of the forward skating stride and the sinusoidal stride pattern. (Pearsall et al. 2000).

2.5. Forward Skating Research

In terms of skating research, the majority of our knowledge concerning mechanics of the forward stride comes from speed skating research. Although the general movement patterns are very similar between both types of skating, there are fundamental differences in equipment, skill, repertoire, and play context (Marino 1997).

There has been a great deal of research concerning the biomechanics of speed skating. It was found that the gliding push-off technique is a very constrained movement due to the fact that the speed skater not only has to keep his trunk horizontal to reduce air resistance, but must also suppress plantar flexion of the foot in order to prevent the tip of the blade from scraping into the ice, causing a reduction in speed and loss of balance (Ingen Schenau 1982; Ingen Schenau et al. 1985; Houdijk et al. 2000). It has been demonstrated that the suppression of plantar flexion limits the contribution of the plantar flexor muscles and is accompanied by an incomplete knee extension at the end of the push-off (Houdijk et al. 2000). This is due to the manner that the rotational velocity from the rotation of the upper and lower legs is transferred into translational velocity of the body's center of mass. The transfer of velocity is constrained by the geometry of the body, leading to a decrease in hip velocity before full extension of the knee as it moves away from the ankle (Houdijk et al. 2000). The decrease in velocity has been shown to occur at a knee angle of about 150 degrees (Ingen Schenau 1985). After this point, due to the inertial forces stemming from the gliding leg and the trunk, the push-off leg is pulled off the ice, and the remaining range of knee extension is performed as the skate is no longer on the ice (Houdijk et al. 2000).

Research conducted on vertical jumping has shown that well-timed, fast hip, knee, and ankle extensions, resulted in greater ranges of motion while in contact with the ground, allowing the muscles around those joints to perform more work (De Koning et al. 2000; Bobbert et al. 1988; De Koning et al. 1991). Therefore, the ability to plantar flex the foot not only allows the ankle muscles to perform more work, but the knee and hip extensors as well (Houdijk et al. 2000). It was hypothesized that a hinged blade under the metatarsal-phalangeal joints would allow the blade to remain on the ice for a longer period of time, allowing the skater to plantar flex his foot, therefore leading to an improvement in performance. The newly hinged skate was named the "klapskate", and following its acceptance, all speed skating records were broken by the 1997-1998 season (Houdijk et al. 2000).

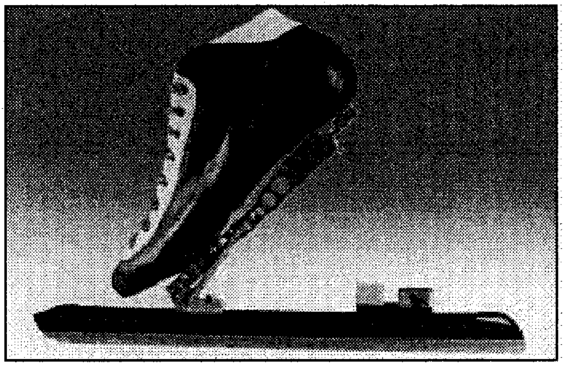


Figure 2.5: The Klapskate.

It is very challenging to conduct sound biomechanical studies focusing on ice hockey skating due to the rapid pace of the game, the complexity of the skills performed, as well as the location in which the sport is practiced, as the skills cannot be analyzed in a laboratory setting. Despite these challenges, a few studies have been carried out. Hoshizaki et al. (1979) investigated the kinematic pattern of the talocrural and subtalar joints during the acceleration phase of the forward skating stride, at maximal velocity. They noted that between touchdown and the heel-off of the contact phase for an accelerating skater, the ankle undergoes dorsiflexion and pronation, which provides a stable base for the forces produced during hip and knee extension, which then follows the ankle actions. Hip and knee extension is then followed by plantar flexion and supination at the ankle. The authors also found that a significant portion of the ice reaction force comes from ankle plantar flexion in both the sagittal and frontal planes, as the skater presses the tip of the skate blade against the ice. In addition, they found that the effectiveness of this action diminishes as the skaters gain speed as they can no longer plantar flex quickly enough to further accelerate their center of mass (Hoshizaki et al. 1979).

Hoshizaki et al's previous findings led them to investigate whether the support from a normal skate boot limits the range of motion at the talocrural and subtalar joints. For this study, identical skates were used, except that one pair had the support above the malleoli removed. The study demonstrated that retaining the support above the ankle did alter the general displacement patterns of the ankle in both the frontal and sagittal planes. Due to the greater degree of plantar flexion and supination at the toe-off and greater pronation prior to heel-off, larger ranges of motion were seen when skaters used the modified test skate. The larger range of motion may have led to the resulting greater horizontal acceleration values, by permitting the skaters to apply force over a larger range of motion (Hoshizaki et al. 1979).

The authors then compared the range of motion for six different skates and the same test skate. The skates were first tested under static loads for dorsal and plantar flexion, supination and pronation, and the subjects were required to perform forward acceleration, starting and stopping, and tight-turns. The authors concluded that the skate boot does affect the range of motion at the talocrural and subtalar joints, but that the molded skates did not decrease the range of motion during the 3 skating tasks investigated in this study (Hoshizaki et al. 1979).

A similar study was conducted where the range of motion, elastic moment, and stiffness of the ankle joint complex where all measured, with and without a variety of hockey skate boots, in order to investigate the influence of a skate on the ankle motion (Hancock et al. 1999). Ten males were studied, using an isokinetic dynamometer that rotated the ankle joint complex at a fixed angular velocity of 3 degrees/sec throughout a full range of dorsiflexion and plantar flexion. The bare ankle was tested first, followed by three test skates: a current model skate, a "minimal skate", which has had all of its structural material above the malleoli removed, and a hinged inline skate. Results demonstrated that the bare ankle and "minimal" skate conditions responded similarly, while the current model skate and the hinged inline skate also showed virtually equivalent values. It was shown that ankle dorsiflexion was not significantly different between any of the test groups. Ankle plantar flexion was reduced in the current model skate and the hinged inline skate due to the rigid achilles tendon guard on the posterior aspect of the skate. The authors suggest that if the joint restriction is excessive a skater may have to adapt a change in skating technique, which could lead to premature fatigue or a decrease in skating performance altogether, and that manufacturers should be aware of these factors when designing a skate boot for optimal performance (Hancock et al. 1999). Further biomechanical research examining the potential effects of the restriction in ankle plantar flexion due to the rigid achilles tendon guard are needed in order to determine optimal skate boot design for the various important ice hockey skating skills.

One development that had facilitated ice hockey skating research is the skating treadmill. Since its development, several studies have used it in order to investigate various biomechanical aspects of the forward power skating stride. Hinrichs (1994) compared lower limb muscle EMG patterns of the power skating stride on ice and on the skating treadmill. The muscle recruitment patterns of the tibialis anterior, medial head of the gastrocnemius, vastus medialis, rectus femoris, adductor longus, biceps femoris, and gluteus maximus were all analyzed. The adductor longus muscle was the only muscle to demonstrate a significant difference between both conditions. The initial activation patterns are similar for both conditions, but the on ice condition elicited a second spike in activation sooner than the treadmill condition (46.3% and 57.8% of the stride respectively). This difference is perhaps explained by the fact that the adductor muscles are thought to act as hip stabilizers during this part of the skating stride, and do not need to become active as early due to a slightly different foot placement because of the skating surface moving under the skate (Hinrichs 1994). The overall results of this study suggest that the muscle recruitment patterns during treadmill skating are similar to on ice skating.

Goudreault (2002) also used the skating treadmill in order to examine muscle activation patterns during the forward power skating stride. She had skaters skate at three different velocities (12, 18, and 24 kph), and looked at the activation patterns of the vastus medialis, biceps femoris, adductor magnus, gluteus maximus, tibialis anterior, peroneus longus, and lateral gastrocnemius. Similar activation patterns to those shown by Hinrichs (1994) were observed, and it was also demonstrated that EMG amplitudes were significantly higher for all of the tested muscles at the 24 kph speed when compared to the 12 kph condition, demonstrating that an increase in velocity results in an increase in the amount of muscle activation, yet the muscle activation patterns remain the same (Goudreault 2002).

Ankle kinematics during power skating were also analyzed using the skate treadmill by Chang (2002). For this study, five elite hockey players skated at 12, 18, and 24 kph, and ankle motion in the frontal plane (inversion and eversion) and in the sagittal plane (plantar and dorsiflexion) was measured using flexible goniometers. They were placed along the posterior aspect of the lower leg and heel allowing measurement across the ankle and subtalar joint complex. In general, the results indicate that as the skating velocity increased, ankle range of motion also increased (Chang 2002).

Plantar pressures during the forward skating stride were analyzed by Loh (2003) and Turcotte (2004). They compared plantar foot pressures in forward skating on ice and on the treadmill at speeds of 22, 24, 26 kph, by using F-Scan™ sensors, recording at 60Hz, which were cut to fit each skaters skate. The purpose of their studies was to further the knowledge base regarding the understanding of the forward power skating stride, and to determine the extent of similarity between skating on-ice to skating on the treadmill. It was concluded that there was a heel to toe shifting of force distribution during the stride, that the force profile of the forward stride was bimodal, and that the pressure on the medial and lateral sides of the heel and forefoot essentially mirrored each other (Loh 2003). It was also shown that with an increase in speed there was a tendency for an increase in peak forces at toe-off, and that the whole foot force-time patterns were essentially equivalent between on-ice skating and treadmill skating for equivalent speeds except for significant differences during heel loading. The treadmill heel loading force values were approximately 30% greater than those observed during on-ice skating. The authors explain that this can perhaps be due to the different skating surfaces, as there is greater friction and a rougher texture on the treadmill, leading to less glide. It was also shown that as the speed increased, the duration of skating forces during the stride support decreased, while stride frequency increased (Turcotte et al. 2004).

Although the research conducted on the forward power skating stride has, for the most part, demonstrated similar biomechanical aspects between skating on ice and skating on the treadmill, research has revealed that a familiarization period is needed in order for the subjects to fully be acclimatized to skating on the treadmill (Broad et al. 2004). Differences were seen in stride rate, heart rate, oxygen consumption, and muscle activation patterns, at the same velocity over five acclimatization sessions. Therefore, it appears to be beneficial to perform on-ice testing when possible, in order to more accurately replicate on-ice situations.

Other studies have looked at pressures during the speed skating stride (De Boer et al. 1987; Jobse et al. 1990). Both studies used similar methodology, measuring push-off forces through the use of two strain gauges. De Boer et al. (1987) placed one strain gauge in the front and the other in the back of the skate, between the shoe and the blade. Jobse et al. (1990) placed his strain gauges into the blade holders. Both studies showed similar results, demonstrating a double peak in force patterns during the stride. The first peak occurred in both the front and back of the skate, corresponding to the period when the skate blade touches the ice. The second spike occurred during the push-off period and was seen at the front of the skate, where the majority of the push-off forces are generated. De Boer et al. (1987) demonstrated that between both spikes there is a period where the measured forces decrease below the skater's body weight (figure 2.6). This period coincides with the glide phase of the stride.

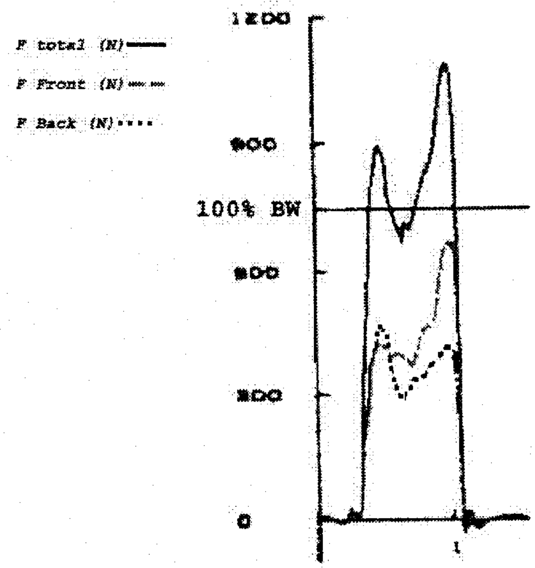


Figure 2.6: Force vs. time graph during speed skating. The dashed line represents the force at the front of the skate. The dotted line depicts the forces recorded at the back of the skate. The solid line represents the sum of the forces at the front and back of the skate (De Boer et al. 1987).

One study conducted on-ice looked at the biomechanics of the foot and ankle during the acceleration and steady-state skating strides of five elite hockey players using kinematic, kinetic, and myoelectric measures (Dewan 2004). An eletrogoniometer was used to measure the angular displacement values of the ankle joint. Myoelectric activation patterns of the vastus medialis, tibialis anterior, peroneus longus, and medial gastrocnemius muscles were all measured. Kinetic pressure profiles of the skate boot-to-foot and ankle interface were also measured using sixteen flexible piezo-resistive sensors taped to discrete anatomical surfaces of the plantar, dorsal, medial, and lateral surface of the foot, well as to the posterior aspect of the heel and leg (Dewan 2004). Few significant results were demonstrated from this study, perhaps due to the relatively small sample size, but many interesting observations were made. For instance, it was shown that the overall shape of the plantar-dorsiflexion and the inversion-eversion curves was similar for the acceleration and steady state strides. Plantar flexion was shown to increase throughout the accelerating strides until it reaches its peak during the steady-state stride. It was also shown that this peak occurs at approximately 63% of the stride, demonstrating that peak ankle plantar flexion occurs while the blade is off the ice during the swing phase (Dewan 2004).

Dewan's study is the only one in which the entire foot was analyzed for pressure patterns during any form of skating. The results demonstrated that the largest pressure points were found on the plantar surface of the foot, including the plantar aspect of the first metatarsal head, medial and lateral heel, and on the ankle, about the medial and lateral malleoli. The study also showed that there is very little pressure generated on the posterior aspect of the foot and ankle, hence the reasoning for not placing any sensors in these locations for the current study. The results also suggested that the plantar lateral pressures become successively lower the more distal (towards the forefoot) the sensor is located. Another interesting finding from this study is that the medial heel rather than the lateral heel bared the majority of the load, which is the opposite of what the running research has demonstrated (Hennig, Milani 2000). Dewan explains that this occurrence is perhaps due to the greater medial-lateral whole body shift that occurs as the body progresses in a sinusoidal pattern within the transverse plane and/or the oblique orientation of the skate boot/blade to the ice (2004). Increasing pressure in the medial calcaneous was shown to coincide with ankle eversion. Also, pressure on the lateral malleolus was shown to increase as the ankle everts and decrease as it begins to invert during the swing phase. The pressure profiles of the medial malleolus and lateral calcaneous both demonstrated an increase in pressure during the early stance phase followed by a substantial lowering as the phase progressed. Peak dorsal pressure was shown to occur at the same time as maximal ankle dorsi flexion, and decrease as plantar flexion increased (Dewan 2004).

2.6. Starting and Stopping Research

Although there are many skating skills that are fundamental to the sport of ice hockey, problems in designing sound experimental conditions for biomechanical assessment has prevented extensive research in this area. "The ability to start quickly from either a stationary or gliding position and reach a high velocity in a short time period is probably one of the most important skating skills in the game of hockey" (Marino 1997). A few studies have looked at starts and stops. For instance, Naud and Holt (1974) compared three different start techniques using 24 professional and amateur skaters. The authors looked at the front start, the cross-over start, and the thrust/glide start. Results indicated that the thrust/glide technique was the fastest for all groups, except for the professionals, who showed no differences between techniques. Naud and Holt (1980) also studied stop/reverse, and start strategies. Two stop techniques were examined, including the parallel stop and a skate inline stop, followed by either a cross-over with the two stops or a thrust/glide start after a parallel start. The results showed that the thrust/glide after the parallel stop was the superior strategy to stop and change directions.

The forces produced by the skate blade against a simulated synthetic ice surface attached to a force plate during the performance of the side, front, and cross-over start was analyzed by Roy (1978). Results demonstrated that the cross-over and side start techniques produced the greatest vertical and forward impulses (Roy 1978).

Moreover, Marino (1983) conducted a correlation study and a multiple regression study (Marino, Dillman 1978) demonstrating that the stride pattern which leads to the fastest acceleration in a front start is composed of a high stride rate, significant forward lean, a low push-off angle, and placement of the recovery foot almost directly under the hip joint, rather than in front of the body.

2.7. The Backward C-cut Stride

The skill of backward skating is a fundamentally important task when playing the sport of ice hockey (Renger 1994; Marino 1997). It is not only essential that defensemen perform the skill with ease, as they must cover their team's flanks against the oncoming opponents, but all of the players on the team who at one time or another will have to play defense. If this is not done effectively the opposing team will have a distinct advantage (Stamm 1989). There are two common forms of backward skating: the C-cut stride and the cross-over technique. The backward cross-over stride is commonly used to accelerate. The skater then switches to the C-cut technique in order to stay directly in front of the oncoming opponents. This technique also keeps the feet in a neutral position, allowing the defender to move easily from side to side to either block or check the adversary. Many skaters prefer using the cross-over technique as it allows one to go faster. This technique can also be dangerous as a defender who crosses over prematurely will be committed to that direction, which could allow the oncoming player to simply go the other way (Stamm 1989).

The C-cut stride can be divided into four parts: the wind-up, the release, the follow-through, and the return. For the wind-up, the skater must put his weight on the pushing foot, and bend his knees. The knee of the pushing foot should be out ahead of the tip of the skate. The pushing foot must be pivoted so that the heel is outward, almost forming a right angle with the opposing skate, meaning toes together with the ankles apart. The inside edge of the pushing foot's skate blade then dig into the ice by everting the ankle and bending the knee so that the skate and lower leg form a 45 degree angle to the ice (Stamm 1989).

The next step is the release. This occurs by using the inside edge of the pushing skate to forcefully cut the letter "C" into the ice. At approximately 50% of completion of the "C", the skater must then transfer his weight onto the front half of the gliding foot, making sure that the entire blade is in contact with the ice however, while continuing to thrust the pushing leg to full extension (Stamm 1989).

Next is the follow-through phase, where one must continue to thrust until the leg is fully extended. The final thrust comes from the front of the inside edge of the skate blade. When it is completed the skater must keep that foot on the ice. It is important that while this is occurring with the thrusting leg, the gliding skate remains aimed straight backward, and the knee of that leg is well bent. The last step is the return. This is when the pushing foot has finished its thrust and has reached full extension, and must quickly be returned under the body to prepare for the next thrust performed by the other foot. To do so, the heel is pivoted inward, and the skate is drawn under the hips, maintaining ice contact the entire time. This should place both feet side be side in an almost parallel position. The cycle then continues with the opposite leg being the thrusting one.

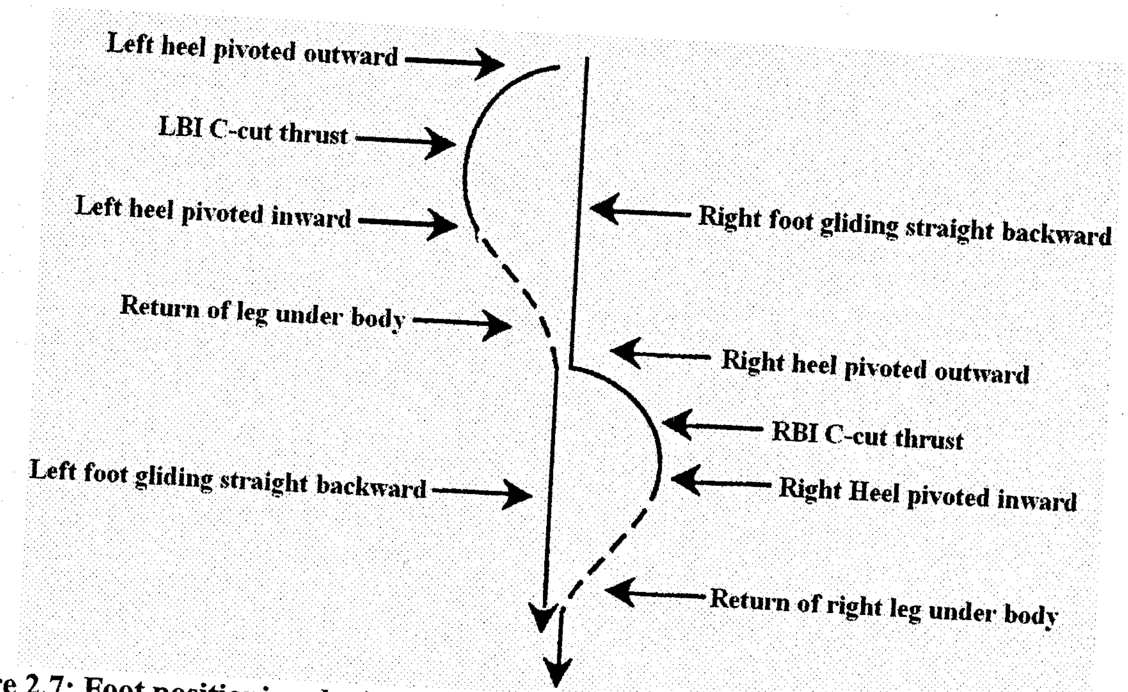


Figure 2.7: Foot positioning during the backward C-cut stride (Stamm 1989).

2.8. Cross-overs

Cross-overs can be performed in both the forward and backward direction, and are used to swerve in and out of traffic, skate corners, or to rapidly gain speed, and are vital to a hockey player's performance. They are the fastest and most effective way of accelerating backward (Stamm 1989). A cross-over stride refers to when a skater passes the outside foot over the toe of the inside foot, as the inside foot is crossing under the body in the process of thrusting. Both the forward and backward cross-overs are composed of two push phases: the stride push and the cross-under push.

In forward cross-overs the stride push is executed by the outside leg and is the one that will cross-over the other skate. The stride is performed by gliding on the outside edge of the skate blade of the inside foot, and the inside edge of the outside foot's skate blade. The skater then places his/her weight on the outside foot, bends at the knees and digs the inside edge of that skate into the ice as to form a 45 degree angle with his/her leg and the ice. The skate blade should also be at a 45 degree angle with the ice, and the skater should push to the side and back with the entire inside edge of the outside foot. The thrust should begin by using the heel area of the inside edge and should progress toward the front of the foot as the stride continues and end with a "toe flick" from the front of the inside edge. At approximately the midpoint of the stride the skater should transfer his/her weight from the inside edge of the outside foot onto the outside edge of the inside foot, or the gliding foot. The knee of the inside foot should remain well bent until the outside foot has been fully extended and has come off the ice. As soon as it comes off the ice the skater should begin crossing it over the front of the inside foot, keeping it as close to the ice as possible. As the skater is crossing the outside foot over the inside foot, the second push is occurring, called the cross-under push. During this push the body weight is placed over the outside edge of the inside foot and the blade to ice angle is decreased by applying more pressure to the outside of the skate boot. The skate should be thrusted outwards and to the back, underneath the skater's body. It should begin by using the heel of the outside edge, and as the strides progresses, the weight should be shifted towards the front of the skate, ending with a toe flick. At about midpoint of the cross-under push, the outside foot should be placed back on the ice, on its inside edge. The skater should continue pushing off this leg until it is fully extended, and then return it quickly to its starting position beside the other foot (Stamm, 1989).

There has not been much research examining the biomechanics of the forward cross-over stride. Most of the knowledge on cross-over skating technique comes from speed skating studies examining skating the curves of a speed skating track. Marino (1979) and Stamm (1989) suggested that the general movement patterns of the forward ice hockey cross-over stride and the cross-over stride in speed skating are very similar. A study by De Boer et al (1987) examined the differences between the inside and outside legs of the speed skating cross-over. The results demonstrated that the inside foot's push-off stride is shorter than the outside foot's, which is due to a shorter gliding phase. It was also shown that the inside foot's push-off angle (angle between the push-off leg and the vertical) was greater throughout the entire stride. The knee angle during the cross-under push was also found to be smaller than the outside knee's during its push-off phase. A higher knee maximal velocity was also found during the inside leg's push. The higher knee maximal velocity and greater push-off angle for the inside leg suggests that the cross-under push is the more powerful of the two push-off phases of the forward cross-over stride.

In another study comparing the inside and outside legs during the speed skating cross-over, De Koning et al (1991) measured the kinematics, muscle activation patterns, and push-off forces in 7 elite speed skaters. Greater net moments at the hip and ankle joints of the inside leg were observed, which was explained by their muscle activation pattern findings. It was shown that the semitendinosus, rectus femoris, and the gastrocnemius muscles of the inside leg demonstrated greater levels of activation than the outside leg. It was explained that this is due to the inside leg being required to maintain a more horizontal positioning throughout the stride, leading to differences in joint moments between both legs.

In backward cross-overs the stride push is essentially the same as the C-cut thrust of the backward C-cut stride, with the exception that on the return phases, the outside foot crosses over in front of the inside foot, instead of centering under the body. Prior to the outside foot contacting the ice for its glide phase, the inside foot, which was gliding on its outside edge, is activated to provide the cross-under push (Stamm 1989). This skill is performed by deepening the inside foot's backward outside blade edge by increasing the pressure against the outside of the boot. The skater's weight should be placed over this edge, knees should be bent, and the inside foot is then thrusted sideways underneath the body. The skater then pushes to the back of the outside edge, shifting his weight forward as the stride progresses, and is completed with a "flick" from the toes as the leg is fully extended. At about the midpoint of the push, the skater should transfer his weight to the outside foot as it touches the ice to enter its glide phase. As soon as the inside leg is fully extended and finished thrusting, it must quickly be brought back under the body next to the outside foot, which is gliding (Stamm 1989). See figures 3.8 and 3.9.

Although the skill of backward cross-overs has been qualitatively explained, and the thrusting directions and blade angle orientation have been described, scientific research must be conducted to "measure the magnitude and especially the direction of the forces producing the motion" in order to expand the knowledge of both the players and trainers to further increase performance (Marino 1997). Surprisingly, only one study has been performed on backward skating, and it only investigated selected mechanics of the backward C-cut stride. Marino (1993) used overhead filming to measure several basic movement characteristics of the stride. Ten highly skilled subjects participated in the study, and the results demonstrated that maximal backward velocity was approximately 82% of maximal forward velocity. Interestingly, a significant correlation between backward and forward velocity was also shown ($r=0.81$, $p>0.05$). This is surprising as backward skating is a skill which is practiced more frequently by defenseman rather than forwards, and one would expect the difference between the forward players, being very fast during forward skating and slower in backward skating to lower the correlation between forward and backward velocity. It was also found that mean backward velocity was 6.57m/s, with a cycle rate of 1.16 cycles per second, and a cycle length of 5.65m. The author concluded that faster backward skaters have lower cycle rates with longer and wider cycles than slower backward skaters.

2.9. Pressure Sensors

The importance of the hockey skate boot relative to its effect on skating performance has clearly been demonstrated in the hockey skating literature. In other sports, it has been shown that athletic footwear can aid and even enhance performance. In order to further our understanding of the effects of shoe design modifications on the mechanics of the foot, many in-shoe pressure measurement studies have been conducted. Their main advantage over data collected via a force plate is the ability to collect multiple steps in a single trial, thus increasing the statistical power of the research. In-shoe pressure studies have not only had an influence on shoe design but also on clinical practices regarding orthotic insoles (Cavanaugh 1992).

The majority of the in-shoe pressure studies have focused on the examining plantar pressures of subjects who have diseases such as diabetes mellitus, Hansen's disease, and rheumatoid arthritis, where elevated pressures can cause injury or pain. It has been demonstrated that among people with diabetes, the development of a foot ulcer is linked to a higher incidence of osteomyelitis and lower limb amputation, which in turn has led to greater health care costs and risk of death (Maluf, Mueller 2003). Evidence has been shown that the diabetic foot is subject to higher plantar pressures than that of the normal foot due to limited joint mobility (Masson 1992). The most common reason for lower limb amputation in people with diabetes is minor trauma to the feet's tissues combined with a lack of protective sensation. Although the minor trauma can be due to many different factors, the most frequent one is excessive repetitive loading of the plantar surface from walking (Maluf, Mueller 2003). Therefore, examining plantar pressures during everyday tasks is of extreme importance for those prone to foot pathologies.

Most studies have focused on examining plantar pressures during normal walking gait in order to improve shoe comfort. It has been shown that by increasing walking speed, plantar pressures under the calcaneous, central and medial metatarsals, and the toes, increase due to the greater force of impact with the ground (Burn, Few et al. 2004). The overall plantar pressure profiles have also been described, with the majority of the impact occurring at heel strike, then as the stride progressed, the pressure is transferred to the mid foot and then to the metatarsal heads. The loading period ends as approximately 53% of the body weight is concentrated under the head of the 1st metatarsal and the hallux (Hayafune, Hayafune et al. 1999).

Examining plantar pressures during athletic endeavors is also of great importance, as the foot must act as a shock absorber, and is therefore subjected to a great deal of stress (Salathe et al. 1990). Running shoe research has shown that by wearing a running shoe, plantar pressures are diminished due to the fact that they are being dissipated over a greater area. This has been shown in a study comparing plantar pressures during barefoot running to shod running. Not only were higher pressures observed during the barefoot condition, but a larger loading rate and a change in the ground reaction force pattern was also seen (De Wit, De Clercq et al. 2000). The relationships between simple footprints, foot pressure distributions, rearfoot motion and foot function were examined during treadmill running using 9 subjects. The study showed that subjects with high-arched, cavus-type feet tended to place the majority of their body weight on the lateral side of the forefoot, causing greater amounts of pressure in this region. The study also indicated that there was reduced mobility of the subtalar joint in the running population that was studied. The results indicated that foot pressure measurements proved to be useful indicators of foot function during running gait and could potentially be helpful in diagnosing and preventing injury (Atkinson-Smith, Betts 1992).

Although the movement pattern may be the same, often during different sporting events the type of footwear worn is not, which may lead to dissimilar pressure patterns. For instance, it has been shown that soccer players generally select a shoe that is a size smaller than a typical running shoe they would normally wear, in order to increase sensory input and therefore increase their performance. This could potentially lead to an increase in pressure as the surface area would decrease with the same level of force, due to the fact that force and area are directly related to pressure (see equation below).

Pressure=force/area

In a study by Santos (2001), looking at plantar pressures within the soccer shoe of 15 soccer players, it was shown that by selecting a smaller sized shoe, the players are decreasing their shoe plantar surface by 8.25%. Also, due to the specialized cleats under the shoe, the plantar pressures are not dissipated over a larger area as they are in normal running shoes. The results of this study have demonstrated a 35% increase in maximal and a 27% increase in mean plantar pressures in the soccer shoe compared to a normal fitting running shoe. Interestingly, elite hockey players also tend to wear skates which are about a size smaller than their regular shoe size in order to increase sensory input.

Therefore, it would seem logical to assume that some skaters must endure very high plantar pressures as well.

An interesting study was conducted by Eils et al (2004), where he investigated plantar pressures of 21 elite soccer players during game type movement. The skills of running, cutting, sprinting, and kicking the ball were all examined. Significant differences were seen in cutting, sprinting, and kicking as compared to running, in terms of relative loads and peak pressures. During the cutting task, a shift of the load was observed to the heel, medial midfoot, medial forefoot, and hallux as compared to the running task. In addition, significantly less pressure was measured during the former in the central and lateral forefoot and the lateral midfoot as compared to the latter. During sprinting, the pressures shifted to the central, medial, and lateral forefoot, as well as to the hallux, second toe, and lateral toes. The midfoot and heel were significantly less loaded areas. The reasoning for this study was to identify areas of high pressure in order to gain insight on how to decrease the high incidence of overuse injuries in soccer. It was suggested that this study combined with future ones could lead to insoles which would dissipate the loaded areas of the foot to the lesser loaded areas, or perhaps to position-specific insoles (Eils et al. 2004). This study has much relevance to the current study, as it covers the overall plantar pressure patterns during a variety of skills.

There has been limited research conducted on pressure patterns during ice hockey skating. The patterns of moments of push-off forces in speed skating were investigated using an instrumented skate comprising two strain gauges, one at the front and the other at the back of the skate, situated between the shoe and the blade. The results demonstrated a double peak force pattern. The first peak occurred in the front and the back of the skate when the blade contacts the ice, and the second occurred in the front of the skate during the period of push-off (de Boer et al. 1987; Jobse et al. 1990).

With regards to ice hockey pressure patterns, only the forward stride has been thoroughly examined (Dewan 2004; Turcotte 2004; Loh 2003). Dewan (2004) demonstrated that plantar pressure studies did not allow for a true understanding of the levering of the foot and ankle in the skate boot during the skating stride, as much pressure was observed on the other surfaces of the foot because of the unique motion one must use in order to transfer forces to the ice, due to its coefficient of friction. The other fundamental skating skills required to be a successful hockey player must also be analyzed in order to improve equipment design and in order to refine skating techniques.

The information from the foot-to-shoe interface is by far the most important of the other possible interfaces between the foot, shoe, and ground (Cavanaugh 1992). Little research has been conducted on surfaces other than the plantar surface of the foot. The pressure patterns between the upper shoe and the foot still remain to be seriously studied in any domain (Cavanaugh 1992). It was felt that measuring the whole foot during the backward cross-over skating skill is of extreme importance due to Dewan's (2004) findings demonstrating high pressure in the forward stride in areas other than the plantar surface. Therefore, in the present study, in order to investigate the pressure patterns of the foot during backward cross-over skating, piezo-resistive pressure sensors called Force Sensing Array (FSA) (Verg Inc, Winnipeg, Canada) were used. Fifteen individual pressure sensors were placed on anatomical landmarks of both the left and right foot. This class of pressure sensors is known as discrete pressure sensors, and there are several advantages to their use. Their main advantage is their small size.

A universal principle of scientific measurement, known as Kelvin's Law, states that the act of measurement should not change the quantity being measured. It is very easy to break this law when attempting to measure the foot-to-shoe interface, as the sensor could potentially alter the local pressures if they are too large (Cavanaugh 1992). Many discrete pressure sensors are the size of coins, but the FSA sensors are very small, measuring only 1.2 x 1.1 x 0.2cm, and therefore are suitable for this type of data collection. They are slightly larger than a 1 x 1 cm sensor that Razian and Pepper (2003) claim to be the largest size suitable for plantar surface pressure collection due to the localized pressure under the metatarsal heads. However, since they are so near the recommended size it was felt that they would be appropriate. Also, almost all devices require trailing cables or the wearing of a waist pack, which can sometimes be rather bulky and heavy and could in fact alter the stride. The FSA data logger system used in this study was small and lightweight, and was worn in a fanny pack around the skaters' waists, and therefore did not alter the skating stride.

It has been proposed that another potential disadvantage of using discrete pressure sensors is inaccuracies due to imprecise placement of sensors under the areas of interest. It has also been shown that these sensors tend to migrate during the data collection period due to shear stress (Cavanaugh 1992). In order to overcome these problems, the sensors were placed on the areas of interest through palpation of the bony landmarks, and always by the same examiner. The sensors were also fixed onto the skin using double layered tape to ensure the sensors remained in place.

2.10. Piezo-Resistive Sensors

It has been shown that piezoelectric copolymer materials can be successfully used to develop in-shoe pressure sensors (Razian, Pepper 2003). Piezo-resistive pressure sensors function due to the piezoelectric effect found in natural materials, such as quartz, and in manufactured materials, such as lead zirconate titanate (PZT). When the materials are deformed a charge is generated, due to the deformation of the crystal lattice in which the atoms of the material are ordered. The electrical activity is recorded and converted into a voltage proportional to an applied force (Cavanaugh 1992). Hence, the importance of the calibration period, where a known force is applied to the sensors and their charges are recorded. From this, a calibration graph is produced allowing for the extrapolation of pressure values of future values. Calibration periods must be done prior to every measurement period in order to ensure accurate readings. It has been shown that with proper calibration procedures there is under a 2% hysteresis with the sensor readings (Jeffcott, Holmes et al. 1999).

From the literature, it seems as though earlier models of piezo-resistive sensors appeared to have certain drawbacks to their use. It was suggested that their response to vertical stress could produce a different output if shear stress is present. It was also suggested that they are very sensitive to bending and it was suggested that they could be affected by temperature changes, which would obviously make their use inappropriate for testing the foot-to-skate boot interface on an ice rink (Cavanaugh 1992). However, a more recent study examined downhill ski boot pressures using piezo-resistive sensors, and demonstrated that the sensors recorded accurate pressure readings and were not affected by the humidity level inside the boot, or the cold temperatures (Duvillard, Rundell et al. 2000). Therefore, the use of the FSA piezo-resistive sensors were deemed appropriate for the type of testing conducted during this study.

2.11. Skill Level and Performance

Many studies have investigated various biomechanical variables between elite and recreational athletes in order to further understand technique differences between the groups. Again, there is limited research comparing biomechanical aspects of the ice hockey skating skills. A study was conducted comparing 5 novice, 6 intermediate, and 6 elite skaters' step length and the angular kinematics of the propulsive leg during the forward skating stride (McCaw, Hoshizaki 1985). The results demonstrated no significant differences in step length between the groups, but step rate was significantly higher for the elite and intermediate groups as compared to the novice skaters. The study also revealed many kinematic differences between the differing skill-leveled groups. For instance, a trend was seen with increasing ability level for both greater joint flexion prior to extension and greater joint displacement. And, both the elite and intermediate skaters' peak and average hip omega values (rads · sec) were significantly higher than the novice skaters', with no statistically significant kinematic difference between the groups at the knee. Another interesting observation in this study is that the hip values for the intermediate skaters were similar to the hip values of the elite skaters, while the knee values for the intermediate skaters were similar to those of the novice group. The authors suggest that this demonstrates a proximo-distal development of joint coordination during the skill of forward power skating, as the intermediate skaters have developed the proper hip movement patterns, but have not refined those of the knee (McCaw, Hoshizaki 1985).

Other skating research has been conducted comparing full body kinematics and muscle activation patterns between 5 elite and 6 trained speed skaters during the speed skating stride. The results indicated no significant differences between the groups when looking at the temporal patterns of the 10 selected leg muscles. Considerable differences were demonstrated between both groups in the curves of joint angles, angular velocities, net moments, and net power output vs. time. In the kinematics of the movements, the greatest differences occurred at the hip and knee joint angles. The elite speed skaters were able to skate with a more horizontal position of the upper leg, and a smaller knee angle during the gliding phase of the stride. The more horizontal positioning aids in reducing air friction, and combined with a higher power output results in higher speeds for the elite skaters (De Koning et al. 1990).

Another speed skating study has also demonstrated kinematic differences between elite and trained skaters. In a study by de Boer et al. (1987) using 14 elite and 10 trained speed skaters, pronounced differences were seen between the groups. The elite group had a shorter stroke and push-off times, with a greater push-off angle during the entire stride, resulting in a better directed push-off (de Boer et al. 1987).

Biomechanical studies regarding other sports have also demonstrated differences between different skill-level performers. For instance, a study involving 6 subjects of varying skill levels, examined arm kinematics during a basketball free-throw. Contrary to the expected results, there was not a clear reduction in trajectory variability with increasing skill level. Improvements in skill level were associated with an increasing amount of intertrial movement consistency from the elbow and wrist joints. The authors suggested that the angular motions of the elbow and wrist joints compensated for each other toward the end of each throw to adapt to subtle change in the release of the ball (Button 2003). Thus, the elite subjects were able to adapt and change their movement coordination patterns in order to better complete the task at hand.

Differences between elite and recreational athletes in terms of response timing and coordination patterns have also been shown in fencing. In a study comprised of 3 elite and 3 novice fencers looking at reaction time, movement time, total response time, accuracy, and muscle coordination patterns in, significant differences were demonstrated between both groups. The elite group had faster reaction times, total response times, and better accuracy. Differences were also seen in muscle activation patterns between the groups regarding both arm and leg muscles (Williams 2000).

With regards to foot pressure patterns, differences between different skill-leveled subjects have been shown in a study examining rowers and another study looking at the golf swing (Elliot et al. 1993; Amano et al. 1995). The rowing study compared the dominant feet of 5 experienced and 5 novice rowers. The results demonstrated that the peak forefoot pressures were significantly higher for the experienced group, and that the novice group had significantly higher rearfoot pressures. Also, the experienced rowers had nearly twice as much pressure in the forefoot as compared to the rearfoot, whereas the novice group had similar pressures for both regions. The authors explain the results by stating that the novice rowers generate less pressure in the forefoot due to a less effective use of the lower body in force generation. The higher rearfoot pressures seen with this group are thought to be due to a decrease in control of the body at the end of the drive and during the recovery phases of the stroke. The greater proportion of forefoot to rearfoot pressure in the experienced group suggests that in order to create force effectively rowers should generate most of the foot pressures in the forefoot (Elliot et al. 1993).

Amano et al. (1995) looked at the relationship between foot plantar pressures and performance during the golf swing. A total of 18 professional and 18 recreational golfers took part in the study. There results indicate that foot pressures between both groups are clearly different. During the top of the swing, the right foot of the professionals generated higher foot pressures on the inside as compared to the outside of the foot, while the amateurs created greater pressure in the toes, heel, and the outside of the foot. It was found that the professionals had a wider pressure area in the right foot at the top of the swing, and in the left foot at the point of impact, creating a wider pressure area. The authors explain that the wider pressure area increases stability, and allows for the professionals to generate more force during their swing (Amano et al. 1995).

Therefore, research has demonstrated that significant differences in the motion in which one performs a task changes as one develops the performed skill. Kinematical differences have been demonstrated during the forward ice hockey skating stride (McCaw, Hoshizaki 1985), and the speed skating stride (De Koning et al. 1990; de boer et al. 1987). Differences in kinematics have also been shown between differing skill-level basketball players when performing a free-throw (Button 2003), and muscle activation patterns, as well as response timing have also been revealed to be affected by skill level during fencing tasks (Williams 2000). Plantar pressure studies, investigating differences due to skill level and have also noted various differences during rowing and the golf swing (Elliot et al. 1993; Amano et al. 1995). As a result, it is expected that pressure patterns within the ice hockey skate boot will differ between elite and recreational hockey players during the backward cross-over stride due to differences in force generation patterns.

Chapter 3: Methodology

Chapter 3

Methodology

3.1 Subjects

A total of sixteen male subjects voluntarily participated in this study. Eight were classified as recreational ice hockey players (82.10 Kg, +/-6.37, 175.63 cm +/- 6.37cm) and eight were classified as elite subjects (86.82 Kg +/- 6.48Kg, 179.69 cm +/-6.74cm). The elite group consisted of McGill Redmen varsity hockey players with varying playing experience at the university level (i.e. 1 to 5 years). The recreational athletes were all participating in recreational organized hockey of lower caliber and had never reached a highly competitive level.

3.2 Procedure

The ethics committee of the Faculty of Education of McGill University approved this research project. The participants presented themselves to the McConnell hockey arena at McGill University for a period of approximately 90 minutes. The subjects were given a verbal and written explanation of the procedures, as well as the potential risks and benefits associated with the study. Each participant signed a consent form, informing them that their participation was voluntary and that they could withdraw at any time.

3.3 Materials

In order to measure the pressure within the skate boot during the examined skill, 15 piezo-resistive pressure sensors (FSA Verg Inc. Winnipeg, Manitoba) were fixed on each foot, directly to the participants' skin using double-sided tape. An additional sensor was reserved for synchronization purposes. The sensors were very small (1.2 x 1.1 x

0.2cm) and flexible and therefore can be placed inside the skate without causing discomfort (Figure 3.1).

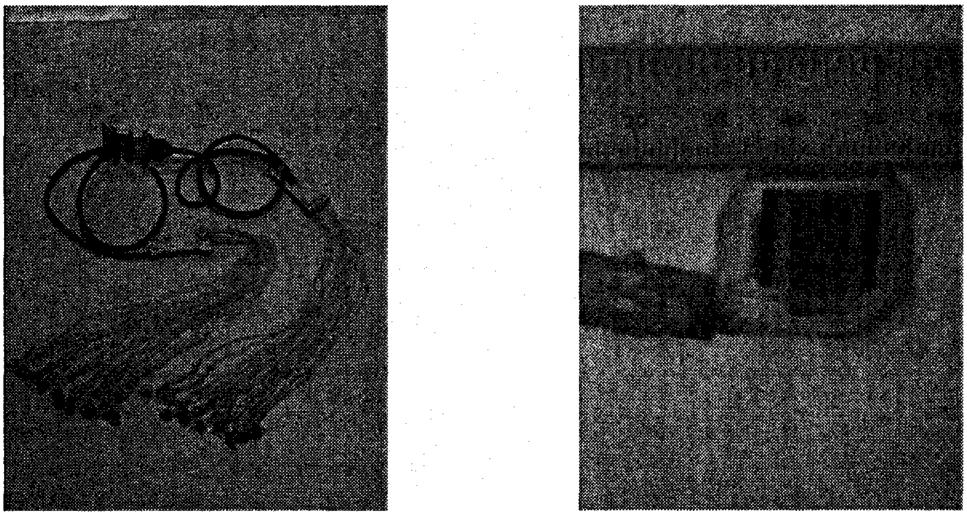


Figure 3.1: The FSA pressure sensors.

Standardized socks were used in order to ensure sensor placement remained constant throughout the skating task and to reduce the influence that different sock types could have on the pressure readings (Maluf, 2004). Tensor bandages were wrapped around the participants' legs to hold the wires in place. The FSA portable data logger was held in a pack, which was worn around the skaters' waists

3.4 Calibration of the FSA Pressure Sensors

The FSA sensors were calibrated by means of an air bladder (Tekscan, West Boston, MA, USA) (Figure 3.2). The protocol used to calibrate the sensors followed the calibration module supplied with the FSA software, which allowed for the reduction of erroneous values due to the phenomena of creep and hysteresis. The air bladder was inflated by using a manual gauge, which applied a known force throughout a range from 0 to 100 PSI to each individual sensor, thus ensuring reliability when measuring within that range of forces. Calibration of the pressure sensors took place prior to every participant's testing period. It has previously been shown that from the calibration process, the sensors maintain pressure readings of ±3 PSI over a 100 PSI range (Dewan 2004).

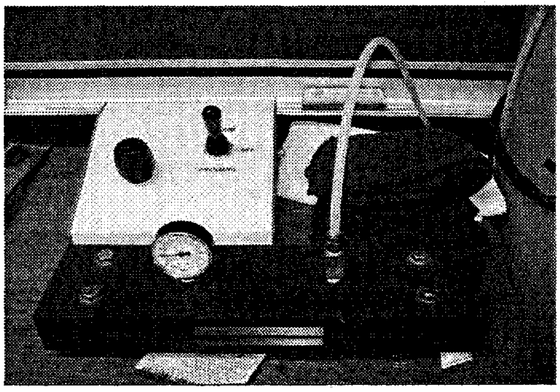


Figure 3.2: The air bladder calibration unit.

3.5 Sensor Placement

The areas selected for sensor placement were based on previous research (Dewan 2004) and determined through pilot work in attempt to provide a general map of the pressures observed in the skate/foot interface during skating skills. During the pilot work the entire foot was mapped with pressure sensors in order to determine the areas with the greatest values (Figure 3.3).

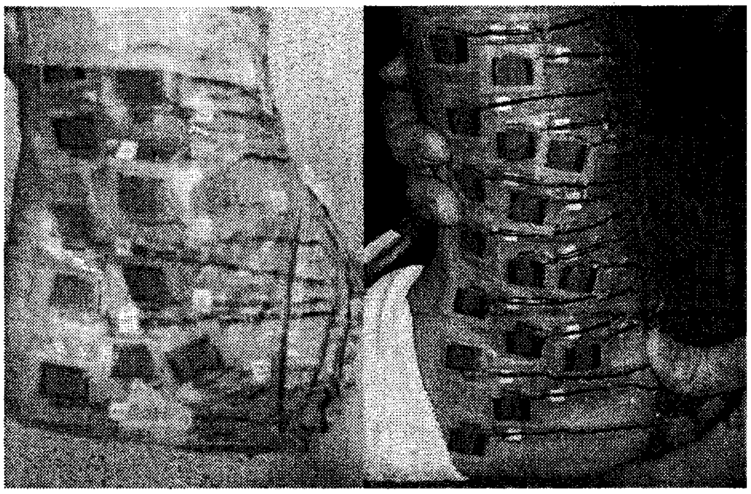


Figure 3.3: Pressure mapping of lateral and medial foot.

For this study the sensors were placed on the sites that were deemed to be the most representative of the pressure points of interest. On the plantar aspect of the foot the sensors were placed on the lateral heel, medial heel, lateral mid-arch, medial mid-arch, base of the 5th meta-phalangeal joint, and base of the 1st meta-phalangeal joint. On the medial aspect of the foot the sensors were placed on the calcaneous, medial malleolus, and the medial aspect of the 1st meta-phalangeal joint. The sensors were placed on the talo-crural joint, 1st tarso-metatarsal joint, and between the 2nd and 3rd meta-phalangeal joint on the dorsal aspect of the foot. On the lateral aspect of the foot the sensors were placed on the calcaneous, lateral malleolus, and the lateral aspect of the 5th tarso-metaphalangeal joint (Figure 3.4).

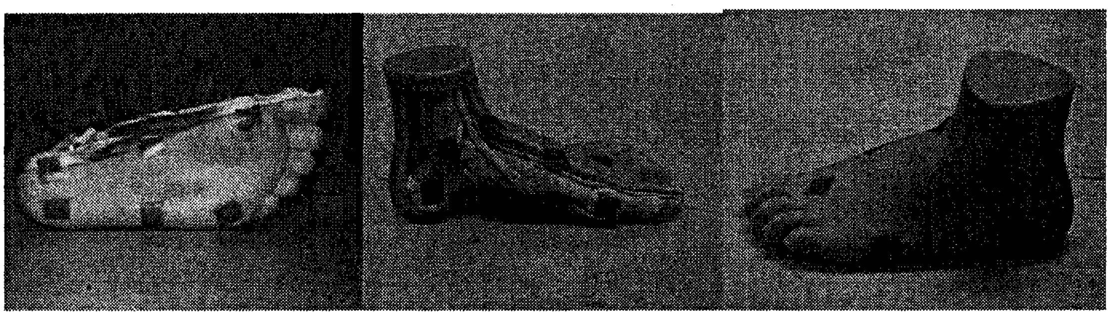


Figure 3.4: Electrode placement.

3.6 Protocol

The participants were required to complete three different protocols: tight-turns, forward cross-overs and backward cross-overs. The order that the tasks were performed was randomized. Only the backward cross-overs are considered in this thesis.

The subjects were required to skate backward using a cross-over technique at maximal velocity from goal line (red line) to goal line. The synchronization light was triggered before each skating trial at each goal line (Figure 3.5). The time period it took the subjects to skate from blue line to blue line (18.3m) was also recorded for determination of skating speed. Each participant performed three trials. They performed the skating task wearing their own skates. Song and Reid suggest that the biomechanics of skating are quite different with and without a hockey stick (1979), therefore, for this reason the participants all carried a hockey stick in order to mimic ice hockey game situations.

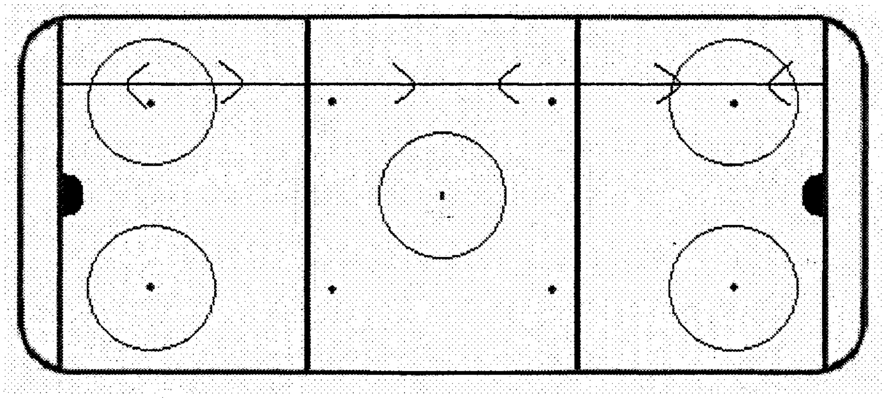


Figure 3.5: The ice hockey skating rink.

3.7 Synchronization of the FSA Pressure Data and Video Imagery

A digital video camera (Panasonic® mini dv pv-ds13) recording at 29.97 Hz was used to record the skating task. In order to synchronize both the pressure data and the video imagery, a pressure sensor was placed on top of an LED (light emitting diode) trigger. When the trigger was pressed an LED, would light up and simultaneously cause a pressure spike with the FSA pressure sensor values (figures 3.6, 3.7 A and B). This procedure was performed prior to each skating trial. The FSA data was downloaded from the portable FSA data logger into a laptop computer (Toshiba Libretto).

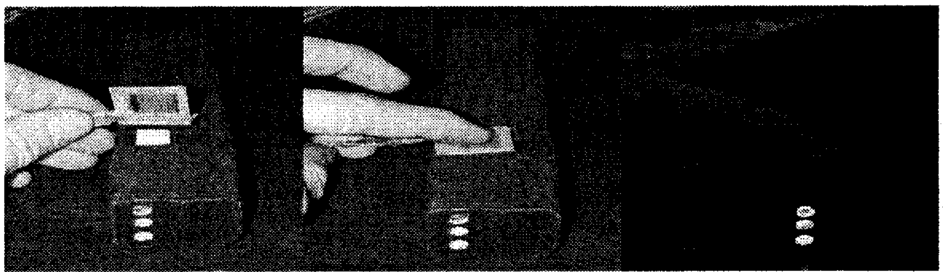


Figure 3.6: The synchronization sequence- the LED being triggered with a pressure sensor on top of the LED switch.

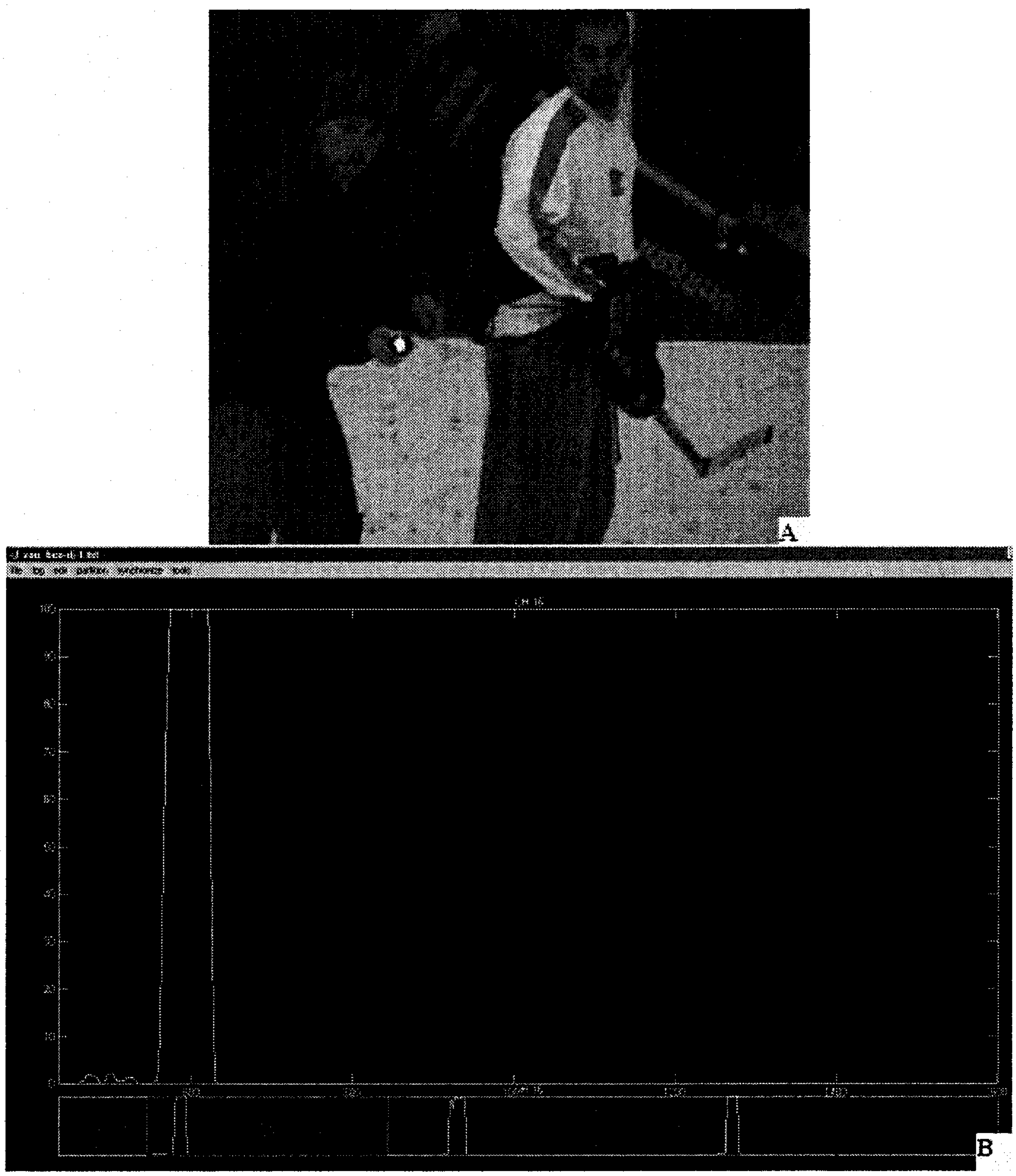


Figure 3.7: The synchronization method: A) LED light triggered by the tester. B) The simultaneous pressure spike seen in the synchronization channel of the pressure data.

3.8 Data Processing

The recorded pressure data was converted into Microsoft Excel® worksheets, where it was organized and non-pertinent data was deleted. The data was then imported into Matlab® (vrs.12, Mathworks, USA) using specialized software subroutines. Three specific modules were created to process the data. The first module de-interlaced all of the digital video files in order to double the sampling rate from 30Hz to 60Hz. The second module was the aligning, event marking and partitioning module. And, the third module was the statistical organizer module.

Aligning, event marking and partitioning

An in-lab program developed using Matlab called ZOO (Loh 2005) was used for the following steps. First, each individual sensor was renamed according to its location on the foot. Second, the average of the sensors in a given region of the foot was calculated to obtain an overall representation of specific areas of the foot. The new channels corresponded to the average of the sensors on the plantar, dorsal, medial and lateral aspects of the foot.

The program enabled for the simultaneous viewing of the FSA pressure data and the digital video images. Therefore, it was possible to mark the event of the LED light turning on with the increase of pressure seen in that specific FSA pressure channel. Since the LED light was triggered before each trial the FSA sampling rate, which varied from testing days, could be calculated accurately. This allowed for the synchronization of the pressure data with the recorded video images, which led to an accurate manner of partitioning the data.

Once the data was aligned, it was then partitioned into left and right backward cross-overs. The cross-overs were cut from the point where the skate blade of the crossing-over foot comes into contact with the ice (L1) to the point where to opposite foot contacts the ice (R4), as seen in figures 3.8 and 3.9.

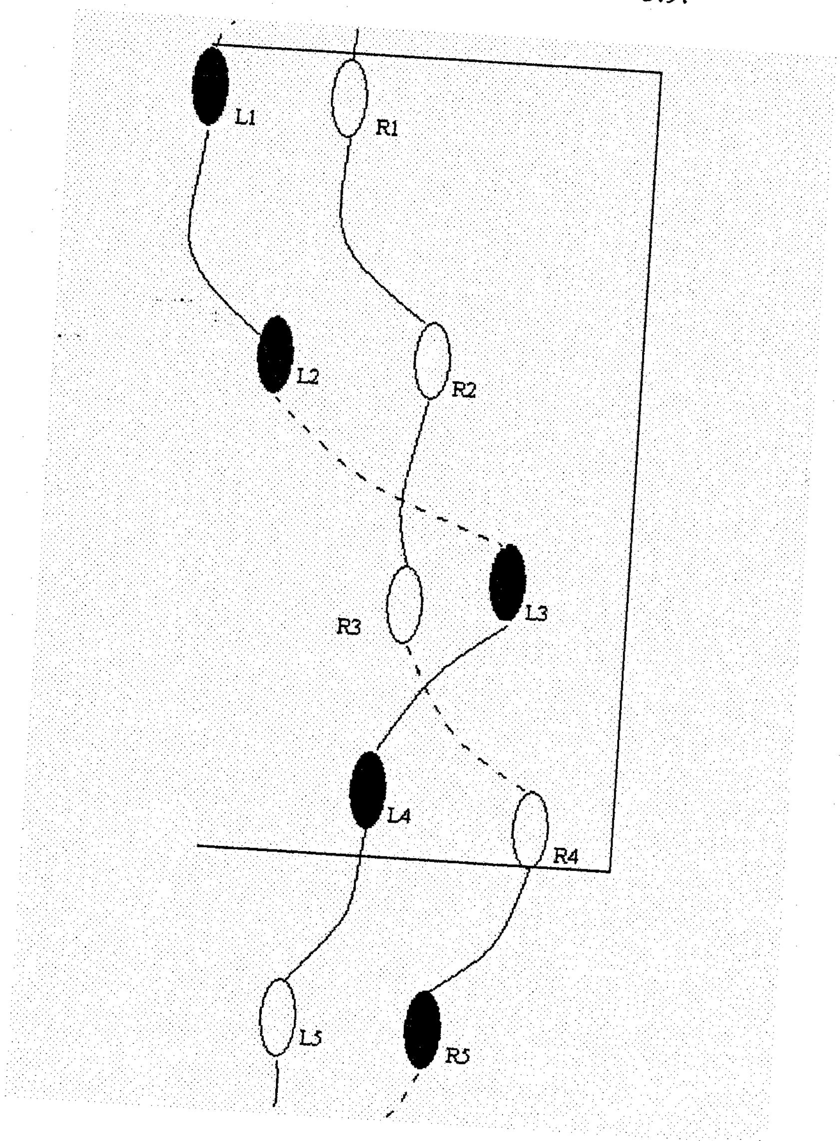
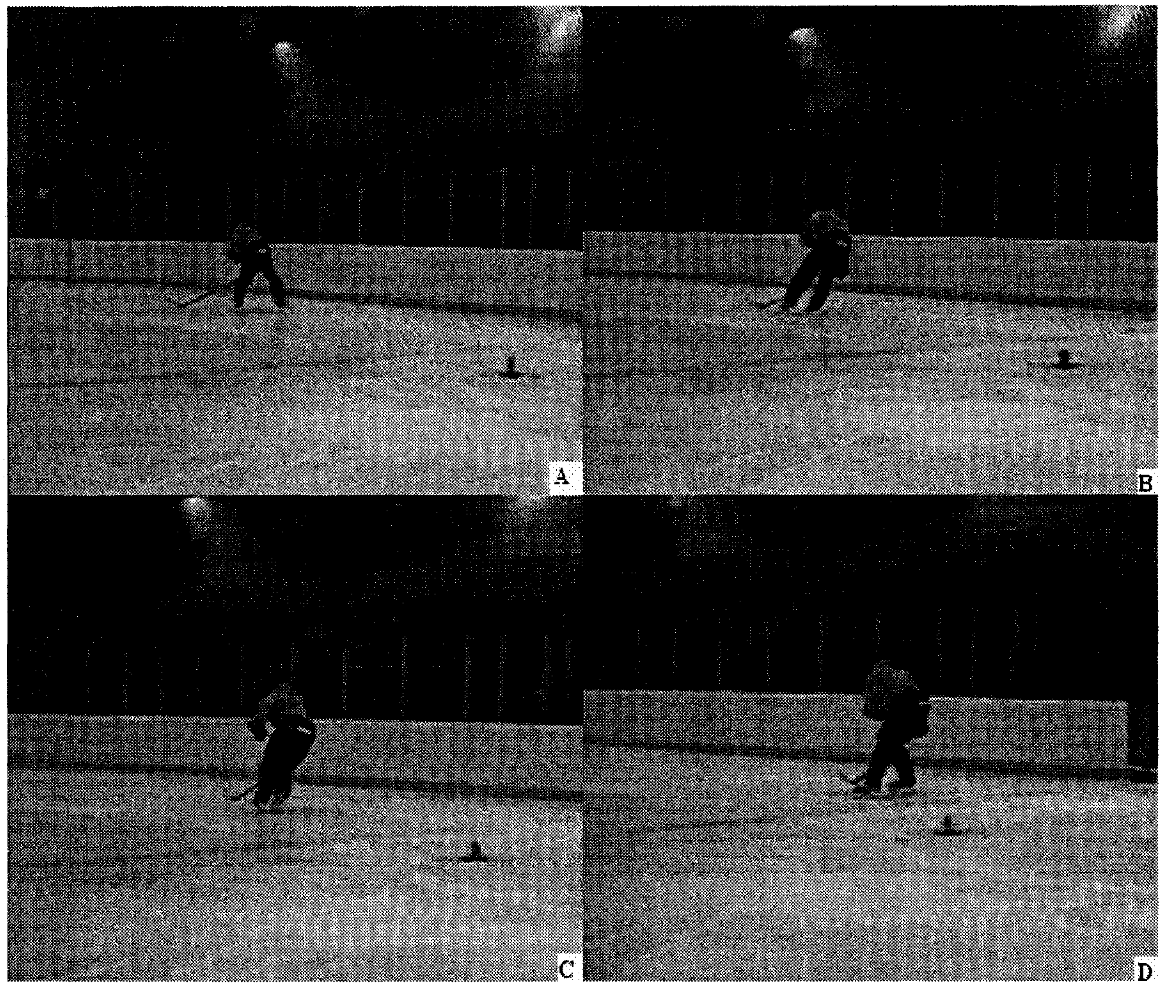


Figure 3.8: Feet placement during a left backward cross-over. The solid lines depict when the foot is in contact with the ice, while the dotted lines represent when the foot is off the ice. The selected area depicts a single stride.


A
B
C
D

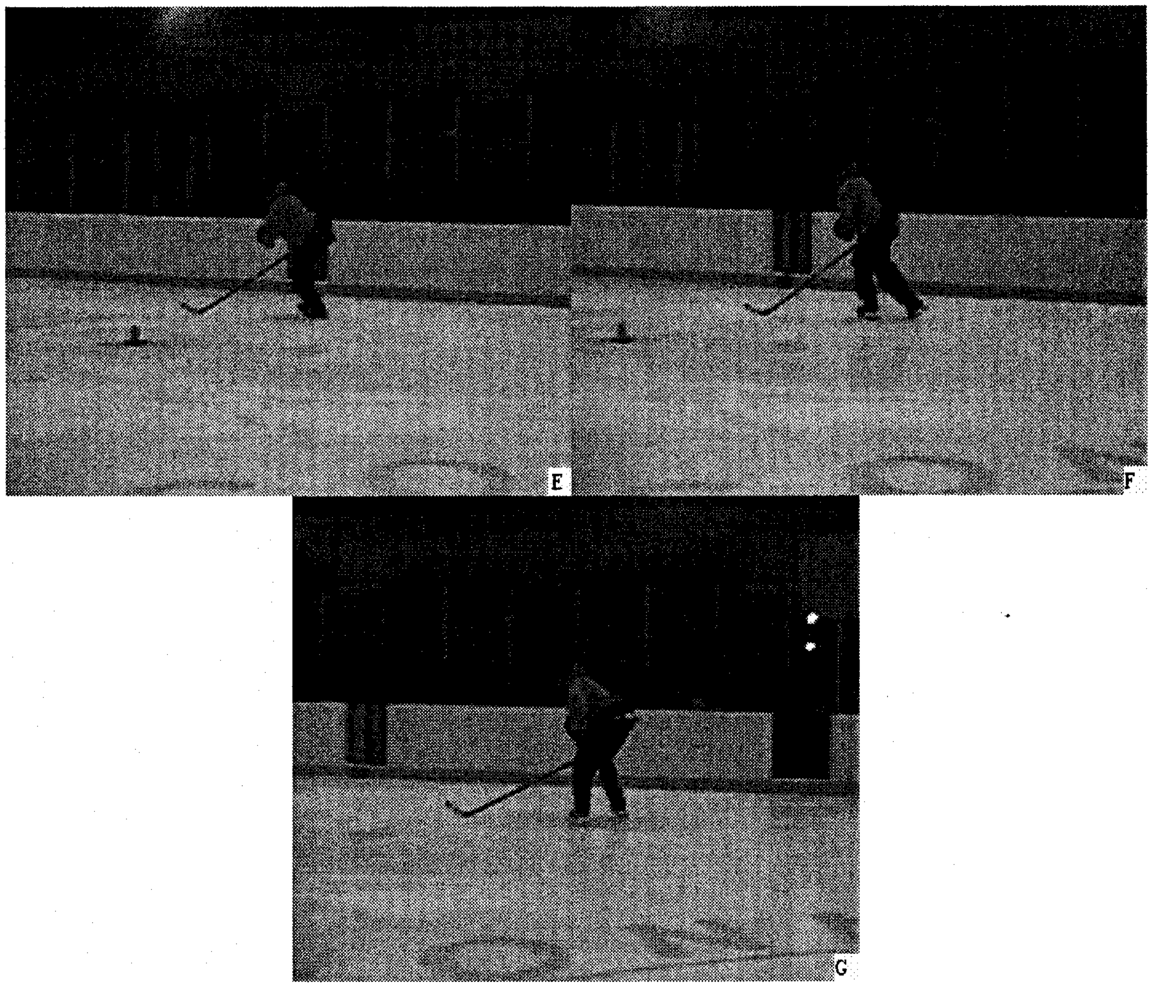


Figure 3.9: The movement pattern of a left and right backward cross-over. A) Left foot comes into contact with the ice and the c-cut thrust begins. B) Left foot leaves the ice and crosses-over in front of right foot. C) Left foot contacts the ice as the right foot leaves the ice. D) Right foot contacts the ice demarking the end of the left cross-over and the start of the right cross-over. The c-cut thrust then begins. E) Right foot leaves the ice and crosses-over in front of the left foot. F) Right foot contacts the ice as the left foot leaves the ice. G) Left foot contacts the ice denoting the end of the right backward cross-over.

The strides were cut using both the visual recording data and the pressure data. The visual recording data was used to ensure the data was aligned properly, but the strides were cut using pressure data channels. The pressure sensors on the base of the 1st meta-phalangeal joints of both feet were used in order to determine when the skate blade left and contacted the ice surface.

During the partitioning phase of the data processing several markers were added to the data, which could later be used in the statistical analysis. Ice contact time for each foot during the stride was determined during this portion of data processing by marking the time both the right and left skate blades came into and lost contact with the ice. This allowed for the calculation of the absolute and relative time that the skater was in single or double support while performing a backward cross-over. After the partitioning and phasing was complete, the Matlab module produced a graph of pressure versus time for each channel. From this graph, peak pressure values (y max values) were marked for further analysis.

After partitioning all of the data into left and right backward cross-overs for both the elite and recreational groups, it was ensembled. This process allowed for the data within the two distinct groups to be individually averaged and then compared.

Statistical Analysis

Once ensembled, a statistical analysis of the data was performed using a program written for Matlab® called So (Loh 2005). This program ran a two-way ANOVA followed by a *post hoc* Tukey HSD using a significance value of $p < 0.05$. The dependent variables were the peak pressures of each sensor, the absolute and relative timing of peak pressures and stride times. The independent variables were skill level, and cross-over direction. Results were given as mean ± standard error of mean (SEM). The data was then imported into Microsoft Excel®, where the data, which was measured in PSI was converted into Kpa, and graphed.

Chapter 4: Results

Chapter 4

Results

The following results were obtained from the processed pressure data recorded from the three trials of backward cross-over skating from goal line to goal line performed by the eight elite and eight recreational level hockey players, for a total of 16 subjects.

4.1. Skating Ability

Skill Level and Peak Pressure Amplitude

The mean speed at which both the elite and recreational level participants skated between the blue lines using the backward cross-over stride was recorded in KPH. The results are presented in table 4.1. There was a significant difference seen between both groups as the elite groups average speed was 22.41 ± 1.60 KPH, while the recreational subjects average speed was 19.14 ± 2.17 KPH ($p \leq 0.05$).

Table 4.1: The average speed in KPH for the elite and recreational participants (mean ± SD). * $p \leq 0.05$.

	Elite	Recreational
Speed (KPH)	22.41 ± 1.60*	19.14 ± 2.17

The peak pressure values for each of the 15 pressure sensors on each foot, for both ability levels during the backward cross-over skating trials are reported in table 4.2. These values were obtained by averaging the greatest pressure reading in each individual sensor for each subject. All of the values are all expressed in kilopascals (Kpa). The results indicate significant differences between groups in peak pressure in 3 of the 15 sensors on the inside foot, and 2 of the 15 sensors of the outside foot ($p \leq 0.05$). No significant differences were seen between ability levels when looking at either feet in any of the sensors on the plantar or dorsal surfaces. For the inside foot, significant differences were found in the medial region on the medial malleolus, and on the lateral surface on the lateral malleolus and lateral head of the 5th metatarsal. The outside foot revealed significant differences in the medial region in the area of the medial malleolus, and on the lateral surface on the lateral head of the 5th metatarsal. In all of these sensors the elite group had significantly higher peak pressure values than the recreational subjects ($p \leq 0.05$).

Table 4.2: Peak pressure values in kilopascals for each channel on the inside and outside foot for each subject group (mean ± SEM). * p ≤ 0.05.

Region	Sensor Location	Inside Foot		Outside Foot	
		Elite	Recreational	Elite	Recreational
Plantar	Lateral Heel	164.25 ± 20.11	162.16 ± 12.95	134.30 ± 17.52	125.42 ± 12.33
	Medial Heel	212.63 ± 24.51	190.17 ± 11.88	164.83 ± 20.37	142.50 ± 11.29
	Lateral Arch	141.36 ± 15.93	130.26 ± 20.53	157.21 ± 18.86	140.04 ± 19.90
	Medial Arch	51.25 ± 7.76	39.52 ± 8.90	18.34 ± 5.16	23.37 ± 7.11
	Head of 5th Metatarsal	102.68 ± 9.68	108.04 ± 10.18	96.79 ± 7.56	119.52 ± 9.02
	Head of 1st Metatarsal	325.77 ± 58.39	386.80 ± 52.55	278.08 ± 54.05	388.98 ± 54.62
Medial	Malleolus	451.14 ± 47.69*	226.09 ± 31.94	351.49 ± 62.66*	205.06 ± 31.24
	Calcaneous	68.56 ± 22.76	42.67 ± 7.31	24.02 ± 8.04	31.13 ± 7.47
	Head of 1st Metatarsal	230.43 ± 28.07	205.90 ± 22.90	183.89 ± 23.10	159.78 ± 20.99
Lateral	Malleolus	185.57 ± 31.96*	93.62 ± 16.68	111.58 ± 20.76	79.67 ± 15.95
	Calcaneous	62.66 ± 22.13	31.46 ± 11.56	81.95 ± 25.39	56.38 ± 17.82
	Head of 5th Metatarsal	127.76 ± 9.51*	81.45 ± 5.28	169.67 ± 12.87*	109.23 ± 7.94
Dorsal	Talo-crural	274.90 ± 34.45	192.63 ± 42.22	231.54 ± 25.41	196.79 ± 41.77
	1st tarso-metatarsal	77.52 ± 16.13	133.61 ± 30.37	57.33 ± 13.88	127.74 ± 30.81
	2nd and 3rd metatarso-phalangeal	0.23 ± 0.23	1.36 ± 1.36	0.07 ± 0.07	0.98 ± 0.93

The pressure profiles of the channels that noted significant differences between both ability levels are demonstrated in figure 4.1. This figure illustrates that in all cases, both groups have similar pressure profiles, except that the peak pressures are higher for the elite group as compared to the recreational group ($p \leq 0.05$), and the overall pressure patterns of these sensors are also greater throughout the entire stride for the elite group. The values depicted in the pressure profiles are the average of all of the values in each individual sensor for each participant throughout the entire stride. They are lower than the peak values previously reported in table 4.2, as the peak values are an average of only the highest values in each sensor.

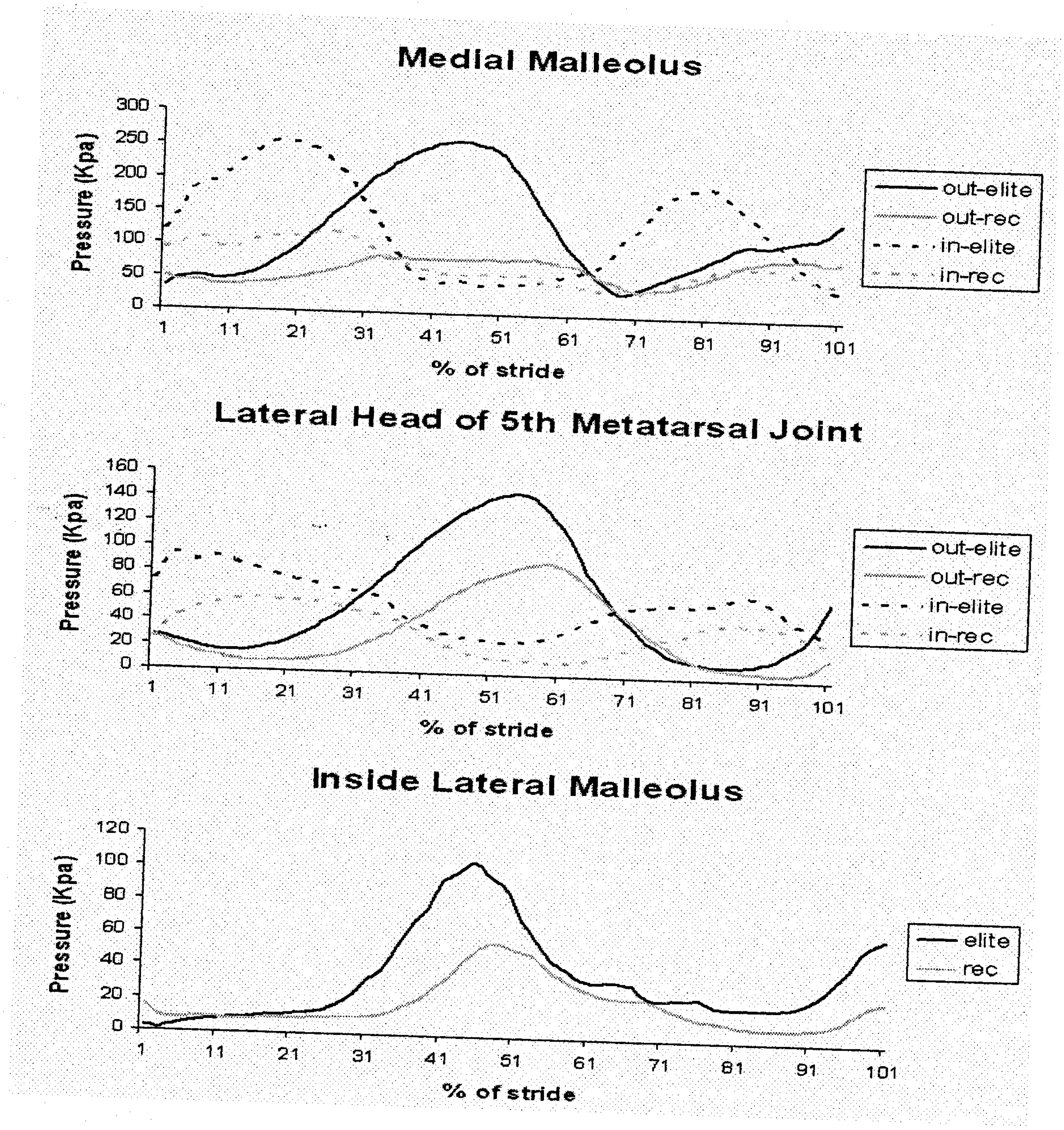


Figure 4.1: The averaged pressure profiles of the medial malleolus, lateral head of the 5th metatarsal joint for both the inside and outside feet, and the lateral malleolus for the inside foot, for both the elite and recreational subjects.

The peak pressure values and profiles for both of the ability levels for each sensor in a given surface region of the foot were summed to give a peak pressure value and pressure profile for that region. For instance, the data from the pressure sensors located on the lateral and medial heels, lateral and medial arches, and heads of the 1st and 5th metatarsals, were summed together in order to obtain a new pressure profile for the plantar region. The same process was repeated for the dorsal, lateral, and medial regions of both feet for both subject groups. The results for the summed peak pressure values are illustrated in figure 4.2, and the summed pressure profiles are displayed in figure 4.3. Significant differences were seen in the peak pressures between ability levels on the medial surface for the inside foot, and on the lateral surfaces of both the inside and outside feet ($p \leq 0.05$). The elite group was shown to have higher peak pressure values in the medial surface of the outside foot, significant at the $p \leq 0.054$ level. No significant differences were seen in the plantar and dorsal regions of the foot ($p \geq 0.05$). The regions which demonstrated significant differences between ability groups showed that the elite subjects generated significantly greater peak pressure values than the recreational level skaters.

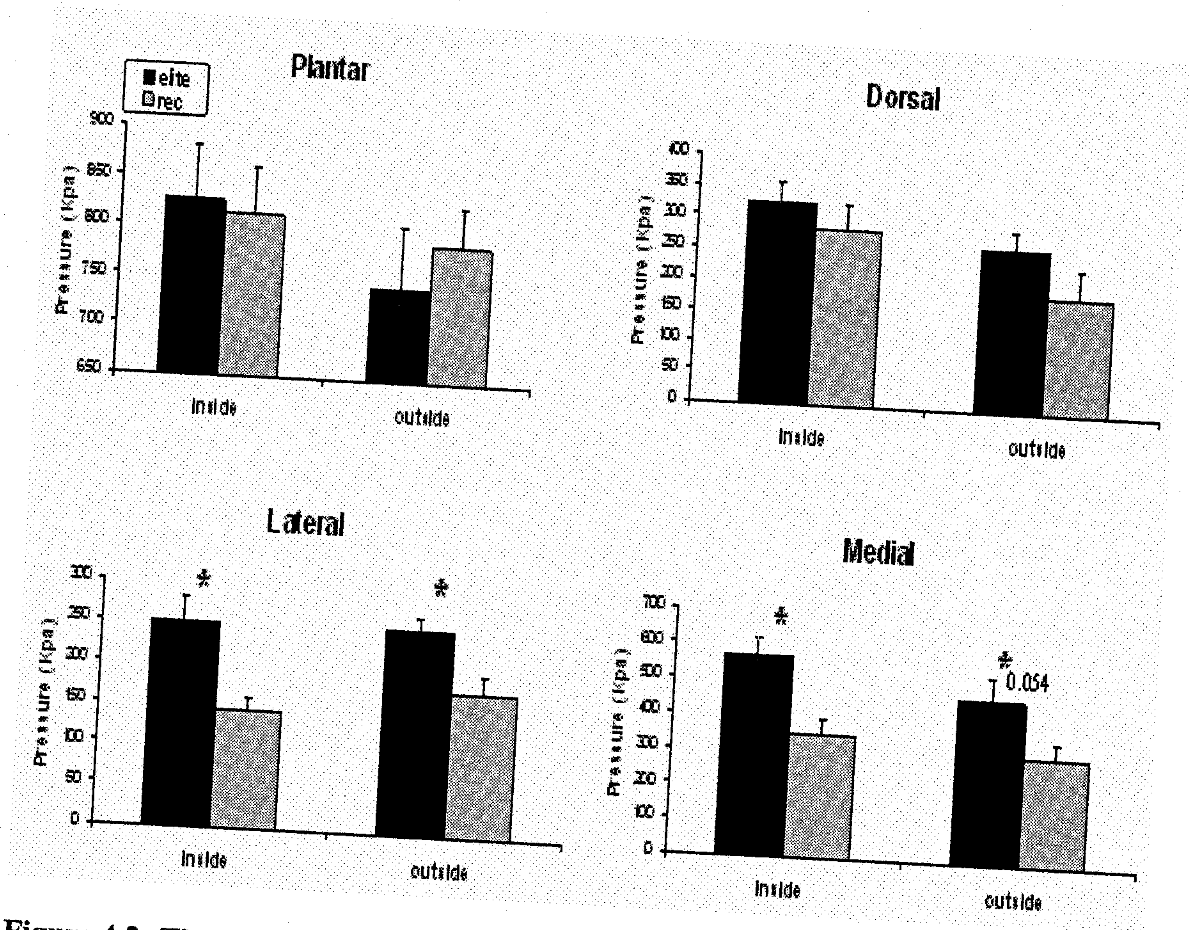


Figure 4.2: The peak pressure values (Kpa) of the inside and outside feet of elite and recreational skaters during backward cross-overs. The values depicted are the average of the peak values of the combined sensors of a given region of the foot (mean ± SEM). *$p \leq 0.05$.

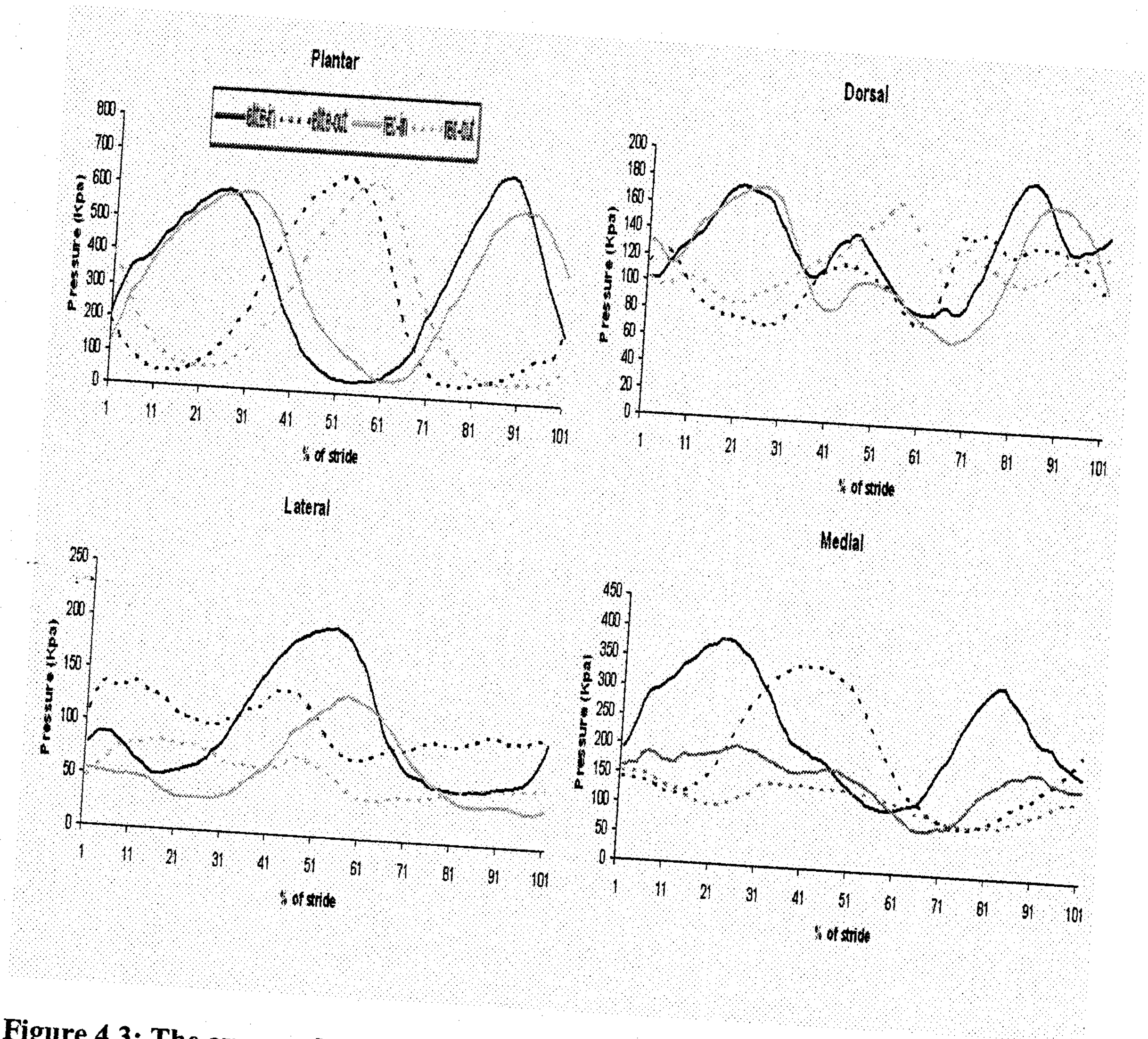


Figure 4.3: The averaged pressure (Kpa) profiles for elite and recreational groups for each regional surface of both the inside and outside feet. The sensors in each region were averaged to obtain the values presented.

Figure 4.3 illustrates the average pressure profiles for the elite and recreational groups for both the inside and outside feet for each regional surface of the foot. This figure demonstrates that the plantar and dorsal pressure profiles are similar for each foot for both ability groups, with no significant differences in their pressure amplitudes ($p \geq 0.05$). One can also see from this figure that the pressure profile for both feet for both subject groups is very similar in the lateral region of the foot, except that significant differences can be seen in the pressure amplitudes between ability levels, with the elite group having greater pressure amplitudes throughout the entire stride ($p \leq 0.05$). It was found that for the medial surface of the foot, the pressure patterns were again similar, except that for both the inside and outside feet, the elite group exhibited greater pressure throughout the stride. However, only the difference between subject groups for the inside foot was deemed to be statistically significant ($p \leq 0.05$), while a trend for greater peak pressure on the outside foot was observed with a p-value of 0.054.

Skill Level and Absolute and Relative Timing of Peak Pressures

The absolute (time in seconds) and relative (percent of the stride) timing of the peak pressure values for both ability levels for every sensor as well as the 4 summed regions of the foot for both the outside and inside foot during the skating skill were analyzed. The results demonstrate that significant differences ($p \leq 0.05$) (elite ± SEM, rec ± SEM) were seen in absolute timing for the inner foot in the lateral arch in the elite and recreational subjects respectively (0.089 ± 0.029, 0.222 ± 0.037) and lateral head of the 5th metatarsal joint (0.127 ± 0.029, 0.231 ± 0.027). Absolute timing differences for the outer foot were observed in the lateral head of the 5th metatarsal (0.302 ± 0.013, 0.385 ± 0.018) and for the summed sensors representing the lateral surface of the foot (0.270 ± 0.027, 0.348 ± 0.020). The results for the absolute timing differences in peak pressure values indicate that the peak values occurred earlier for the elite group than for the recreational group.

In terms of relative timing for the inside foot, significant differences ($p \leq 0.05$) were demonstrated in the lateral arch (15.445 ± 4.862, 35.898 ± 6.137), medial arch (67.443 ± 5.698, 45.110 ± 8.156), lateral malleolus (53.188 ± 3.363, 43.180 ± 3.243), and lateral head of the 5^{th} metatarsal joint (22.213 ± 4.917, 37.350 ± 4.413). It was shown that the peak pressure values for the elite group occurred earlier in the lateral arch and lateral head of the 5^{th} metatarsal joint, and occurred later in the medial arch and lateral malleolus for the inside foot. Relative timing differences for the outer foot were seen in the lateral head of the 5^{th} metatarsal (54.241 ± 0.821, 60.450 ± 1.667), demonstrating that the peak pressure values for the elite subjects occurred earlier in the stride than those of the recreational skaters.

4.2. Inside and Outside Foot Peak Pressures

There does appear to be a trend of higher peak pressures for the inside foot when compared to the outside foot during the backward cross-over stride when looking at the individual sensors in each region. Figure 4.4 demonstrates the elite skaters peak pressure values for each sensor on the inside and outside feet. Although a statistical analysis was not performed, the measured pressures were greater for the inside foot in 11 out of the 15 examined areas. Also, when looking at the average of the peak values from the combined sensors of a given region, it appears that there is a trend for the medial surface of the inside foot to undergo higher pressures than the outside foot (565.83 ± 51.96, 459.29 ± 68.69). The same trend is true for the plantar and dorsal regions of the foot. The inside and outside foot peak pressure values for the plantar region of the foot are 825.81 ± 28.51 and 743.16 ± 62.35 respectively. They are 323.77 ± 35.63 for the inside foot and 262.15 ± 26.8 for the outside foot for the dorsal region. Very similar peak pressure values for both feet were seen in the lateral area of the feet, being 249.4 ± 31.29 for the inside foot and 249.06 ± 16.5 for the outside foot. Figure 4.5 demonstrates the average of the peak values of the combined sensors of a given region of the foot for both the inside and outside feet during the backward cross-over stride for the elite subjects.

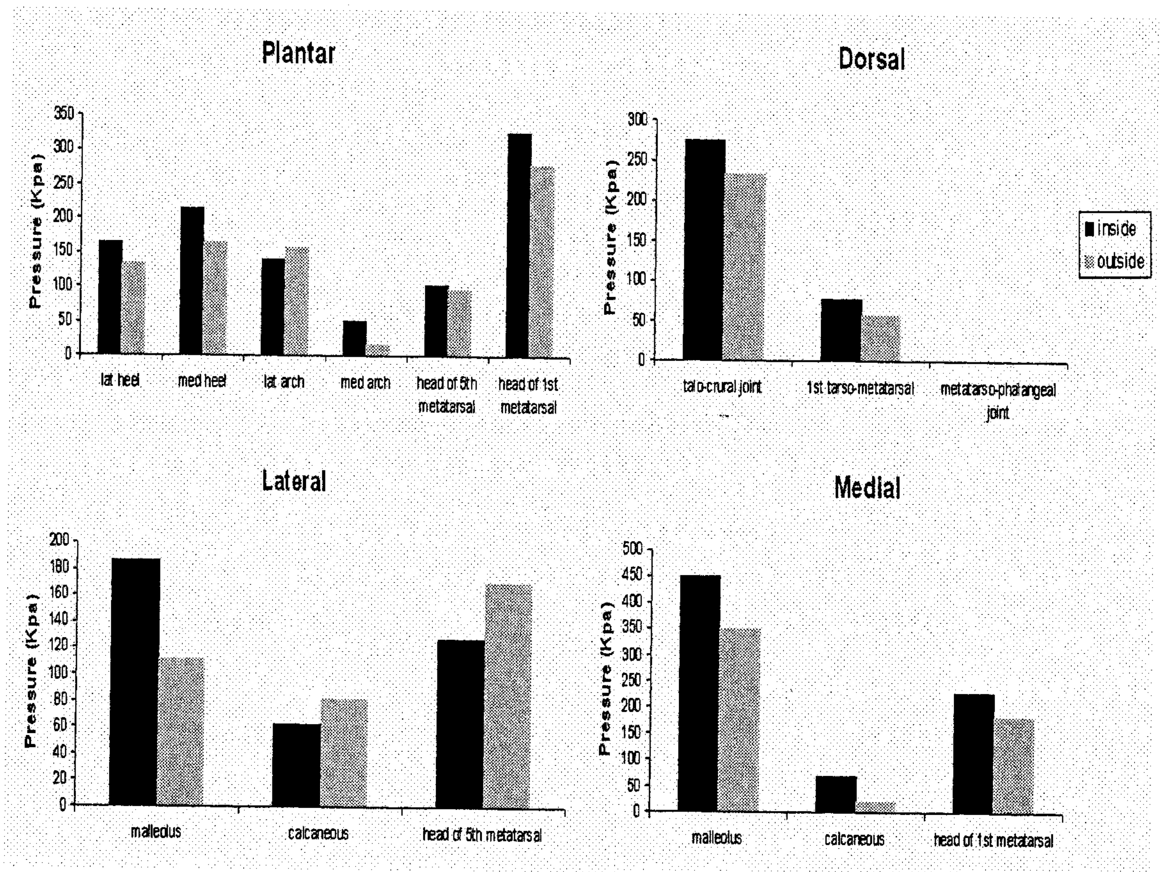


Figure 4.4: Comparison of peak pressures (Kpa) for the inside and outside feet during backward cross-overs for the elite skaters.

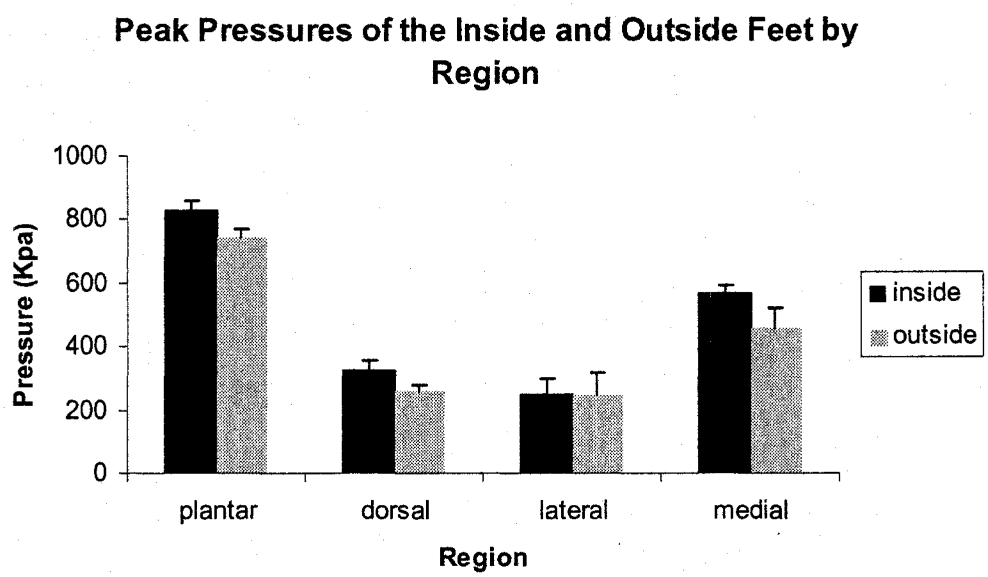


Figure 4.5: Peak pressure values (Kpa) per region for the inside and outside feet during backward cross-overs for the elite skaters. The values depicted are the average of the peak values of the combined sensors of a given region of the foot (mean ± SEM).

4.3. Backward Cross-over Direction.

Backward Cross-over Direction and Pressure Patterns

The peak pressure values recorded for each of the 15 pressure sensors on each foot, for both rightward and leftward backward cross-overs are reported in table 4.3. The results demonstrate significant differences between the cross-over directions in only 1 of the sensors on the inside foot, and on 2 of the sensors of the outside foot ($p \leq 0.05$). For the inside foot, significantly greater peak pressure was observed on the lateral heel during a leftward backward cross-over than during a rightward one. No significant differences were seen in any of the other areas of the inside foot ($p \geq 0.05$). For the outside foot, significantly higher peak pressure was also observed on the lateral heel region, and on the medial calcaneous, with the rightward backward cross-over exhibiting the greater pressures ($p \leq 0.05$). No significant differences were observed in any of the other examined regions of the outer foot ($p \geq 0.05$).

Table 4.3: The peak pressure values (Kpa) for each channel on the inside and outside foot for both cross-over directions (mean ± SEM). * $p \leq 0.05$

Region	Sensor Location	Inside Foot		Outside Foot	
		Leftward	Rightward	Leftward	Rightward
Plantar	Lateral Heel	188.69 ± 14.53*	137.56 ± 14.77	109.53 ± 13.86*	149.51 ± 13.48
	Medial Heel	198.24 ± 18.44	202.83 ± 18.78	149.08 ± 11.51	156.54 ± 19.64
	Lateral Arch	138.15 ± 19.60	132.61 ± 18.06	130.75 ± 17.29	165.18 ± 20.67
	Medial Arch	51.05 ± 8.97	38.82 ± 7.89	17.28 ± 6.55	24.81 ± 6.11
	Head of 5th Metatarsal	95.55 ± 5.70	115.58 ± 12.34	114.24 ± 11.25	103.82 ± 5.80
	Head of 1st Metatarsal	404.59 ± 58.66	312.68 ± 49.69	297.51 ± 54.98	378.09 ± 56.29
Medial	Maleolus	337.45 ± 53.20	322.46 ± 48.71	286.27 ± 56.35	259.01 ± 46.28
	Calcaneous	75.23 ± 18.35	34.00 ± 11.00	11.53 ± 4.22*	44.18 ± 7.72
	Head of 1st Metatarsal	216.96 ± 23.56	217.49 ± 27.35	160.49 ± 22.02	181.34 ± 22.07
Lateral	Maleolus	136.39 ± 31.14	135.74 ± 23.87	106.85 ± 19.34	81.95 ± 17.43
	Calcaneous	36.45 ± 18.65	55.27 ± 15.75	84.83 ± 20.55	51.53 ± 21.77
	Head of 5th Metatarsal	99.85 ± 9.05	105.80 ± 10.70	135.87 ± 12.06	138.44 ± 14.80
Dorsal	Talo-crural	239.06 ± 42.21	222.15 ± 39.63	225.73 ± 40.61	199.93 ± 30.89
	1st tarso-metatarsal	98.65 ± 21.57	116.80 ± 30.79	105.17 ± 32.42	85.31 ± 20.21
	2nd and 3rd metatarso-phalangeal	1.67 ± 1.46	0.00 ± 0.00	0.05 ± 0.04	1.06 ± 1.00

The pressure profile of the sensors that demonstrated significant differences between both directions of backward cross-overs are illustrated in figure 4.6. It can be observed that the pressure profiles are very similar between the leftward and rightward cross-overs, with the exception of the peak pressure amplitudes. The rightward direction backward cross-overs demonstrated significantly higher peak pressure values for the lateral heel and medial calcaneous on the outside foot compared to the leftward cross-overs ($p \leq 0.05$). Conversely, the leftward direction backward cross-overs displayed significantly greater pressure on the lateral heel of the inside foot compared to the rightward crossovers ($p \leq 0.05$).

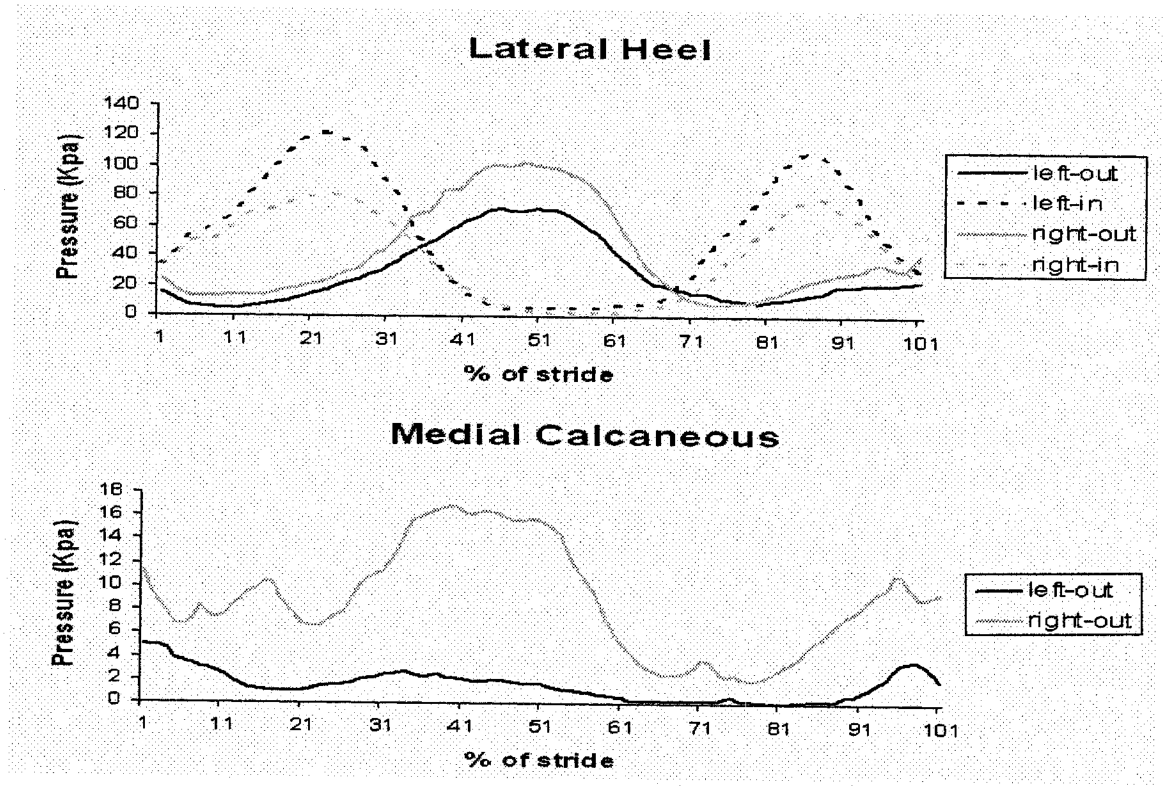


Figure 4.6: The averaged pressure (Kpa) profiles for both the inside and outside feet of the lateral heel, and the average pressure profile of the medial calcaneous for the outside foot, for both rightward and leftward backward cross-overs.

As was done for the comparison of ability levels, the peak pressure values and pressure profiles for both backward cross-over directions for each sensor in a given surface region of the foot were combined and averaged to give a peak pressure value and pressure profile for that region. The results for the combined peak pressure values are shown in figure 4.7 and the combined average pressure profiles are illustrated in figure 4.8. Only one significant difference between the rightward and leftward cross-overs for both the inside or outside foot, on any of the 4 surfaces of the foot was demonstrated. It was shown that the plantar surface of the outside foot during a rightward backward cross-over generated greater peak pressure than during a leftward backward cross-over ($p \leq 0.05$).

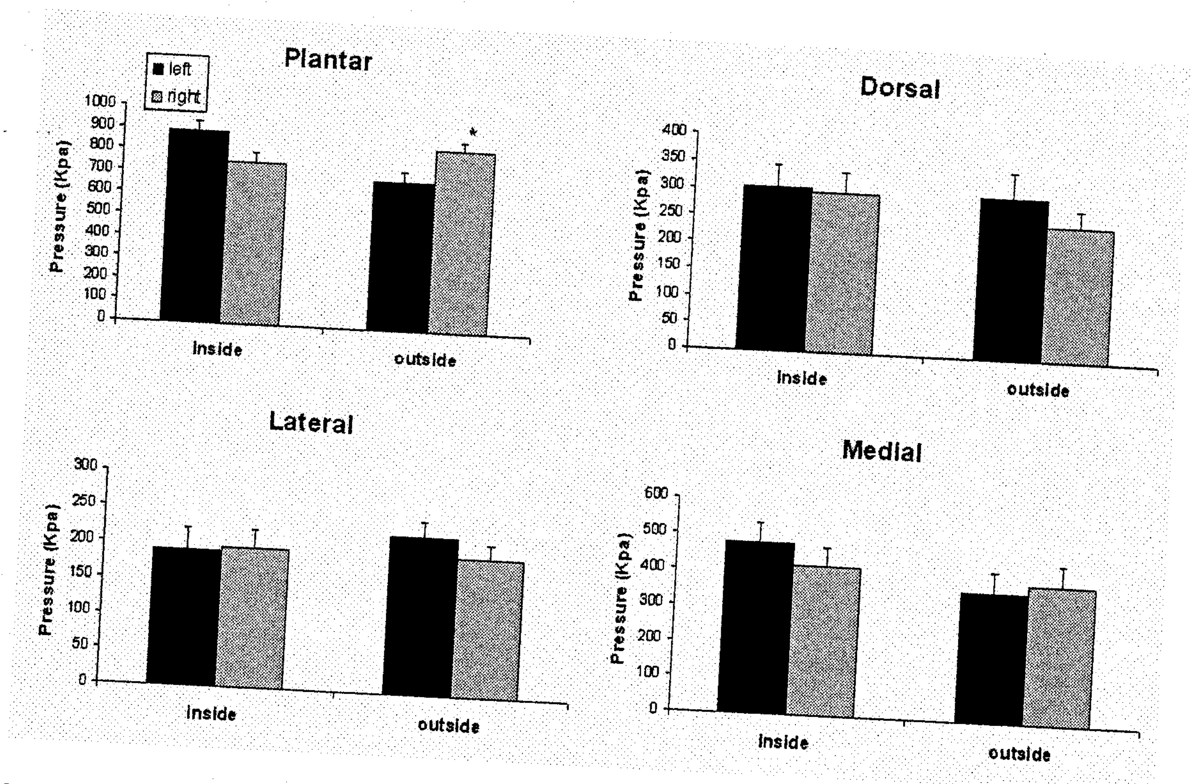


Figure 4.7: Peak pressure values (Kpa) per region of elite and recreational skaters. The values depicted are the average of the peak values of the combined sensors of a given region of the foot (mean ± SEM). *p ≤ 0.05.

From the combined average pressure profiles of the plantar, dorsal, lateral, and medial surfaces of the foot, comparing both rightward and leftward backward crossovers, one can see that the overall pressure patterns are very similar for all of the regions (figure 4.8). There are slight differences in pressure amplitudes, however, with the exception of the rightward cross-over producing greater pressure on the plantar surface of the outside foot, there were no significant differences ($p \geq 0.05$).

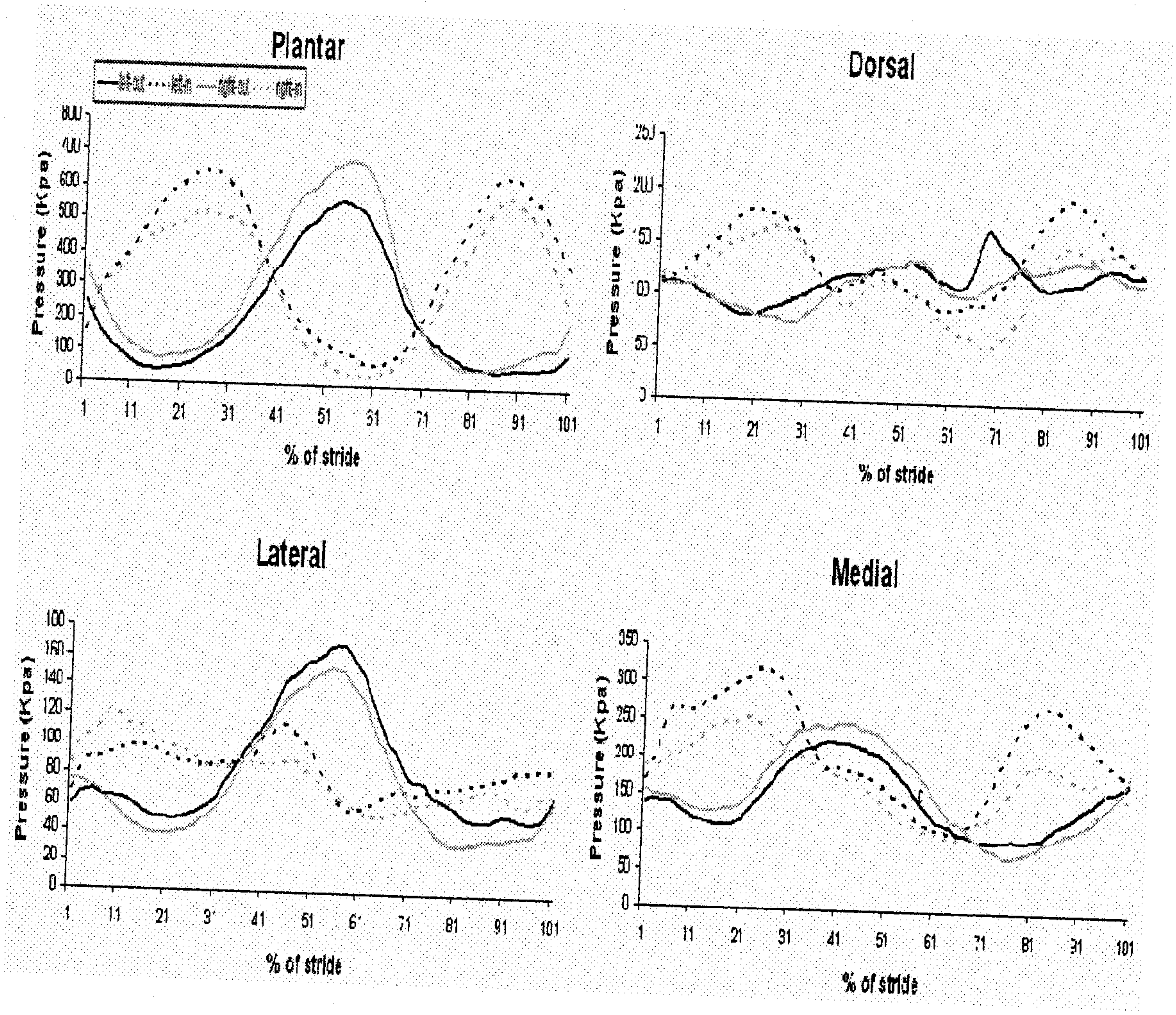


Figure 4.8: The average pressure (Kpa) profiles for rightward and leftward backward cross-overs for each regional surface of both the inside and outside feet. The sensors in each region were averaged to obtain the values presented in this figure.

Turn Direction and Absolute and Relative Timing of Peak Pressures

The absolute and relative timing of the peak pressure values for both backward cross-over directions for every sensor as well as the 4 summed regions of the foot for both the outside and inside feet were analyzed. The results did not demonstrate any significant differences in either the absolute or relative timing of the peak pressure values ($p \geq 0.05$).

Chapter 5: Discussion

Chapter 5

Discussion

The primary purpose of this study was to identify and compare peak pressures and foot pressure patterns within the skate boot between elite and recreational level ice hockey players while performing the backward cross-over stride. The secondary goal was to compare the timing of peak pressures between elite and recreational skaters during the backward cross-over stride. The tertiary purpose was to determine the effect of backward cross-over direction on peak pressure, in both the elite and recreational subjects. The quaternary goal of the study was to compare the peak pressures exerted within the skate boot between the inside and outside feet during the backward cross-over stride.

The main findings of this study indicated that significant peak pressure differences exist in the medial and lateral surfaces of the feet between the elite and recreational groups of skaters during backward cross-overs. No significant pressure differences were found in the plantar or dorsal region of the feet between groups. It was also shown that the average pressure patterns for all of the regions of the foot were similar in both groups. However, the elite group displayed greater pressures throughout the stride on both the medial and lateral surfaces, with the pressures being similar on the plantar and dorsal surfaces. Significant differences were also seen in the speed in which both groups performed the task. The average speed for the elite group was 22.41 ± 1.60 KPH, while the recreational group skated at an average speed of 19.14 ± 2.17 KPH ($p \leq 0.05$). There also appears to be a trend for the inside foot to generate greater pressures in the medial, plantar, and dorsal regions of the foot compared to the pressures generated on the outside foot during the backward cross-over. In terms of cross-over direction, it was shown that the plantar surface of the outside foot during a rightward backward cross-over generated greater peak pressure than during a leftward backward cross-over ($p \leq 0.05$). There were no significant timing differences for the peak pressures when turn directions were compared.

5.1. Skill Level and Peak Pressure Amplitude

When examining the literature comparing elite and recreational athletes in various sports, significant biomechanical differences in technique have been observed (McCaw, Hoshizaki 1985; De Koning et al. 1990; De Boer et al. 1987; Button 2003; Williams 2000; Elliot et al. 1993; Amano et al. 1995). Studies examining plantar pressures during rowing and the golf swing have noted significant differences due to differing skill-levels, as it is hypothesized that the higher skilled athletes are able to generate greater force while maintaining a more stable base throughout their respective sports (Elliot et al. 1993; Amano et al. 1995). There have not been many studies examining biomechanical differences between elite and recreational ice hockey players during power skating. McCaw and Hoshizaki (1985) noted some kinematical differences between skill-level groups in terms of the forward ice hockey stride, demonstrating several differences at the hip and knee joints of the skaters, suggesting that an evolution in technique was evident with increasing skill level, that was not evident in the novice and intermediate skaters. This suggests that the recreational subjects had not fully refined the movement pattern when compared to the elite skaters.

There are no known studies that have looked at biomechanical differences in technique with regards to the backward cross-over skating stride in ice hockey. The majority of our knowledge on skating technique comes from speed skating studies examining skating the curves of a speed skating track. It has been suggested that the general movement patterns of the forward ice hockey cross-over stride and the cross-over stride in speed skating are essentially equivalent in nature (Marino 1979, Stamm 1989). Although there are major biomechanical differences in skill execution, similarities can be seen when comparing the general movement patterns of the forward and backward cross-over strides. Both strides are composed of two major push phases: the stride push and the cross-under push. Also, during both the backward and forward cross-over strides both feet push-off forces are directed in the same direction, meaning that when a skater is turning towards the right, both feet are pushing towards the left, with the inside foot on the outside blade edge and the outside foot on the inside blade edge (De Boer 1988; De Koning 1991).

De Boer et al. (1987) examined the mechanics of the speed skating cross-over stride during the curves. It was found that the elite and trained skaters produced the same amount of muscle tension, however the elite skaters skated faster due to an optimal push-off technique. The elite skaters produced a higher amount of useful work by directing their push-off forces in a more horizontal, rather than vertical direction, ultimately resulting in a greater amount of energy being transmitted into the propulsion of the skater. The elite group demonstrated a greater push-off angle for both legs and a shorter stroke time, leading to an optimal push-off technique, which is as the authors state "the first prerequisite for a good speed skating performance" (De Boer et al. 1987).

The optimal push-off technique for a backward cross-over has not been evaluated in a scientific manner. Although is has been stressed by Stamm (1989) that the knees should be well bent during the glide phase, and that the skate blade to ice angle during push off should be at 45 degrees, technique differences between elite and recreational skaters have not been examined in order to reveal the optimal technique. The current study noted significant differences between the elite and recreational subjects in peak pressures along the medial and lateral surfaces of the foot throughout the backward cross-over stride. No significant differences were observed between both groups when looking at the plantar or dorsal areas of the foot (figure 4.2). Dewan (2000) looked at the ankle kinematics, muscle activation patterns, and foot-to-skate boot pressures during the forward skating stride, and noted that due to the unique motion the skater must use in order to transmit forces to the ice because of its coefficient of friction, the foot must act as a lever. In order to propel the skater, the foot cannot simply be pushed rearwards as in walking or running because the blade would simply slip and would not lead to effective propulsion. Therefore, the skater must push to the side and back, angling the blade in order to allow it to dig into the ice surface. It was demonstrated that significant pressures were not only seen on the plantar aspect of the foot, but also on the dorsal, medial, and lateral aspects as well, thus, indicating that several regions of the foot aid in generating propulsive forces during the forward skating stride.

It is unclear what the optimal push-off pressure patterns in the foot-to-skate boot interface during a backward cross-over would be, however, it does appear that the elite group uses the skate as a lever more so than the recreational group by generating greater pressures on the medial and lateral sides of both feet. It appears that the elite group uses the sides of their feet to a greater extent than the recreational subjects due in order to produce higher amounts of force during the stride. Perhaps this is reflective of the optimal technique for performing a backward cross-over, as De Boer (1987) mentioned with regards to speed skating cross-overs during the curves, which could be responsible for the significant difference seen in the speed with which the two groups performed the task.

5.2. Skill Level and Skating Speed

The speed at which the subjects performed the task was significantly different. The elite subjects performed the task at 22.41 ± 1.60 KPH, while the recreational group skated at an average speed of 19.14 ± 2.17 KPH. These results are not surprising as the elite subjects had much more experience than the recreational group. The elite subjects had played at least one year of university level hockey, while the recreational subjects had never played at such an elevated caliber.

Loh (2003) noted that peak pressures about the plantar surface of the feet were greater as the forward skating speed increased while skating on the treadmill, due to greater impact and push-off forces. It is believed that the pressure differences seen in this study are not due to the speed differences, but rather the speed differences are due to the increased pressures in the medial and lateral surfaces of both feet, which allows for greater force production and reflects an optimized push-off technique in the elite skaters. Interestingly, there was no significant difference between the elite or recreational groups in the plantar region during the backward cross-over, which is the region that had the greatest pressure for both groups (figure 4.2). Therefore, had the speed difference been responsible for the significant differences seen in the medial and lateral surfaces of the foot, one would expect to also see a difference in the plantar region, since it is a major contributor to force production during the push-off.

5.3. Skill Level and Pressure Patterns

The results from this study indicate very similar average pressure profiles for both the elite and recreational subjects in all of the regions of the foot throughout the backward cross-over stride, except that the amplitudes are much higher in the elite group throughout the stride in the medial and lateral surfaces of the foot. Jobse et al. (1990) and De Boer et al. (1987) both looked at pressure patterns during the speed skating stride using strain gauges. The results demonstrated a double peak in force patterns during the stride. The first peak occurred in both the front and the back of the skate and corresponded to blade contact with the ice. The second peak occurred in the front of the skate during push-off in order to generate forces for propulsion (figure 2.6).

When looking at the pressure patterns during the backward cross-over stride, many interesting observations can be made (figure 4.3). For instance, during the C-cut push of the stride, one can see that plantar pressures in the outside foot decrease as the stride progresses, and that the pressures are higher in the lateral surface during this period, meaning that as the outside foot is pushing-off on its inside skate blade edge significant amounts of pressure are placed on the lateral region of the foot. For the dorsal surface of the foot, the pressure was highest at the beginning of the C-cut push due to the ankle being placed in a dorsi flexed position. When the ankle is in such a position the regions of the talo-crural and 1st tarso-metatarsal joints are pressed against the skate boot. As the stride continues, the ankle begins to plantar flex, and the pressure on the dorsal region of the foot decreases. The pressure then increases again in this region as the ankle dorsi flexes in order to lift the skate boot off the ice, and continues to increase throughout blade contact and the glide phase due to the dorsi flexed positioning of the ankle as more of the skater's body weight is placed on that foot. As the outside foot is being placed back onto the ice on the medial edge of the skate blade, a peak is seen in every region of the outside foot. This occurs mainly due to the impact of the foot with the ice surface, and also due to this being the time period where the inside foot has finished the cross-under push and is about to be removed from the ice. Therefore, the skater shifts his/her body weight onto the now gliding outside leg.

It can also be seen that as the C-cut stride progresses, much of the skaters' body weight is placed on the inside foot, as the plantar pressures for this foot are very elevated. It can also be seen that much of the propulsive forces of the cross-under push are generated at first by the plantar surface of the inside foot, and as the stride progresses, by the medial surface of the foot. During this push the body weight is placed over the outside edge of the inside foot's skate blade, and the skate is thrust outwards and to the back, underneath the skater's body (Stamm 1989). During this portion of the stride, a great amount of pressure is seen on the medial surface of the inside foot. As the cross-under push continues, the pressure decreases from the medial surface to the lateral region of the foot as it peaks during the "toe flick" which occurs just prior to the blade losing contact with the ice. Also, during this portion of the stride, a peak can be observed in the dorsal region, as the ankle is first in a dorsi flexed position, causing the the skate boot to be pressed hard against the dorsal region of the talo-crural and 1st tarso-metatarsal joints. The pressure decreases as plantar flexion begins, then a small peak occurs, which is due to the lifting of the skate boot off the ice, and finally another peak occurs preceding blade contact as the inside foot is repositioned beside the outside foot in a dorsi flexed position. As the inside foot comes into contact with the ice a spike in plantar pressure, as well as a spike in medial pressure is observed. Therefore, with regard to the regions of the feet which produce much of the force during both the C-cut push and the cross-under push, it appears that as the push progresses the plantar pressures decrease, and the medial and lateral pressures increase. For the outside foot, which is on its medial edge, the medial and lateral pressures are similar. However, during the cross-under push, the pressures are greatest at the beginning of the stride on the medial region, but as the stride progresses, these pressures decrease and the lateral pressures increase, and peak just prior to toe off. It is also important to note that the average pressure is much higher for the elite subjects in the medial and lateral surfaces of the foot during the push-off phases of the backward cross-over stride, demonstrating their ability to use to medial and lateral areas of the foot in a more efficient manner as a means to perform the task at an elevated level.

5.4 Inside and Outside Foot Differences

Several kinematical differences have been shown when examining the stride technique of both the inside and outside leg during the speed skating cross-over (De Boer et al 1987, De Koning et al 1991). De Boer et al. (1987) performed a study were he examined knee angle and trunk positioning, as well as the push-off angle of 14 elite and 10 trained speed skaters. It was shown that the groups demonstrated the greatest differences during the push-off stride of the inside foot. The elite group demonstrated a higher push-off angle resulting in a better directed push-off, and a shorter stroke time for the inside foot, which were highly correlated to performance (De Boer et al. 1987). In terms of the current study, the pressure differences between both subject groups are similar between both the inside and outside feet. When examining the peak pressure in individual pressure sensors, it was shown that significant differences between the elite and recreational athletes occur in the medial malleolus, lateral malleolus, and the lateral head of the 5th metatarsal of the inside foot, while significant differences between groups were only seen in the medial malleolus and lateral head of the 5th metatarsal of the outside foot (Table 4.2). Also, when looking at the peak pressure of the average of the pressure sensors in a given region, significant differences between the elite and recreational skaters were seen in the lateral and medial surfaces of the inside foot, while significant differences were only observed in the lateral region of the outside foot. Therefore, it appears that unlike De Boer et al.'s (1987) study where differences between elite and recreational speed skaters were demonstrated only with the inside or crossing-under foot, the results of this study denoted significant pressure differences among the groups in both feet, indicating that differences in technique occurred during both the C-cut push and the cross-under push of the backward cross-over stride. This may be due to the skill of backward cross-over skating being less refined in some of the skaters, causing the difference between groups to be greater than the difference between groups during De Boer et al's (1987) study. The participants for that study were all trained speed skaters of differing levels, and were all very proficient in the examined stride. The participants in the current study were all ice hockey players, with differing levels of experience, performing a skill that is not practiced to the same extent, leading to greater technique differences between groups.

De Boer et al (1987) noted other differences between the inside and outside legs during the speed skating cross-over. For instance, it was shown that the inside foot's push-off stride is shorter than the outside foot's, due to a shorter gliding phase. The inside foot's push-off angle (angle between the push-off leg and the vertical) was shown to be greater throughout the entire stride. The knee angle during the cross-under push was also found to be smaller than the outside knee's during its push-off phase. A higher knee maximal velocity was also found during the inside leg's push. It was proposed that the higher knee maximal velocity and greater push-off angle for the inside leg suggests that the cross-under push is the more powerful of the two push-off phases of the forward cross-over stride.

De Koning et al (1991) measured kinematics, muscle activation patterns, and push-off forces in 7 elite speed skaters during the speed skating cross-over. The results indicated greater net moments at the hip and ankle joints of the inside leg. The authors explained their results by their muscle activation pattern findings which indicated that the semitendinosus, rectus femoris, and the gastrocnemius muscles of the inside leg showed greater levels of activation as compared to the outside leg. It is believed that this is due to the inside leg being required to maintain a more horizontal positioning, leading to differences in joint moments between both legs.

Although kinematics and muscle activation patterns were not recorded during this study, pressure differences between the inside and outside feet during backward cross-overs were seen. Greater pressures were observed with regards to the inside foot in 11 out of the measured 15 pressure sensors (figure 4.4). Moreover, it was shown that the plantar, medial, and dorsal surfaces of the inside foot also demonstrated greater pressures when compared to the outside foot (figure 4.5). These results indicate that the inside and outside feet generate differing amounts of propulsive force. In accordance with the speed skating research performed by De Boer et al. (1987) and De Koning et al. (1991), it appears that a greater amount of propulsion is due to the cross-under push of the backward cross-over stride, than is due to the C-cut push in both the elite and recreational subject groups. During the backward cross-over stride, the inside leg is placed in a more horizontal manner than the outside leg, with the hip and knee joints both flexed to a greater extent during the first phase of the stride. This allows for a very powerful leg extension from the inside leg, thus generating a great amount of propulsive forces throughout the stride. This is in agreement with the literature comparing the inside and outside legs push-off mechanics during speed skating. De Boer et al. (1987) noted that during the speed skating stride, the inside leg's push-off angle was greater and the inside knee's angle was smaller, contributing to greater knee maximal velocity, and therefore leading to a more powerful push-off. De Koning et al (1991), suggested that due to the difference in leg positioning throughout their respective push-offs, the inside leg is capable of generating greater amounts of forces, and looked at muscle activation patterns to support their claims.

5.5. Cross-over Direction

There is limited research investigating the side that skaters prefer to turn towards during the sport of ice hockey. All of the speed skating studies have only looked at right foot cross-overs, meaning that the skater is turning towards his/her left. This is due to the nature of the sport of speed skating, as the skaters always perform the task in a counter-clockwise fashion around an oval track. In the sport of ice hockey, skaters must be proficient in many different skating skills in order to excel, however there have not been any reported studies looking at kinematical differences between turning to the right or to the left.

It is generally found that hockey skaters prefer turning in the counter-clockwise direction, therefore having the right foot as the outside foot, which crosses-over the left foot. Conflicting results are demonstrated when the literature concerning the side preference during turning in walking is examined. Scharine et al. (2002) examined the turning side preference of 115 subjects during an experiment where the subjects had to walk down an aisle and look for a target that was on both the right and left sides of the aisle, but could not be seen until the subjects reached the end and chose a direction to turn to once they reached the end. It was noted that most subjects turned to the right. The authors state that this occurred due to genetic handedness, and also to learned traffic rules. In contrast, Mohr et al. (2003) assessed the side preferences in long term spontaneous turns over a 20 hour period, veering deviations while walking blindfolded in a straight line, and the deviations while stepping in the same spot while blindfolded in 36 subjects. It was found that there was a preference for the subjects to turn towards the left side during the long term test.

The data from the current study indicates a significant difference in the plantar pressures between a rightward (right foot crosses-over) and leftward cross-over (left foot crosses-over). It was shown that there are greater plantar pressures on the outside foot during a rightward cross-over (figure 4.7). The peak plantar pressure for the outside foot during this stride occurs as the blade is contacting the ice for its glide phase (figure 4.8). This indicates that the outside foot is repositioned with greater impact during a rightward cross-over than during a leftward cross-over. The reasoning for this is unclear. It is speculated that since hockey players generally prefer turning in a counter-clockwise fashion, meaning that the right foot is crossing in front of the left foot, when skating in the forward direction, perhaps they are also more comfortable crossing the right foot over the left foot when performing a backward cross-over, and are not totally comfortable with the left leg supporting all of their weight during the cross-under push. As a result they reposition the outside foot at higher forces in order to diminish them time spent in single support on the left foot during the rightward cross-over. Scharine et al. (2002) noted that handedness plays a role in determining side preference during turning in walking, and perhaps the skaters are more comfortable on their dominant leg for the majority of the stride, as it has been shown that the outside foot is in contact with the ice for a greater percentage of the stride than is the inside foot (De Boer 1987).

5.6. Considerations for Future Research

The current study only looked at pressures between the foot-to-skate boot interface, and noted some significant differences in peak pressures between elite and recreational ice hockey players, as well as differences between the inside and outside feet during the stride, and a difference in plantar pressures during rightward and leftward cross-overs. It would be beneficial to perform a kinematic analysis using goniometers at the ankle and knee joints of both feet and to measure the muscle activation patterns of the lower limbs during the backward cross-over stride. This would allow for a more complete description of the movements occurring at the ankle and knee joints during the stride, and increase our knowledge about which muscles are used and to what degree throughout the stride. Combining EMG readings with kinematical analysis would allow for a more complete understanding of the importance of the in-boot pressures as they relate to the generation of propulsive forces throughout the stride. In turn, this would further the knowledge about the skill, and allow for the determination of the optimal technique for the backward cross-over stride.

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Appendix

Consent Form for Skating Skills

A comparison of recreational and elite hockey skating

skills: kinematic, EMG and foot pressure.

Investigators: Alex Trumper, M.Sc. Student
Scott McGrail, M.Sc. Student
Nicholas Broad, M.Sc. Student
Dr. Rene Trucotte, PhD

Introduction

This project is intended to quantify lower limb muscle function, kinematics and in-boot dynamic pressure created during selective skating skills. Each subject will be asked to perform a parcours of unique ice hockey skating skills including (a) forward skating; (b) backward skating; (c) start / acceleration / stops; (d) cuts and tight turns in both clockwise and counter clockwise directions; and (e) forward skating crossovers in both clockwise and counter clockwise directions.

Participants taking part in the study:
It is very important that you read and understand the following information. Please feel free to ask the investigators any questions that will help you understand the study and what you are expected to do.

Purpose of the Study:
The purpose of the study is to provide quantitative mechanical information on the foundation agility skill tasks. In conjunction with field testing performance and perception outcome measures, which will provide essential feedback on the skate design, material and construction parameters that positively and negatively influence skill execution.

Procedures:
Your participation for this study will consist of one visit lasting approximately 3 hours. The first hour will be reserved for preparation of the participant. During this time, pressure sensors will be taped onto the foot, goniometers will be fixed in place on the heel and above the ankle and EMG electrodes will be placed on the leg. In order to ensure accurate EMG signals various muscles of the leg will have to be shaven and cleaned. The next two hours will consist of performing the various skillsFor the first skill, participants will be asked to initiate forward skating via a parallel start, accelerate to a constant velocity (24kph) complete the trial by a parallel stop. This skill will be performed 5 times. For the second skill, participants will start backward skating via a C-cut start, accelerate to a constant velocity (12kph) over a linear distance of 20 m, then complete the trial by a V-stop. This skill will be performed 5 times. For the third skill, cuts and tight turns will consist of 90° and 180° changes in direction, respectively, after 3 meters of

forward skating. These skills will be executed in both clockwise and counter clockwise directions. At their maximum speed, participants will skate towards a pilon around which the cut or turn will be executed. For each skill, five trials will be collected. The order of skills will be randomized. For the fourth protocol, forward skating cross-overs in both clockwise and counter clockwise directions will consist of a curvi-linear approach towards a target pilon. Beginning from the blue line, the participants will skate 3 meter foward to a pilon at the outermost edge of the center of the face-off circle. Around this pilon, the subject will execute cross overs about an approximate turning radius of 3 meters. The subjects will complete 180° turn then skate forward to the same blue line. For each skill, five trials will be collected. The order of skills will be randomized. During all trials, the participants will carry their hockey sticks, wearing Bauer Vapor XXV skates and loose fitting clothing. During each trial, continuous pressure, EMG and kinematic measures will be recorded.

Potential Risks and Discomforts

There is a risk that personal injury may take place during the various skill parcours, however, the risk is less than that encountered during a game situation.

Benefits associated with the study

You will not have any personal benefit from participation in this trial but the results from this study may provide valuable information that aids in the improvement of the skate boot and may improve coaching techniques.

Compensation

There will be **NO** compensation for costs, which are directly related to your participation in the study.

Confidentiality

All the records identifying you will be kept confidential. All information contained in reports or publications issued as a result of this study will be coded and presented in such a way that your identity will not be revealed.

Voluntary Participation and Withdrawal

Your participation in this study is voluntary and you may refuse to participate or withdraw from the study, at any time, without penalty.

SUBJECT INFORMED CONSENT
Signature Page

A comparison of recreational and elite hockey skating skills: kinematic, EMG and foot pressure.

Investigators: Alex Trumper, M.Sc Student
Scott McGrail, M.Sc Student
Nicholas Broad, M.Sc Student
Dr. Rene Turcotte, PhD

1. I understand that this is a research study.
2. I have read all the pages of the consent form. The research personnel have explained the information and procedures involved in the study. I have had the opportunity to ask questions and my questions have been answered satisfactorily.
3. I have been informed that my participation in this study is entirely voluntary and that I may refuse to participate, or withdraw at any time, without any consequences.
4. I understand that I will be given a copy of this informed consent to keep for my own information, once it is signed.
5. I understand that I do not give up any of my legal rights by signing this form nor am I freeing the investigators, sponsors, or the health establishment where the study takes place from their civil and professional responsibilities.
6. My signature below indicates that I voluntarily agree to take part in this study.

______________________	______________________	__________
Subject's signature	Name (in block letters)	Date
______________________	______________________	__________
Investigator's signature	Name (in block letters)	Date