Skate boot pressure analysis of elite and recreational ice hockey skaters during the execution of tight turns

By J. Scott G. McGrail

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Abstract

This study describes the biomechanics of the foot during an ice hockey tight turn. Pressure data were collected with flexible piezo-resistive sensors from 15 anatomical points on both left and right feet. Participants included 8 elite (86.82 Kg +/- 6.48Kg, 179.69 cm +/-6.74cm) and 8 recreational level (82.10Kg, +/- 7.49Kg , 175.63cm +/- 6.37cm) hockey players, with the elite players being members of the McGill varsity team and the recreational players participating in recreational organized hockey of lower caliber. The data from three to four turns for both left and right tight turns were collected and normalized, with statistical measures taken for blade contact/turn initiation, peak pressure and peak pressure at push off. Two way ANOVAs showed numerous areas of statistical significance ($p \leq 0.05$) between the elite and recreational participants. The tracking of center of pressure was also investigated leading to some speculations of advanced techniques for the successful execution of a tight turn.

Keywords: Hockey, feet, pressure, tight turns, biomechanics

Résumé

Cette étude décrit les pressions du pied en dedans du patin pendant un virage brisque. Des collections de données de pression ont été collectionnées avec des détecteurs piezo résistifs à 15 endroits anatomiques sur les deux pieds. Les groupes comprenaient 8 joueurs de hockey élites (86.82 Kg +/- 6.48Kg, 179.69 cm +/-6.74cm) et 8 joueurs de hockey de niveau récréatif (82.10Kg, +/- 7.49Kg, 175.63cm +/- 6.37cm). Les joueurs élites étaient tous membres de l'équipe de première catégorie de l'Université de McGill et les joueurs récréatifs participaient tous dans des ligues de hockey organisées mais d'un niveau plus bas. Les données de trois à quatre virages sur le côté droit et côté gauche ont été collectionnées et normalisées. Les variables retirées de cette analyse comprenaient le contact de lame/initiation de virage, pression maximale et « peak push off ». Une analyse statistique (2 way ANOVA) a démontrée plusieurs différences ($p \leq 0.05$) entre les sujets élites et les joueurs récréatifs. Le centre de pression a été tracé et étudié. Cette analyse a servi comme source de réflexion sur les techniques avancées pour exécution idéale d'un virage brisque.

Mots clés : Le hockey, le pied, pression, virage brisque, biomécanique

Chapter I

Introduction

Hockey is a sport that is a mainstay and an important part of the Canadian social fabric. It is widely regarded as the fastest team game in the world, featuring constant motion, rapid changes of direction and bodily contact (Gröger 2001). It is highly competitive and like many other sports continues to evolve. From its origins in the 17th century to its present state, the essence of the game has remained the same but the equipment and skill refinement have evolved extensively from its origins of wooden balls and shepherd's sticks (Robidoux 2002).

Physical activity, whether it is for personal enjoyment, fitness or the joy of competition, provides individuals with the opportunity to enhance physical, psychological and social well being (Grouios 2004). The game of ice hockey is comprised of many skills but skating is considered to be the most important (Pearsall, Turcotte et al. 2000). A survey of 16 professional scouts indicates that skating is the most important skill that can be attributed to predicting success for hockey players of all positions (Renger 1994).

Little research has been conducted in ice hockey in biomechanics (Pearsall, Turcotte et al. 2000). Past studies have been performed on the forward hockey skating stride. These studies consisted of ankle kinematics (Chang 2002; Dewan 2004), lower limb EMG (Goudreault 2002; Dewan 2004), as well as plantar and complete foot pressures (Loh 2003; Dewan 2004).

The studies addressing hockey skills, although very different in application, have drawn parallels with speed skating (De Koning, De Groot et al. 1991). Some specific skills that have been addressed include skating starts, stops and backward skating (Naud and Holt 1980). However, very little has been done to examine the myriad of other skating skills necessary for successful performance in ice hockey.

A maneuvers like the tight turn, "a discrete skill used to reverse a player's direction of motion while maintaining speed" (Pike 2002), is integral to the game of hockey and the quantification of the most efficient way of carrying them out is beneficial to both coaches and athletes (Naud and Holt 1980). Tight turns are an essential part of the inventory of hockey skills required by an ice hockey player, and are therefore skills that must be understood to gain insight into turn execution mechanisms and the areas of pressure during the performance of this skill.

The tight turn is a skill that is refined through practice and experience and it is therefore likely that elite and recreational participant's will differ in the way they exert pressure and in the magnitudes of those pressures incurred during the execution of tight turns. These isolated movement patterns could help in the determination of an improved execution of tight turns.

Through the improvement of sporting equipment, namely the skate-boot, athletic performance could be facilitated and enhanced (Cavanagh, Hewitt Jr. et al. 1992). Through the documentation of plantar pressures and pressure in surrounding areas of the foot, a clear picture of pressures generated during skating can be documented. The use of plantar pressures has been commonly used to evaluate the foot-shoe (skate-boot) relationship as well as their functionality (Cavanagh, Morag et al. 1997; Hosein and Lord 2000). However, it has been noted that the propulsive forces and directional initiation arise from more than the plantar surface (Dewan 2004). The investigation of pressure itself rather than other acquisition methods can be justified since the interface found between the foot and footwear is the site of mechanical stresses; pressure and shear (Hosein and Lord 2000).

Through the measurement of plantar pressures the determination of shifts in the center of pressure (COP) during skill execution will be determined. This is a pertinent area of study as the COP is commonly used to monitor the shifts made by individuals while maintaining their balance (Krishnamoorthy, Latash et al. 2003). An ice hockey tight turn is truly a test of balance as it deals with the combination of many different forces (Haché 2002).

1.1 Purpose of the Study

The purpose of this study is to observe the pressures generated in the various areas of the foot/skate interface during the execution of tight turns and to compare the differences in pressures between elite and recreational level ice hockey players. This pressure data will detail the events which occur during the tight turn and allow for a quantification of the differences between the two groups.

This study will enable the evaluation and documentation of the foot and ankle pressures generated by elite and recreational level hockey players during the execution of a tight-turn. The documentation of the pressures generated during tight turns will result in the determination of key areas of pressure generation. These measures of pressure of elite and recreational athletes will be compared.

1.2 Nature and Scope of the Problem

In order to effectively compete in ice hockey a player must be able to master a number of skating skills. Tight turns are one of the selected indicators for a defensive player's on ice performance indicators. These include both sharp turns to the right and left (Hansen and Reed 1979). The pressure development throughout the tight turn will be evaluated and the patterns of elite and recreational athletes will be compared to examine the manner of skill execution. To effectively investigate the tight turn the foot-skate interface must be examined. Since the skate is the direct interfacing agent for the human body and the turning implement, by maximizing this interface there could be a heightened potential for the improvement of skating performance.

1.3 Significance

Understanding the differences between elite and recreational players may provide clues regarding appropriate pressure generation for proper execution of a tight turn. Documentation of pressures of the skate boot/foot interface has never been done for the tight turn. The pressure measurements in the plantar areas and other areas of the skate may have implications regarding the proper fit of the skate and the tracking of the COP may lead to a better understanding of an efficient technique for the execution of the tight turn.

1.4 Hypotheses

I. The elite athletes will perform the tight turn with a smaller radius, creating a shorter and higher peak pressure pattern then the recreational athletes.

II. There will be higher pressures recorded on the inside foot of the turn regardless of the skill level of the participants.

III. There will be a relatively equal pressure development of the inner and outer feet for the elite participants whereas the recreational skaters will have more fluctuations between the inner and outer feet.

IV. The pressure of the ankle will be higher on the inside malleolus and surroundings during turn initiation and will shift to the outside malleolus and surroundings as the apex occurs.

1.5 Operational Definitions

Tight turn:	The action of reversing ones direction while maintaining speed.
Plantar surface:	The surface of the sole of the foot.
Dorsal surface:	The surface of the dorsum of the foot.
Posterior surface:	The surface of the posterior foot and ankle.
Medial surface:	The surface of the medial foot and ankle.
Lateral surface:	The surface of the lateral foot and ankle.
BC/TI:	The blade contact/turn initiation aspect of the turn, occurring when the skates initiate their deviation from a straight line and commence the tight turn.
PP:	Peak pressure recorded during the execution of the tight turn. The highest pressure value recorded.
PPO:	Peak push off is the highest recorded value at the time of foot push off, arrived at during the terminal aspect of the tight turn.

1.6 Limitations

I. The piezo resistive sensors only measured the pressure normal to the surface of the foot (i.e. shear forces were not measured).

1.7 Delimitations

I. Participants included both forwards and defensemen.

II. Only tight turns were evaluated.

III. Only males were chosen as participants.

Chapter II

Review of Literature

Hockey is a sport which is an important part of the lives of many Canadians, as well as people around the world. The game evolved during a period of social reform in Canada (Robidoux 2002) and is believed to have originated in eastern Canada during the mid 19th century (Minkoff J 1994). It has been cited that the origins of the game date farther back to the 17th century in Huronia, Ontario where the game was then played with a wooden ball paired with shepherd's sticks used upside down (Robidoux 2002). This shepherd's stick, which was known in the French language as hoquet, is believed to be the origin of the naming of the sport. The first organized games were reported by J. W. Fitsell to have been played in 1875 (Robidoux 2002). The game has gone through considerable changes from that time and is now a fast paced game, full of hard checking and 100 mph slap shots. The game has also moved from the shepherd fields to a multi-million dollar industry with the National Hockey League. It has followed a steady progression, beginning with the Ontario Hockey Association in 1890, followed by the creation of the National Hockey League in 1917 (Davidson and Steinbreder 1997) and its acceptance into the Olympics in the 1920s, prior to World War II. Due to the increased pressure of performance and the continuous search for advantages over the competition, many areas of the sport are being investigated to aid the players and progression of the sport itself.

There are only likely a small number of aspects to the game of hockey which can be altered in the attempt to increase performance. The equipment based aspects of hockey that can be changed in an attempt to augment performance are the hockey stick, protective equipment and the hockey skate. The skate is directly related to the linking of the athlete's legs and feet(the power source) and the ice (Minkoff J 1994). Maximizing the efficiency of this link could provide a great potential for performance improvement.

2.1 The Skate

The skate has a history that has origins in activities unrelated to the sport of hockey. It dates back to the Renaissance when individuals used carved animal bones strapped to their boot soles as skates. There are pictures dating back to the 1400s of individuals skating (Koning, Houdijk et al. 2000). Some of these early skating scenes occurred in Scandinavia and by the late 1880s the use of bone was replaced by a metal blade strapped to a wooden layer which was fitted to the sole of the boot. Further modification included a complete metal blade which increased weight and decreased skating speed (Minkoff J 1994). This was one of the first design features which brought to light the fact that changes to skate construction affected skating performance. Weight was decreased with the implementation of tubular skate blades in the 1950s (Pearsall, Turcotte et al. 2000). Materials began to go through changes at this point with experimentation using plastics, composites and fiberglass (Pearsall, Turcotte et al. 2000). It has been theorized that the alteration of variables such as the blade hollow, sharpness, geometry, as well as boot construction all affect the performance capabilities of the athlete (Minkoff J 1994). These changes could drastically affect the skate and its performance. By decreasing the radius of the skate's blade, the turn radius will decrease. In addition, the sharpness of the skate blade will affect the ease of push off and stopping ability. A sharper blade makes it easier to push off but with the tradeoff of a more difficult stop (Pearsall, Turcotte et al. 2000). Players often customize their skates to suit the perceived needs and demands of the positions that they play in during a game.

From the research on running shoes it has been shown that an optimal shoe design is one that supports the movement pattern specific to the activity, therefore reducing muscular activity and increasing comfort (Reinschmidt and Nigg 2000). Thus, by creating a shoe that is specific to the sport and its demands, (i.e. movement patterns) energy expenditure could in theory be reduced and performance could then be optimized (Reinschmidt and Nigg 2000).

2.2 Hockey research

There has been limited research done on foot pressure patterns during ice hockey skating tasks. Forward skating tasks have been examined (Loh 2003; Dewan 2004) but skills outside of this area have yet to be explored in depth. Skating skills have been examined in previous research; starts and stops have been examined (Roy 1978), Kinematic description (Marino and Dillman 1978) and Backwards skating "Selected" Mechanics (Marino and Grasse 1993), however none of the studies were undergone with regards to the pressures incurred during a tight turn.

In Loh's study (Loh 2003)comparisons were made of the plantar pressures between the forward ice hockey stride on ice and on a skating treadmill. It was shown that the treadmill based skating altered the pressures upon initial contact, with pressures on the treadmill being higher. All other aspects of the pressure profiles were otherwise the same.

In Dewan's study (Dewan 2004), the whole foot was studied during constant velocity forward skating. The pressures, myoelectric and kinematic data were all examined with the pressure data leading to a descriptive analysis of the forward skating profile. It was shown that the plantar pressures shifted from medial to anterior position of the COP during the stance phase of skating (Dewan 2004). The work of Dewan and Loh both showed an initial loading of the medial heel, followed by the lateral heel (Loh 2003; Dewan 2004) which is in contrast to the running literature which shows a initial loading of the lateral heel, followed by the medial heel (Hennig and Milani 2000).

In one study performed by Marino (Marino 1977), the biomechanics of hockey skating skills were examined (Marino 1977). This included summaries of previous research in starts, constant velocity skating and backwards skating. These skating skills have been examined in by Roy (1978) who investigated the force generation during different start techniques.

In one kinematic analysis of the forward skating stride it was shown that through an increased range of motion at the hip and knee, athletes were able to generate higher skating velocities (McCaw and Hoshizaki 1987). This increased range of motion was the result of increased joint flexion at the ankle prior to extension.

Due to the nature of hockey and the multitude of skills associated with playing the game, it should be an advantage to match the skate boot to the tasks which will be completed. The tasks themselves must therefore be analysed before any technological changes can be imposed. This study will focus on the tight turn, described as being "a discrete skill used to reverse a player's direction of motion while maintaining speed" (Pike 2002). From a survey of 16 professional scouts, it has been found that skating is the most important skill predicting success for hockey players of all positions (Renger 1994). Of all the skating skills turning ranked 4th in importance for defensive players and 7th for offensive players (Renger 1994). The skills which preceded turning were; power/mobility, stride/backward skating and balance for the defensive aspect and balance, quickness, speed, acceleration, agility and power/mobility for the offensive players (Renger 1994). In addition to these skills, players must have body coordination and good balance while skating (Hansen and Reed 1979). These skills are all important determinants of a well executed tight turn.

The tight turn is a skill which is used many times during the three periods of a hockey game. It is likely that this type of abrupt movement results in the generation of different pressure patterns than those exerted during the execution of normal skating strides. It is a technical skill which with appropriate training can be refined, increasing the ability to maintain speed going in and coming out of a turn while maintaining a tight radius of curvature. Maintaining a tight turn radius enables players to change direction in less time while curtailing the amount of energy expended (Haché 2002). This can be shown with the formula for the inward acceleration of a body moving in a circle:

$$a = \frac{v2}{R'}$$

Equation 1: The equation for centripetal acceleration, where R' represents the radius of the turn, v represents velocity and a is the inward acceleration.

This motion of tight turn will affect the manner in which a skater will position themselves. The centripetal forces that are encountered will cause the skater to lean towards the center point of the turn, moving their center of mass inside and away from their base of support (Pearsall, Turcotte et al. 2000). The level of centripetal force created will dictate the radius of curvature, with a higher level of centripetal force representing a tighter radius, creating a higher level of force and a quicker turn (Pearsall, Turcotte et al. 2000). This can also be achieved by increasing the amount of lean as the turn is performed.

If a tight turn is performed in highly skilled manner it is likely that significant differences between skilled and unskilled skaters would be seen. It may be that the magnitude and the points on highest pressure would be different in these two groups of skaters. Identification of various types of pressure patterns in these two groups may help determine specific technical characteristics of different tight turns and aid coaches and players to improve the skillful execution of tight turns. In addition, such information may be helpful in identifying pressure points in different parts of the foot-skate interface and may lead to innovative ways of designing the skate boot to facilitate proper skill execution.

2.3 The Foot

The foot is made up of 26 bones and is in contact with the two bones of the lower limb; the tibia and fibula. There are 4 layers of muscle on the plantar surface and many bones provide insertion points for muscles of the lower limb. The 26 bones are divided into 3 groups; the tarsal bones, the metatarsal bones and the phalanges (Moore and Dalley 1999). These bones are all held together with an intricate array of ligaments, muscles, and tendons. This network of connective tissue and bones creates an arch shaped structure which carries the loads applied by the tibia and fibula (Salathe Jr., Arangio et al. 1986). There are two main responsibilities of the foot and ankle area; to be flexible enough to absorb loading and rigid enough to act as a lever arm (Towers M.D., Deible M.D. et al. 2003). By meting both of these needs the foot has an interestingly dynamic nature, acting as a shock absorber during a multitude of activities. This is carried out in a specific manner to effectively adjust to weight bearing (Nyska, Linge et al. 1997). The adaptation of the human foot under heavy loads is done by the maintenance of the arches of the foot (Nyska, Linge et al. 1997). In order for the foot to store and release energy, ligaments are used in storing elastic energy. The Achilles tendon, running vertically from the calcaneous into the gastrocnemius and soleus muscle can store 35 joules of energy and the ligaments of the plantar surface can store 17 Joules (Salathe Jr., Arangio et al. 1990). This is important as the foot acts as the main shock absorber of the human body (Nyska, Linge et al. 1997) while also acting as a means of energy storage. In order to cope with the different forces exerted on the foot as well as the different environmental constraints, it is by nature multiplanar (Towers M.D., Deible M.D. et al. 2003). The different axes create a three dimensional movement pattern. This is encompassed by motion about the horizontal axis: plantar and dorsi flexion, where the toes move down and up, respectively. Rotation about the horizontal axis is known as medial and lateral motion. The last dimension of motion is about the anteroposterior axis, were the foot goes through inversion and eversion; rotating inwards and outwards respectively (Towers M.D., Deible M.D. et al. 2003).

The foot distributes the load of the body mainly across the heads of the five metatarsals and the tuberosity of the calcaneous (Salathe Jr., Arangio et al. 1986). (Figure 1) Due to the plantar surface's role as a contact point and main load bearing surface, there a layer of compartmentalized plantar fat which is anatomically designed to spread loads. This heel pad is made up of dense fibrous septae which forms a fat containing lattice, preventing the displacement of the fat globules thereby maximizing support (Jahss, Michelson et al. 1992). This is especially important over the areas of bony prominences such as the area of the metatarsal heads and the calcaneous (Towers M.D., Deible M.D. et al. 2003). This fat pad is most effective when it is in a position of maximal loading such as that found in a shoe with a tightly fitting heel cup (Towers M.D., Deible M.D. et al. 2003). This has been explored in depth in the area of diabetic patients, due to their predisposition of foot ulceration (Chen, Ju et al. 2003) In order to reduce plantar pressures in this group, total contact insoles have been successfully used (Chen, Ju et al. 2003)

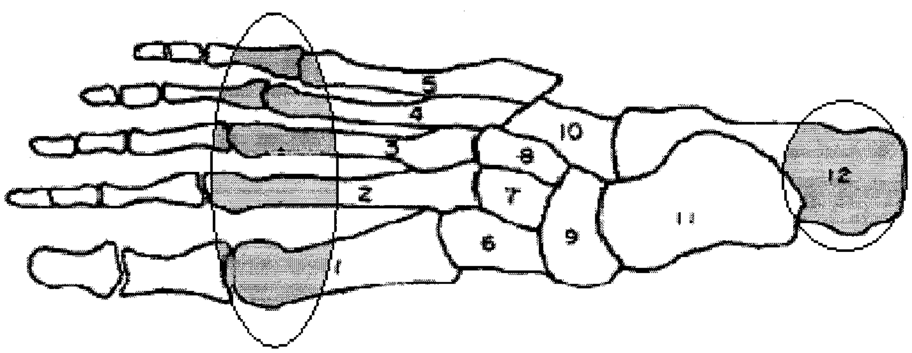


Figure 1: The foot, adapted from Salathe Jr. et al. showing the 1-5 metatarsals; 6-8 cuneiforms; 9 navicular; 10 cuboid; 11 talus; 12 calcaneus. The highlighted areas depict were maximum pressure is found. (Salathe Jr., Arangio et al. 1986)

2.4 Foot Pressures

2.4.1 Pressure Sensing

The collection of plantar pressures is a good way of collecting relevant information on foot structure (Reinschmidt, Nigg et al. 1994). The distribution of in-shoe pressures has been shown to have great value in orthopaedic and biomechanical clinical settings (Chen, Nigg et al. 1994). From the literature it has been shown that in order to create a comfortable shoe the plantar pressure should be minimized (Chen, Nigg et al. 1994). The foot plays an important role in control of balance and motion. The central nervous system(CNS) relies on input from the cutaneous receptors on the sole of the foot to generate necessary motor patterns which enable controlled posture and locomotion (Nurse and Nigg 2001). This feedback is tracked by the mechanoreceptors of the foot and in the form of spatial origin, amplitude, as well as the rate of change of the pressure being experienced (Kavounoudias, Roll et al. 1998). Not only does this information provide the CNS with constant feedback, enabling split second changes to gait but it also affects the planning of future movement patterns (Nurse and Nigg 2001). This pressure sensing is carried out by the Golgi and cutaneous receptors (Nurse and Nigg 2001), and triggers the responses which bring together the body position and the equilibrium position (Kavounoudias, Roll et al. 1998). It has been shown that when the ability to sense pressure on the sole of the foot is altered there are adaptive measures which are taken. This lack of pressure sensing is primarily due to disease, anaesthesia or exterior stimulation (Chen, Nigg et al. 1995) and will result in redistribution of the plantar pressure. Studies investigating this phenomenon have looked at altering the normal movement patterns through the use of partial plantar anaesthesia (Nurse and Nigg 2001; Eils, Nolte et al. 2002), changing the sensory input by varying the texture of an altered sock in the mid and forefoot areas (Chen, Nigg et al. 1995) as well as through the exterior application of stimulus to the plantar aspect of the foot (Kavounoudias, Roll et al. 1998; Nurse and Nigg 1999). These studies showed that when the sensory input to the plantar aspect of the foot was altered, the plantar pressure patterns differed as well. When the plantar surface was subjected to ice induced anaesthesia its pressure decreased during normal gait (Nurse and Nigg 2001). These decreases in pressure occurred at the heel, hallux and toe region. In the E. Eils et al. (2002) study, ice was also used to anaesthetize areas of the plantar surface and resulted in changes in the peak pressure, contact time and relative impulses. The areas which were iced all had a reduction in pressure, with those under the heel and toes proving to be significant when compared to a control group of non anaesthetized participantss. There was a significant increase in contact time for the fore and midfoot areas, showing that the participantss had an earlier contact time with a prolonged duration in time, hinting towards an increase in apprehensiveness by the participant.

In a study by Nurse and Nigg (1999) the relationship between pressure and vibration stimuli was examined. It was shown that when the foot is subjected to vibration of different cutaneous areas on the plantar surface of the foot that there is a negative relationship between the stimuli and the pressure patterns while running and walking. This was significant in the area of the hallux while being subjected to a stimulus of 125Hz. These results support the theory that the foot and its actions are subject to the sensory input that they encounter. By stimulating or removing the ability to sense stimuli, the foot shifts pressures accordingly. In general, it has been shown that the loading of the plantar surface of the foot is directed towards the sensitive areas and away from the insensate ones during gait (Nurse and Nigg 2001), with these shifts being seen in a movement of the COP to the sensitive areas. These sensory based changes in the pressure profiles can be related to the innate attempt to maximize comfort, balance and control. The sensory inputs are linked to the central nervous system and dictate how the body reacts to maintain a maximal level of balance and comfort (Chen, Nigg et al. 1995).

From these studies it can be theorized that there should be a maximal contact area in the skate boot to increase sensory potential and diminish local pressures by dissipating them over a larger area.

2.4.2 Morphology

The structure of the foot has been identified as the most important factor determining plantar pressure (Morag and Cavanagh 1999). The normal walking gait is affected by intrinsic and extrinsic factors. The anatomical changes or deformities to the foot will affect the general gait and pressure patterns of individuals. There are numerous conditions which alter the morphology of the foot and its anatomical features; pes cavus feet are those with a excessively high arch (Burns, Crosbie et al. 2005), hallux valgus and limitus feet are those with deformities at the metatarsophalangeal(MTP) joint, with hallux valgus defined as having a hallux abductus angle greater than 15 degrees and hallux limitus defined as painful limitation of passive MTP 1 joint motion (Bryant, Tinley et al. 1999). When an individual suffers from pes cavus feet, their high arch reduces contact surface of the foot, thereby increasing the pressures subjected to the areas that maintain contact. The shock absorbing characteristics of the foot arch is limited as well, reducing the dynamic pressure absorbing nature of a healthy normal arch (Burns, Crosbie et al. 2005). The pes cavus foot is subject to longer contact times as well as increased pressures beneath the heel surface when neuropathic and idiopathic pes cavus feet are compared to normal feet (Burns, Crosbie et al. 2005). The majority of individuals with pes cavus feet(67%) complain of pain and discomfort compared to only 23% of the population with normal feet (Burns, Crosbie et al. 2005). Hallux valgus feet tend to have higher pressure recorded beneath the first, second and third metatarsal heads whereas hallux limitus is prone to higher pressures under the third, fourth and fifth metatarsal heads when compared to normal feet (Bryant, Tinley et al. 1999). These two shifts in the plantar pressure profiles can be explained through their adaptation of normal walking gait. A normal gait pattern follows a heel to toe trajectory. This shift in loading can be tracked through the movement of the COP which starts medially at the heel, shifting to the lateral midfoot where it lingers during mid support and then shifts medially to the forefoot (Rose and Gamble 1994). In the cases of hallux valgus and limitus, this terminal stage of gait leaves the foot with pressure on the forefoot area. Due to the painful and limiting nature of hallux limitus, pressure is shifted away from the affected areas and with hallux valgus having a widened base of support, the pressure is shifted to that widened area (1st metatarsal head) as mentioned in other literature (Morag and Cavanagh 1999).

The possible predictors of peak plantar pressures follow in Table 1.

Heel	Midfoot	MTH1	Hallux
Structure			
Age	Age	Foot length	Hallux length
Inferior calcaneal inclination	Height	Rear foot width	Hallux width
First metatarsal inclination	Body weight	Mid foot width	Rear foot width
Fifth metatarsal inclination	Leg length	Hallux length	Talocrural dorsi flexion PROM
Heel pad thickness(unloaded)	Midfoot width	Inferior calcaneal inclination	MTP1 dorsi flexion PROM
Heel pad stiffness	Eversion PROM	Chopart's angle	First metatarsal inclination
	Arch index	Proximal first phalanx inclination	Metatarsal 1 thickness
	Inferior calcaneal inclination	Sesamoid height	Interphalangeal 1 angle
	Fifth metatarsal inclination	Morton's index	Sesamoid height
Function			
Horizontal foot velocity at heel strike	Toe out angle in walking	Talocrural dynamic ROM	MTP1 dynamic ROM
Vertical foot velocity immediately after heel strike	Contact time	Talocrural joint plantar flexion velocity	MTP1 velocity
Contact time	Talocrural joint plantar flexion vel.	Average gastrocnemius activity during the third quarter of stance	Subtalar joint dynamic ROM (adduction/abduction)
Subtalar abduction at heel strike	Subtalar joint dynamic ROM (inversion/eversion)	Average gastrocnemius activity during the second quarter of stance	

Table 1: Summary table of the possible structural and functional peak plantar pressure predictors. Adapted from E. Morag et al. (Morag and Cavanagh 1999)

2.4.3 Movement patterns

Movement patterns and intensity play a large role in determining the resultant plantar pressures. By altering aspects of gait, such as speed, the plantar pressure will increase (Morag and Cavanagh 1999; Burnfield, Few et al. 2004). When walking speed increases, the impact incurred significantly increases the peak and mean pressures under the heel, central and medial metatarsals as well as the toes (Burnfield, Few et al. 2004), due to the increased force of impact.

One of the main reasons for a decrease in plantar pressure is that when individuals wear running shoes the contact area is increased, thereby dissipating the plantar pressure.

This can be seen with a significantly higher pressure pattern in barefoot running when compared with shod running (De Wit, De Clercq et al. 2000) Along with higher pressures, there is a notably larger loading rate for barefoot running and a change in the ground reaction forces (De Wit, De Clercq et al. 2000). The loading rate becomes much sharper and is composed of multiple peaks rather than the smooth double peak nature of shod running (De Wit, De Clercq et al. 2000).(Figure 2)

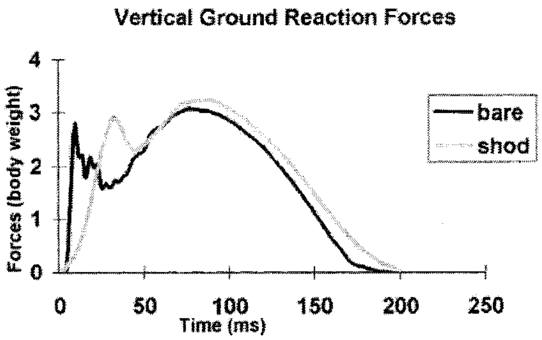


Figure 2 : Vertical ground reaction curves of 1 representative person at a velocity of 4.5m/s^2 Adapted from B. De Wit et al.(De Wit, De Clercq et al. 2000)

Since the impact forces are concentrated primarily over the calcaneal region and the metatarsal heads, it is important to investigate both of these regions. During the last part of foot contact body weight is transferred from the mid foot to the metatarsal heads and toes (Hayafune, Hayafune et al. 1999). This loading terminates with the concentration of body weight on the big toe and under the head of the 1st metatarsal(MTH1) with 53% of body weight being concentrated on that area (Hayafune, Hayafune et al. 1999).

It has been speculated that with an increase in duration and the intensity of activities that there can be changes to the force distribution on the plantar surface (Reinschmidt, Nigg et al. 1994). This is due to the breakdown of the materials present in the soles of shoes. In a study evaluating the durability of the running shoe sole, pressure data was collected. The experiment consisted of jogging for ten minutes on a treadmill with the plantar pressures at 1, 5 and 10 minutes being the focal points of the investigation. It was shown that the shoe's sole characteristics change with use. The tests were repeated three times to evaluate the longevity of the materials. Testing was carried out when the shoes were new, at 250 Km of use and at 500 Km of use. The same participants ran at controlled velocities for all of the trials to ensure validity. The repeated stresses of running impacts cause deterioration of to the ethylene and vinyl acetate (EVA) foam found in running shoes (Verdejo and Mills 2004). EVA midsoles are the most common type in running shoe production and are absorptive in nature. This caused an increase in peak plantar pressures. After 10 minutes of running there was a consistent increase in plantar pressures for all participants. This was compounded over the duration of the study when the shoes were retested after the shoes had sustained the 500Km of use, leading to a 100% increase in peak pressure over the total run distance (Verdejo and Mills 2004).

2.4.5 Athletes

When running there are repeated heel strikes, causing repetitive impacts on the feet. Running shoes use padded midsoles to limit peak plantar pressures by absorbing some of the impact forces as well as dissipating the pressure over a larger surface (Verdejo and Mills 2004). This pressure pattern has maximum values upon heel contact, as there is a minimum contact surface and impact is largest. This pressure pattern is reduced by the anatomical heel pad as well as the materials present in running shoes which have shock absorbing characteristics. The shoe acts as a shock absorber as well as a dissipating agent, spreading the impact forces over a larger surface area. Since pressure is directly related to area (Equation 2) it can be seen how the area directly affects the pressure values.

$$pressure = \frac{force}{area}$$

Equation 2: The pressure equation showing its relation to area.

Running is in essence simply an augmentation of gait speed. This alteration of speed affects pressures and is pertinent in all aspects of gait. In a study by Burnfield, Few et al. (2004) the walking speed of older adults was investigated with regards to plantar pressures. It has been shown that with age there is a decrease in the plantar fat pad thickness (Jahss, Michelson et al. 1992) as well as a reduction in the longitudinal arch height (Hutton and Dhanendran 1979; Hutton and Dhanendran 1981). Both of these phenomena will negatively affect the way the foot is able to deal with the plantar pressures to which they are subject during locomotion. In Burnfield, Few et al.'s study (2004) it was shown that there was a significant increase in plantar pressure when the walking speed of the participants increased from a slow pace of 57 meters/minute to a fast pace of 97 meters/minute. This increase in pressure was prominent under the heel, central and medial metatarsals and toes with a 47% increase in peak pressure under the heel when comparing the slow and fast walking speeds (Burnfield, Few et al. 2004). Burnfield et al. concluded that the increase in pressure with walking speeds was due to increased peak force values.

When evaluating the pressure patterns of athlete's feet, several factors have to be taken into consideration. Due to the different playing conditions and the specific athletic footwear that is associated with each sport, different conditions will arise. The common soccer player will select a cleat that is narrow in the mid foot region and is tight fitting to increase sensory input. This equates to a shoe which is a size smaller than their normal shoe (Santos 2001). The nature of the shoe and its specialized sole create an increase in plantar pressure which is caused by the concentration of the player's weight on 6 to 12 studs, decreasing contact surface. When soccer players squeeze their feet into a smaller sized cleat, they are thereby decreasing their in-sole contact area. This has been quantified in a study of 15 soccer players to be a decrease by 8.25% in the cleat sole contact area (Santos 2001). From this same study it was shown that there was an increase of 35% in the peak plantar pressures of the soccer cleat when compared with the pressures found in a normal fitting running shoe. This was concluded to be due to the decrease in the plantar surface within the cleat (Santos 2001).

In a study on 21 elite soccer players, Eils et al. (2004) looked at the plantar pressures of soccer players during game specific movements. The running, cutting, sprinting and kicking skills were investigated and significance was found for relative loads and peak pressures in all areas (Eils, Streyl et al. 2004). When the cutting maneuver was compared with running, it was shown that there was a significant shift of plantar pressures to the heel, medial midfoot, medial forefoot and hallux. The central and lateral forefoot and lateral midfoot all had significant decreases in pressure. This is compared to the loading areas of the running data, where the primary pressure points were under the heel, the metatarsal heads and the hallux, which is very similar to the normal breakdown of plantar pressures. When the running and cutting pressure data was compared, it was shown that there were 220% and 160% increases in plantar pressure for the medial heel and forefoot in cutting (Eils, Streyl et al. 2004). Interestingly enough, despite the smaller nature of the soccer cleat and the reduced contact surface, the pressure data in this study while running was found to be similar to those of running with standard running shoes, however, when the walking data with soccer cleats was compared to that of walking in running shoes, the plantar pressures were higher for the cleated foot (Eils, Streyl et al. 2004). The high force generation from cutting when paired with the smaller cleat both mimic the conditions that are expected to be found with the ice hockey tight turn, due to the small nature of the skate boot, and for sensory reasons, the reduced contact surface of a blade and the vigorous nature of the tight turn. From these points it can be hypothesized that there will be higher pressures recorded in the skate boot than would be found in a running shoe or comparable footwear.

2.4.6 Disorders

There are many factors which can affect the plantar pressures to which the feet are subjected. These factors include footwear, gait and anatomical features. Motor and sensory neuropathies can lead to abnormal gait (Masson 1992) and therefore alter the normal pressure patterns found in locomotion. Gait alterations can occur for numerous reasons and the diabetic population is especially vulnerable to foot disorders altering walking pattern (Veves, Fernando et al. 1991; Masson 1992; Maluf and Mueller 2003). There is evidence of limited joint mobility in the diabetic foot which has been linked to higher plantar pressures than in control normal participants (Masson 1992). There is a clinical relevance to the stresses that feet are subjected to at the foot-shoe interface. One of the major areas of these foot pathologies is of foot ulceration in the diabetic patient (Hosein and Lord 2000). There have been many studies which have linked excessive plantar pressures with the formation of neuropathic foot ulcers (Maluf and Mueller 2003). In an attempt to reduce these foot ulcers, patients with diabetes have had to reduce plantar tissue stresses through decreases in activity and the use of therapeutic footwear (Maluf and Mueller 2003). It has also been shown that high plantar pressure which is present in individuals who are free of neuropathy or other risk factors will probably not incur the formation of ulcers (Masson 1992).

2.5 Injuries

Through the practice of repetitive activity individuals put themselves at risk for injuries (Grouios 2004). The plantar pressures that individuals are subjected to are of important significance in the comprehension of the mechanisms of damage to the plantar tissues (Lord 1997). These high pressures can cause the deformation or reduction of the fatty pad which is located under the calcaneal tuberosity (Lord 1997).

Skating of all types generates moments of high pressure on the foot which is potentially harmful when looking at Brand's statement "Pressure is the critical quantity that determines the harm done by force." (Brand 1988) These elevated plantar pressures have been associated with the increased chance of injury to insensate feet (Cavanagh, Morag et al. 1997). Of individuals participating in sporting activities, competitive athletes are those with the highest risk of injury and the development of traumatic skin disorders (Grouios 2004) . An athlete's feet are among the most stressed aspect of their body, succumbing to the stressors through the formation of corns and calluses (Grouios 2004). These injuries carry both intrinsic and extrinsic causes. Extrinsic factors include competition skill level, and shoe type (Murphy, Connoly et al. 2003). Due to the nature of skin and its direct relationship with the elements to which it falls prey the many abuses of the surrounding environment, feet are victims to repeated impacts, pressure, and friction to name a few. Two of the most common skin injuries which are caused by mechanical trauma are those of corns and calluses (Grouios 2004). Corns are by definition "a circumscribed, sharply demarcated area of hyperkeratotic plaques over the bony prominences of the feet and toes" (Grouios 2004) whereas calluses are "broad based or diffuse hyperkeratotic lesions of relatively even thickness, which may spread across the ball of the foot or along the outer edge of the heel, but are most commonly found under the metatarsal heads" (Grouios 2004).

Along with foot function, foot morphology has a lot to do with its ability to cope with the extraneous factors that activity provides. If a foot has a high arch it is more susceptible to stress fractures of the tibia and fibula (Cavanagh, Morag et al. 1997; Murphy, Connoly et al. 2003), but there is little significant data to substantiate the motion increase that foot morphology dictates the likelihood for injuries. Some literature has shown that there is a significant difference between the athletes suffering from knee pain and those with feet that had been designated with pronated or supinated foot positioning (Murphy, Connoly et al. 2003) showing that foot positioning will affect other anatomical regions.

Fifteen percent of inline skating injuries arise from the foot and ankle area (Schieber and Branche-Dorsey 1996). One case study showed the onslaught of tarsal tunnel syndrome, an entrapment neuropathy (Watson, Algahtani et al. 2002). An ice hockey player wearing inflatable hockey skates which had a poor fit caused the entrapment of the posterior tibial nerve. This type of injury is found with poorly fitted footwear causing pressure points and the entrapment of the nerve.

2.6 Force Sensing Array

In the present study, the collection of pressure data will be done by a commercially developed pressure sensing device, Force Sensing Array (FSA) (Verg Inc, Winnipeg, Canada). The system used in this study consisted of two octopi sets of sixteen sensors each. The sensors measured 12 mm x 11 mm x 2 mm thick. This type of sensor and its use are known as discrete devices. This type of device is defined as the placement of sensors on anatomical landmarks on the plantar aspect of the foot (Cavanagh, Hewitt Jr. et al. 1992). It has been proposed that anything larger than a 10mmx10mm sensor is unsuitable for plantar surface collections due the localized pressure under the metatarsal heads (Razian and Pepper 2003). However, due to the closeness in size of the FSA sensors, it was felt that they would prove to be acceptable. Because the FSA piezo-resistive sensors are very thin they also follow the universal principle of scientific measure which states "that the act of measurement should not change the quantity being measured." (Cavanagh, Hewitt Jr. et al. 1992) The FSA system is well suited for ice hockey research as these sensors monitor the pressures while in the skate boot during functional activities and is not dependant of the type of shoe(skate) worn (Mueller and Strube 1996).

2.7 Piezo-resistive sensors

Piezoelectric copolymer materials have been successfully used in the development of in-shoe vertical force transducers (Razian and Pepper 2003). The manner in which the piezo resistive sensors function is due to their physical and electrical properties. When subjected to stress-induced strains, the resistance of the sensing material changes (Li, Zohar et al. 2000). This change in electrical activity is tracked. The electrical charges alone would not be very insightful and they must therefore be related to a pressure value. This is done through a calibration period where known pressures are applied and their respective charges are recorded. This generates a calibration graph which is used for extrapolating pressure values for future collections. These calibration periods are done prior to each measurement period to minimize any possible aliasing and it has been shown that with proper calibration there is under two percent hysteresis (Jeffcott, Holmes et al. 1999). The use of piezorestive sensors is especially applicable with ice skating as it is not affected by the level of humidity or temperature that is encountered during such a task (Duvillard, Rundell et al. 2000). This has been showen in ski racing data collection, which cultures harsh testing conditions.

Chapter III

Methodology

3.1 Participants:

A total of 16 participants participated in the study; 8 recreational athletes and 8 elite athletes.(Elite: 86.82 Kg +/- 6.48Kg, 179.69 cm +/-6.74cm, Recreational: 82.10 Kg, +/-6.37, 175.63 cm +/- 6.37cm) The elite players were members of the McGill Redmen, a varsity hockey team, and the recreational athletes were all participating in recreational organized hockey of lower caliber. The McGill varsity team is considered elite and is one of 31 teams in the men's division of the Canadian Interuniversity Sport (CIS) organization. The CIS was founded in 1961 from the amalgamation of different Canadian amateur sport organizations. In 1962 it was known as the Canadian Interuniversity Athletics Union (CIAU) but in June of 2001 the organization was changed to the CIS to better represent what it was comprised of and who it represented (www.cisport.ca, 2006). The CIS has partial financial support from the Canadian government with the hopes of increasing the level of excellence of the players as well as identifying talent and developing international contenders in different areas of amateur sport(www.cisport.ca, 2006). The recreational athletes were considered as such if they played organized hockey at least twice a week.

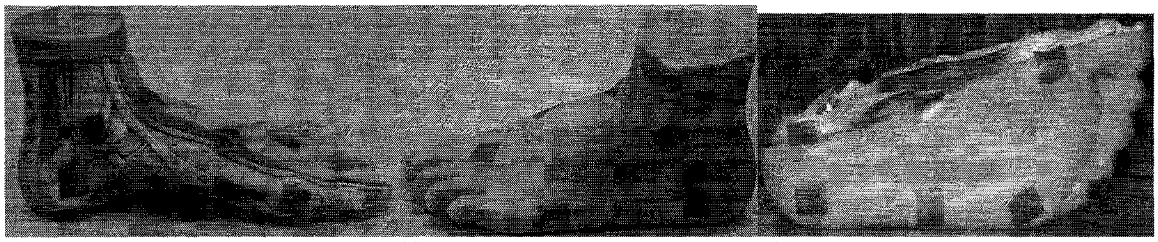
All participants were free of known neurological and lower extremity musculoskeletal disorders during participation of this study. The details of the study and what was to be expected of the participants were explained to the participants before the study began. This included a clear explanation of the potential risks and benefits of the information gained. They then read and signed the consent forms (Appendix A) before participating in the research. This research was approved by the ethics committee of the Faculty of Education, McGill University. (Appendix A)

3.2 Sensor placement:

The sensors used for this study where piezo resistive sensors. These were selected due to their thin and flexible nature. (12 mm x 11 mm x 2 mm thick). The sensors record pressure in pounds per square inch (PSI), ranging from 0 to 100 PSI . The sensors were calibrated prior to each period of data collection in order to main standard collection parameters. Sixteen sensors, with one sensor for signal synchronisation purposes, were placed on each of the participants' feet and ankles in predetermined locations. These sensor locations were determined during pilot testing at which time a matrix of sensors was used to map the activity of the whole foot and ankle (Figure 3).

Figure 3: The medial, lateral and dorsal aspect of the foot with the initial sensor matrix.

This procedure was carried out on multiple occasions to ensure that the whole foot was mapped accurately and that the results would truly reflect the pressures elicited in the various areas of the foot during the execution of the tight turn. Once the mapping was completed the preliminary data was collected and a smaller, more precise mapping of the foot was completed (Figure 4).



a) b) c)

Figure 4: Placement sites for the 15 sensors. a) Medial, b) lateral c) plantar view shown.

3.3 Calibration:

Prior to the collection of pressure data the sensors were calibrated using an air bladder (Tekscan, West Boston, MA, USA) into which the sensors were inserted. Once inside the bladder, which was inflated via a manual pressure gauge to ensure accuracy of the pressure which was applied, the sensors were calibrated following the calibration module included with the FSA software (Verg inc, Winnipeg, Canada). This process consisted of a gradual increase and decrease of pressures from 0 to 100 PSI. This was done to ensure that there was a minimal amount of hysteresis or aliasing in each of the sensors. This procedure allowed for the tracking of any changes in pressure readings during a sustained pressure application and to recognize erroneous values. The procedure was repeated prior to each testing session and with each subject. From the calibration process it has been previously shown that the sensors maintain pressure readings of ±3 PSI over a 100 PSI range. (Dewan, 2004)

3.4 Collection:

The placement of the sensors on the participants' feet was completed by the same researcher for each subject so as to minimize any inter-individual differences in sensor placement. The plantar aspect of each of the participants' feet was then photographed with an adjacent ruler to give correct scaling for later work in the derivation of the center of pressure (Figure 5).

Figure 5: The plantar sensors in place with a measuring device for scale.

This was done for both left and right feet with visible labeling of a given subject's initials for identification purposes. Once the documentation of the sensor placement was completed the participants put on provided athletic socks. Participants then laced up their personal skates as they would normally and were given a warm up period on ice. Once they were adequately warmed up (a time period of approximately 10 minutes(Dewan 2004))a static standing collection was taken. These data were collected online and had an approximate duration of 2 seconds at 100 Hz (FSA Verg inc., Winnipeg, Canada)

3.5 Protocol:

Three different skating protocols were completed by each subject. The order of completion of each of the three protocols was randomized. This was done to ensure that fatigue and task order did not affect the results in any way. The participants chose an order of the numbers 1, 2, and 3, where 1 represented tight turns, 2 represented forward skating cross overs and 3 represented backwards cross overs. Only the tight-turns are considered in this thesis.

The tight turn was completed between two face-off circles, over a distance of 48 feet (Figure 6). The participants were instructed to skate around two designated points, which were delineated by pylons at either end, as fast as possible and to make the tightest turn possible at either end. The participants were free to choose which side of the turn they wanted to do first and all started from a standstill beside the pylon of their choice. The turns were executed in a figure 8 pattern so as to get both left and right hand turns (Figure 7). Fatigue was not a concern during this collection period as it comprised approximately thirty seconds of cumulative skating which is less than the average shift of forty-five seconds during a hockey game. (Pearsall et al., 2000)

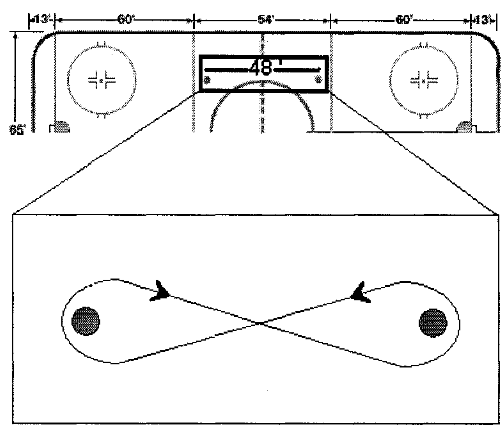


Figure 6: Rink dimensions with tight turn skating pattern delineated.

Figure 7: A elite skater completing a tight turn around a pylon.

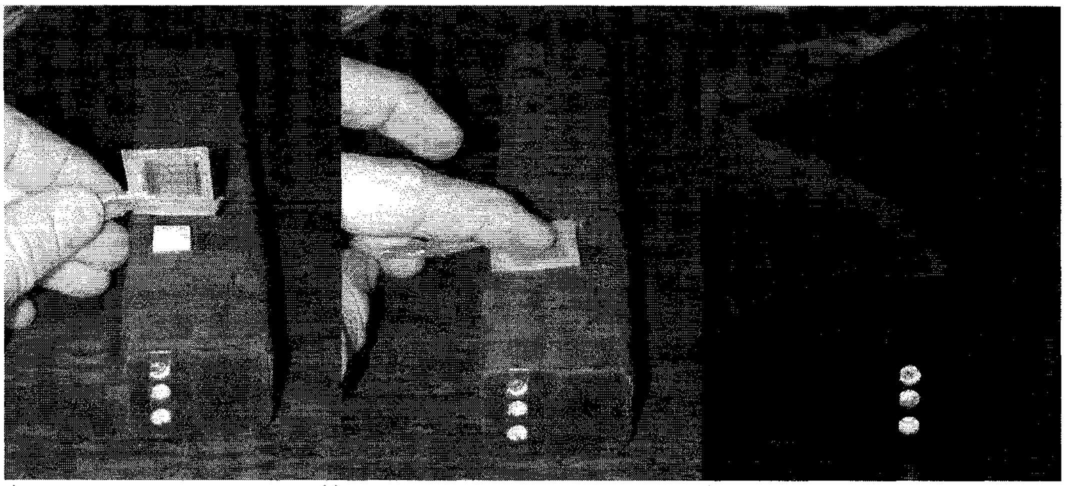
3.6 Data Collection

The data collection for the tight turns was completed off line using a offline data logger. (FSA Verg inc., Winnipeg, Canada) The data logger was placed inside of a hip sack which the participants wore during the tasks. The hip sack was assumed not to be a hindrance to the athletes as it was minimal in size and not restricting to motion. The data logger had a recording period of approximately one minute, allowing for a complete collection of data per subject per trial. After the completion of the tight turns, the subject would skate to the side of the rink where a laptop (Toshiba Libretto) was located and an online uploading of the data was completed. The offline pressure data collection was paired with a video filming of the tight turns. A digital video camera (Panasonic mini dv pv-ds13) was used to film all of the participants during the completion of the tight turns. The camera was located on a tripod and the filming was done at 30 Hz.

A trigger for the FSA data collection was initiated manually. The sensor was placed on the trigger and was activated simultaneously with a LED (light emitting diode). This allowed for the synchronisation of the pressure sensors with the video recording of the tight turns (Figure 8). After the synchronisation process was completed the participants where instructed to skate and complete 4 turns on each side.

The video synchronisation was carried out perpendicular to the event. A tripod mounted digital video camera was located approximately 10 meters perpendicular to the center of the two cones allowing for minimal distortion and panning from turn to turn.

Once completed, the collection was manually halted by depressing a switch on the data logger at which point the data was uploaded to a portable laptop. (Toshiba Libretto)



a) b) c)

Figure 8: The trigger shown with the allocated pressure sensor (a & b) and when the LED lights had been lit up through depression (c).

3.7 Data processing:

After completing the data collection, the data was downloaded to a PC and exported from the FSA software to Excel (Microsoft corporation) where the non pertinent data and channels were cut from the worksheet. It was then exported into ZOO, an in house (Loh, 2005) program written with Matlab^{tm} (vrs. 12 , Mathworks, USA) that enabled a full process of steps to be undertaken from partitioning to a full statistical analysis.

The data was first cut into left and right turns, using the pressure patterns of the lateral heel sensor as a reference. Cutting in this manner was clear due to the lack of pressure before and after the turn, making cutting data simple and reproducible. The initial heel contact spike can be seen followed by a dip and then rise in pressure as the whole fool became in contact and the turn was executed. (Figure 9). This partitioning also included the addition of several markers which could later be used in the statistical analysis. The peak pressure was marked by the program and was defined as the point with the highest pressure recorded. The blade contact point was defined as the point where an increase in pressure was seen immediately after the absence of pressure, and the peak push off pressure was defined as the peak pressure prior to the pressure drop off at the end of a tight turn.

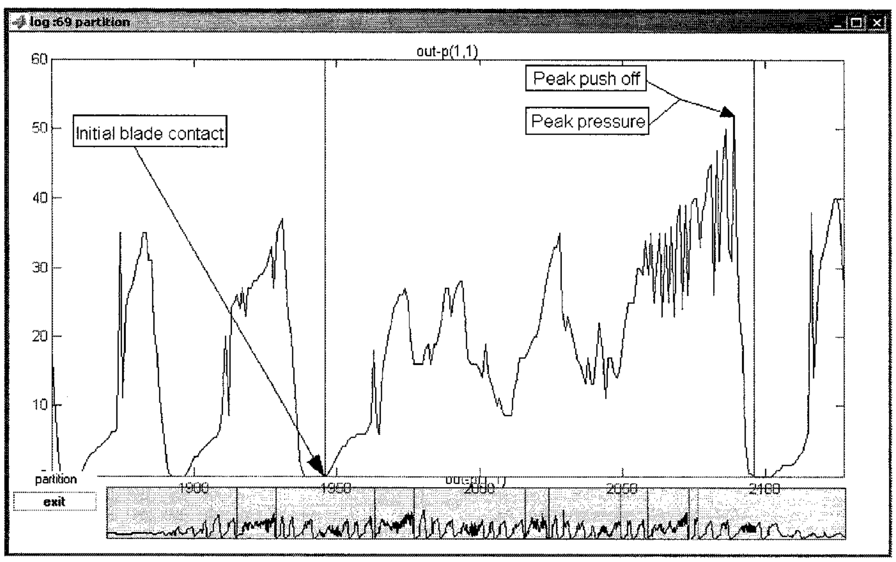


Figure 9: Partitioning in Matlabtm program Zoo. Blade contact, peak pressure and peak push off can be seen. The lower window of the screen is the overall view of eight tight turns in succession, while the main panel represents the isolation of one

Once the data had been partitioned for both the left and right hand turns it was ensembled. This process enabled all of the data in the elite and recreational groups to be averaged independently and compared. This isolation and comparison was done subsequent to delineation of the different levels of analysis in the ensembling module. Prior to cutting the data a folder tree was created in which the data was saved. This tree was integral in the final ensembling and statistical analysis (Figure 10). The Matlab[tm] software program used the listing of the different levels, found the folders with the appropriate names and extracted and averaged the associated data.

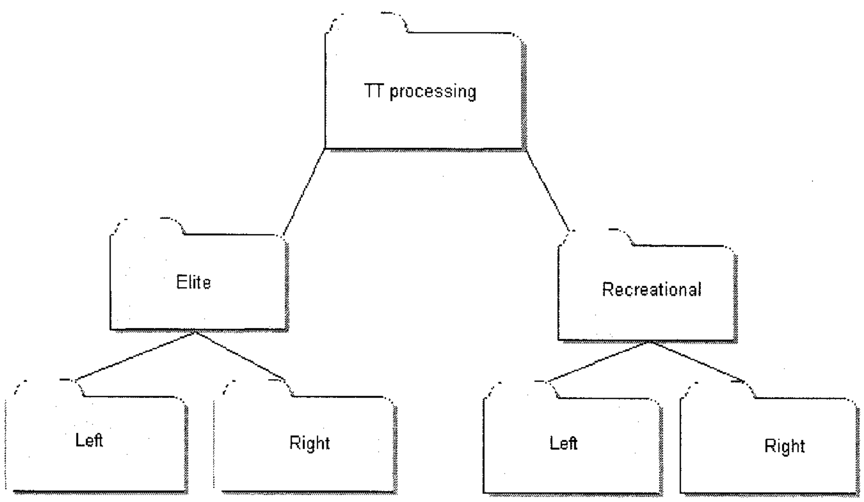


Figure 10: The data was saved in their respective folders facilitating the ensembling and statistical analysis.

Once ensembled, the statistical aspect of the program could be used, running statistical analysis of the data. These statistical analyses where run through Matlab[tm] and where included in a sub program to Zoo called So. The statistical analysis was comprised of a 2-way ANOVA followed by a *post hoc* Tukey HSD using a significance value of $p < 0.05$. Following the statistical analysis, the program created three independent folders which included the three delineated points; peak pressure, blade contact and peak push off. The folder contained the statistical data for each sensor as well as the summed sensors.

Chapter IV

Results

Participants of both elite and recreational skill levels were told to execute tight turns at a maximal velocity. The pressures were ensembled and time normalized to a 1 – 100 percentage and examined for significance at three predetermined areas of the turn's pressure profile: *blade contact/turn initiation* (BC/TI), *peak pressure* (PP) and *peak push off* (PPO). These were the three dependant variables that were examined for each condition. These areas were examined and comparisons made to inspect the differences between ability levels. These comparisons consisted of inter group analysis for the elite and recreational participants. All of these areas were examined for statistical significance, occurrence of event in the time normalized scale as well as for the true time of events. The X axis represents the time that the event occurred, the Y axis represents the magnitude of pressure at the event and the time value represents the true time in seconds that the event occurred. The pressures that were significantly different ($p \leq 0.05$) were then placed into tables to facilitate interpretation. (Table 6, Table 7 & Table 8, and Appendix B; Table 8) The tables themselves were then sub-divided in two for each parameter of investigation: inner foot and outer foot. The turn direction was the factor that dictated which foot was the inner or outer foot. When a subject completed a right hand turn, the right foot was the inner foot with the left foot being the outer foot. This was the opposite for the left hand turns. The left and right pressures were averaged as to have two values; inner and outer foot pressures for both elite and recreational participants regardless of left or right foot or turn direction.

4.1 Plantar pressures; Elite versus recreational participants

The plantar pressure area consisted of pressure collection from six sensors; medial and lateral heel, medial and lateral midfoot, and the medial and lateral forefoot (Figure 11).

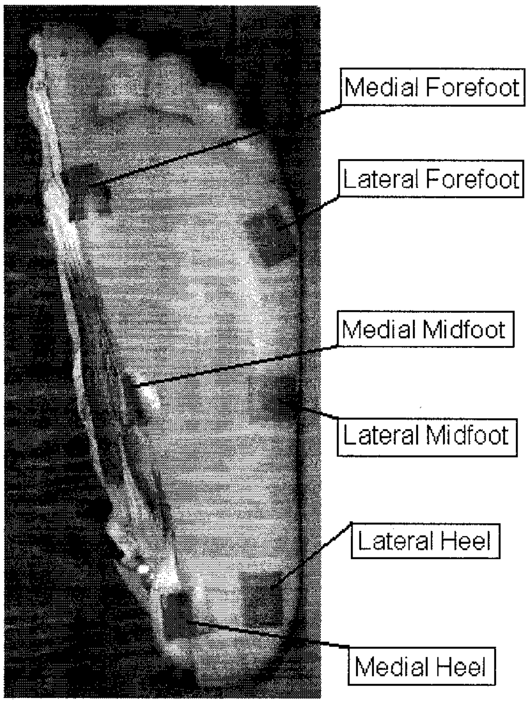


Figure 11: Plantar view of a model foot with the sensor placements of the plantar sensors; medial and lateral heel, medial and lateral midfoot, and the medial and lateral forefoot.

4.1.1 Inner and outer feet

Significant differences in the plantar area were found ($p \leq 0.05$) in the heel, midfoot and forefoot regions. This was the case for both the inner and outer foot, however, the inner foot only had higher pressures in the midfoot only whereas the outer foot had elevated pressures in all three plantar regions.

The typical breakdown for the tight turn can be seen for the medial midfoot in figure 12. The graph highlights the three areas of investigation; blade contact/turn initiation, peak pressure and peak push off. In this graph the peak pressure and peak push off are separate; however there were some points on the where PPO and PP coincided.

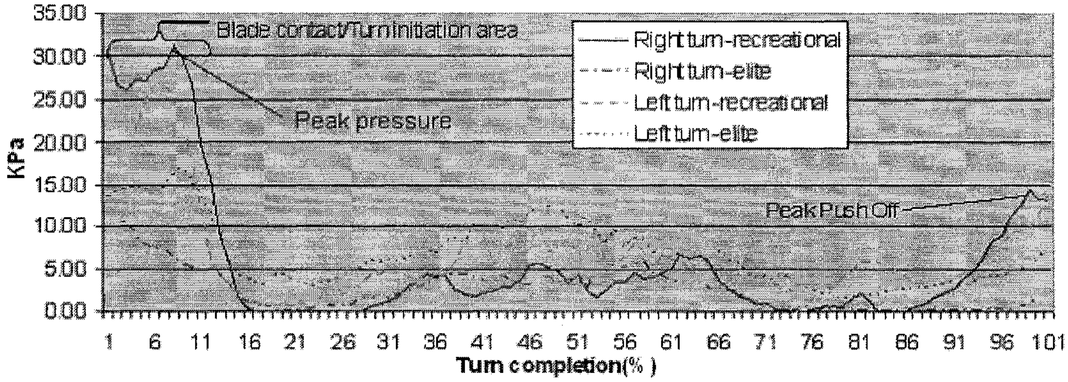


Figure 12: Medial midfoot pressure patterns of the inside foot during execution of elite and recreational participants in right and left tight turns. The points of blade contact/turn initiation, peak push off, and peak pressure are all isolated. Note the higher pressures for the recreational subject's left and right turns at both BC/TI and PPO. This can be seen during the first and last 10% of turn completion.

The areas of significance are highlighted in table form for the plantar surface. The table presents the averaged left and right turns for both inner and outer feet of the participants. All values were recorded in Kilopascals (KPa) and the displayed values in the table were significant ($p \leq 0.05$).

		Averaged right and left turns; Plantar surface			
		Inner Foot		Outer foot	
		Elite	Recreational	Elite	Recreational
Lateral Malleolus	Bc/Ti				
	Peak				
	Peak Push off				
Lateral Calcaneous	Bc/Ti				
	Peak			56.33 ± 9.69KPa ($p \leq 0.04$)*	45.82 ± 4.76 KPa ($p \leq 0.04$)*
	Peak Push off				
Lateral aspect of the 5th Tarsal-Metatarsal Joint	Bc/Ti	11.10 ± 2.67 KPa ($p \leq 0.05$)	18.65 ± 4.28KPa ($p \leq 0.05$)		
	Peak				
	Peak Push off	5.66 ± 5.56KPa ($p \leq 5.56$)	10.00 ± 2.65KPa ($p \leq 5.56$)	13.14 ± 2.27KPa ($p \leq 0.009$)	23.47 ± 7.44KPa ($p \leq 0.009$)
Lateral Midfoot	Bc/Ti			6.69 ± 1.97KPa ($p \leq 0.018$)	25.48 ± 6.90KPa ($p \leq 0.018$)
	Peak			59.89 ± 8.79KPa ($p \leq 0.007$)	82.54 ± 11.58KPa ($p \leq 0.007$)
	Peak Push off			59.89 ± 8.79KPa ($p \leq 0.007$)	82.54 ± 11.58KPa ($p \leq 0.007$)
Medial Heel	Bc/Ti				
	Peak			322.53±29.34KPa ($p \leq 0.04$)	221.95±23.00KPa ($p \leq 0.04$)
	Peak Push off				
Lateral Heel	Bc/Ti				
	Peak				
	Peak Push off				

Table 2: Areas of significance ($p \leq 0.05$) for the plantar area of the foot during turn execution by both elite and recreational participants. *Values that were representative of both the peak pressure as well as the peak push off.

In the lateral forefoot area a significantly greater pressure at PP ($p \leq 0.04$) and PPO ($p \leq 0.04$), were observed for the recreational turns when compared to the elite turns (Figure 13). The PPO occurred at 98% of turn completion and the PP at 41% turn completion for the recreational right turn and at PPO for the recreational left turns. The elite PP and PPO both occurred at push off (~98%) turn completion.

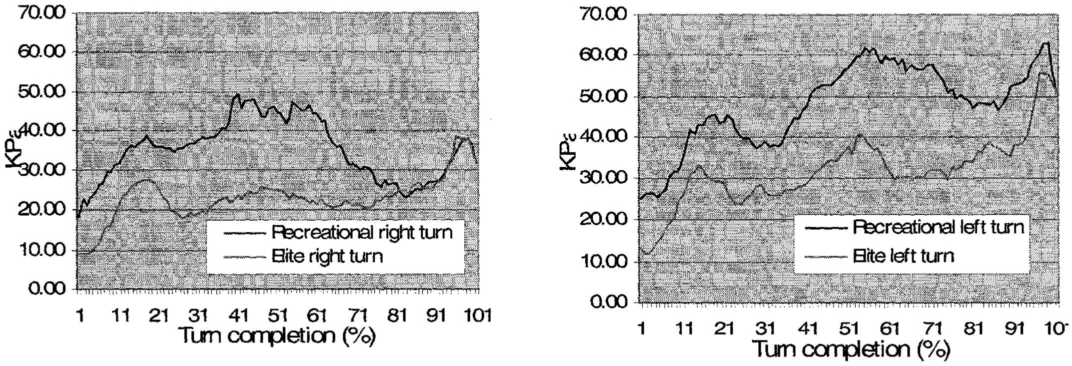


Figure 13: Lateral forefoot area of the outer foot with respect to elite and recreational right and left turns. Note the higher peaks for the recreational participants' pressure profile for both left and right turns when contrasted with the elite's.

The patterns of pressure generation for the inner foot (Figure 14) were more similar than the outer (Figure 15), with both elite and recreational subjects having the same patterns for all sensors. This pattern consisted of a large peak in the middle of the turn completion, paired with pressure drops before and after, at 20 and 80% respectively, turn completion. Although the medial forefoot sensors for the elite subjects had the same patterns as the recreational subjects during the right turn, the left turn showed some differences.

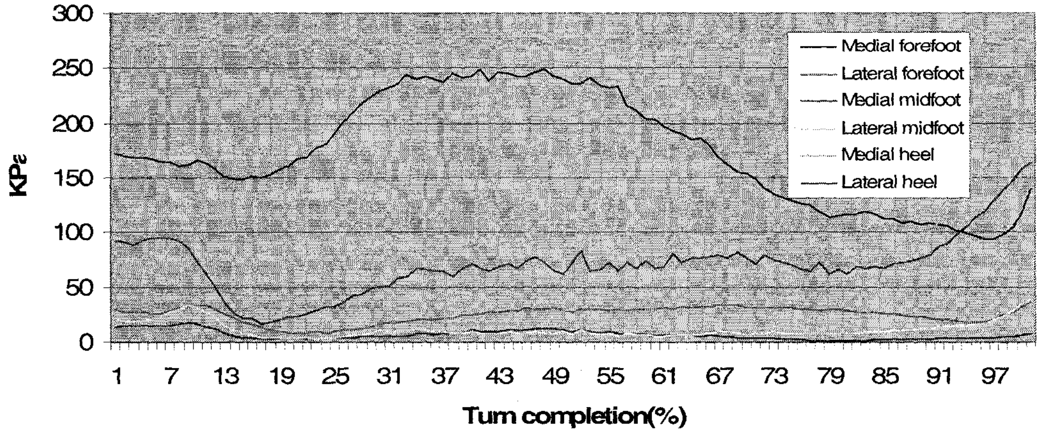


Figure 14: Plantar pressures of the inner foot of an elite left turn. Note the higher pressure profile when compared with the recreational data (Figure 15) although the general pattern of a pressure dip at 20% of turn completion, followed by a rise in the mid portion.

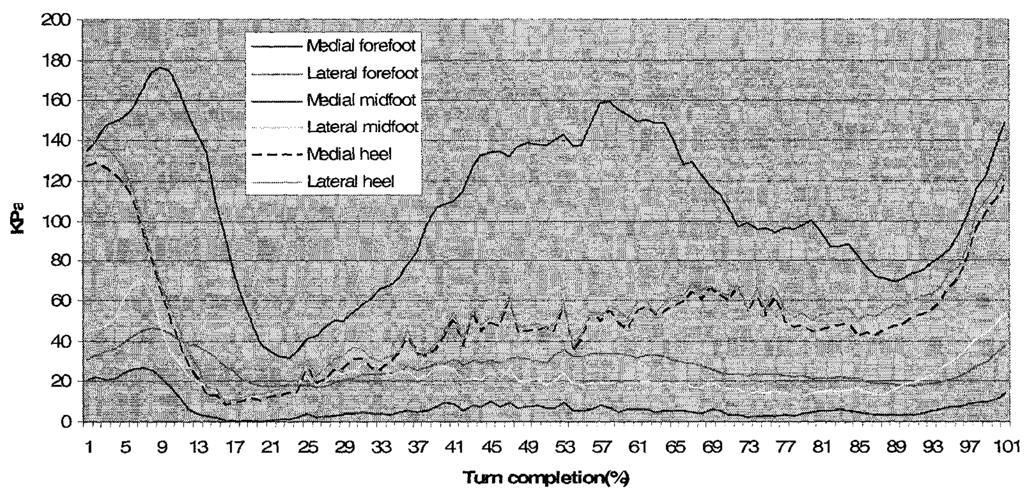


Figure 15: Plantar pressures of the inner foot during a recreational left turn. Note the similar trend of a high pressure pattern for the medial midfoot which can also be seen in the elite trials.

When all the plantar pressure sensors were observed together general trends could be seen. The inner foot had a bimodal pressure pattern and the outer foot had a continually escalating pressure profile (Figure 16 & Figure 17).

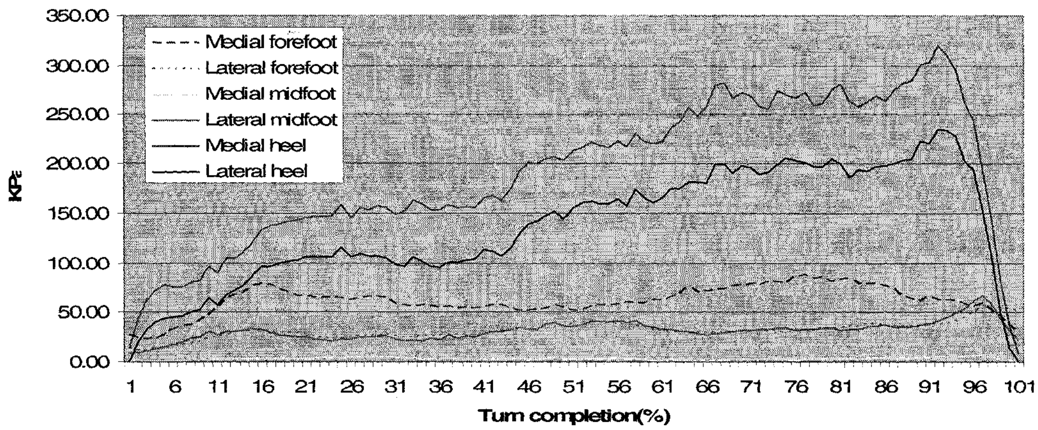


Figure 16: The outer foot's plantar pressures of an elite left turn. Note the escalating pressure pattern for the heel sensors.

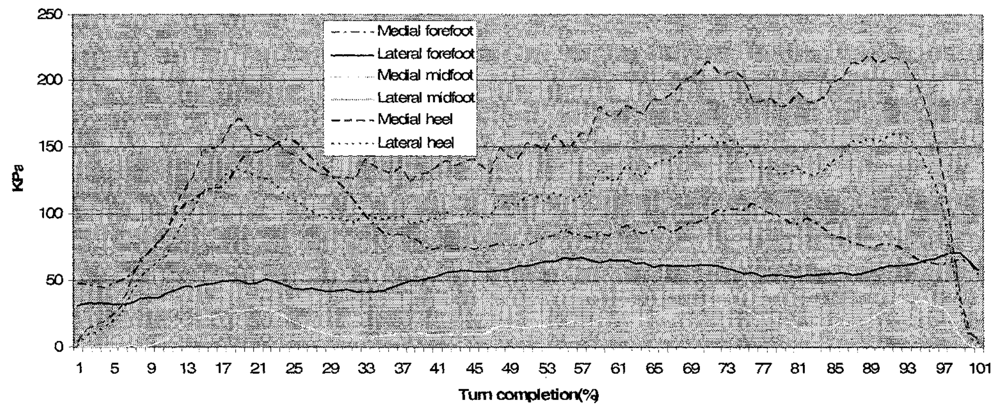


Figure 17: The outer foot's plantar pressures of a recreational left turn. Note the bimodal nature of the peaks in the heel pressure patterns.

4.2 Lateral pressures

4.2.1 Inner and outer feet

The lateral portion of the foot consisted of three points of pressure measurement; the lateral calcaneous, lateral malleolus and the lateral aspect of the 5^{th} tarsal-metatarsal joint. (Figure 18) Although there were no recorded statistical significances ($p \geq 0.05$) for the lateral malleolus of the inner foot, the lateral calcaneous and the lateral aspect of the 5^{th} tarsal-metatarsal joint of the inner foot reached statistical significance for BC/TI, PP, and PPO ($p \leq 0.05$).

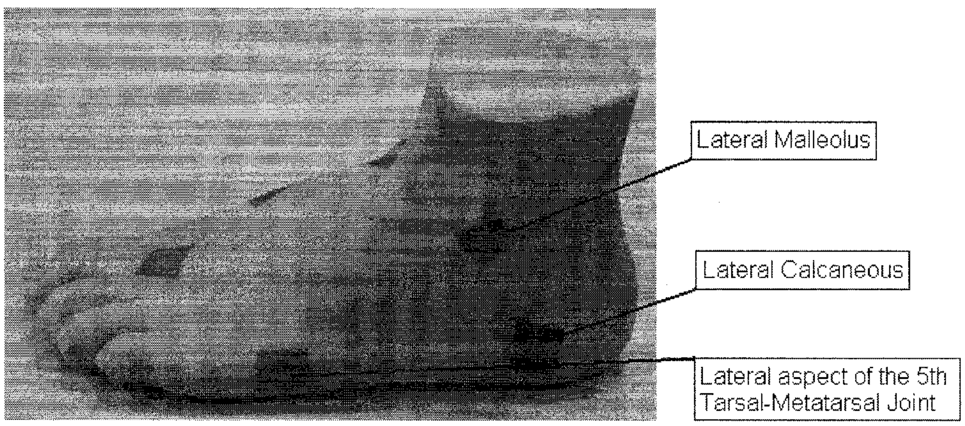


Figure 18: Lateral aspect of the foot, showing the three areas of pressure data collection; the lateral calcaneous, lateral malleolus, and the lateral aspect of the 5th tarsal-metatarsal joint.

The points of significance for the lateral aspects of the foot were placed in table format (Table 3) and were found in all areas of the lateral surface. As with the plantar surface, more significant differences in pressure generation were noted on the outer foot than the inner foot.

		Averaged right and left turns; Lateral surface			
		Inner Foot		Outer foot	
		Elite	Recreational	Elite	Recreational
Lateral Malleolus	Bc/Ti				
	Peak			108.77 ± 22.2KPa ($p \leq 0.004$)	37.37 ± 8.31KPa ($p \leq 0.004$)
	Peak Push off				
Lateral Calcaneous	Bc/Ti	40.96 ± 11.31KPa ($p \leq 0.009$)	2.27 ± 0.25KPa ($p \leq 0.009$)		
	Peak	98.19 ± 23.41KPa ($p \leq 0.016$)*	13.72 ± 7.03KPa ($p \leq 0.016$)*	72.47 ± 17.03KPa ($p \leq 0.008$)	10.21 ± 4.0KPa ($p \leq 0.008$)
	Peak Push off			53.20 ± 10.93KPa ($p \leq 0.016$)	2.90 ± 1.66KPa ($p \leq 0.016$)
Lateral aspect of the 5th Tarsal-Metatarsal Joint	Bc/Ti				
	Peak	14.21 ± 1.38KPa ($p \leq 0.02$)*	7.39 ± 1.06KPa ($p \leq 0.02$)*	72.02 ± 9.14KPa ($p \leq 0.0007$)	54.88 ± 8.93KPa ($p \leq 0.0007$)
	Peak Push off			70.64 ± 7.10KPa ($p \leq 0.05$)	25.72 ± 4.73KPa ($p \leq 0.05$)

Table 3: Areas of significance ($p \leq 0.05$) for the lateral area of the foot during turn execution by both elite and recreational participants. *Values that were representative of both the peak pressure and the peak push off.

The PP in the lateral calcaneous was different between elite and recreational and was also different when turn direction was considered ($p \leq 0.02$) (Figure 19). Consistently higher pressures throughout the tight turn were achieved by the elite participants compared to the recreational participants, who had expected minimal pressures throughout the turn in the lateral calcaneous.

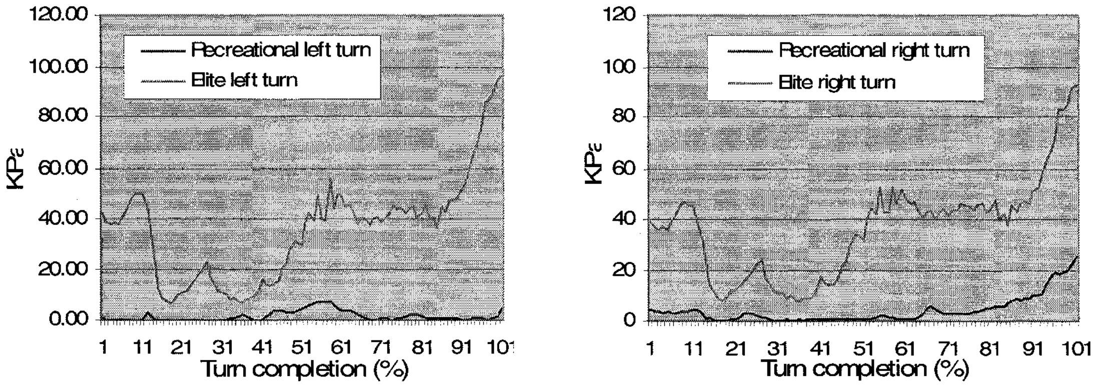


Figure 19: Lateral calcaneous of the inner foot during elite and recreational right and left turns. Note the higher pressure profiles for both left and right elite turns when compared with the recreationals. This is most prevalent at the initiation and termination of the tight turn and is indicative of their increased levering of the skate boot.

4.3 Medial pressures

The medial aspect of the foot was evaluated by examining pressures at three points; the medial calcaneous, the medial malleolus and the medial aspect of the 1st metatarsal-phalangeal joint (Figure 20).

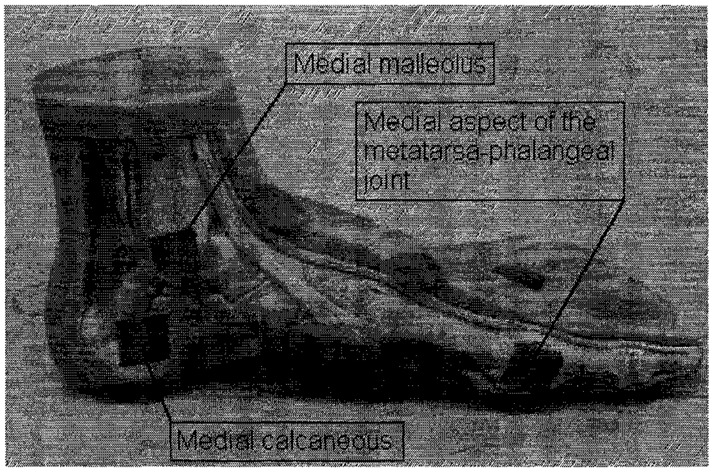


Figure 20: Medial aspect of the foot showing the three areas of pressure data collection; the medial malleolus, medial calcaneous, and the medial aspect of the 1st metatarsal-phalangeal joint.

4.3.1 Inner and outer feet

The significant ($p \leq 0.05$) data were pooled into table form for the medial aspect of the foot and showed areas of significance (Table 4).

		Averaged right and left turns; Medial area			
		Inner Foot		Outer foot	
		Elite	Recreational	Elite	Recreational
Medial Malleolus	Bc/Ti	172.23 ± 23.58KPa ($p \leq 0.04$)	116.01 ± 26.44KPa ($p \leq 0.04$)		
	Peak				
	Peak Push off				
Medial Calcaneous	Bc/Ti				
	Peak				
	Peak Push off				
Medial aspect of the metatarsal-phalangeal joint	Bc/Ti				
	Peak				
	Peak Push off				

Table 4: Areas of significance ($p \leq 0.05$) for the medial area of the foot during turn execution by both elite and recreational participants.

The PP for the medial metatarsal-phalangeal joint of the inner foot occurred at significantly different points for the elite and recreational participants ($p \leq 0.04$). The elite left turn incurred a PP at 8% of turn completion and the recreational PP occurred at 12% turn completion, compared with the right turn where the PP was at 67% of turn completion for the elite participants and 62% for the recreational participants (Figure 21).

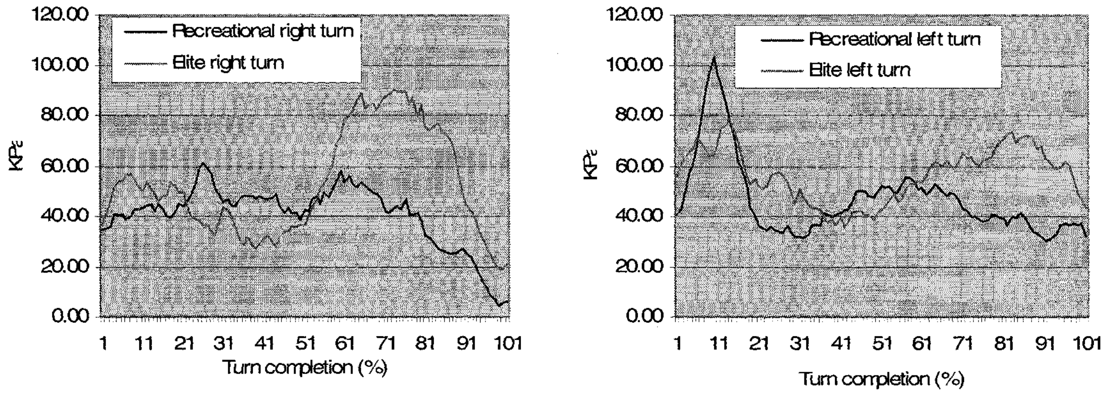


Figure 21: Medial metatarsal-phalangeal joint of the inner foot during elite and recreational right and left turns. Note the PP occurring in the first 20% of the turn completion for the left turn and at approximately 65% for the right turn.

The PP for the elite right turns was 127.56KPa ± 19.44KPa for the medial calcaneous and the respective recreational right turn PP was 54.95KPa ± 9.45KPa (Figure 22). These were both greater than the left turn's PP values, where the elite participants generated 28.34KPa ± 8.96KPa and the recreational participants reached a PP of 14.34KPa ± 5.10KPa. The difference between right and left turns was significant ($p \leq 0.0006$) in both groups.

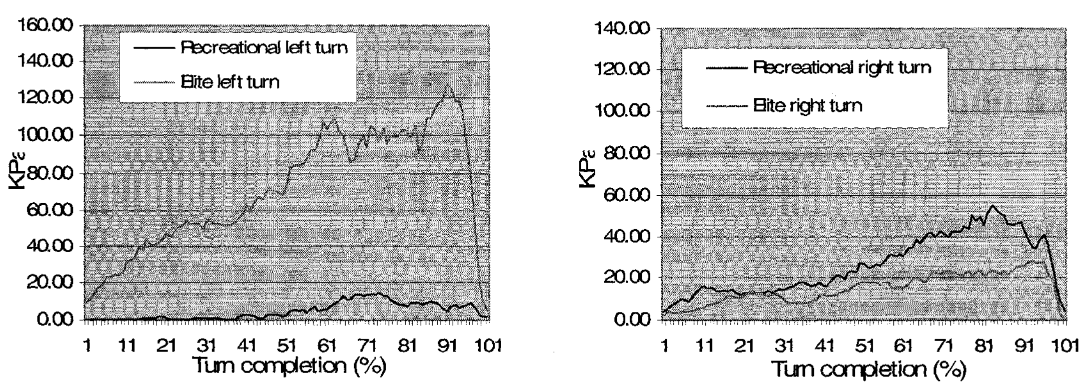


Figure 22: Medial calcaneous pressure profiles of the outer foot during elite and recreational right and left turns. Note the double peak for the elite right turn with the PP at 90% turn completion whereas the recreational PP was at ~76% completion.

The timing of the PP for the medial calcaneous was significantly different ($p \leq 0.03$) with the elite participants PP occurring at 9 and 18% turn completion for left and right turns, respectively while the recreational participants incurred PP occurred at 59 and 60% turn completion, respectively. (Figure 23)

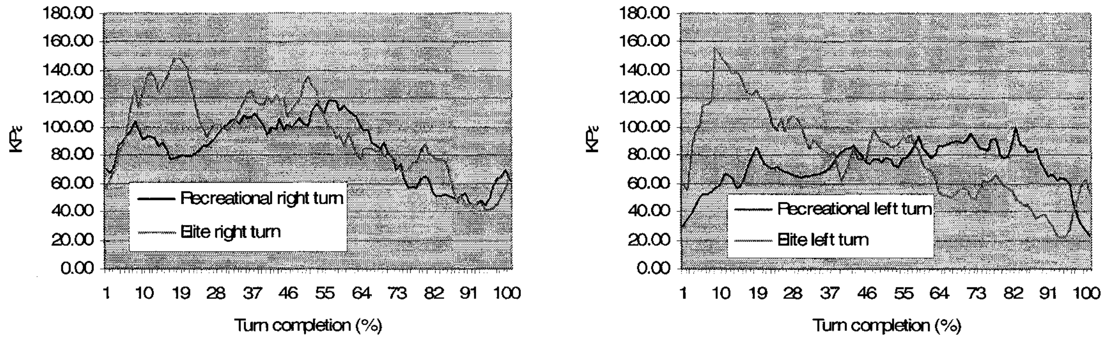


Figure 23: Medial malleolus pressure profiles of the outer foot during elite and recreational right and left turns. Note the peak pressure for both left and right elite turns at 9 and 18% turn completion while the recreational participants peaked at 59 and 60% turn completion for the left and right turns, respectively.

4.4 Dorsal pressures

The pressure data collection for the dorsal aspect of the foot was made up of three areas; the dorsal aspect of the talo-crural joint, the 1st tarsal-metatarsal joint and the metatarsal-phalangeal joint (Figure 24)

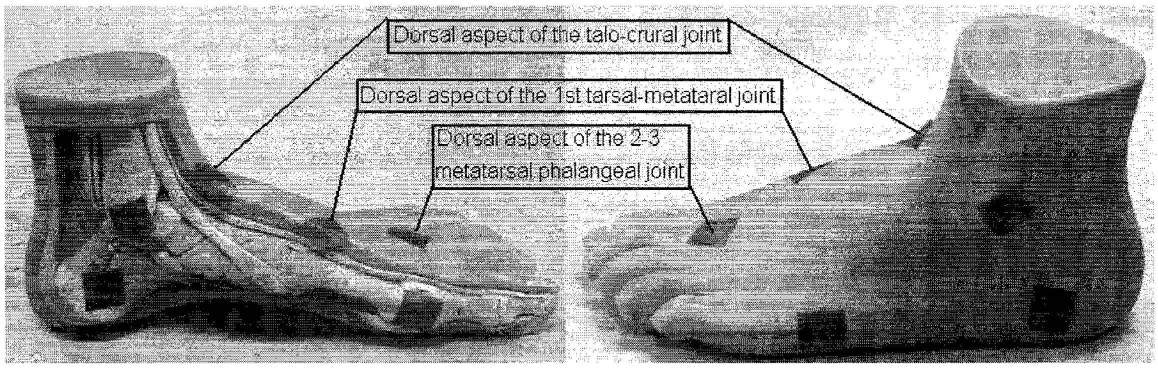


Figure 24: Dorsal aspect of the foot showing the three areas of pressure data collection; the dorsal aspect of the talo-crural joint, the 1st tarsal-metatarsal joint and the metatarsal-phalangeal joint.

4.4.1 Inner and outer feet

Due to the consistently low pressures that occurred in the dorsal area of the foot during tight turn execution, no differences were seen ($p \geq 0.05$) between elite and recreational participants on the dorsal area of the inner foot during tight turn execution.

The outer foot PP and PPO at the dorsal aspect of the 1st tarsal-metatarsal joint of the recreational participants were significantly greater than the PP and PPO of the elite participants' tight turns. This can be seen in table 5 where the values are presented.

		Averaged right and left turns; Dorsal area			
		Inner Foot		Outer foot	
		Elite	Recreational	Elite	Recreational
Dorsal aspect of the talo-crural joint	Bc/Ti				
	Peak				
	Peak Push off				
Dorsal aspect of the 1st tarsal-metatarsal joint	Bc/Ti				
	Peak			36.17 ± 6.41KPa ($p \leq 0.024$)	63.71 ± 15.24KPa ($p \leq 0.024$)
	Peak Push off			36.17 ± 6.41KPa ($p \leq 0.05$)	52.97 ± 9.97KPa ($p \leq 0.05$)
Dorsal aspect of the 2-3 metatarsal phalangeal joint	Bc/Ti				
	Peak				
	Peak Push off				

Table 5: Areas of significance ($p \leq 0.05$) for the dorsal area of the foot during turn execution by both elite and recreational participants.

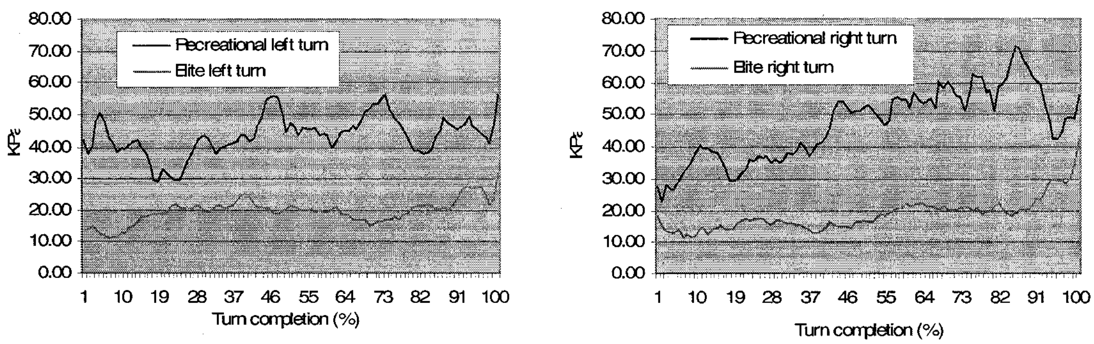


Figure 25: Dorsal aspect of the tarsal-metatarsal joint of the outside foot during elite and recreational right and left turns. Note the higher pressure profiles for the left and right recreational turns when compared with the left and right turn profiles. This was statistically significant for the PP and the PPO, seen in the later part of the turn completion ($p \leq 0.05$).

No other differences were found in the dorsal sensors during tight turn execution.

Chapter V

Discussion

Through the collection and evaluation of foot pressure data, the events of an ice hockey tight turn were quantified and differences between elite and recreational participants were measured. The pressure readings were taken from simultaneous left and right foot recordings using pressure sensors located at specific anatomical locations.

The fifteen piezo resistive sensors on each foot and ankle were successfully used to quantify the pressures exerted in the different areas of the foot during the execution of both left and right tight turns. The pressure data from the four main areas of collection; plantar, lateral, medial and, dorsal, were sufficient to create a general image of the pressure patterns of the foot and ankle during the tight turn execution. In general the pressure patterns observed in the elite and recreational participants imply the prominent use of leveraging of the foot and ankle by the elite participants compared with the recreationals who had concentrated loading on the plantar area of the feet. This edging is comparable to the edging angle seen in skiing, defined as the angle between the ski to the center of mass of the skier with the normal of the surface of the ski slope (Jentschura et al., 2004).

It seems reasonable to assume that with adequate ice hockey training elite athletes learn to use the hockey boot to their advantage in supporting themselves during the execution of a tight turn. This is shown with the higher pressure profiles found on both medial and lateral sides of the foot suggesting use of the medial and lateral aspects of the skate to direct the skate boot. This was seen on both feet for both turn directions and could therefore lead to the inference that higher skill level is paired with the ability to reproduce a movement pattern and to be able to perform in this manner in both the left and right turns.

The augmented medial and lateral pressures could be paired with previous research. Ski research has looked at the carving aspect of alpine skiing focusing on the lean angles of the ski. The areas investigated showed that the navigable turn radius is a direct function of the ski waist, on edge angle, and ski flexion (Muller et al., 2003). Since a skate blade has minimal if any flexion and no waist, the variable that coincides with the present study is the on edge angle. These on edge angles can be seen in the video investigation and pair with the augmented medial-Lateral pressures.

5.1 Pressure patterns

Differences in pressure patterns between the elite and recreational participants showed increased outer foot loading by the recreational participants when compared with the patterns of the elite participants. This could be interpreted as a lack of balance or simply poorer turn execution by the recreational participants although it pairs with Muller's ski research which shows that during the steering phase, the greatest load is found on the outer ski, with a maximum of 180% load during the final steering phase(Muller et al., 2003). The attribution of higher skill with an outer weighting of a ski seems to therefore be paradoxical when compared with skating, which showed a higher outside weighting for the recreational participants. The nature of the turns in both cases are different, with the ski turn being a little less drastic in essence when compared with the rapid change of direction in a hockey tight turn.

There was a general non uniformity in the recreational data which was most likely attributed to the larger range of skill levels found in the recreational participant group. The elite participants were closely paired in their respective skill levels which were confirmed visually with video investigation in contrast to the recreational participants where a variance in skill was apparent. The videos show that different techniques and skill levels exist.

This heightened control of the skate boot can be linked to the much greater experience and skill level of the elite participants. The elite participants follow an intense and regimented training and game schedule leading to increased skill refinement. These data also show where and what a refined training program leads to with regards to turning dynamics.

5.2.1 Plantar pressures

There were many areas of similarity in pressure patterns but considerable differences in pressure magnitudes for the two subject groups with respect to plantar pressures. On the outer foot, the pressures of the medial midfoot sensor were considerably lower than the pressures recorded in other plantar sensors for both elite and recreational subject groups (Figure 12).

The medial midfoot pressures are highly susceptible to anatomical features of the foot, as noted by Morag and Cavanagh (Morag, 1999). The structure of the foot has been identified as the most important factor determining plantar pressure (Morag and Cavanagh 1999). It should be expected that an athlete with a high arch would have lower pressures in the medial midfoot when compared with an individual with a flat foot. Thus pressures measured with this sensor are open to interpretation. Although there were often areas of statistical significance ($p \leq 0.05$) in this area of the plantar surface of the foot, the question arises as to what mechanisms accounted for these differences. It is likely that differences were due to technique in turn execution but they could also be due to anatomical differences. In retrospect, measurement of the subject's arch height would have been a valuable measure to aid in the interpretation of the data collected for this sensor.

The medial and lateral heel data were the areas of highest plantar pressure, suggesting that these areas served as a pivot point for tight turn execution. An extreme example of this is seen during the turn execution by one recreational athlete (Figure 26).

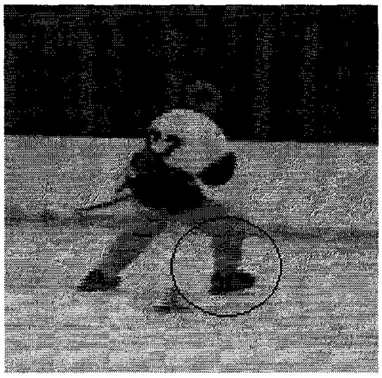


Figure 26: A recreational subject performing a right tight turn. Note the contact area is solely on the heel of the inside foot.

It was hypothesized that the elite inner and outer feet would display similar pressure profiles. This was not the case however, since the inner foot had a bimodal pressure pattern and the outer foot had a continually escalating pressure profile (Figure 16 & Figure 17)

The plantar pressure pattern between subject groups was also different. The elite participants showed a continually escalating trend (Figure 16) and the recreational participants had a double peaked pattern (Figure 17), starting at 15% turn completion followed by a dip in pressures and a new escalation of pressure again at 70% of turn completion.

Although it was hypothesized that the inner foot would have a higher plantar pressure profile than that of the outer, the results were opposite. Both elite and recreational groups had higher plantar pressure profiles for their outer feet in both turn directions. Upon investigation of the pressure data and the video images, it could be seen that, in extreme cases, some of the recreational participants carried out a majority of the turn solely on the outer foot with the inner foot skipping on and off the ice. This proved to be in agreement with the ski research performed by Muller stating that the outer ski was loaded to the greatest extent (Muller et al., 2003) when compared with the inner ski. This was the opposite to curved walking research which showed an increase in inner weighting which aided in the continuity of motor performance (Courtine et al., 2003). This is not necessarily related as the dynamics of a walked turn and those of a turn executed along a carving edge are different in nature, with the walking turn being done slower than the skating or skiing turn. Along with different velocities, the dynamics of turning on an edge is not the same as turning while wearing shoes.

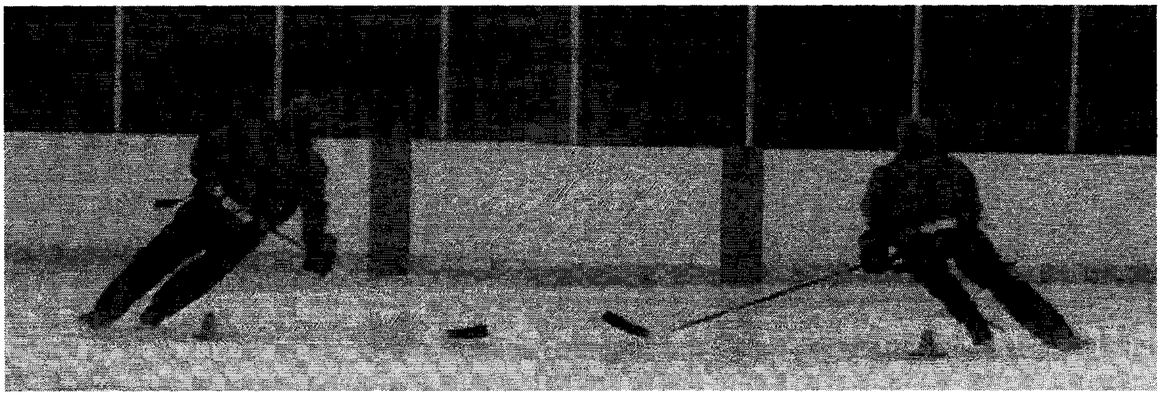


Figure 27: A high level recreational subject performing both left and right turns. Note the uniform position when turning right and the more vertical nature of the subject's inner foot during the left turn. This is paired with the left and right feet differing in their respective paths.

The hypothesis that the elite participants would complete the tight turn with a tighter radius than the recreational participants was validated visually through video investigation. Although there were no quantifiable data to substantiate this statement, visual observations showed a clear difference between the two subject groups. Through the viewing of the videos correlated with the pressure data, it was seen that the elite participants reached a greater lean angle, both with their body as well as their skate bald angle. This is a factor in the determination of the magnitude of the turn radius. Jentschura states that with carving skis the steering angle automatically becomes large when the tilt angle increases, all contributing to a smaller radius of curvature (Jentschura et al., 2004).

One recreational subject did complete the tight turn in a tight radius but did so using a stopping motion rather than a turning motion. This was the only subject who used this approach and it seemed to create a much slower exit speed than the rest of the participants, although the subject had an increased level of stability compared to other recreational participants. The nature of a skidded turn has been addressed stating that the skidded turn is slower in nature due to the inherent frictional forces working against the maintenance of turn velocity (Jentschura et al., 2004). This was also addressed by Muller where edging angle was proposed as a method of skid prevention leading to the conclusion that the experienced skier was able to create a larger edging angle than those of the recreationals ($p \leq 0.05$) (Muller et al., 1998). In Jentschura's the edging angle of the ski was noted to range between 60 and 80 degrees (Jentschura et al., 2004).

The ability to maintain a more central pressure profile in the medial lateral plane suggests that there is a more even pressure distribution in this area. This could lead to increased control as well as lower net pressures on any given area of the foot. The higher plantar pressures in the heel sensors that the elite participants' heel sensors experienced compared to the recreational participants' heel sensor pressures can be explained by the tighter turn radius in the elite participants. This was visible in video viewing and can be paired with equation 1:

$$a = \frac{v2}{R'}$$

By decreasing the radius the acceleration increases, increasing force and thus higher pressures. This can be seen with the higher recorded pressures of the elite participants.

Although there is no previously described literature with regards to the pressure analysis of the whole foot during tight turns, literature describing similar movement patterns in soccer currently exists. Eils et al describe (Eils, 2004) the comparison of running and cutting in soccer, looking at the plantar pressures. The medial hallux, forefoot, midfoot, heel and lateral heel all had significant increases in pressure when cutting compared to running data, which is similar to some of the findings in this study.

However, the running data was averaged for the event as well as for inner and outer feet, giving a very brief image of what is occurring. With this in mind, there are similarities in the pressure increases of on land and on ice sudden changes in direction when looking at the plantar pressures.

5.2.2 Lateral pressures

The lateral surface of the feet seemed to show that the elite participants utilized lateral leverage of their inner foot more than the recreational participants. This was shown with consistently greater pressure patterns on the lateral part of the foot during turn execution than the recreational participants (Figure 19) ($p \leq 0.05$).

The greater lateral pressures for both inner and outer feet could be linked to the elite participants' ability to fully utilize the skate boot to their benefit during a tight turn. This is hypothesized to be the result of increased lower limb leverage or through an increased amount of lean, both of which could generate increased pressures and decrease turn radius. The amount of lean has been paired with maintenance of balance, shown in walking trials following a curved path (Courtine et al., 2003, Courtine et al., 2004). This lean can be linked to the regulation of the center of mass which has been shown to be a key strategy in the control of locomotion (Moritz et al., 2004). This control of the center of mass distribution with respect to direction and stance would lead to the inferable link between center of mass being a regulated aspect by the central nervous system (Henry et al., 2001). This leads to the furthering of potential depth in the study of hockey skills. The dynamics of a skill is only the end result of a myriad of sequences beginning with afferent information to the central nervous system.

Figure 28: Elite and recreational participants executing a right turn. Note the elite subject (lower individual) and the sharper blade angle of his skates when compared with the more vertical recreational subject's skates.

5.2.3 Medial pressures

The medial and lateral aspects of the foot were most similar during right and left turns, where the elite participants generated greater pressures than those of the recreational participants($p \leq 0.05$), especially at the medial malleolus(Figure 23) as well as the medial calcaneous sensor of the outer foot (Figure 22), with the peak point being approximately 100 KPa greater for the elite participants than that of the recreational participants($p \leq 0.05$) . However, the medial calcaneous only increased in pressure for the elite participants during the left turn and not the right. This should not have happened if the turns were being executed in the same manner due to the manner that the feet were classified: inside and outside feet.

The increased pressures of the medial and lateral aspects of the foot may have arisen because elite participants likely utilize the medial and lateral parts of the skate boot in the turn to a greater degree than the recreational participants. These differences between the inner and outer feet are in agreement with the findings of Courtine et al. stating that the left and right feet behaved differently when walking along a curved path (Courtine et al., 2003).

It was hypothesized that the elite participants' medial malleolus sensor would have more pressure at the turn's initiation and that the pressure would then shift to the lateral malleolus as the turn was completed. The pressure data did not substantiate this hypothesis since there were no discernable pressure patterns seen on this pressure sensor during the execution of the tight turn.

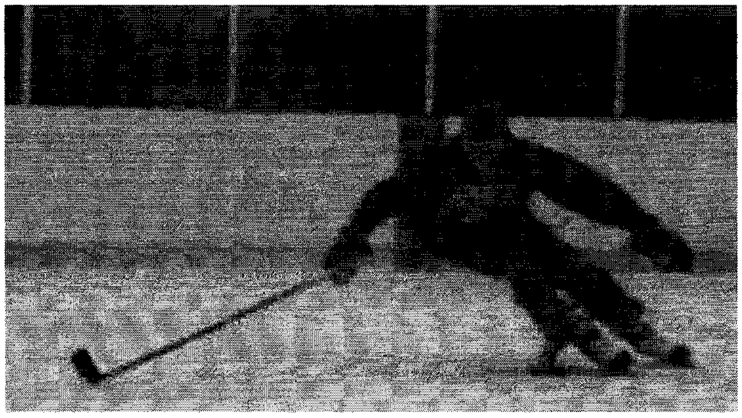


Figure 29: An elite subject executing a right tight turn. Note the steep lean angle of both feet, putting pressure on the medial and lateral aspects of both feet.

5.2.4 Dorsal pressures

On the dorsal aspect of the foot there was a general lack of differences in pressure patterns which were likely due to the minimal amounts of pressure in most of the sensors in this area of the foot. The dorsal aspect of the talo-crural joint and the metatarsal-phalangeal joint were not significantly different ($p \geq 0.05$) whereas the 1st tarsal-metatarsal joint was different ($p \leq 0.05$) when comparing the pressure magnitudes of elite participants with those of the recreational participants for peak pressure, peak push off as well as blade contact/turn initiation. These results showed the recreational participants attaining consistently higher pressure values than those of the elite participants. Some research has shown that there are anterior postural shifts when attempting to counteract any perturbations to balance (Sinha and Maki 1996). Previous research has shown that participants going through anterior posterior shifts leaned forward, with a higher amount of lean correlating with a higher level of disturbance to their positioning (Sinha and Maki 1996). These anterior shifts are brought about through ankle flexion, which in a skate boot would be seen as increased pressure profiles of the anterior portion of the ankle. Thus more pressure would have been seen in this area during the tight turn if there was a flexion based attempt at balance control. The higher pressure noted in this area for the recreational participants strengthens the notion of better balance and control executed by elite participants. With the added control in turns of the elite participants, there is a decreased need to struggle for balance, and therefore resulting in a decrease in the dorsal pressures.

Chapter VI

Future considerations

Although measuring the pressures generated during the execution of an ice hockey tight turn is novel, there are other means of recording data that could aid in the establishment of a clearer picture of the biomechanics of tight turn execution. Although the skate boot is a tight fitting piece of footwear, there are most likely shear forces being generated which cannot be measured with the currently used piezo resistive sensors which solely measure the forces normal to the area of collection. For this reason, it would be beneficial to pursue further pressure research with sensors that would enable a more complete pressure data collection profile including shear forces.

The ankle movement that is incurred during the turn as well as the muscular forces generated to create this movement should also be measured. Collecting electromyographical (EMG) data for the muscles used during the tight turn would lead to further differentiation between the elite and recreational subject groups further deepening our understanding of the characteristics of a well executed tight turn. Ankle movement could be tracked using goniometers, measuring both inversion-eversion and dorsi-plantar flexion of the foot. Through the combination of pressure, shear forces, EMG, and ankle kinetics, a precise image of the characteristics utilized in tight turn execution could be determined, creating a clearer image of the biomechanics of the tight turn execution.

Conclusion

In conclusion, this study has described pressure generation patterns for the first time in ice hockey tight turns. The data has led to the quantification of pressure patterns at the skate boot/foot interface. Pressure patterns measured in this study have shown that recreational participants are different from elite participants, with the elite participants by and large generating higher pressures, medially and laterally which was likely due to an increased leveraging of the skate boot causing a higher blade angle which generated a tighter turn radius with higher turn entry and exit speeds.

The elite participants utilize the full skate boot and therefore presumably distribute foot pressure through the medial, lateral, dorsal and plantar surfaces when compared to the recreational participants who tended to maintain the majority of their foot pressure on the plantar area of the foot, which can be seen with their higher plantar pressures when compared with the elite participants. The elite participants were also able to distribute their total pressures over both feet to a greater extent whereas the recreational participants tended to load their outer foot to a greater extent.

The elite participants proved to have greater control of the skate boot and used both skates to a seemingly increased potential, whereas the recreational participants struggled with clean execution therefore generating pressure points and imbalanced pressure patterns throughout the foot.

These data show that in the coaching realm it could be beneficial to instruct players to use the leveraging process during turn initiation, thereby decreasing plantar pressures through a greater distribution of pressure throughout the foot and ankle area. This could help players develop a more efficient turning dynamic and prepare them for a higher level of play. Drills could be run fine tuning the edge control of the skater. Since the tight turn is an integral aspect in the game of hockey (Pike, 2002) it could be speculated that by bettering a player's turn ability would thereby better the player as a whole. Coaches could focus on sensory based drills getting the players to focus on using the whole skate boot. This could be followed with turning drills and more specific isolation drills.

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Appendix B

Summary table of significances: blade contact/turn initiation.

Sensor Position Inner Foot	Log name	Ability X, Y, or T	Direction X, Y, or T	Ability & Dir	Right turn	Left turn	Elite R vs. L	Recreational R vs. L
1 Lat heel	p(1,1)							
2 Med. Heel	p(1,2)							
3 Lat Mid-foot	p(2,1)							
4 Med Mid-foot	p(2,2)	Y						
5 5th met-phal jt	p(3,1)							
6 1st meta-phal jt	p(3,2)							
7 Calcaneous	m(cal)							
8 Med Mal	m(mal)							
9 Meta-phal jt	m(1st)							
10 Talo-crural jt	d(1)							
11 1st Tarso-meta jt	d(2)							
12 2-3 meta-phal jt	d(3)							
13 Calcaneous	l(cal)	Y						
14 Mal	l(mal)							
15 5th tarso-meta jt	l(5th)							

N.B. For right turns, the inside foot is the right foot
-For left turns, the inside foot is the left foot
-X represents the X axis, which denotes time and the occurrence of the peak value, along that axis.
-Y represents the Y axis, which denotes the magnitude of the pressure value in question.
-T represents the time in relation to the event.

Sensor Position Outer Foot	Log name	Ability X, Y, or T	Direction X, Y, or T	Ability & Dir	Elite Vs. Recreational Right turn	Left turn	Elite R vs. L	Recreational R vs. L
1 Lat heel	p(1,1)							
2 Med. Heel	p(1,2)							
3 Lat Mid-foot	p(2,1)	Y						
4 Med Mid-foot	p(2,2)							
5 5th met-phal jt	p(3,1)							
6 1st meta-phal jt	p(3,2)							
7 Calcaneous	m(cal)							
8 Med Mal	m(mal)							
9 Meta-phal jt	m(1st)							
10 Talo-crural jt	d(1)							
11 1st Tarso-meta jt	d(2)							
12 2-3 meta-phal jt	d(3)							
13 Calcaneous	l(cal)							
14 Mal	l(mal)							
15 5th tarso-meta jt	l(5th)							

N.B. For right turns, the outside foot is the left foot
-For left turns, the outside foot is the right foot
-X represents the X axis, which denotes time and the occurrence of the peak value, along that axis.
-Y represents the Y axis, which denotes the magnitude of the pressure value in question.
-T represents the time in relation to the event.

Table 6: The areas of statistical significance for the perios of blade contact/turn initiation.

Summary table of significances: peak pressure.

Statistical Summary Table

Sensor Position	Log name	Ability X, Y, or T	Direction X, Y, or T	Ability & Dir	Elite Vs. Recreational Right turn	Elite Vs. Recreational Left turn	Elite R vs. L	Recreational R vs. L
Inner Foot								
1 Lat heel	p(1,1)					T	T	
2 Med. Heel	p(1,2)					T	T	
3 Lat Mid-foot	p(2,1)					T		T
4 Med Mid-foot	p(2,2)					T		T
5 5th met-phal jt	p(3,1)						T	T
6 1st meta-phal jt	p(3,2)		T, X					
7 Calcaneous	m(cal)		Y		T			
8 Med Mal	m(mal)	Y						
9 Meta-phal jt	m(1st)	X						
10 Talo-crural jt	d(1)						T	
11 1st Tarso-meta jt	d(2)							
12 2-3 meta-phal jt	d(3)							
13 Calcaneous	l(cal)	Y		X				
14 Mal	l(mal)				T			
15 5th tarso-meta jt	l(5th)	Y						

N.B. For right turns, the inside foot is the right foot
-For left turns, the inside foot is the left foot
-X represents the X axis, which denotes time and the occurrence of the peak value, along that axis.
-Y represents the Y axis, which denotes the magnitude of the pressure value in question.
-T represents the time relation of the event.

Sensor Position	Log name	Ability X, Y, or T	Direction X, Y, or T	Ability & Dir	Elite Vs. Recreational Right turn	Elite Vs. Recreational Left turn	Elite R vs. L	Recreational R vs. L
Outer Foot								
1 Lat heel	p(1,1)						T	
2 Med. Heel	p(1,2)	Y					T	
3 Lat Mid-foot	p(2,1)	Y				T	T	
4 Med Mid-foot	p(2,2)	Y						
5 5th met-phal jt	p(3,1)	Y						T
6 1st meta-phal jt	p(3,2)				X	T		
7 Calcaneous	m(cal)		Y					
8 Med Mal	m(mal)	T, X						
9 Meta-phal jt	m(1st)							
10 Talo-crural jt	d(1)						T	
11 1st Tarso-meta jt	d(2)	Y			T			
12 2-3 meta-phal jt	d(3)							
13 Calcaneous	l(cal)	Y						T
14 Mal	l(mal)	Y			T			
15 5th tarso-meta jt	l(5th)	X					T	

N.B. For right turns, the outside foot is the left foot
-For left turns, the outside foot is the right foot
-X represents the X axis, which denotes time and the occurrence of the peak value, along that axis.
-Y represents the Y axis, which denotes the magnitude of the pressure value in question.
-T represents the time relation of the event.

Table 7: The areas of statistical significance for the period of peak pressure.

Summary table of significances: peak push off.

Statistical Summary Table

Sensor Position	Log name	Ability X, Y, or T	Direction X, Y, or T	Ability & Dir	Elite Vs. Recreational Right turn	Elite Vs. Recreational Left turn	Elite R vs. L	Recreational R vs. L
Inner Foot								
1 Lat heel	p(1,1)							
2 Med. Heel	p(1,2)							
3 Lat Mid-foot	p(2,1)							
4 Med Mid-foot	p(2,2)		Y			T, Y		
5 5th met-phal jt	p(3,1)							
6 1st meta-phal jt	p(3,2)							
7 Calcaneous	m(cal)						T	
8 Med Mal	m(mal)							
9 Meta-phal jt	m(1st)							
10 Talo-crural jt	d(1)							
11 1st Tarso-meta jt	d(2)							
12 2-3 meta-phal jt	d(3)	T		T				
13 Calcaneous	l(cal)	Y			X			
14 Mal	l(mal)				T			
15 5th tarso-meta jt	l(5th)	Y						

N.B. For right turns, the inside foot is the right foot
-For left turns, the inside foot is the left foot
-X represents the X axis, which denotes time and the occurrence of the peak value, along that axis.
-Y represents the Y axis, which denotes the magnitude of the pressure value in question.
-T represents the time in realtion to the event.

Sensor Position	Log name	Ability X, Y, or T	Direction X, Y, or T	Ability & Dir	Elite Vs. Recreational Right turn	Elite Vs. Recreational Left turn	Elite R vs. L	Recreational R vs. L
Outer Foot								
1 Lat heel	p(1,1)							
2 Med. Heel	p(1,2)							
3 Lat Mid-foot	p(2,1)							
4 Med Mid-foot	p(2,2)	Y						
5 5th met-phal jt	p(3,1)	Y						
6 1st meta-phal jt	p(3,2)							
7 Calcaneous	m(cal)		Y		T			
8 Med Mal	m(mal)	X						
9 Meta-phal jt	m(1st)							
10 Talo-crural jt	d(1)							
11 1st Tarso-meta jt	d(2)	Y						
12 2-3 meta-phal jt	d(3)							
13 Calcaneous	l(cal)	Y		X	T			
14 Mal	l(mal)	Y			T			
15 5th tarso-meta jt	l(5th)	Y						

N.B. For right turns, the outside foot is the left foot
-For left turns, the outside foot is the right foot
-X represents the X axis, which denotes time and the occurrence of the peak value, along that axis.
-Y represents the Y axis, which denotes the magnitude of the pressure value in question.
-T represents the time in relation to the event.

Table 8: The areas of statistical significance for the period of peak push off.