Comparison of skate boot pressure of elite and recreational hockey players during the performance of forward crossovers

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ABSTRACT

The purpose of this paper was to characterize and compare pressure patterns in the skate boot of elite and recreational players during the forward crossover turn. In-skate pressure patterns of eight elite 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) were measured using fifteen piezo-resistive sensors per foot during the forward crossover skating stride. Each participant performed three trials in both the clock-wise (CW) and counter clock-wise (CCW) directions. For each trial the pressure profiles of three strides were cut and averaged according to ability groups and turn directions. The results showed that the elite skaters performed the skill quicker than the recreational skaters (6.85 (sec) ± 0.114 vs 7.62 (sec) ± 0.125), respectively ($p < 0.01$). Other significant differences ($p < 0.05$) were found in peak pressures on the plantar, medial and lateral surfaces between groups. No significant differences were found when turn directions were compared. These results show that recreational skaters differ from elite skaters by displaying higher peak pressures on the plantar surface and lower peak pressures on the lateral and medial surfaces. Also, pressures on the plantar, medial and lateral surfaces appeared to be higher on the inside foot when compared to pressures on the outside foot for both groups.

RESUME

Le but de cet article était de caractériser et de comparer le profil de la pression dans le patin de hockey entre les joueurs élites et récréationnels pendant le patinage vers l'avant en courbe. Le profil de la pression a été obtenue dans huit joueurs de hockey de niveau universitaires (écart-type moyen de ± SD: taille (m) = 1.80 ± 0.07; poids (kg) = 87 ± 0.06) et huit joueurs de hockey récréatif (écart-type moyen de ± : la taille = 1.76 ± 0.06 poids = 82 ± 0.07) a été mesurée à l'aide de quinze sondes piezo-resistive fixes sur chaque pied pendant le patinage en courbe vers l'avant. Chaque participant a exécuté trois épreuves vers la droite et la gauche. 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 (elites vs. recreatif) et de la direction de la courbe (sens des aiguilles vs. contre). Les résultats ont démontrés que les patineurs du niveau élite ont exécutés l'épreuve plus rapidement que les patineurs récréatifs (6.85 (sec) ± 0.114 vs 7.62(sec) ± 0.125; $p < 0.01$) respectivement. Autres différences significatives entre les groupes ($p < 0,05$) ont été trouvées dans les pressions maximales sur les surfaces plantaires, médiales et latérales du pied. Aucune différence significative n'a été trouvée quand les directions de tour ont été comparées. Ces résultats suggèrent que le profile de pression chez les patineurs récréationnels diffèrent de celui des patineurs élite en montrant des pressions maximales plus élevées sur la surface plantaire et des pressions maximales moins élevées sur les surfaces latérales et médiales du pied ($p < 0.05$). En outre, les pressions sur les surfaces plantaires, médiales et latérales semblaient être plus hautes sur le pied intérieur comparées aux pressions du pied extérieur pour les deux groupes.

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CHAPTER 1: REVIEW OF LITERATURE

1. The Evolution of Hockey

The game of ice hockey has become one of the fastest team sports, featuring the most athletic and talented athletes in the world. For as long as hockey has been around, the issue of where the game originated from has been a very controversial one. It is believed that the earliest form of skating dates as far back as 2000 BC and emerged in Persia. Numerous archeological discoveries and old Scandinavian and Icelandic legends have depicted images of prehistoric men moving on snow and ice on pieces of wood looking for food (Bird 1979). Sharpened sticks assisted with the locomotion over the ice in a fashion similar to modern day cross country skiing. Although this mode of transport has very little resemblance to contemporary skating, the concept of gliding on bone is still celebrated in the Dutch name "schenkel" or shank, which is the term used to describe blades in modern skates. In essence, it was the introduction of skate blades made of polished bone, which created the distinction between these two modes of locomotion.

The most distinct aspect of the skating technique is probably the sideways push-off which is most often credited to Holland. The only piece of evidence to support this association is a wood carving from the 15th century, showing that skating on skates with iron blades existed in Holland for at least 600 years (Ingen Shenau G.J. Van 1989). Other proposed locations for the origin of the skating technique include Scandinavia, Northern Germany and Poland.

Despite the early appearance of skating, the game of hockey did not develop until the 19th century. The earliest evidence of the origins of hockey exists in the form of drawings on stained glass windows which were found in medieval Europe. These drawings depicted men playing a game with hooked sticks that resembled hockey sticks.

There are many conflicting theories on when and where the game of hockey started but for all accounts the game evolved out of the Irish field game called Hurley. Originating in Ireland, Hurley was played year round on a field with a ball and a stick. In Canada, this game was played regularly in the fields of Nova Scotia back in the early 1800's. Due to the rough winter conditions, the game was moved onto the ice. This new version of the sport started at King's College in Windsor in Nova Scotia and became very popular over the next fifty years. The game took on several names such as Rickets and Shinny but was eventually called Hockey in the later parts of the 1800's. The popularity of hockey in the past is quite possibly related to the local climatological environment which offered the required conditions to allow the sport to be played. This is perhaps the reason that skating has become a very popular sport in places like Holland, Norway and Canada. In these regions, the winter seasons brought temperatures cold enough to form ice and thus led to the development of the sport. Only recently, with the development of indoor hockey arenas, has skating been possible in locations of warmer climate.

1.1 Progression of hockey skate boot

It is not surprising that with the long history of hockey, the skate boot has also experienced an extensive progression in terms of design. The earliest records reveal that the skate blade evolved from a wooden blade, then bone and finally progressed into an iron blade (Goodman 1882). The aim was to create a boot that allowed for near frictionless gliding at times but also allowed for friction to be generated at other moments. The remains of one mans earliest attempts to solve this problem were found during the ninth century in Sweden and came in the form of a skate blade made of bone

(Vaughan 2001). In the fourteenth century, the skate was then fitted with a metal blade permanently fixed to the skate boot by means of a wooden support. This blade attached directly to the boot and had the advantage of allowing a shorter distance between the foot and the ice, which increases the stability of the skater by lowering the center of gravity. However, this design reduces the skater's ability to perform skills which require small angles between the ice and the skate boot, such as at the end of the push-off. In the seventeenth century, skates made entirely of iron were introduced. In the 1850's, boots and blades were sold separately and put together using leather straps or keys (Vaughan 2001; Vaughan website © 2001). The introduction of a spring-clamping mechanism around 1880 made assembly easier. The blade and boot were later permanently fixed together allowing for greater control and durability, but consequently added considerable weight to the skate, thus reducing skating speed. With the introduction of tubular skates in the 1950's, the weight of the skate was reduced without adversely affecting the maneuverability or resilience of the skate. Leather would give way to plastic, and by the 1970's the skate boot had transformed into a similar form that it takes today, a hybrid of materials further reducing weight and better support, strength and mobility (Pearsall, Turcotte et al. 2000; Chin 2001; Vaughan 2001).

Figure 1: Pictures demonstrating the evolution of the skate boot.

It is evident that since the original design of the skate boot, the hockey industry has evolved drastically into a multi-million dollar industry. The increased popularity of the sport and the intense training that players experience has led to the improvement of hockey equipment. While it is known that these design changes improve durability and provide a lighter skate, kinematic and kinetic parameters need to be investigated further to determine potential improvements to the skate boot design (Pearsall, Turcotte et al. 2000).

1.2 Construction of skate boot

The research concerned with the optimal development of equipment for sporting activities is essential. The sport industry constantly strives to develop and market the best shoe or protective equipment to optimize comfort, protection and performance (Turcotte 2001). These design changes are the result of the ongoing evolution and demands of specific sports. There currently exists extensive research on sports footwear for sports such as running(Cavanagh 1980; Salathe Jr., Arangio et al. 1990; Atkinson-Smith and Betts 1992; Reinschmidt, Nigg et al. 1994; Reinschmidt and Nigg 2000) and walking (Hutton and Dhanendran 1979; Salathe Jr., Arangio et al. 1990; Atkinson-Smith and Betts 1992; Cavanagh, Hewitt Jr. et al. 1992; Chen, Nigg et al. 1994; Hayafune, Hayafune et al. 1999; Morag and Cavanagh 1999; Chesnin, Selby-Silverstein et al. 2000; Hosein and Lord 2000; Reinschmidt and Nigg 2000; Eils, Nolte et al. 2002; Chen, Ju et al. 2003) attempting to quantify the mechanical characteristics and durability of these products. Unfortunately, similar research concerned with the hockey skate boot design is not as thorough (Lamontagne 1983; Broadbent 1989; Hoshizaki 1989)

1.2.1 Characteristics of the skate

The interaction between the skate and the ice is the fundamental backbone of skate boot design. There are two main properties of the hockey skate which may be modified in order to alter the performance of the skate boot. These two properties are boot stiffness and blade features. Each of these characteristics acts independently to affect the performance of each skill.

a) Boot Stiffness

Many elite ice hockey players are primarily concerned with the stiffness of the skate boot, as it is perceived as a crucial aspect for optimal support and performance during skating activities (Turcotte 2001). The skate boot stiffness is primarily determined by the materials used (i.e. leather, polyethylene shells, lacing), and the manner in which these materials are assembled to generate the final product (i.e. stitching, gluing, material orientation and layers) (Pearsall, Turcotte et al. 2000). Since the emergence of the sport, the skate boot design has evolved dramatically, as the first amateurs of the sport used their own pair of everyday shoes made entirely from leather. This style of boot offered very little stability. In contrast, today's ice hockey skates are made of a combination of materials to yield a stronger and lighter skate boot (Chin 2001). The skate boot we know today consists of an outer covering of leather or composite material, an ankle support, a toe box, a heel counter, a rigid sole, a skate blade housing, and finally the metal blade (Pearsall, Turcotte et al. 2000).

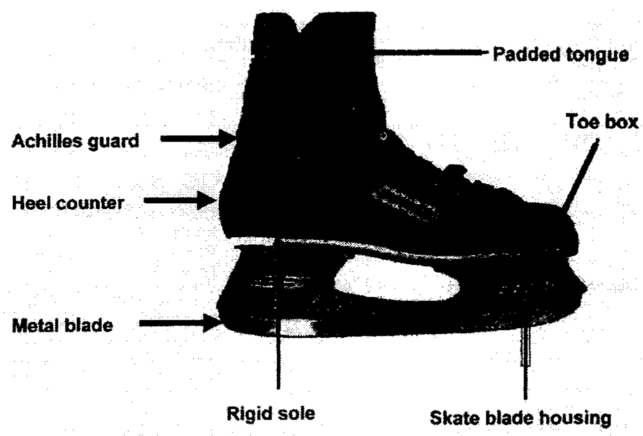


Figure 2: Modern skate boot features (Pearsall, Turcotte et al. 2000)

Furthermore, the modern high-cut boot offers crucial medial-lateral support needed for the ankle during stopping and tight turns. However, it has been shown that this design impedes dorsiflexion during push-off and therefore can be detrimental during the force production phase of the stride (Pearsall, Turcotte et al. 2000). The current design of the skate boot may offer the best combination of comfort and performance. However, it is likely that regional variation of skate boot stiffness characteristics may help optimize skating performance (Hoshizaki 1989). Unfortunately, kinematic and kinetic performance characteristics of skating have not yet been thoroughly investigated in order to justify specific design changes.

b) Blade Features

The second hockey skate feature which can be modified is the skate blade. The ICE (Ice Skating Conditioning Equipment Corporation) research on blade and boot design confirms that numerous variables impact skating performance. These important characteristics include the center of curvature, radius of curvature (rocker) of the blade, its center of curvature, edge sharpness, blade thickness and the alignment of the blade with the boot and foot (Broadbent 1989). Although this study was performed on figure skaters, these findings show the importance of equipment testing and suggest that hockey skill execution may be affected by manipulating the same skate blade features in a different configuration.

Blade hollow and edges

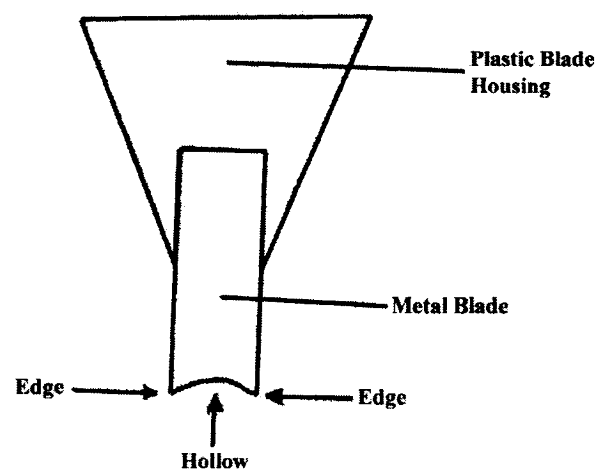


Figure 3: Frontal view of skate blade with two edges and hollow (Minkoff J 1994).

Each skate blade is made up of two edges separated by a hollow. The depth of the hollow has been shown to change the performance characteristics of the skate. A deep hollow results in a sharper edge that cuts more easily into the ice allowing for a more powerful force generation and thus greater agility (Pearsall, Turcotte et al. 2000). However, as a consequence to this sharp edge smooth stops are compromised. On the other hand, a shallow hollow will permit the skater to perform smooth stops but reduce agility and push-off force (Minkoff J 1994). Players are very conscious of the sharpness of their edges. Both inside and outside edges are vital in the execution of different skills and influence the stability, agility and power of the skater. The inside edge is the most medial side of the skate blade and used during forward skating in the generation of force. The outside edge is more lateral and used primarily in executing stops, turns and backward skating. A blunt edge will limit the amount the blade is able to cut into the ice effectively and the desired skill will not be accomplished properly.

Blade thickness

Blade thickness has also been manipulated to determine its effect on performance. A reduction in the thickness of the blade will increase the ability of the blade to penetrate into the ice by increasing the force per unit area (Minkoff J 1994). This results in a more powerful stroke while reducing the friction component at the blade. Consequently, this reduction in blade thickness poses a problem in attaining a sufficient hollow during the sharpening process.

Center and radius of curvature

Skate blades are designed with a curved blade called the rocker or radius of curvature. Although no research has been completed to determine the influence of the radius of curvature on performance, elite players have reported increases in stability when rocker radius is increased (Figure 4A). Conversely, accounts of improvements in agility have been reported with a decreased in the radius of curvature (Figure 4B) (Minkoff J 1994).

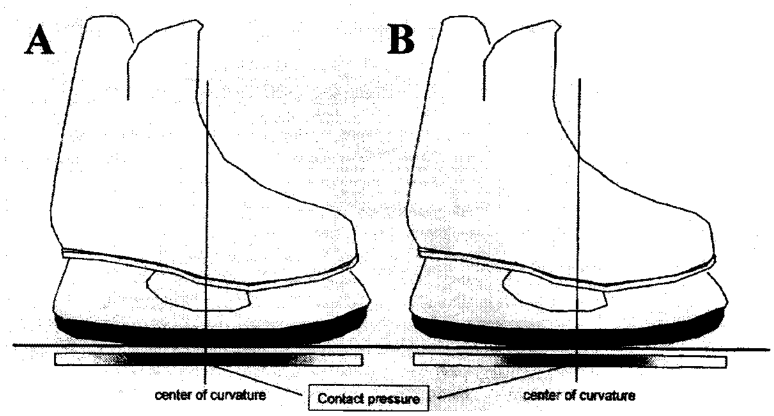


Figure 4: Radius of curvature and its effect on surface contact. Radii vary from 3m (A) to 2m (B). (Pearsall, Turcotte et al. 2000)

The center of rocker is another critical factor that affects balance and stability. If the center of curvature is too far forward or backward, stability and balance will be adversely affected, thus, potentially negatively influencing all aspects of hockey performance (Pearsall, Turcotte et al. 2000). The center and degree of curvature differs among manufacturers and skate models, however it can be manipulated through skate sharpening. The optimal location of the center and amount of curvature provides the correct level of balance and stability without compromising the performance of the skater (Minkoff J 1994). As mentioned earlier due to the lack of research on blade design the best rocker configuration is yet to be determined.

The nature of skate boot design is a complicated process. Designers are often faced with the reality that altering one of the skate boot's characteristics may increase a player's ability to perform one skill while diminishing the execution of another. For example, it is believed that an increase in the radius of curvature of the skate blade improves the player's ability to perform sharp turns but consequently reduces their skating speed. Unfortunately, the lack of research specific to hockey has hindered our ability to critically define the optimal skate design for the highest level of performance. Very few of these variables have been manipulated scientifically to determine their impact on skating performance. Nonetheless, it is widely believed that slight changes in these ice hockey skate boot variables could have a drastic effect on a skater's ability to perform skill such as linear skating, crossovers, turning, stopping, passing, and/or shooting (Minkoff J 1994). For this reason, Hansen and Reid (23) suggested that skate boot design should vary according to a given player's position. After interviewing professional players, scouts, coaches and managers they compiled a list of skills and reasoned that specific skate boot designs may be beneficial given the highly specific nature of skills for a particular playing position (i.e. forwards, centers, wingers, defense, and goalies). Further research is needed to examine the optimal trade off required between support and flexibility to achieve the most advantageous skate boot design to perform the various hockey skills (Pearsall, Turcotte et al. 2000).

The skate design is an important aspect of skating performance because of its effects on comfort and skating efficiency. Hancock et al. (Hancock 1999) performed a study on ten healthy males which looked at the range of motion in the ankle in three skate boots of different stiffness. From their research, the authors concluded that the functioning of the ankle joint complex is drastically affected by the design and construction of the hockey skate boot, and these factors should be considered by skate manufacturers in the development of the optimal skate for performance. Ice hockey equipment manufacturers are continuously striving to design a better, more efficient skate boot. In the sport of hockey, there are numerous biomechanical factors that interact to affect skating performance (Hay 1993). Skate design represents one of these factors, and more research is needed to understand how each of the skate boot characteristics interacts to affect skating performance (Pearsall, Turcotte et al. 2000).

2. The Skating Stride

2.1 Skating the straights

There exists little data describing the biomechanics of the ice hockey skating stride which is partly due to the difficulties of measuring critical variables on ice (Marino 1979; Pearsall, Turcotte et al. 2000). The limited research may also be attributed to the limited number of skilled subjects available for recruitment (Marino 1995). Most of the research that has been done to describe the biomechanics of the skating stride primarily comes from research on speed skating (Ingen Schenau 1985; Boer 1987; Ingen Shenau 1987; Ingen Shenau G.J. Van 1989; Jobse 1990; Miller 1990; Koning 1991). Although major differences exist between the two sports, the forward skating stride during speed skating or ice hockey skating at a constant velocity can be considered equivalent in nature in terms of general movement patterns (Marino 1979; Stamm 1989).

For both hockey and speed skating, the forward skating stride is a biphasic, cyclical and symmetrical form of locomotion which is made up of the support phase and the swing phase (Boer 1987; Ingen Shenau G.J. Van 1989). The support phase can be further divided into two distinct temporal phases, single support and double support (Marino 1979; Stamm 1989). In this respect, skating is similar to other forms of locomotion. However, a closer examination of the direction of propulsive forces reveals that skating is biomechanically unique when compared to other forms of human locomotion (Ingen Shenau 1987). In most forms of locomotion, such as walking and jumping, the propulsive push-off required to produce movement takes place against a fixed point on the earth, parallel to the direction of motion but in the opposite direction of the body's center of mass. However, due to low coefficients of friction between the skate blade runner and ice, little force can be elicited by pushing off parallel to the long axis of the skate blade. In comparison, the propulsion technique of skating requires the skater to transmit forces perpendicular to the skate blade such that the push-off maneuver is made at a ninety degree angle to the gliding direction of the skate (Boer 1987; Ingen Shenau 1987; de Boer 1988; Ingen Shenau G.J. Van 1989; Dewan 2004). This concept contradicts the intuitive notion of an effective push-off in that if you want to go in a certain direction one should push-off in the opposite direction. Furthermore, in order to maintain the proper skating technique, it is essential that on initial contact with the ice, the push-off skate must be placed directly under the center of gravity (COG) as both the skate and the COG continue to shift forward simultaneously during actual force production. Consequently, through out the stroke, the point of force production continually moves as the skate glides forward along the ice (Boer 1988). These points are illustrated in Figure 5. The trajectory of the COG is represented by the broken line while the solid line denotes the right skate. On blade contact, the right skate is placed directly underneath the COG as it moves along the ice (V_1). As the right skate continuously glides forward, force is generated at a ninety degree angle to the skate blade (V_2). The propulsion from the right leg (V_2) is summed with the initial vector (V_1) and results in the final trajectory of the COG (V_3). This process is then repeated on the left side.

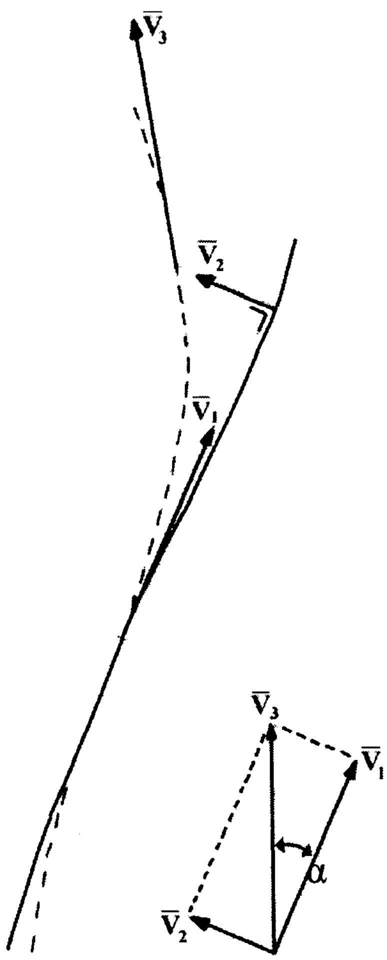


Figure 5: Trajectory of the center of gravity (CG, broken line) and of the right skate (solid line) in speed skating. V_1 represents the velocity of the CG just before push-off. V_2 represents the direction of force production due to a sideward push-off at a 90 degree angle to V_1. V_3 is the product of V_1 and V_2 represents velocity just after push-off. The push-off results in an increase of kinetic energy and causes a change of the direction α (Boer 1987; Boer 1988; Ingen Shenau G.J. Van 1989).

Propulsion is achieved by setting the blade on edge, externally rotating at the hip and pushing laterally. This allows the skater to elicit the large reactive forces necessary to drive the body forward. This unique method of locomotion does not result in linear movement. Instead, the sideward push-off results in a change of direction of the skater's COG with respect to the ice. This sideward push-off results in a sinusoidal trajectory of the skater's COG as seen in Figure 6 (Boer 1987; Boer 1988; Ingen Shenau G.J. Van 1989; Pearsall, Turcotte et al. 2000).

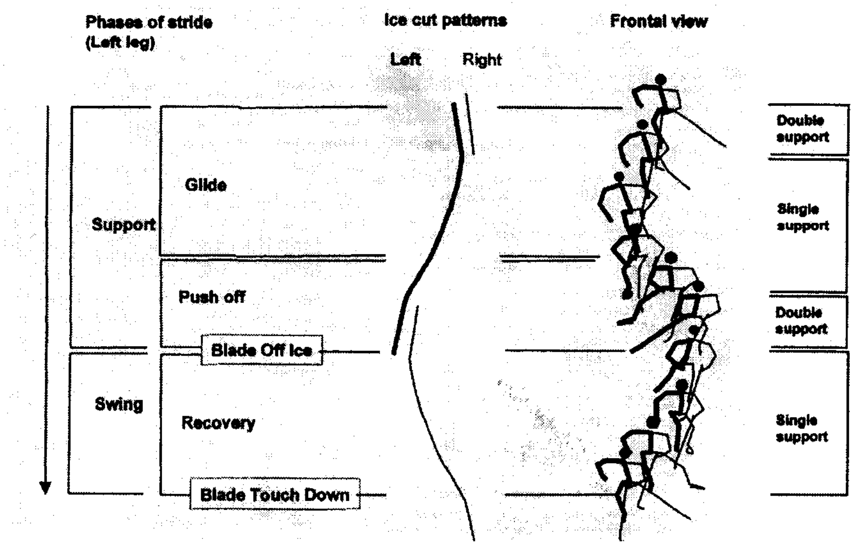


Figure 6: Lateral displacement of the body during the forward skating stride. Ice cuts and COG depict sinusoidal skating pattern in the transverse plane (Pearsall, Turcotte et al. 2000).

Although, it has been suggested that the general movement patterns of the forward skating stride are similar for speed skating and hockey skating, very little kinematic or kinetic research has been preformed in ice hockey to substantiate this claim. The field of ice hockey research would benefit significantly with similar kinematic studies to those done in the field of speed skating, thus revealing the similarities and differences in the skating techniques of each sport.

2.2 Skating the curves

Research on angular skating is another aspect of ice hockey that has not been widely studied, even though it is just as important a skill as forward or backward skating. In fact, angular skating is often performed as a transition from forward to backward skating (Pearsall, Turcotte et al. 2000). In order to understand how a skater performs a turn, it is essential to understand the principles of the forces that govern this type of movement.

2.2.1 Newton's Laws of Motion:

Newton's Laws of Motion were developed and explained by Sir Isaac Newton in the 17th century. He developed three laws that explained the behavior of stationary or moving objects.

> First Law of Motion: An object at rest tends to stay at rest and an object in motion tends to stay in motion with the same speed and in the same direction unless acted upon by an unbalanced force (Wolfson 1995).

The first law predicts the behavior of objects for which all existing forces are balanced. If the forces acting upon an object are balanced, then the acceleration of that object will be zero (m/s/s). Objects in equilibrium, the condition in which all forces balance, will not accelerate (Figure 7).

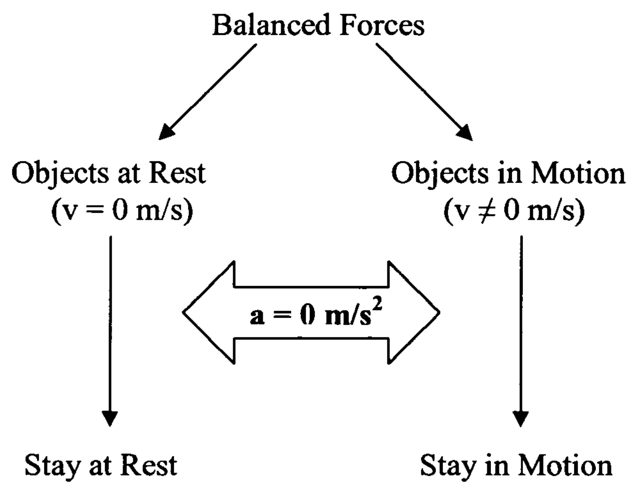


Figure 7: Explains the two components of Newton's first law of motion - behavior of stationary objects and the behavior of moving objects.

Second Law of Motion: The acceleration of an object as produced by a net force is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass of the object (Wolfson 1995).

According to Newton's second law, an object will only accelerate if there is an unbalanced or net force acting upon it. The presence of an unbalanced force will accelerate an object - changing its speed, its direction, or both (Figure 8). This law states that the acceleration (a) of an object is dependent upon two variables - the net force (F) acting upon the object and the mass (m) of the object.

Equation 1:

$$F = m * a$$

where a and F are both vectors pointing in the same direction.

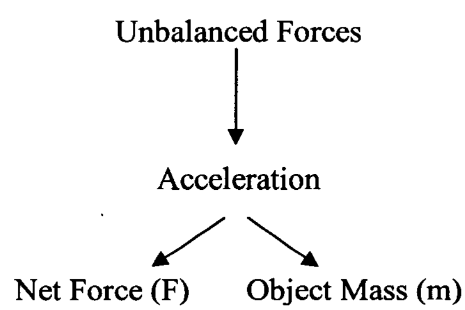


Figure 8: Explanation of Newton's second law

Third Law of Motion: for every action there exists an equal and opposite reaction (Wolfson 1995).

This law states that forces are always produced in pairs with opposite directions and equal magnitudes. For example, if body #1 acts with a force F on body #2, then body #2 acts on body #1 with a force of equal strength and opposite direction.

2.2.2 Centripetal Force

According to Newton's first law, any motion in a curved path signifies a change in direction and therefore, cannot be balanced. Consequently, if the forces are unbalanced, Newton's second law reveals that it is a dynamic system and thus must follow Equation 1. In rotational motion, radial acceleration (a_r) is equal to the velocity (V) squared divided by the radius of curvature (r). Equation 1 can be altered for rotational motion by substituting the acceleration component with equation 2 to give equation 3.

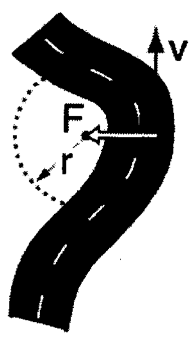
Equation 2:

since in radial acceleration $$a_r = \frac{V^2}{R}$$

Equation 3:

$$\Sigma F = m \times \frac{V^2}{R}$$

The source that unbalances the system represents the acceleration component of the equation and is the result of a force directed toward the center of curvature of the path. This force is called the centripetal force which means "center seeking" force. For example, when a car turns a corner, the velocity vector (V) attempts to keep the car going in a straight line (Figure 9). The centripetal force (F) changes the direction of the car by acting in towards the center point of the turn radius.



$$F_{centripetal} = m \times \frac{V^2}{R}$$

Figure 9 : Diagram showing how centripetal forces cause angular motion.

F = centripetal force

V = Velocity vector

r = radius of curvature

Note that the centripetal force is proportional to the square of the velocity and inversely proportional to the radius. This implies that a doubling of speed will require four times the centripetal force to keep the motion in a circle or a reduction by half of the radius will necessitate an increase in the centripetal force by two fold. In many cases, such as turning in ice hockey, friction determines the centripetal force and an increase in speed could lead to an unexpected slip which may cause the skater to fall if friction is insufficient.

2.2.3 Kinetic description of skating the curves

In the sport of ice hockey, angular movements can occur about the skater's longitudinal axis however, most turns occur about points external to the body. The farther the axis of rotation is from the body the larger the radius of curvature, and the lesser the centripetal force. The reverse is also true such that the smaller the radius of curvature of the skater, the greater the centripetal force. This centripetal force can be offset by increasing ice friction by leaning the trunk towards the center of the turn where the axis of rotation resides. This will position the player's center of gravity outside and lateral to the base of support (Pearsall, Turcotte et al. 2000) and increase the skate blades' effectiveness to cut into the ice. The skater's enhanced ability to carve into the ice produces a reactive force at the blade-to-ice interface. The reactive forces on the blade can be broken down into two components. The vertical component represents the reactive force pushing against and equal gravitational force. The horizontal component of the reactive force is the centripetal force which causes a shift in direction towards the center of rotation producing a turn.

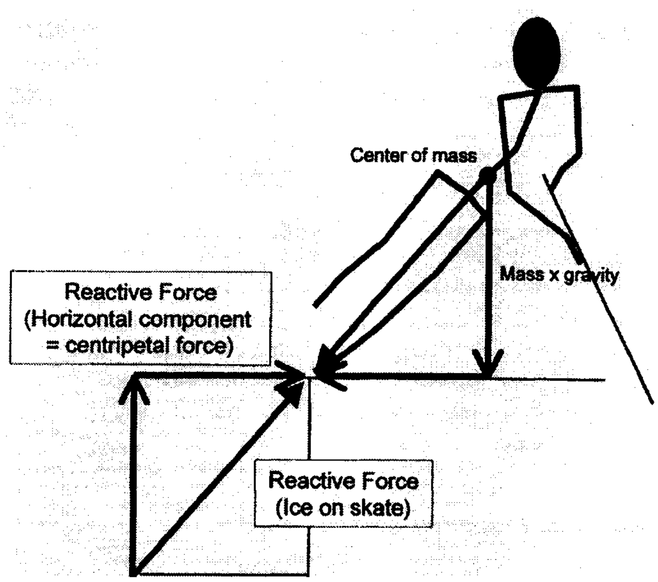


Figure 10: Generation of centripetal force in skating the turns (Pearsall, Turcotte et al. 2000).

In terms of skate blade placement, the skill of angular skating requires the use of both the inside and the outside edges of the blade, since propulsion is generated by push-off forces directed to the same side of the body (Pearsall, Turcotte et al. 2000). The outside leg, which is the leg furthest from the center of rotation, will press with the inside edge, which is similar to forward skating. The inside leg, which is closest to the center of rotation, will press with the outside blade edge as it glides under the body (Stamm, 1989). Depending on the game situation, a hockey player can use two different techniques to execute a turn from the forward skating stride position. Figure 11 illustrates the kinematic differences between the two types of turns. The first technique is performed through a series of crossover steps and is termed the crossover turn (Figure 11A). The second method requires the skates to be parallel and is termed the pivot turn (Figure 11B). (Pearsall, Turcotte et al. 2000).

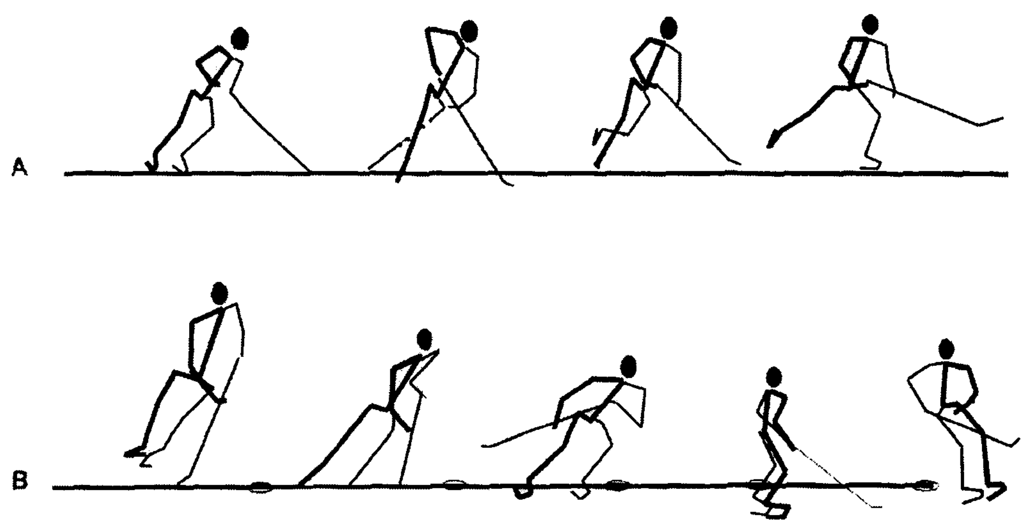


Figure 11: Movement sequence during crossover (A) and pivot turns (B) (Pearsall, Turcotte et al. 2000)

One of the major advantages of the crossover technique is that this method allows for the generation of propulsion throughout the turn. Furthermone, the radius of curvature will be much larger in the crossover turn compared to turning with blades in parallel. Each mode will be used in particular playing situations depending on the desired turn radius and purpose of turn. For example, turning with blades in parallel allows for quick, tight turns, although there is a loss in net energy. This loss in energy translates to a loss in velocity since the skater is unable to produce propulsive forces.

2.2.4 Comparison of inside and outside legs during skating the curves

As previously mentioned, skating the curves follows an asymmetrical movement pattern of the legs since both legs are directed to the same side of the body. Not only are push-off forces oriented in the same direction for both legs but individual differences between inside and outside legs also exist. In a study of seven elite male speed skaters, Koning et al. (1991) measured kinematics, EMG and push-off forces while speed skating the curves. Their results showed larger net joint moments at the hip and ankle joints in the inside leg. These variations in joint moments can be explained by the activation levels of several leg muscles. For example, the semitendinosus, rectus femoris and the gastrocnemius demonstrated higher levels of activation in the inside leg during the middle portion of the stride compared to the right leg. The authors suggest that the differences in joint moment can be explained by the more horizontal position of the upper inside leg which requires a greater level muscle force of the hip and knee extensors. Therefore, the inside leg is forced to produce more work when skating the curves. This phenomenon has been previously observed qualitatively as speed skaters often complain that fatigue usually occurs earlier in the inside leg than in the outside (Koning 1991). Similar results were found in a study by Boer et al. (1987) who studied lower body kinematics during speed skating the curves. In addition, they also confirmed a more horizontal position of the inside leg which they attributed to the "leg over" technique of the crossover stride. This technique forces the skater to lift the outside skate over the inside skate and place it more forward and vertically on the ice. A vertical orientation of the skate at ice contact is a less favorable position for power production and results in a longer stroke due to longer glide phase compared to that seen in the inside leg. In addition, the sequential pattern in the movements of the trunk, upper leg, lower leg, and foot in the proximodistal direction seen when skating the straight, is not observed for the left leg when skating the curve. It is believed that a sequential pattern in the proximodistal direction delays the end of push-off, which implies that the muscular shortening possibilities can be used more efficiently. However, a proximodistal sequence was observed in the right leg do not result is higher work outputs, therefore, other constraints may influence the proximodistal formulation.

2.2.5 Comparison of skating the straights and skating the curves

According to Boer et al. (1988) there is no essential difference in the propulsion mechanics of speed skating in a straight line or in the curves because in both situations the direction of the push-off must be perpendicular to the gliding direction. As mentioned previously, skating in a straight line requires the push-off of the left leg to change the direction of body's center of mass towards the right, while the push-off to the right changes body's center of mass to the left (Koning 1991). In skating the curves, the push-off forces are produced in similar directions for both skates since propulsion is generated by driving the legs on the same side of the body (Boer 1988). Therefore, when the skater is turning to the right, both legs are pushing to the left and when a left turn is being performed then both legs are producing propulsive forces to the right (Koning 1991). This results in the center of gravity (COG) following a pseudo-circular path compared to the sinusoidal trajectory seen with forward skating (Figure 12) (Boer 1987; Boer 1988; Ingen Shenau G.J. Van 1989; Pearsall, Turcotte et al. 2000).

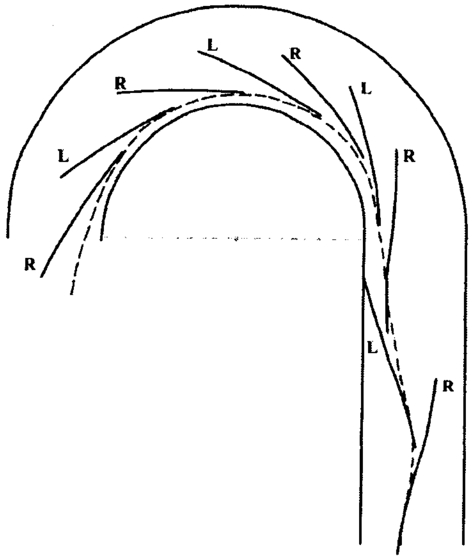


Figure 12: Path of the center of gravity while skating the curves. Center of gravity (*dotted line*) outlines the arc of a circle because both skate blades are pushing off to the same side on the body (right side in this case). Also shown are the ice cut patterns of the left (L) and right (R) legs (Ingen Shenau G.J. Van 1989).

Another disparity, which reinforces the distinctiveness of angular skating from forward skating other cyclical modes of locomotion exists in the fact that most cyclical movements are symmetrical in nature while skating the curve follows a highly asymmetrical movement pattern of the legs (Koning 1991).

As is the case for most skating skills, the kinetics of skating the curves has only been examined in the sport of speed skating (Ingen Schenau 1985; Boer 1987; Boer 1988; Ingen Shenau G.J. Van 1989). Numerous speed skating coaches believe that proper technique for skating the curves is more vital for the determination of success in competitive skating than the technique for skating the straights (Ingen Shenau G.J. Van 1989). Similarly, turn execution in ice hockey also plays a crucial role in a player's level of performance. A review article by Ingen Shenau (1989) compared the push-off forces of a speed skater skating the curves and the straights at the same speed. The differences in push-off forces between the two conditions are shown in the graphs below (Figure 13).

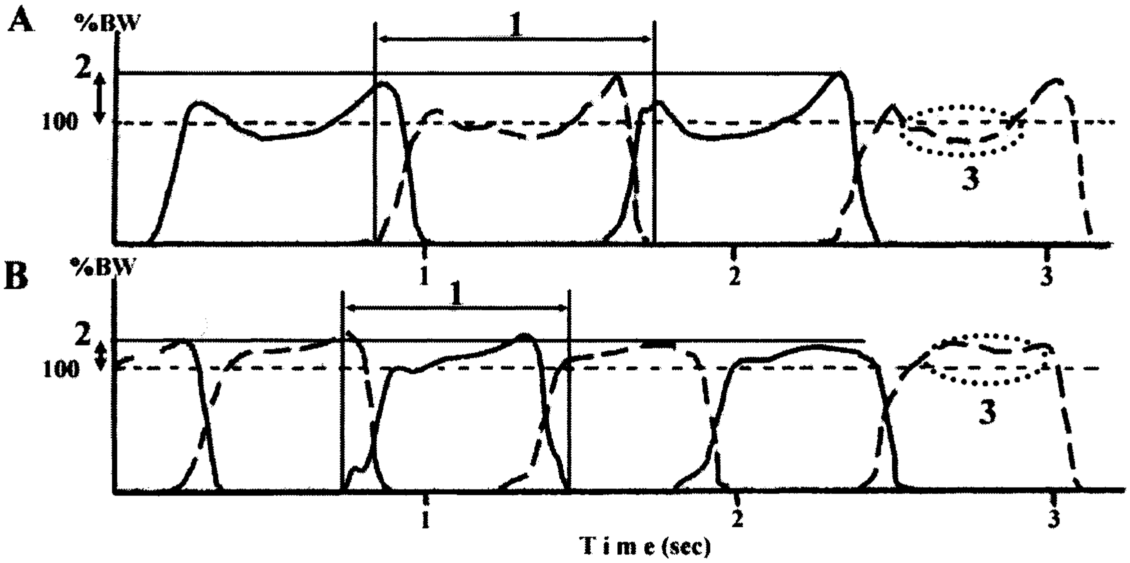


Figure 13: Push-off forces observed at the same speed during skating the straights (A) and skating the curves (B) as expressed as a percentage of body weight. Dashed line represents left leg and solid line the right. (Ingen Shenau G.J. Van 1989).

The main differences in push-off forces observed between skating the straights and the curves are the shorter stroke duration, the lower peak forces at the end of push-off, and the lack of the glide phase where the total pressure drops below body weight. The absence of the glide phase while skating the curves is due to the orientation of the skate at ice-contact which allows the production of force almost immediately unlike in skating the straights where on blade contact the skater must allow the skate boot time to travel from directly underneath the body to a more lateral and posterior position where force can be produced (Ingen Shenau G.J. Van 1989). The absence of a pronounced glide phase results in decreased stride times or increased stride frequency which may account for the reduction in peak forces at the end of push-off (Ingen Shenau G.J. Van 1989).

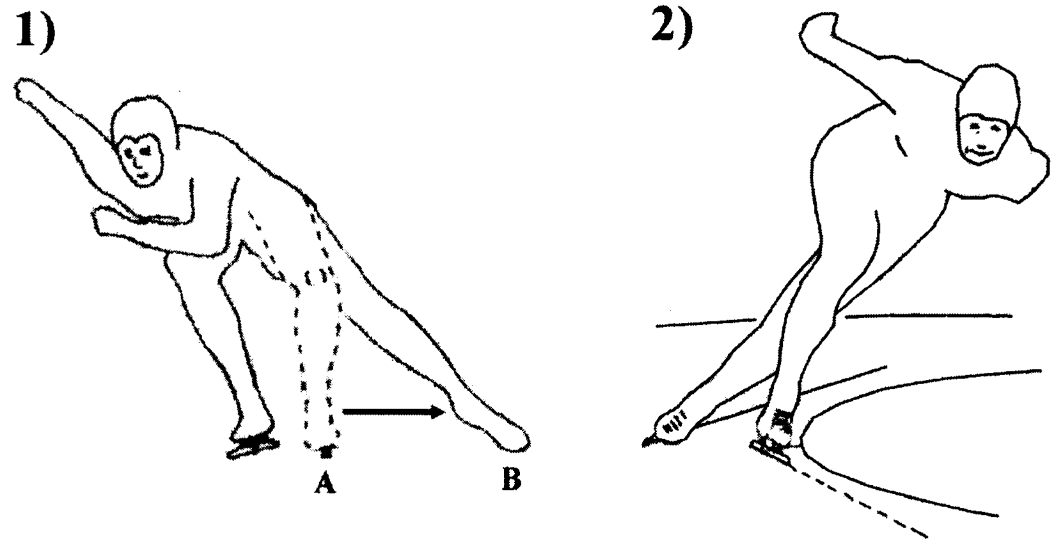


Figure 14: Differences in orientation of the blade at ice contact between skating the straights and skating the curves 1) Skating the straights; demonstrates how the skate must travel laterally and posteriorly from first contact (A) to end of push-off (B). 2) Skating the curves; upon initial blade contact, leg and skate are orientated in such a way as to facilitate force production immediately (Ingen Shenau G.J. Van 1989) .

Another possible explanation for the different stride frequencies observed between skating the straights and skating the curves is the ability to control the stroke frequency during the straight but not during the curves. (Ingen Shenau G.J. Van 1989). A previous study performed by Ingen Schenau (1985) showed that when speed skating the straights the amount of work per stroke is a constant property, independent of speed, for a skater of a given performance level. Therefore, stride frequency can be freely chosen by the skater to deliver a certain output. In contrast to the straight sections of the rink, the stroke frequency and thus the power production in the curves cannot be chosen freely by the skater. The amount of turn that can be elicited by each stroke during a turn is dependant on velocity. For example, a skater traveling along will push-off to the side with a given force thus changing the direction of the COG. For a skater traveling at five meters per second a change in direction per stroke of twenty-six degrees has been found to be typical (Ingen Shenau G.J. Van 1989) (Figure 15b). Conversely, for a skater traveling at thirteen meters a second and generates the same sidewards push-off, will cause only a ten and a half degree change in direction of the COG (Figure 15a).

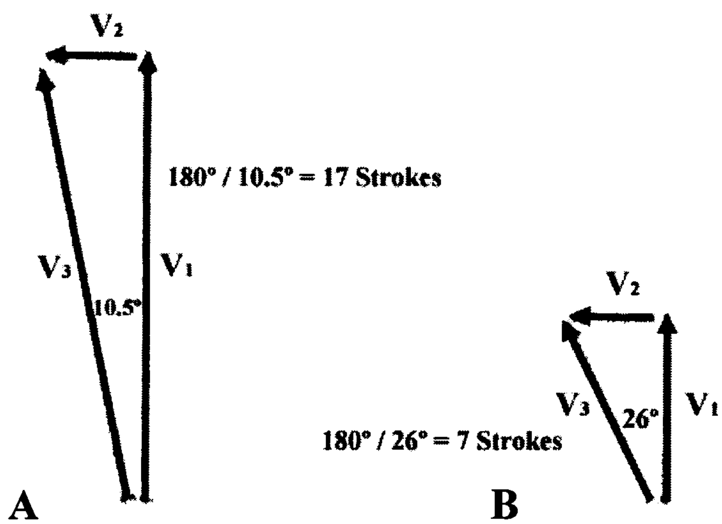


Figure 15: The change in direction as a result of the same push-off force (V_2). Diagram A shows the vector diagram of a skater skating at 13m/s and B of a skater at 5m/s. V_1 represents the original speed and direction of the skater. V_3 represents the speed and direction as a result of the push-off (V_2) (Adapted from Ingen Shenau G.J. Van 1989).

Since the turn of a speed skating track covers a full 180 degree turn it is possible to calculate the number of strokes needed for each skater to make the turn given that the speed remains constant. The stroke frequency is obtained by dividing the total degrees of the curved section of the rink by the degrees traveled per stroke. Using this calculation, it can be determined that the faster skater would need 17 strokes to perform the turn, while the slower skater would need 7 strokes to complete the same turn. The restriction in the stroke frequency used in the execution of the turn will influence the amount of total power produced throughout the turn since power is determined mainly by stroke frequency (Ingen Shenau G.J. Van 1989). Consequently, the author states that it is expected that differences in push-off mechanics among skaters of different performance levels will prove to be the most pronounced in speed skating the curves due to the more restrictive nature that the execution of skating the curves entails.

3. Pressure

Pressure sensing devices have become increasingly useful tools in the determination of the pressure distribution patterns within the shoe. The evolution of these devices has enabled the scientific community to further understand the effect of changes in pressure on the foot structures, which has led to the development of specialized footwear for orthopedic purposes or for the enhancement of sport performance. The following section will provide an in depth overview of these devices and their effects on the clinical and athletic community.

3.1 Plantar pressure measurements

Up to the past decade, the majority of the studies examining plantar pressures have focused on the foot-to-floor interface using force plates as the main instrument for data collection. In essence, the principle of force plates is based on Newton's third law of motion which states that for every action there is an equal and opposite reaction. An example of this law is seen while walking, where there exists an interaction between the ground and the body. As the foot strikes the ground, the ground responds by exerting a reaction force, called the ground reaction force (GRF). These GRFs can be measured by sensors built into the feet of the force plate. Some investigators have opted to used strain gauges which function in much the same way as force plates (Boer 1987; Jobse 1990; Houdijk 2000). For example, de Boer et al. (1987) examined the patterns of moments of push-off forces in two well-trained speed skaters. While the skaters completed one lap of a standard 400-m ice rink, measurements of push-off forces were obtained using an instrumented skate which contained two strain gauges, one situated at the front of the skate and the other at the back, fixed between the shoe and the blade. Their results revealed a double peak force pattern for the forward speed skating stride (Figure 16).

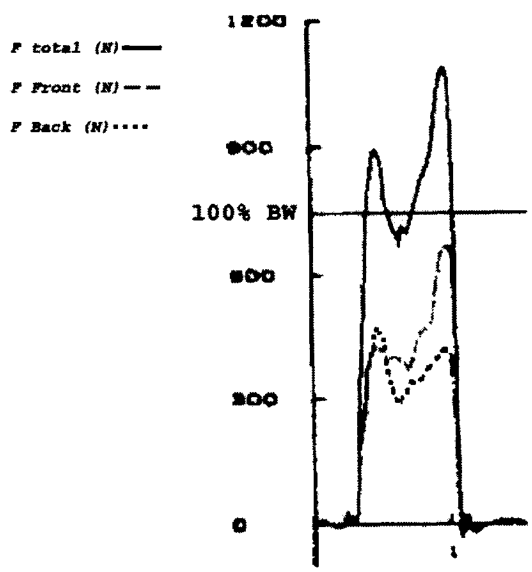


Figure 16: Force vs time graph of the right leg during speed skating. F front (*dashed line*) represents forces at the front of the skate. F back (*dotted line*) denotes the forces at the back of the skate. F total (*solid line*) is the sum of forces at the front and back of the skate(From Boer 1987).

The authors found that the first force peak corresponded to the blade coming in contact with the ice, as can be seen as a pressure spike in both the front and back part of the skate. The second peak was attributed to push-off forces which are generated to a greater extent at the front of the skate. The two peaks are separated by a period where force declines below the skater's body weight. This diminished force interval was attributed to the glide phase of the stride in preparation for push-off. The shape of the curves and the magnitude of the peaks are in accordance with a similar study performed by Jobse et al. (1990) who used a comparable skate design with strain gauges mounted into the blade holders. These results are illustrated in Figure 17 with the front forces, the back forces and the total forces presented.

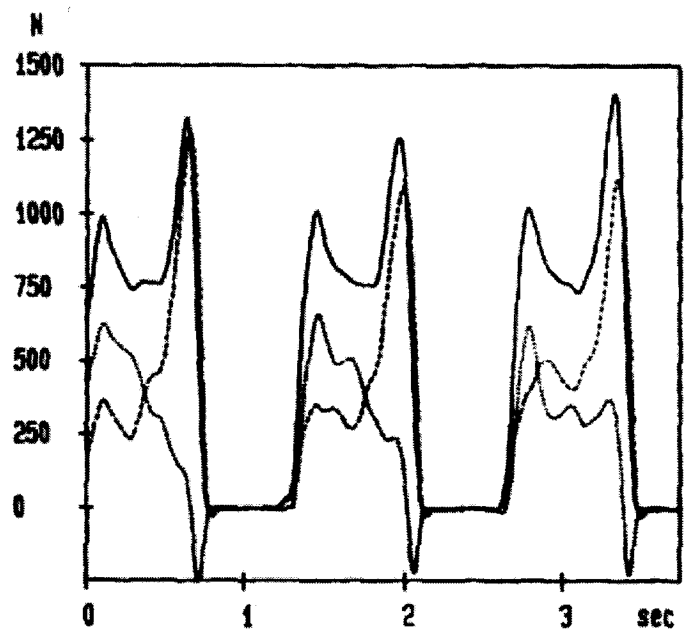


Figure 17: Normal forces during skating the straightaway. Forces measured at forefoot (*dashed line*), forces measured at the heel (*dotted line*), Total normal force(*solid line*) (From Jobse 1990).

Unfortunately, this method of evaluating foot pressure distribution has suffered some level of criticism. For example, Miller (1990) warns of the sensitivity of these force measurement devices stating that they only reflect on the acceleration of the center of mass (COM) of the individual and do not reflect stress of the individual structures of the foot. For this reason, research on plantar pressures has recently shifted to a more descriptive area, the interaction of the foot-and-shoe (Cavanagh, Hewitt Jr. et al. 1992). This shift has caused a reduction in the use of force plates since this instrument cannot measure forces acting inside the shoe.

Pressure distribution inside the shoe is of great importance for orthopedic and biomechanical considerations. Particular clinical attention has been accorded to areas of high pressure under the feet because of their potential to cause mechanical damage to the plantar tissue (Lord 1997). For example, elevated plantar pressure during walking has been implicated in foot pain and foot ulceration. However, there is no clear understanding of the factors which contribute to the elevated pressure and thus the approach to treatment and relief of symptoms is largely empirical (Morag and Cavanagh 1999). The development of in-shoe pressure measurement devices has allowed researchers the ability to collect multiple steps of a given activity more easily than when compared to platform data collection. This increases the power of the experiment, and thus allows for stronger statistical claims of the characteristics examined. In addition, versatility is improved with in-shoe measurements. Activities that could not ordinarily be studied can now be examined in the proper environment such as ice skating and skiing. In-shoe pressure measurements provide a means to better understand the effects of shoe design modification on the mechanics of the foot and this has the potential to influence both shoe design and clinical practice (Cavanagh, Hewitt Jr. et al. 1992).

3.2 General principles and types of transducers

Numerous types of in-shoe pressure devices have been developed since the emergence of plantar pressure research. Each device carries its own advantages and disadvantages that are primarily based on the ability of the devices to produce accurate and reproducible results. While conducting research, it is essential to ensure that the collection equipment does not interfere or alter the foot-to-shoe interface. Kelvin's Law is a universal principle of scientific measurement that states that the act of measurement should not change the quantity being measured (Cavanagh, Hewitt Jr. et al. 1992). Respecting this law is crucial to ensure that data collected accurately depicts pressures seen when measurement devices are not present. This law is easy to break when measuring inside the shoe since the transducer can act in several ways to alter the foot-to-shoe interface. Large sensors reduce the room available for the foot in the shoe and consequently may inflate local pressures (Sims 1985). Furthermore, the majority of devices necessitate cabling and the wearing of a waist pack (Hennig 1982). Any one or combination of these measurement device factors could alter data collection in a way that no longer represents the pressures of in-game situations. Technological advancements in pressure measurement devices has led to the development of thinner transducers and sensor matrices without the need for umbilical attachments (Maalej 1988; Cavanagh, Hewitt Jr. et al. 1992). The following section provides a short overview of the types of pressure transducers that have been developed.

3.2.1 Microcapsules

The use of microcapsules was one of the earliest systems of in-shoe pressure collection. Small dye filled capsules are placed between two layers of foam and inserted into the shoe (Brand 1969). At pre-determined pressures the capsules would rupture and release the dye. This method left a visual mark on the sock but gave very little in terms of quantitative results.

3.2.2 Projection devices

The well known Harris mat (Harris 1947) had been adapted for in-shoe use (Brand 1988). This device uses small rubber ridges of different heights that deposit ink, onto a "film", underneath the mat. As the regional forces increase, the ridges come into contact with the film, depositing more ink. This visibly denotes areas of greatest stress. Grieve and Rashdi ((Grieve 1984) used a more technologically sophisticated method that operated on a similar principle to the Harris mat. Pressure deformed pyramidal projections in an aluminum sheet during gait. The amount of deformation was measured using an optical scanned and the resultant pressure was calculated.

3.2.3 Capacitance devices

A capacitor is an electrical device that temporarily stores charge. It consists in general of two conducting plates separated by a dielectric which acts as an insulating layer (Cavanagh, Hewitt Jr. et al. 1992). In-shoe capacitor transducers use a compressive dielectric material such that deformation, as a result of pressure, decreases the separation between the two conductive plates. Since the capacitor's ability to store charge is inversely proportional to the distance between the two conducting plates, a reduction in the separation would increase the charge stored by the capacitor. The charge stored by the capacitor is continuously monitor and compared with a predefined calibration curve to determine the amount of pressure evoked.

3.2.4 Force Sensing Resistors (FSR)

The FSR typically consists of two parts, one is a film covered in resistive material and the second is a set of digitating contacts applied to another film (Maalej 1988). The resistive material serves to make an electrical path between the two sets of conductors on the other film (Putnam 1996). As pressure is applied, the sensor deforms resulting in a better connection, increasing conductivity between contacts. When a force is applied to this sensor, a better connection is made between the contacts, hence the conductivity is increased. Early versions of the FSR tended to act somewhat like switches, they were either off or completely on, offering rather poor resolution of pressure on the critical range for biomechanical applications (Maalej 1988). Differences in sensitivity between transducers and changes in sensitivity during periods of use have been further problems for accurate clinical investigations.

3.2.5 Piezoelectric methods

Piezoelectricity literally means "pressure electricity" and may be defined as the electric polarization produced by a mechanical strain in crystals. In other words these types of transducers use a material that generates an electric charge when mechanically deformed, this phenomenon is called the piezoelectric effect. These unique materials are naturally occurring in many crystals such elements as quartz and in manufactured materials such as PbZT (lead zirconate titanate) (Cavanagh, Hewitt Jr. et al. 1992; Lind 2001). By applying a compressive force to the hexagon, the structure is deformed and the two positive charges are compressed closer together at one end while the two negative charges are squeezed together on the other side (Figure 18). This modification in structure forms a dipole where one end of the array is positive and the other negative (Lind 2001).

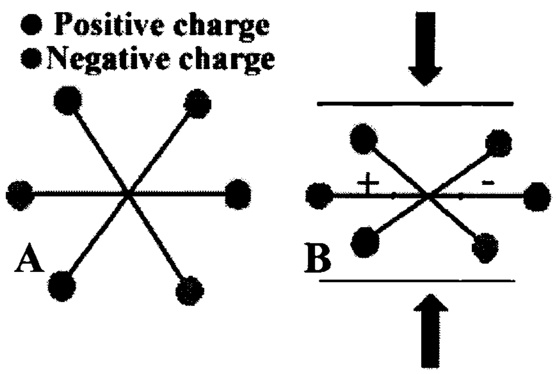


Figure 18: Deformation of atomic structure forming the peizoelectric material. A) Unperturbed crystal structure B) Compressed crystal lattice which results in polarization of the material (Lind 2001).

The amount of depolarization is recorded and compared to a predetermined calibration establish the amount of pressure evoked (Hennig 1982). The use of piezoelectric transducers avoids the need for an external voltage source, as required with capacitance, strain gauge and FSR transducers.

3.2.6 Discrete and Matrix Devices

Most of the above pressure sensing techniques can be purchased in either discrete or matrix configurations. Discrete devices refer to placement of individual pressure sensors in anatomical locations. Although Lord (Lord 1981) has cautioned that care must be taken in placement of the individual sensors since imprecise positioning may lead to inaccuracies. Similarly, shear stress may cause the sensors to migrate which may also cause erroneous data. In initial trials, discrete sensors acted as a foreign body in the shoe and broke Kelvin's Law by altering the conditions at the foot-shoe interface. This problem was solved by recessing the sensors into the sole of the shoe (Maalej 1988), although care must be taken not to recess the sensors too deeply into the sole as this will affect the results. Modern discrete sensors are very thin and flexible and allow for specific local events to be investigated in multiple areas simultaneously. However, recessing the sensors may lead to the difficulties when using the same sensor configuration to analyze plantar pressures in feet of different girths. Conversely, matrix devices consist of multiple pressure sensing elements arranged together into rows and columns (Cavanagh, Hewitt Jr. et al. 1992). Unlike discrete systems, this array pattern permits a larger area, usually the entire plantar surface of the foot to be monitored at one time without the need for prior decisions about the regions of particular interest. Although this comprehensive pressure measurement devices allows for a holistic view of the plantar surface, it runs the possibility of changing the foot to shoe interaction by altering the coefficient of friction or by acting to distribute pressure in its own right (Cavanagh, Hewitt Jr. et al. 1992).

It is evident from the above-mentioned summary of pressure measurement devices that each method has its respective advantages and disadvantages based on the principles of Kelvin's Law. The choosing of the appropriate device is a key element in the success of a study since the researcher must understand and be aware of the limitations of each system in order to obtain valid and reproducible results. Given the above knowledge, an informed decision may be made on the correct pressure measurement device to be used which is the first step in the establishment of a sound methodology.

3.3 Studies on Plantar Pressure

In recent years, much focus has been placed on the investigation of in-shoe plantar pressures, which allows for the determination of the loading of individual foot structures(Hennig 1982). Most of the research has examined clinically-relevant populations such as individuals suffering from diabetes mellitus and rheumatoid arthritis, who are at risk of, or are experiencing a variety of foot problems (Bauman, Girling et al. 1963; Brand 1969; Birke, Sims et al. 1985; Sims 1985; Brand 1988; Nawoczenski, Birke et al. 1988; Schaff and Cavanagh 1990; Veves, Fernando et al. 1991; Masson 1992; Chen, Nigg et al. 1995; Gill 1997; Murphy, Connoly et al. 2003). It is a common belief that the role of footwear is not only to facilitate and enhance athletic performance but also to reduce the risk of injury (Cavanagh, Hewitt Jr. et al. 1992). In-shoe pressure measurements have been especially important in the design of therapeutic footwear, braces and orthotic inserts. Many studies have compared the pressures for various sole configurations in order to establish the best design to prevent foot pathologies (Bauman, Girling et al. 1963; Birke, Sims et al. 1985; Nawoczenski, Birke et al. 1988; Schaff and Cavanagh 1990). Research on sport-specific footwear examining such variables as the in-shoe pressure distribution, is an essential step in the design of optimal footwear. In sports, in-shoe pressure measurements have been used to investigate the safety and comfort of many varieties of footwear, which may determine whether or not a shoe is well suited for a certain activity (Schaff 1987). It is not surprising that with the increased popularity of jogging and running in the last couple of decades, that most of the research on sports footwear has focused on running (Cavanagh 1980; Atkinson-Smith and Betts 1992; Chen, Nigg et al. 1994; Reinschmidt, Nigg et al. 1994; Reinschmidt and Nigg 2000; Verdejo and Mills 2004). For example, Cavanagh et al. (1980) suggested that during running, the shoe sole should produce minimal pressure or force between the foot and the insole. In-shoe plantar pressure measurements have also been done in rowing (Elliott 1993), soccer (Eils, Streyl et al. 2004), in cycling (Sanderson 1987; Sanderson 2000), and football (Santos 2001). Evidence from the studies suggests that different sports generate different plantar pressure distributions patterns, thus emphasizing the need to design sport-specific footwear.

In the sport of ice hockey little research exists describing the physical characteristics of the ice hockey stride due to the difficulty of measuring important variables on ice. Only one study on ice hockey measured pressure of the entire plantar surface of the foot during forward skating stride. Turcotte et al. (Turcotte 2004) used a matrix device which compared plantar foot force measurements of ice skating and treadmill skating. Four male varsity hockey players skated at three speeds (22, 24 and 26km/h) on both the ice surface and the skating treadmill. Their results showed an increase in skating speed produced an increase in peak plantar pressures on both skating surfaces. Also, pressure patterns were equivalent for both skating modes with the exception of significant differences during the heel loading, which were approximately 30% greater on the skating treadmill than those seen during ice skating. The increase in pressure at the heel was attributed to the differences in skating surfaces. The skating treadmill is made from polyethylene slates which form a rougher surface in comparison to the ice surface. The increased unevenness increases friction leading to an increase in plantar pressure at the heel during blade contact. However, this increased peak pressure observed during heel loading may be inconsequential since this phase of the skating stride is the absorptive component of the hockey stride and therefore insignificant when evaluating propulsion and power generation. Although there proved to be pressure differences during heel loading, the authors stated that the skating treadmill replicates the overall pressure pattern seen during forward ice skating.

4. The Influence of Skill Level on the Biomechanics of Sports

Numerous studies have compared several variables in both elite athletes and recreational athletes to further understand the biomechanical characteristics that differentiate these groups. The table below summarizes these studies in terms of activity, variable measured and presence or absence of significant difference.

Table 1: Results of studies that have investigated differences between ability groups.

Activity	Subjects	Dependant Variable	SD	Author, year
Golf Swing	18 pro 18 amateur	Plantar pressure	Yes	(Amano 1995)
Golf Swing	13 total	Knee joint kinetics	No	(Gatt 1998)
Rowing	5 experienced 5 novice	Plantar pressure	Yes	(Elliott 1993)
Football Throw	20 elite 14 recreational	EMG	No	(Kelly 2002)
Running	7 elite 8 trained	Running Economy	No	(Pereira 1997)
Fencing	3 elite 3 novice	EMG	Yes	(Williams 2000)
Tennis backhand	8 expert 8 novice	Wrist Kinematics	Yes	(Blackwell 1994)
Basketball Free-throw	6 total	Arm kinematics	Yes	(Button 2003)
Cycling	12 elite 17 recreational	Plantar pressure	No	(Sanderson 2000)
Climbing	10 elite 10 recreational 10 phys. active	Finger strength and endurance	Yes	(Grant 2001)
Speed skating	5 elite 6 trained	Full body kinematics Lower body EMG	Yes No	(Koning 1991)
Speed Skating	14 elite 10 trained	Leg kinematics	Yes	(McCaw 1985; Boer 1987)
Power hockey	6 elite 6 recreational 5 novice	Leg kinematics	Yes	(McCaw 1985)

SD, significant differences

4.1 The Influence of Skill Level on Plantar pressures

Of the studies reported above, only three studies have compared the plantar pressure patterns between the skill levels. Elliot et al. (Elliott 1993) investigated the effect of experience on peak in-shoe pressures of the forefoot and rearfoot in five novice and five intermediate collegiate rowers. They also examined the mediolateral and anteroposterior center of pressure of the dominant foot during rowing on a rowing ergometer as a measure of stability and length of the foot used during force generation. Their results showed that forefoot peak pressures were significantly higher while rearfoot peak pressure were significantly lower in experienced rowers compared to novice rowers. Furthermore, the ratio of forefoot peak pressures was 1.95 times greater than rearfoot pressures in the experienced rowers which were significantly different from the forefoot pressure ratio in the novice group of only 0.88 times that of the read foot. Given these results, differences in COP would be expected, however, no significant differences were reported. The authors stated that "high deviations between subjects precluded finding significant differences" in anteroposterior COP. In addition, no explanation was provided on the calculations executed to determine COP. The exclusion of this information renders the results on COP meaningless and incomprehensible. Nevertheless, this research demonstrated that foot function was modified with experience. In the case of rowing, higher peak forefoot pressures and lower peak rearfoot pressure were observed as knowledge of the skill increased. Another study attempted to determine the relationship between the plantar pressures and performance during the golf swing (Amano 1995). Eighteen professional and 18 amateur players had a high resolution pressure sensitive insole sensor placed in their shoe and were instructed to driver ten balls for maximum distance. The furthest drives of each participant were used for analysis. Results showed clear differences in pressure patterns at the top of swing between professional and amateur players. Higher foot pressure were observed on the inside of the foot than on the outside in professional players, whereas, amateurs displayed greater plantar pressures on the outside of the foot. Also, professional players exhibited pressure over a larger area at the top of swing in the right foot and at impact in the left which is superior in terms of balance.

4.2 The Influence of Skill Level on Psychomotor Skills

Elites are called elites not just because they perform skills better but because of some psychological differences as well. Some studies have examined these non-physiological variations of knowledge in domains such as chess, mathematics and physics (Chi, Fletovich & Glaser, 1981), computer programming (McKeithen, Reitmen, Rueter, & Hirtle, 1981), teaching (Leinhart & Smith) and hockey. Differences in pattern recognition were seen in elite chess players when compared to recreational chess players. This increased pattern recognition stems from previously experienced positions that have been stored in memory and allows the skilled player to derive more meaning for the position and spend less time on low-level processes than a novice (Schultetus 1999, Allard & Burnett, 1985; Newell & Barclay, 1982; Rumelhart & Ortony, 1977). In addition, differences have been recorded in basketball, ice hockey, and gymnastics between novice and elite athletes in where they fix their gaze (Bard & fleury, 1976, 1981; naumaier, 1982; Vickers, 1984). When it comes to the actual development of physical skills, it has been shown that athletes establish the most effective way of moving their muscles/joints to perform the desired task (Vickers, 1986). Koning et al. (1991) compared EMG and kinematics of five elite and six trained male speed skaters. Their research concluded that elites can be distinguished in their: Smaller pre-extension knee angle, mainly caused by a more horizontal upper leg position, their considerably higher amount of work per stroke and higher stroke frequency. They also exhibit a higher knee extension velocity that creates a short lasting more powerful push-off due to a more horizontally directed push-off. No differences were observed in the activation sequence of the legs muscles between the groups. Therefore, the difference in performance was not attributed to an increase in power production but to the elite skater's ability to control their joints in such a way as to maximize the horizontal impulse in a more direct manner which results in a more efficient force production. These results are in accordance with those found when comparing kinematics of elite and trained speed skaters while skating the curves. Boer et al. (Boer 1987) recorded the skating motion of fourteen and ten elite and trained men, respectively, in the curves during a 5000m race. Their findings indicated that the most pronounced differences in speed skating technique while skating the curves was a shorter stroke and push-off times and the greater push-off angle during the whole stroke for the elite group when compared to the trained group. The authors believe that this will result in a better directed push-off component thus increasing the amount of useful work per stroke, which explains performance differences between the two ability levels. Therefore, the studies suggest that the reason for the discrepancies in performance between ability levels is not due to increase power production from muscles but a more efficient stride due to a better directed push-off. The authors believe that the power produced by the muscles will not be the soul factor in determining skating ability, the direction in which the power is elicited must also be taken into consideration. Although skating is a fairly closed sport many factors influence performance and further research in the ice hockey stride and skating skills is necessary to determine exactly what these factors are and how they interact to affect performance.

5. Statement of Problem

The research in the field of ice hockey is very limited especially considering the large numbers of skills that each player must execute in just one shift of an ice hockey game. The majority of the studies that have described the biomechanics of skating have been performed in the sport of speed skating. Although some similarities may exist between the two sports, no single study has confirmed this assumption. The high intensity and unpredictable nature of the sport of ice hockey would suggest that the biomechanics of hockey skating may differ from that of speed skating. The pressure distribution patterns within the skate boot are only one aspect of the biomechanics of ice hockey that have not been examined. The characterization of these pressure patterns may provide a better understanding of the foot structures that undergo moments of high and low pressure throughout the skating stride. In addition, the determination of areas of low and high pressure in the skate boot could provide essential information for equipment manufacturers to design better hockey skates

This project thus proposes to identify the pressures generated within the skate boot of an elite hockey player during the execution of the skating the curves and how these pressures compare to those generated by a recreational hockey player.

5.1. Study Objectives

The primary objective is: To characterize and compared the peak pressures and pressure profiles that take place inside the ice hockey skate boot for elite and recreational skaters during the forward crossover stride.

The secondary objectives are:

- To compare the timing of peak pressures, in seconds and as a percent of the stride throughout the forward crossover stride between elite and recreational skaters during the forward ice hockey crossover stride.
- To determine the effect of direction on peak pressure and pressure patterns during the forward ice hockey crossover stride.

5.2 Experimental Hypotheses

Primary hypothesis:

The peak pressures will be higher in elite skaters than in recreational skaters.

Secondary hypothesis:

- The absolute timing, in seconds, of peak pressures will occur sooner in elite skater's but no difference in relative timing, as a percent of stride, of peak pressures will occur between elite skaters and recreational skaters.
- There will be an effect of direction for the recreational skaters but no effect will be observed for the elite skaters.

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CHAPTER 2: EXPERIMENTAL ARTICLE

Introduction

In order for a player to excel in the game of ice hockey they must be proficient in a plethora of ice hockey skating skills. Skating is considered to be the most important skill in the game of ice hockey (Pearsall, Turcotte et al. 2000). In a survey of sixteen professional scouts, Renger et al. (1994) concluded that skating is the most important skill for both forward and defensemen alike. Although skating is an integral part of hockey, little biomechanical research has been conducted on the forward skating stride in ice hockey (Pearsall, Turcotte et al. 2000). The research that has currently been completed has focused on ankle kinematics (Chang 2002; Dewan 2004), lower limb EMG (Goudreault 2002; Dewan 2004) and foot pressures (Loh 2003; Dewan 2004). Other hockey skills that have been briefly studied include skating starts, stops and backward skating (Naud and Holt 1980).

There has been no research that has examined a critical hockey skating skill; the forward cross-over turn. The crossover turn is an essential skating skill which is crucial to high level hockey performance, because it is used in various game play situations such as the transition between forward and backward skating or in the transition plays between possessions (Pearsall, Turcotte et al. 2000). To date, the only published research that exists on skating the curves has been performed in the sport of speed skating (Boer 1987; Boer 1988; Ingen Shenau G.J. Van 1989; Koning 1991). However, only a few studies have looked at the kinetics of the skill, despite the fact that several speed skating coaches believe that proper technique for skating the curves is more vital for the determination of success in competitive skating than the technique for skating the straights (Ingen Shenau G.J. Van 1989). According to Boer et al. (1988) there is no essential difference in the propulsion mechanics of speed skating in a straight line or in the curves since in both situations the direction of the push-off must be perpendicular to the gliding direction. However, this is the extent of the similarities between the two skills. In skating the curves, the push-off forces are directed to the same side of the body (Boer 1988), unlike in skating in a straight line where propulsion forces alternate between left and right sides (Koning 1991). As a consequence, the body's center of mass follows a sinusoidal path compared to a pseudo-circular path when skating the curves (Boer 1987; Boer 1988; Ingen Shenau G.J. Van 1989; Pearsall, Turcotte et al. 2000). Another disparity, which reinforces the distinctiveness of angular skating from skating the straights exists in the fact that most cyclical movements are symmetrical in nature while skating the curve follows a highly asymmetrical movement pattern of the legs since both legs are driving on the same side of the body (Koning 1991).

The sport of hockey requires the use of specialized equipment which is often designed with a goal to increase protection without compromising performance. It is a common belief that the role of footwear in sports is not only to facilitate and enhance athletic performance but also to reduce the risk of injury (Cavanagh, Hewitt Jr. et al. 1992). In ice hockey, the design of hockey skates has evolved drastically since the emergence of the sport in the 19^{th} century. The skate boot we know today consists of an outer covering of leather or composite material, an ankle support, a toe box, a heel counter, a rigid sole, a skate blade housing, and finally the metal blade. Unfortunately, little, if any, research, has examined in-shoe pressure distribution patterns during various hockey skills with the current skate design. Up until the past decade, the majority of the studies examining plantar pressures have focused on foot-to-floor interface using the concept of force plates as the main instrument for data collection. This instrument provides only a basic understanding of the pressure patterns during skating and only reflects the acceleration of the center of mass (COM) (Miller 1990). Two studies have examined the pressure patterns of push-off forces in two well-trained speed skaters using an instrumented skate which contained two strain gauges, one situated at the front of the skate and the other at the back, fixed between the shoe and the blade (Boer 1987; Jobse 1990). Measurements were performed while the subjects completed one lap of a standard 400-m ice rink. Similar results were obtained in both studies such that a double peak force pattern was observed for the forward speed skating stride. The first peak corresponded to the initial contact of the blade with the ice and the second peak was attributed to the force produced to create propulsion. These results are descriptive but the instrumentation used restricts the advancement of research beyond this point. As a result of this limitation, the focus in recent years has shifted from the interaction of the foot with the ground to the foot-to-shoe interface (Cavanagh, Hewitt Jr. et al. 1992). This shift has caused the common use of force plates to become ineffective since this instrument does not reflect stress of the individual structures of the foot inside the shoe. In-shoe pressure measurement devices are useful since they allow for the determination of the loading of individual foot structures.

It has been a goal in the scientific community to understand the progression of skill-learning in hopes of identifying what characteristics separate high level athletes from the rest of the field. Numerous studies have compared several variables in both elite athletes and recreational athletes to further understand the biomechanical characteristics that differentiate these groups. Of these numerous studies only three have looked at plantar pressures differences between athletes of varying abilities. Distinct plantar pressure patterns have been observed to distinguish between varying ability levels in rowing (Elliott 1993) and golf (Amano 1995). Another study compared elite cyclists to recreational cyclists (Sanderson 2000) but found no differences in plantar pressures at various intensities and pedal velocities. The authors suggested that the absence of differences could be attributed to the simplistic nature of the movement. Unfortunately, studies to compare in-shoe pressure patterns in the hockey skate boot between elite and recreational have not been performed.

The purpose of this study is to characterize and compare pressure patterns in the skate boot of elite and recreational players during the forward crossover turn. This will allow for the determination of areas of high pressure and low pressure and could help us gain valuable insight into the differences in pressure patterns between skill levels during the performance of the forward crossover.

Methodology

Study Population:

Sixteen male hockey players voluntarily participated in this study. The participants were selected on the basis of their hockey experience. Eight players were classified as elite. These players were members of the McGill University varsity hockey team. These subjects had various levels of playing experience at the varsity intercollegiate level, ranging from 1 to 5 years. In addition, eight other participants were classified as recreational players since they all have previously played recreational hockey in local leagues but either never reached a highly competitive level or had not played at a high level for a number of years. The anatomical characteristics of the participants are shown in Table.

Table 1: Characteristics of participants (means ± SD)

	Height (m)	**Weight (kg)**
Recreational	1.76 ± 0.06	82 ± 0.07
Elite	1.80 ± 0.07	87 ± 0.06

Experimental protocol and procedures

Each subject presented themselves at the McGill University hockey arena for a period of about 90 minutes. Upon arrival, each participant was verbally explained the procedures of the study and also given a written explanation of the procedures which included the potential risks and benefits inherent to the research. Each participant signed a consent form demonstrating that they understood that their participation was strictly voluntary and they could withdraw at any time. This research project was approved by the ethics committee of the Faculty of Education of McGill University.

Preparation

Prior to data collection, pressure sensors (FSA Verg Inc. Winnepeg, Manitoba) were fixed to both of the participants' feet using double–sided tape. A total of thirty sensors were affixed to the skaters' feet (fifteen sensors on the right foot and fifteen on the left foot). One sensor was reserved for signal synchronization purposes. Tensor bandages were used to secure the wires around the skater's legs. For standardization purposes, all skaters used the same brand of sock in order to prevent the influence of different sock thicknesses on pressure values and also as a protective measure to ensure sensors did not move (Figure 1). In addition, all trials were performed with a hockey stick in order to ensure that the proper skating kinematics where not disturbed. Pressure data was collected using a portable data logger which was stored in a fanny pack worn around the participants' waist.

Figure 1: Picture of participant affixed with sensors and wires secured with tensor bandages.

Calibration of Pressure Sensors

The peizo resistive sensors (FSA Verg Inc. Winnepeg, Manitoba) were calibrated using an air bladder (Tekscan, West Boston, MA) that applied known uniform forces across the entire matrix of sensors. Using the FSA software the calibration process minimized the errors of creep and hysteresis and ensured accurate pressure readings. The sensors were calibrated before each participant's testing session.

Sensor placement

Sensor placement was chosen based on previous research (Dewan unpublished master's thesis, 2003) and pilot testing, thus providing a general map of the pressures in the skate/foot interface seen while performing hockey skills. During pilot testing, a sensor matrix was constructed from the individual sensors to map the entire surface of the foot. Areas of high and low pressures where resolved while performing various hockey skills on roller blades. Roller blades were used as an alternative to hockey skates due to the unavailability of the ice rink. Despite this limitation, the pressure patterns observed using roller blades were similar to those found by Dewan et al. (2003), who measured pressure in the skate boot while performing hockey skills on ice.

Sensors were placed on the plantar surface of the foot (lateral and medial heel, mid-lateral arch and mid-medial arch, and head of the first metatarsal and head of the fifth metatarsal) in order to obtain contact and push-off pressures. On the medial side of the foot, the bony landmarks of the medial maleolus and medial side of the first metatarso-phalangeal joint were shown to have high pressures and the medial side of the calcaneous was of interest (Figure 2B). Similarly, on the lateral side of the foot, the lateral maleolus, the lateral aspect of the fifth metatarsal and the lateral aspect of the calcaneous where established to be sites of pressure sensors (Figure 2C). The last three sensors were placed on the dorsal aspect of the foot including the frontal aspect of the talo-crural joint, the superior surface of the first tarso-metatarsal joint and the in between the second and third metatarso-phalangeal joints (Figure 2B-C).

Figure 2: Sensor placement A) Plantar surface of the foot, B) Lateral aspect of the foot, C) Medial aspect of the foot.

Data Collection

Participants were given five minutes in which they performed a self-selected warm-up. Skaters were then instructed to start skating all-out from the blue line, near the boards, and skate towards the goal line around a series of cones placed in a semi-circular fashion and to stop at the same blue line on the opposite side of the ice to complete one trial (Figure 3). The skater was instructed to repeat this maximum effort skill in the opposite direction. In total, six trials were performed (3 clockwise (CW), 3 counter-clockwise (CCW)).

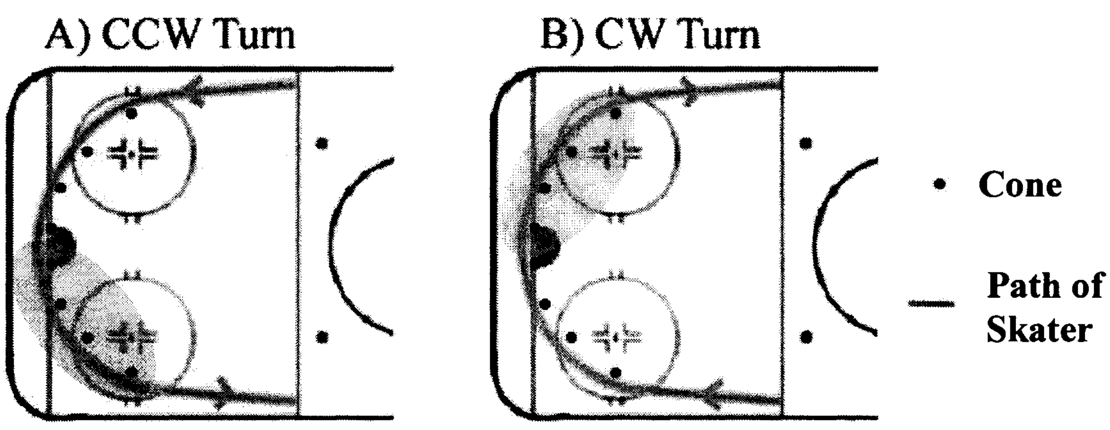

Figure 3: Schematic diagram of the path completed by each participant. Shaded area represents the location of stride selection.

After three trials, the subjects were given time to recuperate in order to minimize the effect of fatigue and this rest period also allowed sufficient time for the downloading of pressure data from the portable data logger into a portable computer (Toshiba Libretto).

Video analysis

A digital video camera (Panasonic mini dv pv-ds13) was set up on a tripod on the blue line at the center of the ice. The video recording provided a visual account of the skill which enabled identification of phases, such as foot ice contact and release, as well as to determine the strides to be partitioned for the analysis of pressure data. The digital camera recorded at a frequency of 30Hz.

Synchronization of pressure and video data

At the beginning of each trial, synchronization of film and pressure data was performed. The examiner used the reserved pressure sensor and applied pressure to a switch, which simultaneously turned on a LED light and sent a pressure reading to the portable data logger. Once this sequence had been completed the participant was instructed to start skating.

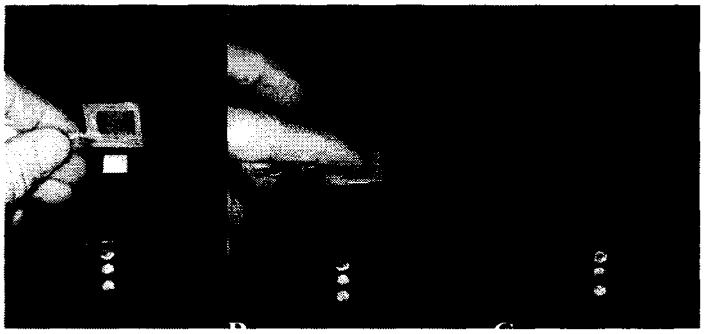

Figure 4: Synchronization Sequence A) Pre-synchronization, B) Sensor applied to light switch, C) Synchronization light turns on as a result of pressure applied on sensor.

Data Analysis

The pressure data in pounds per square inch were downloaded from the data logger and imported into an Excel worksheet where they were converted into Kilopascals (KPA). The Excel worksheet was then processed using specialized software subroutines created in Matlab^{tm} (vrs. 12 , Mathworks, USA). Three modules were created to process the data in the following steps: (1) De-interlacing of video files, (2) Aligning, event marking and partitioning module, and (3) Statistical organizer module. A separate

Matlab® module was created in order to calculate center of pressure (COP) for each of the skaters. Each digital video file was run through a matlab module that de-interlaced the video file thus doubling the video sampling rate to 60Hz.

Aligning, partitioning, phasing and event marking module

First for a given participant, each channel was named according to the location of the sensor on the foot. Secondly, four new channels were named and created by summing the channels corresponding to a specific region of the foot. For example, pressure values from sensors located on the lateral and medial heel, mid-lateral arch and mid-medial arch, the head of the first metatarsal and the head of the fifth metatarsal where summed together to give the total pressure of the plantar surface. Similar calculations were performed with the sensors located on the medial, lateral and dorsal surfaces. The following data processing procedures were performed on the original thirty channels (fifteen from each foot) in addition to the eight channels that were manually created (four total surface pressure channels per foot) for a total of thirty-eight channels (nineteen channels per foot).

For each subject, the synchronization light of the digital video recording was aligned with the activation of the sensor on the light switch in order to synchronize the digital video data and the pressure readings. This enabled event placement and partitioning of the pressure data using the visual cues from the digital video recording. Subsequently, the digital video was analyzed to establish specific events. For each subject, three skating strides were partitioned during the second half of the forward crossover turn.

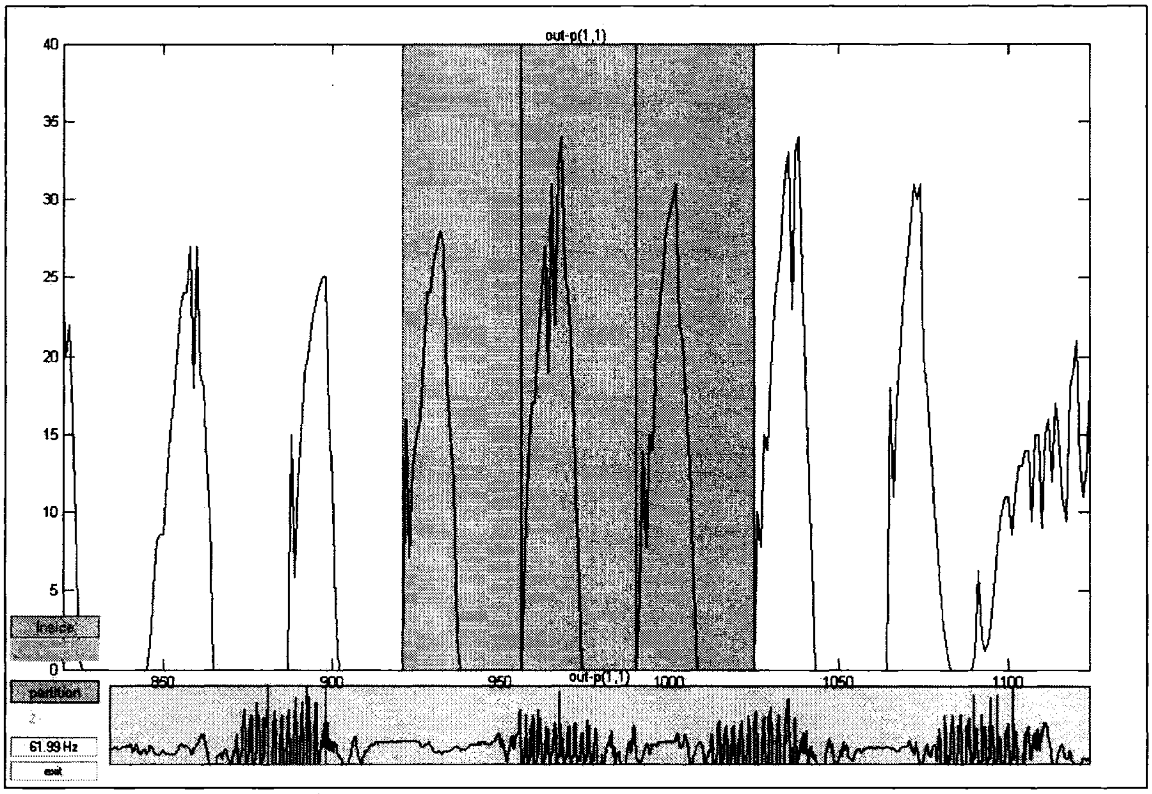

Figure 5: Partitioning of three strides.

One stride consisted of the blade contact to blade contact of the outermost foot. In a clockwise turn, the outside foot is the left foot while on a counter-clockwise turn it is the right foot. Furthermore, ice contact was determined for both inside and outside skates by toggling "on" the event phasing marker when the foot came into contact with the ice and turning it off when the skate left the ice. The program was then able to determine the amount of time each skate was in contact with the ice for each turn direction. For example, Figure 6 demonstrates blade contact time of each foot, which was obtained from the horizontal component of the bolded sections of the curves.

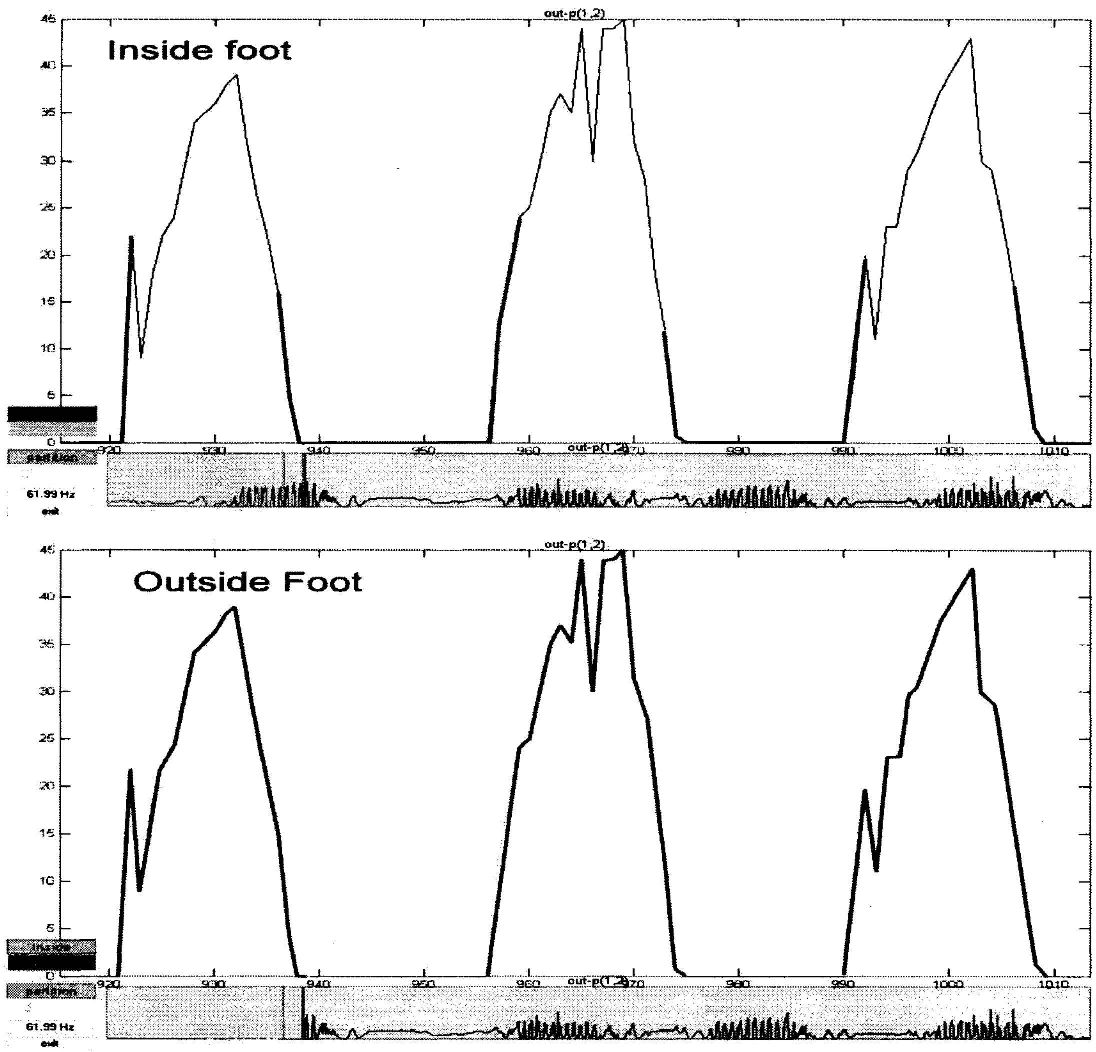

Figure 6: Example of how blade contact was obtained. Inside foot blade contact time (top) and outside foot blade contact (bottom) was obtained from the horizontal component (units = frames) of the bolded sections of the curve.

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. For the pressure sensors placed on the heel, two peak values were marked, while for all other channels one event of peak pressure was marked for each of the strides.

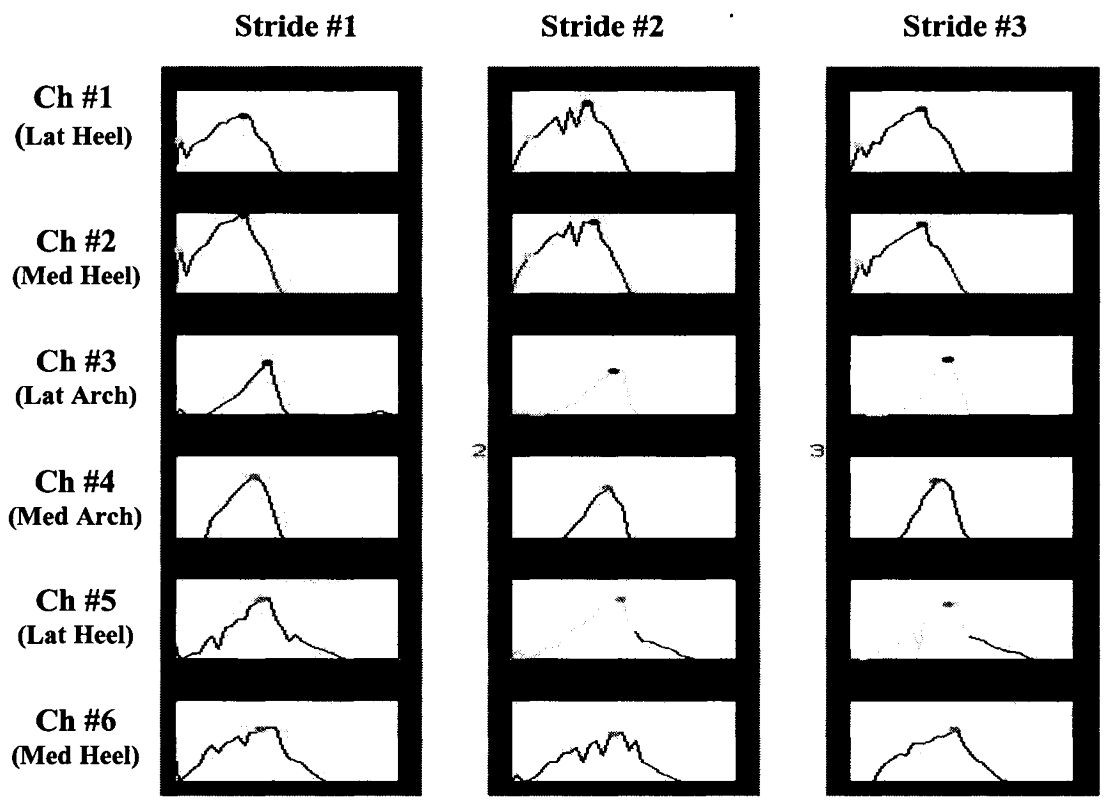

Figure 7: Example of marked peak pressures. Each partitioned stride is displayed in a column with channels displayed in rows. Peak pressures are denoted as little dots on the graph.

Absolute mean peak pressure calculation

a) Skill level comparisons

Once the peak pressure values were marked for all six strides (three CW and three CCW), they were averaged to give an *individual* mean peak pressure value for each channel on a given foot, for a given participant, regardless of the direction of the turn. The individual mean peak pressures were then averaged over all participants in the elite and recreational groups to produce a *group* mean peak pressure value for a given ability level and foot. In summary four mean peak pressure values were obtained for each sensor (Elite/outside foot vs. Rec/outside foot, Elite/inside foot vs. Rec/inside foot). This process was also performed on the eight channels that represent the four distinct surfaces of each foot.

b) Turn direction comparisons

Individual mean peak pressure values were also determined for each channel on a given foot, for each turn direction (CW vs. CCW), regardless of the skill level of the participant. For each turn direction, the corresponding individual mean peak pressure values were then averaged over all participants to produce a *direction-specific* mean peak pressure value for a given direction and foot. The four mean peak pressure values obtained for each channel were CW/inside foot vs. CCW/inside foot and CW/outside foot vs. CCW/outside foot. This process was also performed on the eight channels that represent the four distinct surfaces of each foot.

Mean pressure profile determination

a) Skill level comparisons

Individual mean pressure profiles of each sensor, for each participant, was calculated by averaging the pressure profiles of their six trials (three CW and three CCW). The individual mean pressure profiles for each ability level were then averaged to give a mean pressure profile for the elite group and a mean pressure profile for the recreational group regardless of turn direction. In summary, a mean pressure profile for each channel was obtained for a given skill level (elite vs. rec) and foot (inside vs. outside). This process was also performed on the eight channels that represent the four distinct surfaces of each foot.

b) Turn direction comparisons

Similarly, one pressure profile for each channel was generated per turn direction, per foot irrespective of skill level. These mean pressure profiles were obtained by averaging the profiles of each sensors for all subjects in a given direction. This process was also performed on the eight channels that represent the four distinct surfaces of each foot.

Statistical analysis of mean peak pressure calculations

The dependant 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 (Elite vs Recreational) and turn direction (CW vs CCW). The statistical program written for Matlab performs mean comparisons using a two-way ANOVA and Tukey post hoc ($p<0.05$) on each of the events defined in the previous section. Results are given as mean ± standard error of mean (SEM). A P-value of < 0.05 was considered statistically significant. For analysis purposes, only identical channels between turn direction and skill level are compared.

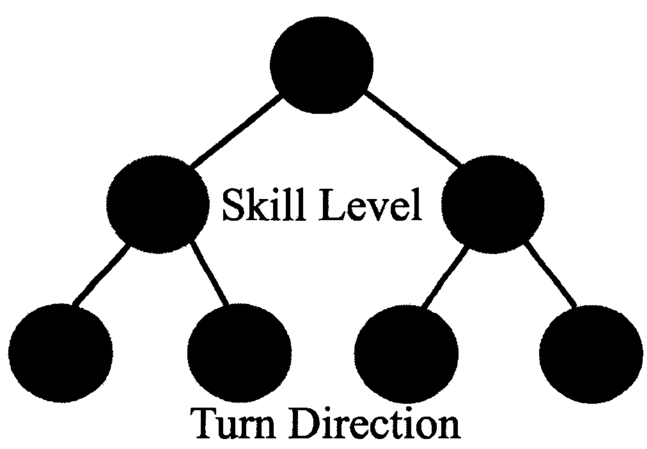

Figure 8: Tree root for statistical analysis

Results

The following results are based on the processed pressure readings obtained from three trials of skating in a curve performed in both the clockwise (CW) and counter-clockwise (CCW) directions for a total of six trials in each of the 16 subjects evenly split between recreational and elite skill levels.

The effect of skating ability

Influence of ability on pressure amplitude

Table 2 shows the mean length of time, expressed in seconds, required to complete one trial in the CW and CCW directions by the elite and recreational participants. There was a significant difference between the groups, in the time taken to execute the skill, for a given direction (CCW: 6.85 ± 0.114 vs 7.62 ± 0.125; CW: 6.84 ± 0.122 vs 7.72 ± 0.116, respectively)($p \leq 0.001$).

Table 2: Average time in seconds taken for recreational and elite participants to skate the curve in the CCW and CW directions (mean ± SEM).

	Elite	Recreational
CCW	6.85 ± 0.114*	7.62 ± 0.125
CW	6.84 ± 0.122*	7.72 ± 0.116

CCW, counter-clockwise; CW, clockwise.
*$p \leq 0.001$

Table 3 presents the peak pressure values, expressed in kilopascals (kpa), for each of the 15 channels placed on each foot for each of the ability levels during each of the skating trials. The results reveal that there were significant differences in peak pressure values in ten out of the fifteen channels located on the inside foot and nine out of the fifteen channels located on the outside foot.

Table 3: Peak pressure values in kpa for each channel on the inside and outside foot for each subject group (mean ± SEM).

Region	Sensor Location	Inside Foot		Outside Foot	
		Elite	**Recreational**	**Elite**	**Recreational**
Plantar	Lateral Heel	196.23 ± 8.88*	222.57 ± 11.19	239.46 ± 12.08	248.63 ± 12.38
	Medial Heel	270.28 ± 14.06	290.97 ± 15.07	323.10 ± 13.24	324.82 ± 15.66
	Lateral Arch	87.22 ± 5.04	107.01 ± 10.46	92.05 ± 7.23	116.59 ± 10.64
	Medial Arch	24.27 ± 2.62*	35.72 ± 5.42	36.96 ± 3.45*	46.27 ± 7.33
	Head of 5th Metatarsal	79.57 ± 4.35*	106.39 ± 6.45	93.43 ± 5.72*	96.53 ± 6.80
	Head of 1st Metatarsal	332.41 ± 30.31*	422.87 ± 33.97	195.40 ± 17.13*	275.94 ± 27.24
Medial	Maleolus	376.95 ± 26.69*	241.60 ± 24.93	192.44 ± 18.42*	166.38 ± 12.46
	Calcaneous	31.99 ± 6.64	32.89 ± 6.49	74.19 ± 11.91*	50.20 ± 7.62
	Head of 1st Metatarsal	168.17 ± 21.38*	91.29 ± 10.80	203.82 ± 19.04	172.31 ± 16.65
Lateral	Maleolus	117.15 ± 18.2 *	55.50 ± 8.54	175.62 ± 16.91	86.81 ± 10.34
	Calcaneous	126.94 ± 22.01*	66.47 ± 14.74	62.54 ± 12.09*	10.69 ± 3.10
	Head of 5th Metatarsal	144.11 ± 6.8*	104.53 ± 6.39	97.50 ± 5.71*	57.85 ± 4.42
Dorsal	Talo-crural	206.09 ± 9.64	178.79 ± 20.43	234.50 ± 12.61*	175.13 ± 26.27
	1st tarso-metatarsal	58.88 ± 7.37*	121.35 ± 16.48	82.26 ± 7.05*	133.07 ± 16.52
	2nd and 3rd metatarso-phalangeal	0.021 ± 0.018	0.827 ± .488	0.296 ± 0.159	0.097 ± 0.057

*$p < 0.05$

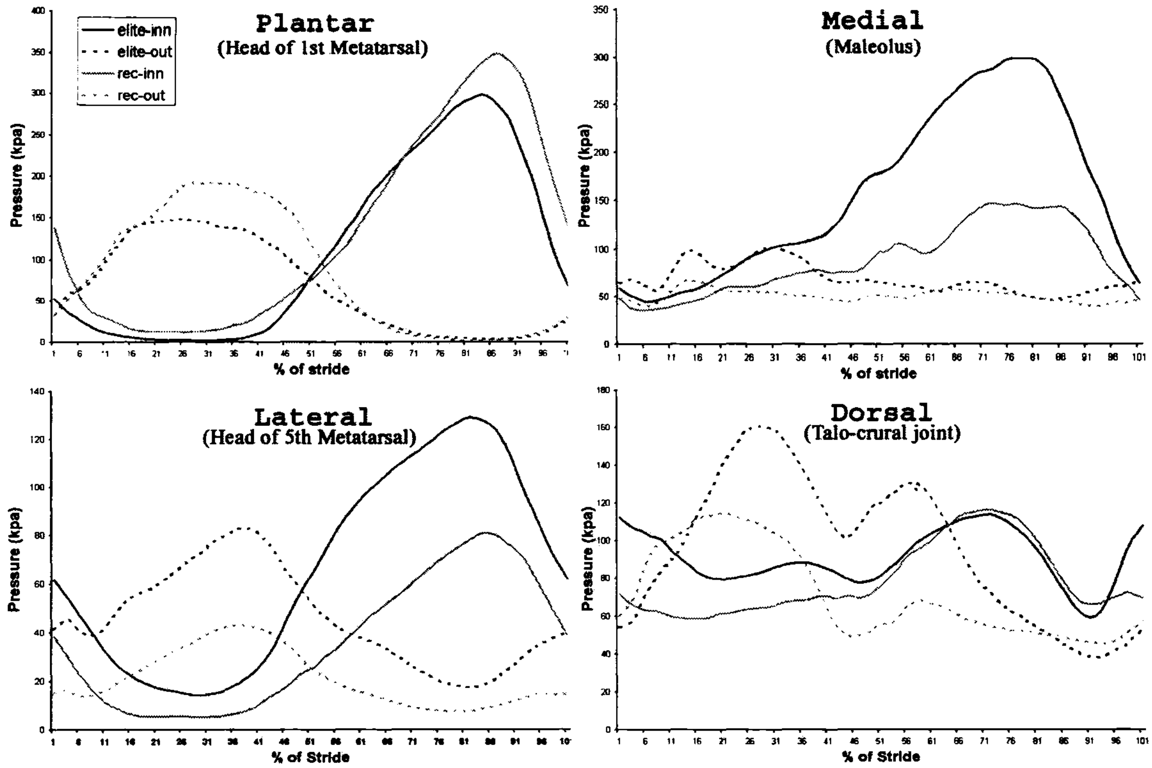

Figure 9: Typical mean pressure profile of one sensor located in each of the different surfaces of the foot.

Figure 9 shows one typical mean pressure profile of one sensor located in each of the different surfaces of the foot. These graphs illustrate some of the significant differences shown in Table 3. For example, in the plantar region four out of the six channels revealed significantly lower peak pressures in the elite skaters compared to the recreational skaters. Figure 9 illustrates the pressure profile of one of those channels, namely the one located on the plantar surface of the head of the first metatarsal. The graph shows a similar pressure profile between the groups in terms of the shape of the curve but the recreational skater's exhibit higher peak pressures ($p \leq 0.05$). Figure 9 also shows the elite group producing higher peak pressures ($p \leq 0.05$) for the channels located in the medial and lateral regions, as well as higher pressure production throughout the stride. In the dorsal region, the sensor at the talo-crural displayed similar pressure profiles between the groups, at any given percent of the stride of the inside foot, however, some significant pressure differences were seen in the outside foot with the recreational players experiencing higher peak pressures in the 1st tarso-metatarsal channel (not shown) and the elite exhibiting high peak pressures in talo-crural joint channel ($p \leq 0.05$).

The pressure profiles for each sensor in a given pedal region i.e. plantar, medial, lateral and dorsal, were summed to obtain a new pressure profile for that region. The peak pressure values for each region obtained for each foot and each subject group is presented in Figure 10. There were significant differences in peak pressures between the two groups in the plantar, medial and lateral region for the both the inside foot and the outside foot. The recreational group generated significantly higher peak plantar pressures of both the inside and outside feet, while in the medial and lateral regions the elite players demonstrated significantly higher peak pressures ($p \leq 0.05$). No significant differences in peak pressure were found between the groups in the dorsal region for both the inside and the outside foot ($p \leq 0.05$).

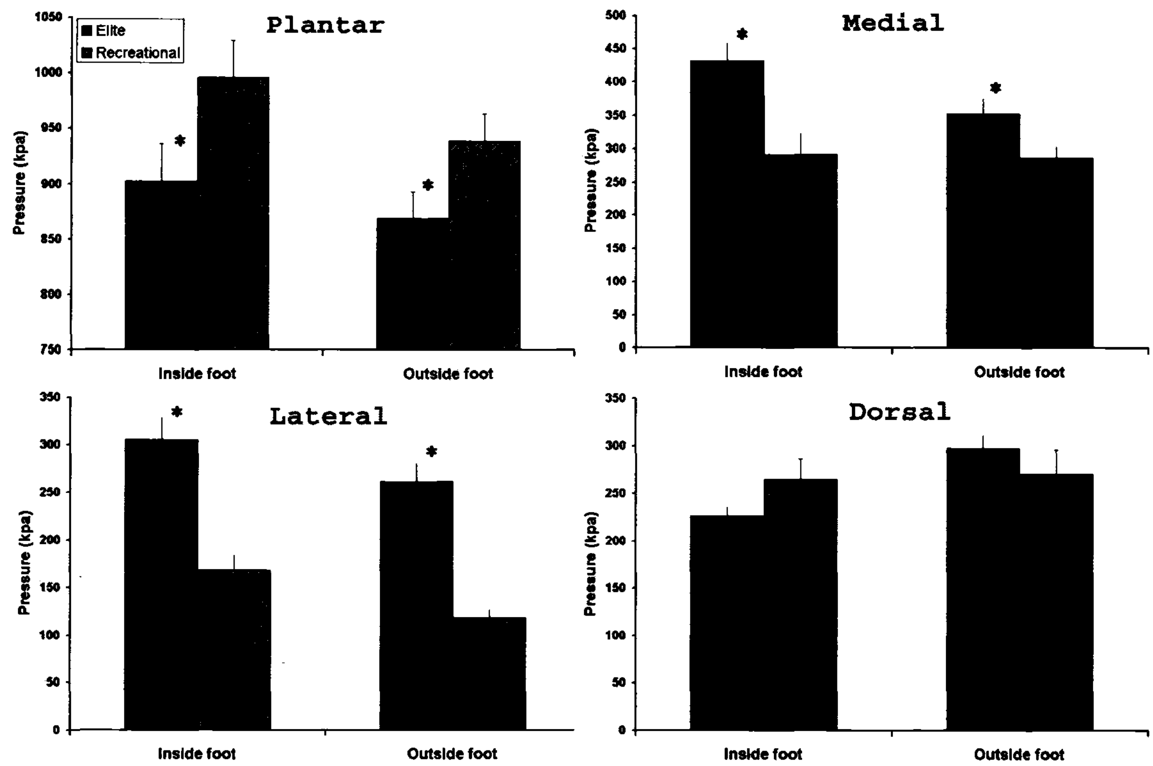

Figure 10: Peak pressure values in kilopascal (kpa) of elite and recreational skaters obtained from the sum of the pressure profile of the sensors located in the plantar, medial, lateral and dorsal regions (mean ± SEM).
$*p \leq 0.05$

Figure 11 represents the summed pressure profiles for each sensor located in a designated anatomical region of the foot. For example, the plantar graph in Figure 11 represents the sum of the pressure profile of the sensors located on the lateral heel, medial heel, lateral arch, medial arch, head of 5^{th} metatarsal, and head of 1^{st} metatarsal. The plantar pressure profiles of each group is similar, although the elite group exhibited significantly lower peak pressures in the plantar regions compared to the recreational subjects ($p \leq 0.05$). In the medial region and the lateral region, the elite group exhibits higher pressures than the recreational group, across all phases of the stride in both the inside and outside feet as well as higher peak pressures ($p \leq 0.05$). In the dorsal region, the elite subjects generated lower pressures in the inside foot and higher pressures in the outside foot compared to the recreational subjects although no significant differences were found between the two groups.

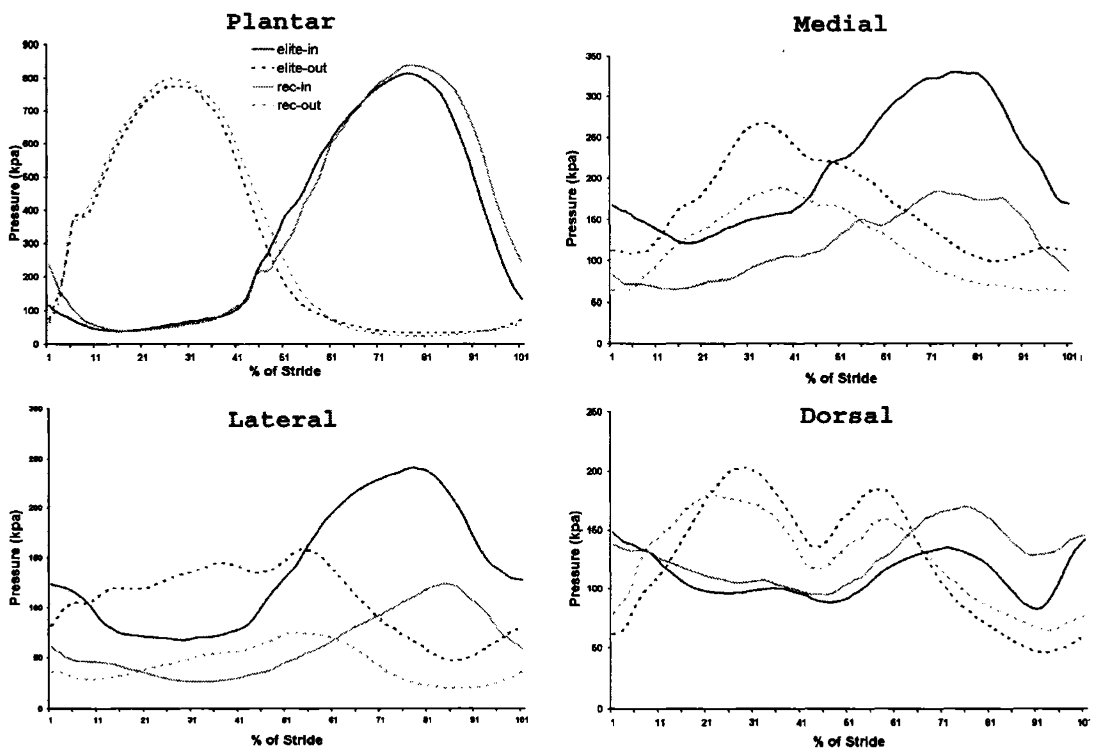

Figure 11: Sum of pressure profiles for elite and recreational groups for each regional surface of both inside and outside feet.

Influence of ability on absolute and relative timing of peak pressures

Timing differences of peak pressure values between the ability levels in seconds (absolute) and as a percent of stride (relative) were determined for each of the 18 channels on both the inside and outside feet. There were significant relative timing differences in peak pressure values between the elite and recreational groups in the medial maleolus sensor of the inside foot (70.66 ± 2.04, 63.16 ± 3.22) in the medial arch channel on the plantar surface (31.95 ± 1.39, 11.43 ± 2.30) and the sum of the lateral channels of the outside foot (41.94 ± 2.04, 47.80 ± 1.79). Significant absolute timing differences of the peak pressures were found for the sum of the plantar sensors of the inside foot (0.291 ± 0.005, 0.311 ± 0.009), the medial sensors (0.120 ± 0.006, 0.141 ± 0.007) and lateral sensors (0.154 ± 0.003, 0.168 ± 0.006) on the forefoot of the plantar surface, the medial maleolus (0.131 ± 0.008, 0.163 ± 0.013) and the sum of the channels on the lateral surface of the outside foot (0.163 ± 0.008, 0.194 ± 0.008). The results of absolute timing show that the elite subjects peak pressure values occurred consistently earlier than the recreational skaters peak pressures.

The effect of inside and outside leg

There does not appear to be a trend of higher peak pressures in either the inside foot or the outside foot in any individual sensors for either the elite or recreational skaters. Figure 12 shows the peak pressures of the inside foot and outside foot side by side for the elite skaters. However, when the sum of the sensors on a particular surface of the inside and outside legs are compared (Figure 10) it appears that the inside leg experiences greater pressures then the outside leg for the plantar, medial and lateral surfaces.

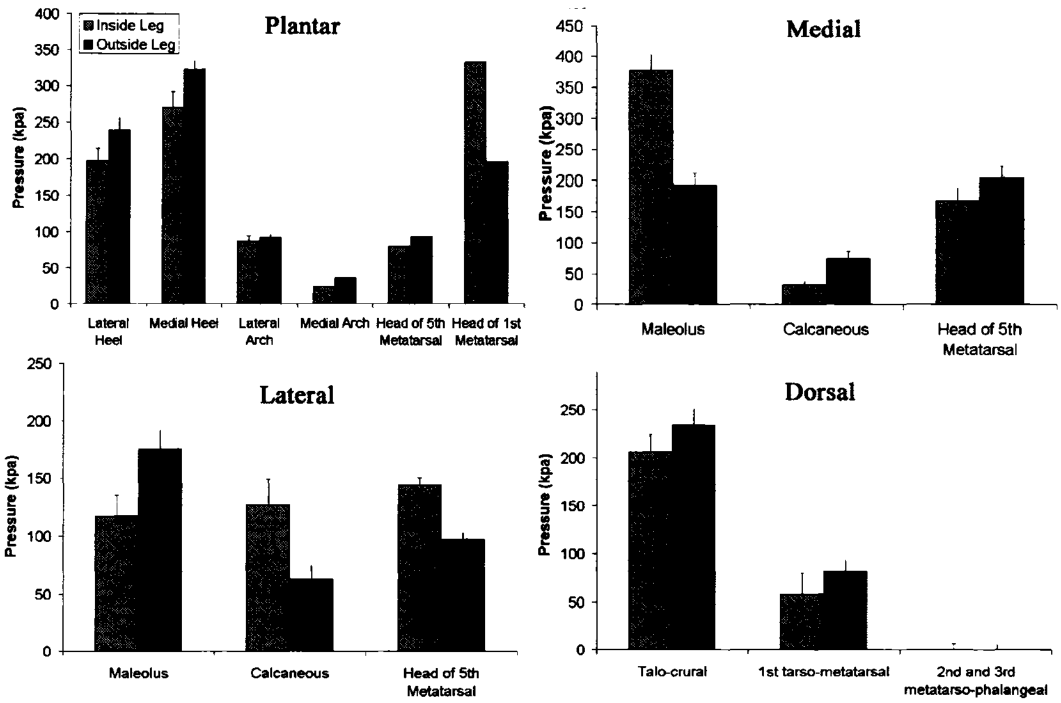

Figure 12: Comparison of peak pressures of the inside and outside feet of the elite skaters.

The effect of direction

Influence of direction on pressure patterns

Table 4 shows the peak pressure values for each of the 30 channels placed on the inside and outside feet for the two turn directions, CW and CCW. Significant differences in peak pressure values were obtained in four out of the fifteen channels located on the inside foot and four out of the fifteen channels located on the outside foot ($p \leq 0.05$).

Table 4: Peak pressure values in kpa for each channel on the inside and outside foot for each turn direction (mean ± SEM).

Region	Sensor Location	Inside Foot		Outside Foot	
		CCW	CW	CCW	CW
Plantar	Lateral Heel	217.47 ± 9.31	203.95 ± 10.97	246.15 ± 13.35	240.77 ± 11.10
	Medial Heel	296.32 ± 12.47	289.59 ± 16.47	332.96 ± 13.97	314.62 ± 14.52
	Lateral Arch	102.53 ± 9.51	89.01 ± 5.13	103.36 ± 8.29	102.32 ± 9.57
	Medial Arch	34.54 ± 4.09	23.93 ± 3.82	36.27 ± 5.25	45.99 ± 5.34
	Head of 5th Metatarsal	83.02 ± 3.53*	99.77 ± 7.00	104.87 ± 7.31*	84.46 ± 4.22
	Head of 1st Metatarsal	396.32 ± 31.78	347.16 ± 33.21	188.72 ± 14.08*	273.66 ± 27.28
Medial	Maleolus	291.66 ± 23.72	344.20 ± 31.63	163.55 ± 18.84	198.92 ± 13.51
	Calcaneous	51.57 ± 47.85*	12.69 ± 28.96	24.55 ± 4.55*	101.56 ± 12.17
	Head of 1st Metatarsal	138.87 ± 17.21*	129.97 ± 20.99	188.79 ± 15.51	191.27 ± 21.13
Lateral	Maleolus	86.39 ± 7.13	93.91 ± 4.36	134.45 ± 14.78	139.00 ± 17.79
	Calcaneous	76.47 ± 19.99*	124.94 ± 19.86	48.47 ± 11.81	30.96 ± 8.85
	Head of 5th Metatarsal	134.04 ± 8.02	119.35 ± 6.48	76.05 ± 6.62	84.19 ± 5.40
Dorsal	Talo-crural	187.48 ± 14.45	202.78 ± 15.35	219.95 ± 21.33	196.71 ± 17.46
	1st tarso-metatarsal	89.15 ± 10.74	83.36 ± 14.39	112.04 ± 13.86	96.81 ± 10.22
	2nd and 3rd metatarso-phalangeal	0.752 ± .424	0.00 ± 0.00	0.021 ± 0.007*	0.400 ± 0.027

CCW, counter-clockwise; CW, clockwise
*$p<0.05$

In Figure 13, the peak pressure values are shown in kilopascal (kpa) for the clock-wise and counter-clockwise directions, which were obtained from the sum of the pressure profile of the sensors located in the plantar, medial, lateral and dorsal regions of the foot. Results demonstrated that the only significant differences in peak pressure as a function of the direction of skating was observed in the sensors located on the medial region of the outside foot.

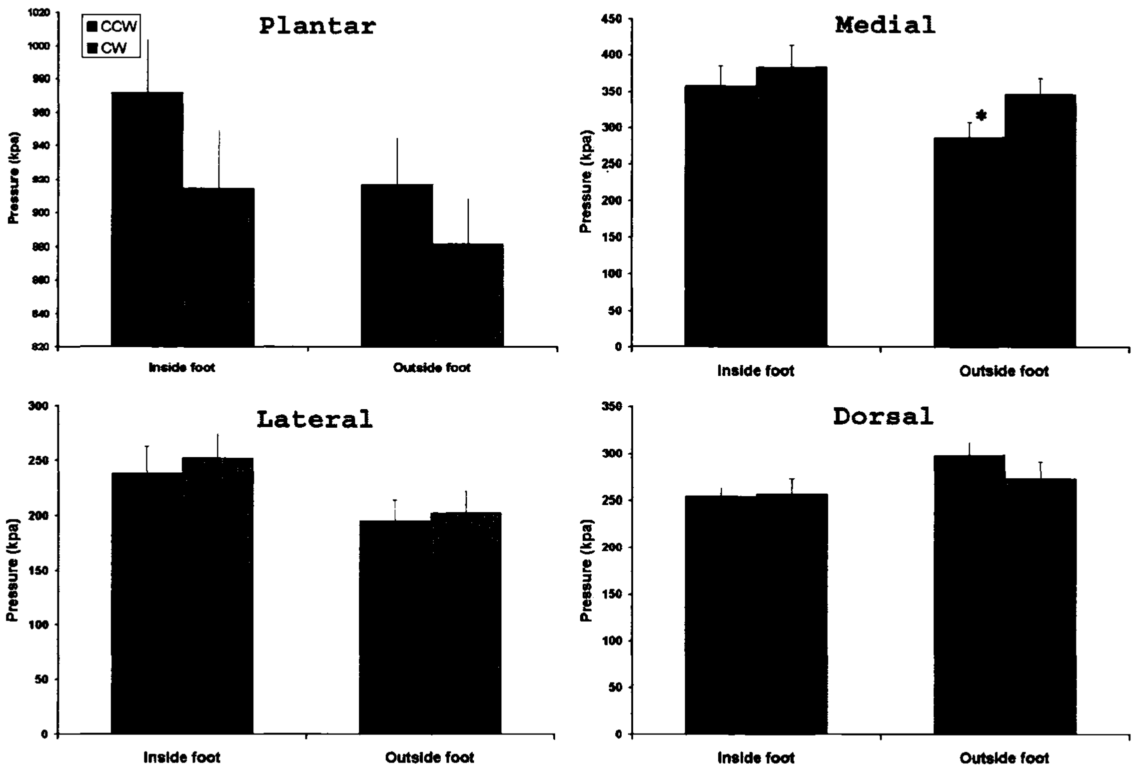

Figure 13: Peak pressure values in kilopascal (kpa) for the CW and CCW directions obtained from the sum of the pressure profile of the sensors located in the plantar, medial, lateral and dorsal regions of the foot (mean ± SEM).
$*p < 0.05$

Figure 14 illustrates the pressure patterns of the sum of the sensors in the plantar, medial, lateral and dorsal regions for the CW and CCW directions. Although statistical analysis was not performed, the pressure patterns appeared to be similar between the turns directions in all regions except for the medial region during the CCW turn.

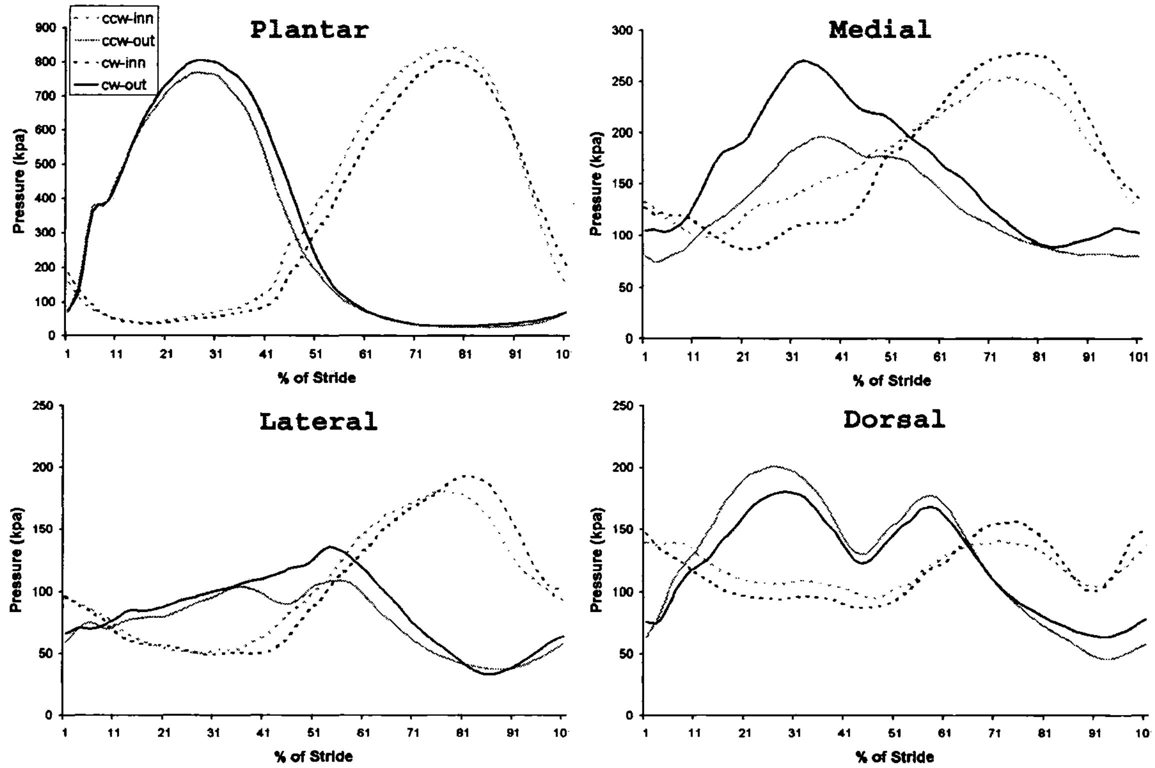

Figure 14: Sum of pressure profiles for each regional surface of both inside and outside feet in CCW and CW directions.

Influence of direction on the absolute and relative timing of peak pressures

Peak pressure timing differences were determined for turns in the CW direction and CCW direction, in seconds (absolute) and as a percent of stride (relative) were determined for all 18 channels on both the inside and outside feet. There were significant differences (CCW(%) ± SEM, CW(%) ± SEM) in relative peak pressure timing in the medial calcaneous (45.10 ± 4.05, 23.03 ± 4.25) medial head of the first metatarsal (56.65 ± 3.76, 37.80 ± 3.94) and lateral calcaneous channel of the inside foot (34.24 ± 5.36, 58.08 ± 4.63), in the medial maleolus (40.69 ± 2.55, 32.29 ± 2.46), lateral calcaneous (19.30 ± 3.51, 7.43 ± 1.65) and the sensor placed between the 2nd and 3rd metatarso-phalangeal joint (0.223 ± 0.223, 2.28 ± 3.27) of the outside foot. Significant absolute peak pressure timing differences were found for medial calcaneous (0.176 ± 0.016, 0.078

± 0.018), lateral calcaneous (0.136 ± 0.022, 0.230 ± 0.019) and head of the first metatarsal (0.222 ± 0.015, 0.153 ± 0.016) on the medial surface of the inside foot and, the medial maleolus(0.161 ± 0.11, 0.129 ± 0.10), medial calcaneous(0.077 ± 0.009 ,0.100 ± 0.006), lateral calcaneous (0.073 ±0.013, 0.028 ± 0.006) and the sensor between the 2nd and 3rd metatarso- phalangeal joint (0.001 ± 0.001 ,0.009 ± 0.004) of the outside foot.

Characteristics of skating the curves

The mean on and off ice-contact times, expressed in seconds (absolute) as well as a percent of the total stride (relative) of the inside and outside feet are presented in Table 5. The results revealed significant differences between the elite and recreational skaters in terms of the absolute *off*-ice contact time in both feet (Inside: 0.168 ± 0.003 vs. 0.183 ± 0.005; Outside: 0.177 ± 0.005 vs. 0.190 ± 0.004, respectively)($p \leq 0.05$). There were no significant differences between the groups in terms of absolute *on*-ice contact time, relative *off* and *on* ice-contact times expressed as a percentage of the total stride.

Table 5: Mean ice contact times for the inside and outside feet. Time shown in absolute time (seconds) and relative time (% of stride) (mean ± SEM).

	Inside foot		Outside foot	
	Elite	**Recreational**	**Elite**	**Recreational**
Off Time (Sec)	0.168 ± 0.003*	0.183 ± 0.005	0.177 ± 0.005*	0.190 ± 0.004
On Time (Sec)	0.233 ± 0.005	0.236 ± 0.006	0.223 ± 0.004	.230 ± 0.007
Total Time (sec)	0.401	0.419	0.400	0.420
Stride Frequency (Strides/min)	149.6	143.2	150.0	142.9
Off Time Relative (% of Stride)	41.90	43.68	44.25	45.24
On Time Relative (% of Stride)	58.10	56.32	55.75	54.76

*p < 0.05

Discussion

The main findings of this study are that significant peak pressure differences exist in the plantar, lateral and medial surfaces of the feet between the elite and recreational groups. However, there were no significant differences in peak pressure on the dorsal surface between groups. In addition, on average the pressures patterns follow the same pattern for both groups, however, the elite players displayed higher pressures at a given percent of the stride in the lateral and medial surface.

Influence of ability on the pressure patterns

There is little research in skating, if any, that has attempted to characterize the in-shoe pressure patterns of skating the curves in ice hockey. Most of the research that exists has been performed in the sport of speed skating (Pearsall, Turcotte et al. 2000). The influence of skating ability on the biomechanics of skating has been somewhat determined in speed skating only. One study by Boer et al. (1987) recorded characteristics of the stroke mechanics of trained and elite speed skaters while skating the curves. They found that elite skaters use an optimal push-off technique resulting in a higher amount of useful work per stroke. This optimal technique allows the elite skaters to skate faster than trained skaters even though the same amount of muscle tension is produced by both groups. This is due to the elite skaters directing the push-off forces in a more horizontal manner, which results in more energy going directly into the propulsion and less energy being wasted in the vertical direction. Consequently, a more efficient transmission of push-off forces results. It is unknown how a more efficient push-off would be reflected in pressures patterns inside the skate boot, however, our results show the elite group generating higher pressures on the lateral and medial surfaces of the foot compared to the recreational group. These higher pressures may indicate that the elite skaters transmit more forces through the lateral and medial surfaces of the foot to the skate and blade since there were no differences observed in plantar pressures. The increased pressures in the lateral and medial surfaces of the foot may indicate that the elites orient the skate boot in a different configuration that reflects an optimized push-off technique as demonstrated in research by Boer et al. (1987).

Boer et al (1987) also examined the kinematic differences between elite and trained speed skaters and showed that there were more kinematic differences between the groups in the stroke of the inside leg during the skating of the curves. The skating kinematics of elite speed skaters are similar to that of trained speed skaters for the outside leg while the kinematics of the inside leg differ greatly between groups. Our results revealed that significant differences in peak pressures were found in 10 of the 15 sensors for the inside foot and 9 of the 15 sensors of the outside foot. Therefore the differences between groups were prominent in both feet, suggesting that the study by Boer et al. (1987) used subjects that were too closely matched since differences between groups were only observed in the inside foot.

Characteristics of the skating the curves: the influence of skating ability

The results of the present study demonstrated that the elite players performed the skill faster than the recreational players in both directions, which is expected considering the elite group has accumulated more years of experience at a higher level than the recreational group. The elite players have had at least one year of playing experience at the varsity level whereas the recreational skaters have not had any playing experience at the varsity or equivalent level. While the elite skaters performed the trial faster than the recreational group, the time that the elite skaters feet spent on the ice during a given stride was not significantly different when compared to that of the recreational group for both feet. However, the elite skater's feet spent significantly less time off the ice during a stride then did the recreational group. These results reveal that the elite group completed a stride in a shorter period of time compared to the recreational group and therefore executed the skill at higher stride frequencies. These results are in accordance with the study by Boer et al (1987) in speed skating, which showed that elite speed skaters have a significantly shorter stroke time compared to trained skaters. They found that both the inside leg and outside leg stroke times were significantly correlated ($p < 0.05$) to performance. Another study by Ingen Schenau et al. (1985) performed on ten speed skaters, determined that the higher power outputs produced by elite skaters appeared to be related to the higher stroke frequencies and not to higher amounts of work per stroke. The authors also found that the amount of work per stroke was kept relatively constant at different power outputs with an increase in stride frequency accounting for the increase in power output.

Comparison of inside foot to outside foot during the skating of the curves

Observations of the pressure profiles of the lateral, medial and dorsal surfaces appear to be different when the values of the inside foot are compared against those of the outside foot. One reason which may explain these differences is the asymmetrical nature of the forward crossover stride which has been extensively documented in speed skating research (Koning 1991). The cause of this asymmetry is directly related to the direction of the push-off forces of the legs. Compared to skating the straights, the propulsion forces of the legs in skating the curves are generated on the same side of the body. Additionally, another reason for the differences in pressure profiles between feet may be related to the generation of different power outputs by each leg. Koning et al (1991) demonstrated the asymmetrical movement pattern of the legs with their results on the differences between the work per stroke of each leg. They calculated the net power output about the hip, knee and ankle joints by multiplication of net joint moments and joint angular velocities, determined by analyzing markers placed on the hip, knee, ankle and toe. The work per stroke for each leg was then determined by summing the net joint power produced at the hip, knee and ankle joints. The average external power output was then calculated from the work per stroke of each leg and the stroke duration. Using these calculations Koning et al. (1991) showed that the inside leg produces larger net moments at the knee than the outside leg due to the a more horizontal position of the upper inside leg throughout the whole stroke, which requires higher force levels of the hip and knee joint muscles. These increased muscular force levels cause higher net moments at the knee which translate into larger power outputs. This study demonstrated that the outside and inside legs produced a power output of 3.00 ± 0.63 and 4.38 ± 0.48 W/kg, respectively. The authors suggest that the differences in power outputs of each leg can be attributed to the position of the body and the legs during the performance of the skill. Additional evidence supporting the differences observed between the inside and outside leg is the fact that speed skaters often indicate that fatigue occurs sooner in the inside leg than in the outside leg (Ingen Schenau 1989). Our results substantiate this claim since the peak pressure values in the sum of the sensors on the lateral, medial and plantar surfaces appear to be higher in the inside leg compared to the outside leg in the recreational skaters and this trend is even more pronounced for the elite group. The differences between legs can also be observed in figure 11 in the sum of the pressure profiles of the lateral, medial and dorsal sensors. These results show that the inside and outside legs are creating propulsion at different amounts which reflects the constraints in push-off mechanics of each leg.

Closer examination of the peak pressures at the individual sensors reveals an interesting phenomenon. It appears that the foot and ankle of both feet are acting as levers inside the skate boot (Figure 15).

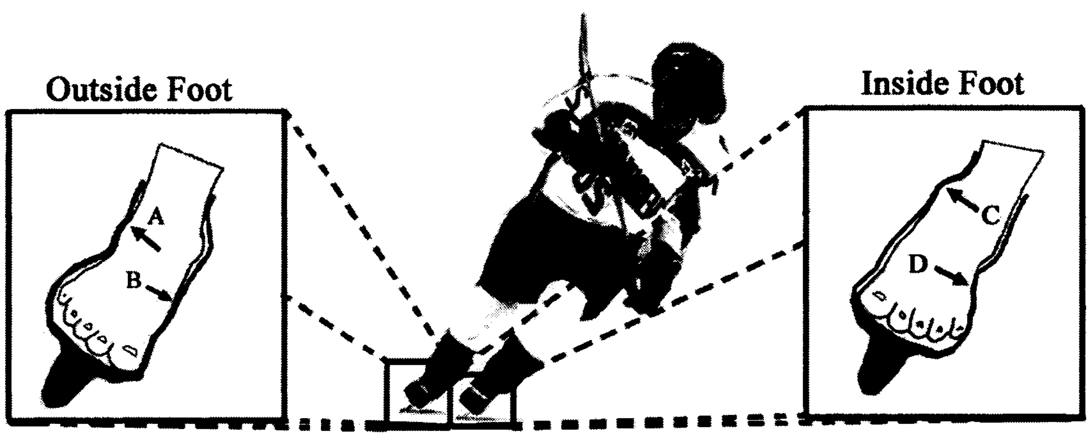

Figure 15: Arrows indicate which sensor, compared to the sensor on the opposite side of the foot, demonstrates the highest amounts of pressure. On the outside foot the lateral maleolus (A), medial calcaneous (B) and on the inside foot the medial maleolus (C), lateral calcaneous (D) displayed the highest pressures which demonstrates a levering effect of the ankle and foot in the skate boot.

On the outside foot, the sensor on the lateral maleolus (Figure 15a) displayed higher pressure than the reciprocal sensor, the medial maleolus, located directly opposite on the other side of the foot. This trend was also observed for the medial calcaneous (Figure 15b) and its reciprocal sensors located on the lateral calcaneous. The sensors on the inside foot followed a similar pattern but on the opposite side of the foot. The medial maleolus (Figure 15c) and lateral calcaneous (Figure 15d) sensors displayed higher pressures than the lateral maleolus and medial calcaneous, respectively. The gravitational forces of the skater's center of mass act downward and due to the angle of the skate cause the high pressures observed in sensors B and D. This gravitational force causes a moment that acts about the blade-ice interface and attempts to force the boot flat with the ice. Forces at A and C, resulting in high pressures observed at these sensors, counteract this moment and allow the boot to remain upright preventing the skater from losing an edge and falling. In summary, the pressures perceived in sensors B and D act to flatten the boot against the ice while the sensors A and C ensure that the boot stays upright.

Influence of skating direction on pressure patterns

The current literature has failed to document the effect of direction on any performance variables in ice hockey. However, it is not uncommon to find that hockey players feel more comfortable skating in the counter-clockwise direction compared to the clockwise direction. Despite this trend, when combining the results of the elite skaters with the recreational skaters, our results do not show an overall effect of direction on the pressure profiles or peak pressures in the any of surfaces of the feet.

Comparisons to speed skating

Stride frequency

In terms of general movement patterns, the forward crossover stride during speed skating or ice hockey skating at a constant velocity can be considered equivalent in nature (Marino 1979; Stamm 1989). Boer et al. (1987) closely examined the speed skating stride in the curve and concluded that the left stroke is shorter compared to the right, due to a shorter glide phase. They attributed this difference to the leg over technique used by speed skater's in the curve. During the inside leg push-off, the outside leg passes over the inside leg and the outside skate has to be placed more vertically and forward on the ice compared to the inside skate. They also believed that the shorter stroke time of the inside leg is a consequence of the orientation of the inside leg at ice contact since a large part of the glide phase is by- passed. In contrast to this research on speed skating, the results of the present study show that during the ice hockey crossover stride at maximum effort, there is no difference between the inside and outside legs in terms of the time required to complete a stride. In this case, the contrasting results may be related to the fact the two skills are performed at different intensities around different radiuses of curvature. In the study conducted by Boer et al. (1987), results were recorded during a 5000m race on a 400m track, whereas the results of the present study were obtained under maximal effort in a much smaller radius of curvature, equivalent to skating around the hockey net from the blue line to blue line. Although the general movement patterns are the same, the differences between these two tasks highlight the disparities in skating between the two sports. Therefore, one must take care when attempting to extrapolate results from a skill performed in speed skating and equating them to what is thought of as the same skill in ice hockey.

Pressure patterns

Ingen Schenau et al. (1989) recorded the push-off forces with strain gauges affixed to the skates of a speed skater skating around the curve. Figure 16 demonstrates the differences in kinematics data between force measurements recorded in the skate blade holders, at the skate boot-to-blade interface of the speed skater(Figure 16A), and the pressure measurements obtained at the plantar surface of the foot-to-skate boot interface from the present study (Figure 16B).

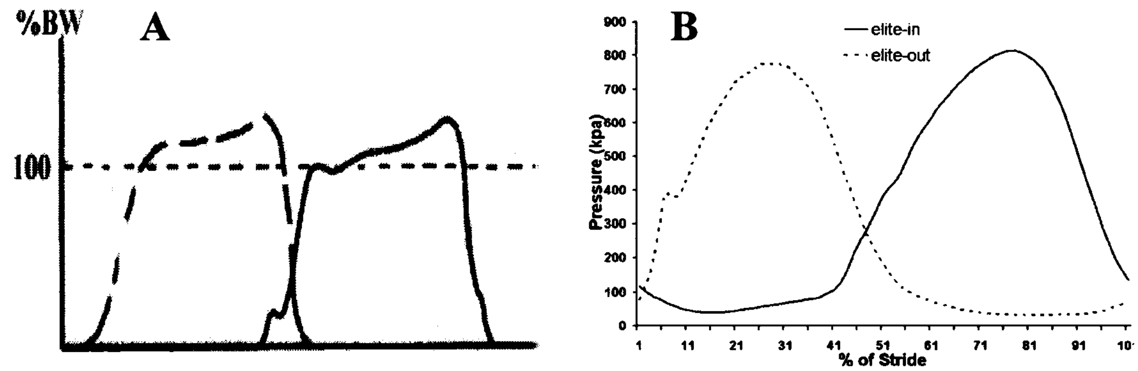

Figure 16: Speed skating push-off forces (A) ice hockey sum of the sensors in the plantar region (B) while skating the curves.

The data obtained from the strain gauges placed in the speed skate boot only show forces when the blade is in contact with the ice and only reflects the acceleration of the center of mass (COM) of the individual and does not reflect the stress on the individual structures of the foot (Miller 1990). In contrast, the plantar pressure data shows a constant residual pressure exerted throughout the entire stride, which demonstrates that the push-off force data does not give a global understanding of the forces acting on the foot at the foot to skate boot interface.

Limitations of the study

For control purposes participants were instructed to skate at maximal velocity around the outlined curve. There was no given pace to control the participants' speed. Also, only one radius of curvature was examined. These are limitations when studying the forward crossover stride since game speed and the radius of curvature differ from situation to situation in the game of hockey. In addition, the use of individual pressure sensors allowed for data collection of only selected local pressures in fifteen locations over the entire surface of the foot. Although these locations were designated important anatomical landmarks, large areas of the foot were excluded from research.

Considerations for future research

Due to the aforementioned limitations research should continue to look at the pressure patterns of different degrees of curvature at multiple speeds. In addition, recording pressure patterns along with kinematics and muscle activation would more clearly reveal the differences between ability levels and lead to a more descriptive characterization of the forward crossover stride. Furthermore, it may shed some light on the interaction of pressure patterns with kinematics and muscle activation (e.g. how pressure patterns relate to kinematics and how they affect muscle activation).

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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 skills. For 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

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