Quantifying Fit in Ice Hockey Skate Boots

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ABSTRACT

Quantifying Fit in Ice Hockey Skate Boots

Purpose: This study quantified fit of ice hockey skate boots by measuring the pressure (MP) at the foot/ankle-to-boot interface using three skate sizes. The relationship between perceived pressure (PP), perceived comfort (PC) and measured pressures (MP) also were documented. **Methods:** 18 male subjects participated. Thirty piezo-resistive sensors recorded MPs from seven areas with the foot/ankle in various positions. A Visual Analogue Scale was used for subjective assessment of PP and PC. **Results:** Overall fit MP was estimated at 34.2 KPa though significant mixed interactions ($p<0.05$) occurred between areas, foot/ankle positions and sizes. MP correlations with PP, PC, and foot/ankle dimensions were low though a strong inverse relationship was identified between PP and PC ($r = -0.63$). **Conclusions:** The technology and protocol adopted was effective in discriminating "fit" between regional pressure differences as well as responsive to foot/ankle positions. Further examination of other footwear products and different populations is feasible and warranted.

RESUMÉ

Mesuré l'Ajustement des Bottes de Patin d'Hockey

But: Cette étude a mesure l'ajustement des bottes de patin d'hockey sur glace en mesurant la pression (MP) à l'interface entre le pied et la botte en utilisant trois grandeurs de patins. Le rapport entre la pression perçue (PP), le confort perçu (PC) et les pressions mesurées (MP) également ont été documentés. **Méthodes:** 18 sujets masculins ont participés. Trente sondes piezo-resistive ont enregistres MPs de sept secteurs avec le pied/cheville dans diverses positions. Une mesure analogue visuelle a été employée pour l'évaluation subjective de PP et du PC. **Résultats:** Le MP global d'ajustement a été estimé à 34.2 KPa bien que les interactions mélangées significatives ($p<0.05$) se soient produites entre les secteurs, les positions de pied/cheville et les grandeurs. Les corrélations de MP avec PP, le PC, et les dimensions de pied/cheville étaient basses bien qu'un rapport inverse fort a été identifié entre PP et le PC (r = -0,63). **Conclusions:** La technologie et le protocole adoptés étaient efficaces en distinguant le confort en se servant des différences régionales de pression et etaient sensibles aux positions de pied/cheville. Cette recherche devrait être utilisee avec d'autres produits et chaussures et différentes populations et le protocole et la technologie rend cette recherché possible.

TABLE OF CONTENTS

LIST OF TABLES

TABLE OF FIGURES

1. INTRODUCTION

1.1 PURPOSE OF THE STUDY

The purpose of this study was to quantify fit as related to ice hockey skate boots by measuring the pressure values at the foot/ankle to boot interface. In addition, the relationship between perceived and measured pressures and between foot / ankle anthropometrics and measured pressures will be explored.

1.2 NATURE AND SCOPE OF THE PROBLEM

The majority of the studies concerning pressure values have focused on the plantar pressure of the human foot. Few approaches have considered the pressure magnitude and its distribution around the foot and ankle (Dewan, 2004; Jordan & Bartlett, 1995). At present, there has been limited research focused on determining the pressure profile around the foot and its relation to fit and perceived comfort. These measures can aid the designers to 'refine' their final skate products and for the athletes (hockey players) to optimize their skating performance with minimal discomfort and risk of injury.

1.3 SIGNIFICANCE (OF THE PROBLEM)

Ice hockey is an exciting, fast-paced team sport whose popularity has increased tremendously over the past century. Frequently referred to as the fastest team sport in the world, ice hockey involves skilful stick handling, tactics, speed, and grit. As we know it today, it is one of the most popular Canadian sports (IIHF, 2001). Ice hockey players wear specialized equipment, which is specifically designed for performance and safety.

The skates are a fundamental piece of hockey equipment. Hockey players need to consider their skates as part of their feet. Skates should be chosen with relation to proper size and potentially play style. If a pair of skates fit too snugly or too loose around the foot and ankle they may cause chaffing, stability problems, and discomfort. Common complaints include "hot spots", blisters and skin alcerations over protruding bone structures, bursal enlargements over the malleolae and Achilles tendon, extensor tenosynovial inflammations (tibialis anterior and extensor hallucis longus muscles), and painful venous thromboses of the superficial veins (Minkoff *et. al*, 1994). Although not well documented, long term implications of improper footwear are suspect such as altered foot arches and metatarsal phalangeal deformities. Skaters may experience foot pain because the individual cannot find skates that fit their feet properly. Further, some feet do not fit very well into the standard or generic sizes and shapes of most 'off the shelf' skate boots. Even the most experienced skaters, with full-customized hockey skate boots molded for their feet (i.e. thermoforming), can experience some degree of foot discomfort. Little research has been performed in ice hockey biomechanics (Pearsall *et al.*, 2000). Previous hockey studies evaluated the ankle kinematics (Chang, 2002; Dewan, 2004), lower limb electromyography (Dewan, 2004; Goudreault, 2002), and foot pressures distribution (Dewan, 2004; Loh, 2003). The vast majority of research done in relation with athletic footwear comfort focused on the running shoes (Chen *et al.*, 1994; Goonetilleke & Luximon, 2001; Jordan & Bartlett, 1995; Mundermann *et al.*, 2002). Similarly, a sound knowledge of all the aspects of comfort (skate boot fit, climate, cushioning, anatomical characteristics, and foot sensitivity) in ice hockey, may lead indubitably to increased performance and low injury incidence.

Comfort is of great importance to leisure and sport footwear manufacturers. To determine what makes a shoe comfortable, the relationships between perceived comfort and relevant physical measures at the foot-shoe interface must be explored (Jordan & Bartlett, 1995). If fit relevant physical measures can be found then guided alterations to footwear design can be achieved.

For a shoe to be comfortable the internal shape must closely approximate the shape of the foot. This implies that a detailed knowledge of foot shape and dimensions are a fundamental pre-requisite in the determination of shoe comfort

(Hawes & Sovak, 1994). Footwear size, shape, flexibility, style, weight, inside shoe climate, materials, tread, cushioning are all factors affecting footwear comfort. For a shoe to be comfortable, it needs to give the "right feel" and at the same time avoid any discomfort or pain (Goonetilleke & Luximon, 2001). In terms of sports footwear, comfort affects performance, fatigue and injuries (Mundermann *et al.*, 2002). Further, comfort is subject specific, affecting kinematics and/or kinetics of a movement (e. g. pressure distribution) (Chen *et al.*, 1994; Jordan & Bartlett, 1995). Hence, footwear comfort is one of the most important aspects for shoe manufacturers. Market testing often relies solely on subjective assessment of products. However, opinion based surveys of comfort are difficult to interpret since they are influenced by numerous social and psychological factors.

As noted, one factor for determining shoe comfort is shoe fit, that is the match between foot shape and shoe shape (Hawes *et al.*, 1994; Witana *et al.*, 2004). However, matching foot and shoe shapes is no trivial task given the numerous anthropometric variations of the former within the population (Tremaine & Awad 1998). To optimize fit, it would be desirable to quantify the degree of fit; that is, to provide an estimate of contact areas and pressures between the two shapes. In particular, pressure measurements provide a unique insight into the interaction between the human body, footwear, and the ground (Hennig & Milani, 2000). Further, pressure at the human-product interface is generally considered to be an important parameter in comfort evaluation. However, the ideal pressure distribution between the human body and any surface of a given application has yet to be defined (Goonetilleke, 1999). To date, little attempt has been made to quantify comfort and the relationship between perceived comfort and pressure distribution has not been established (Chen *et al.*, 1994).

1.4 AIMS AND OBJECTIVES OF THE STUDY

The study's objectives are as follows:

- to measure pressure values inside the hockey skate boots in seven pre-determined areas around the foot and ankle using individual sensors;
- to assess the amount of comfort or discomfort perceived by the participants and the pressure magnitude by using a ratio scale (more sensitive and reliable), overall and in eight other areas of interest;
- to measure the foot and ankle in ten determined areas of interest;
- to measure the inter-eyelets distance in three pre-determined areas;
- to determine the magnitude and relationships between the targeted variables (i.e. pressure, perception, and anthropometrics).

1.5 HYPOTHESES

The following hypotheses were considered in the present study:

- there are significant differences in measured pressure between the skate sizes tested;
- there are significant differences in pressure values at the 'foot-boot' interface between sensors placement area;
- there are significant differences in the pressure magnitude between tasks (non-weight and weight bearing);
- significant differences exist as a result of interactions between placement area, performed task, and skate sizes;
- perceived comfort and pressure is affected (to some degree, directly or inverse) by the skate size;
- a strong relationship (direct or inverse) exists between the pressure magnitude and subjectively evaluated comfort and pressure;
- a strong relationship (direct or inverse) can be determined between foot/ankle anthropometrics and measured pressure, and foot anthropometrics and perceived pressure and comfort;
- the eyelets lace spacing varies with site and skate boot size.

1.6 OPERATIONAL DEFINITIONS

The study presents the following operational definitions:

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.
Visual Analog Scale (VAS):	A ratio scale used to rate the sensation intensity and affective magnitude.
Measured pressure (MP):	The pressure measured using individual sensors.
Perceived comfort (PC):	The magnitude of subjective perceived comfort.
Perceived pressure (PP):	The magnitude of subjective perceived pressure.
Rear(hind)-foot:	Comprises the calcaneus and the talus.
Mid-foot:	Forms the main arch.
Fore-foot:	Forms the toes (phalanges) and the ball of the foot (metatarsals)
EVA:	Ethyl-vinyl-acetate.

1.7 LIMITATIONS

The study's limitations include:

- only Bauer-Nike 'Vapor XX' skates were evaluated, sizes between 7½ – 8½ U.S. (width D);
- upper measurement limit for pressure magnitude was 689.5 KPa;
- the piezo-resistive sensors measure the pressure normal to the surface of the foot (i.e. shear forces are not measured).

1.8 DELIMITATIONS

The study's delimitations include:

- all participants were evaluated using static tests in the lab and at the room temperature;
- polyethylene was used to simulate the ice;
- participants were recreational players;
- all participants were male.

2. LITERATURE REVIEW

2.1 FOOTWEAR COMFORT

Comfort is a subjective trait of great importance in sport and leisure footwear (Chen *et al.*, 1994; Jordan & Bartlett, 1995). Yet the opinions of the wearer are often limited to descriptive terms that cannot quantify the causes of comfort or discomfort (Kos & Duhovnik, 2002). To determine what makes a shoe comfortable for a given population, the relationships between perceived comfort and relevant physical measures at the foot-shoe interface must be explored. If physical measures can be found then alterations to footwear design can be based on physical causality rather than subjective reports (Jordan & Bartlett, 1995).

Attempts to define footwear comfort and the factors that affect it have been explored. In large part, for a shoe to be comfortable the internal shape must closely approximate the shape of the foot; hence, a detailed knowledge of foot anatomy, anthropometrics and sensitivities are a fundamental pre-requisite in optimal shoe design for both fit and function (Hawes, 1994; Reinschmidt & Nigg, 2000).

Comfort is a very complex and multi-faceted entity. Factors "such as size, shape, flexibility, style (running shoe, hiking boot, skate boot), weight, inside shoe climate (humidity, temperature), materials, tread, cushioning all affect footwear comfort (Goonetilleke & Luximon, 2001)." In order for a shoe to fit a person's foot, the fitting should be more than just length and width: proper fit means achieving the right fit in terms of heel width, heel-to-ball length, top-line fit, toe box space, etc. In other words, proper fit requires a good understanding of the total 3-D shape. For a shoe to be comfortable, it ought to give the right feel and at the same time not cause any discomfort or pain (Goonetilleke & Luximon, 2001).

Most people can quickly identify comfortable or non-comfortable footwear situations. Increasing interest in footwear comfort resulted in several investigations that associated comfort with plantar pressure distribution, vertical impact force, rearfoot motion, foot and leg shape and alignment, and foot sensitivity. Further, it has been speculated that comfort is related to muscle activation and, thus, to fatigue and performance. The specific design, physical properties and construction of footwear have been shown to affect these variables and, thus, seem to be important factors for footwear comfort (Mundermann *et al.*, 2002).

The quantification of comfort is still an outstanding problem. Assessments of comfort are difficult to interpret given their subject specific nature that cannot be easily generalized. However, there may be a relationship between perceived comfort and certain measurable physical parameters such as force, pressure and energy cost (Chen *et al.*, 1994). This is the objective of the current study in the specific context of ice hockey skates. The following text will review relevant topics related to footwear fit.

2.2 FOOTWEAR DESIGN

The manufacturer with shoes that best fit a consumer needs (literally and figuratively) has a decided advantage over its competitors. Next to fashion, shoe fit is a fundamental selection criterion (Kos & Duhovnik, 2002): athletic footwear is no exception. Both functional (e.g. performance, comfort and injury prevention) and non-functional factors (e. g. price, fashion, style, and durability) are important in the design process of athletic footwear (Reinschmidt & Nigg, 2000). Unfortunately, fashion often wins over function resulting in footwear discomfort.

Conventionally, most consumers select footwear size based exclusively on foot length and width, even though these two measures alone are insufficient for proper fitting (Goonetilleke & Luximon, 2001). Not surprising, achieving optimal fit is a problem. For instance, taken from surveys Collazzo (1988) reported that fit problems are prevalent for both men and women: common complaints include excessively tight fit pertaining to width (20%), narrow toes (9%), poor arches (14%), and sloppy fit (i.e. excessively loose; 9%). Given the three-dimensional variation of the foot shape proportions (i.e. anthropometrics) within the population, the match between feet and footwear is quite variable (particularly in the fore- and mid-foot; Tremaine & Awad 1998) and can be quite unacceptable even with the same brand of shoes (Hawes *et al.*, 1994; Witana *et al.*, 2004; Luximon *et al.,* 2003).

In the manufacturing process, shoe shape is determined primarily by the surrogate foot forms or "lasts", around which the shoe is assembled. A shoe last is developed to represent an 'average' foot. However, there is substantial inter- and intra-subject variability. 'Same size feet' may have quite different foot shapes. As well, left and right feet of the same person may be quite different in shape. Hence, a shoe model built from a particular last may only suit a specific group of athletes with the same shoe size (Reinschmidt & Nigg, 2000). Foot shape differs also significantly across different ethnic groups (Hawes *et al.*, 1994) and genders (Wunderlich & Cavanagh, 2000). To make unique shoe lasts to match all possible foot shape variations is economically, if not technically, a challenge. In response, various strategies have been developed by athletic footwear manufacturers to increase the (individual) fit of athletic footwear such as: special lacing systems, variable air compartments in the upper, different insoles, padding, variable shoe widths, different lasts, and sock-liners (Reinschmidt & Nigg, 2000). Potentially, when three-dimensional laser scanning procedures become practical (Kos & Duhovnic, 2002; Luximon *et al.*2003) custom tailor shoes may be possible in combination with the internet's experimental e-shoe business (Kos & Duhovnik, 2002). Subsequent section in this review will explore issues of foot geometry further.

Another footwear design factor that mediates our perception of fit and function is in-shoe climate control. This includes the management of temperature (both hot and cold extremes) and wetness (due to intrinsic perspiration and extrinsic fluid penetration) that, in turn, may influence potential dermatophyte infections (Watanbe *et al.*, 2000; Zimmerer *et al.*, 1986), and friction blisters (Sulzberger *et al.*, 1966).

An insufficient temperature and humidity exchange with the environment may result in an uncomfortable shoe climate. These properties are thought to be controlled by both the type of socks worn (Herring, 2003) as well as the ventilation systems and breathable materials incorporated in the footwear upper (Reinschmidt & Nigg, 2000). Socks fibres are generally grouped into three major categories (Herring, 2003): natural fibres (wool, cotton); synthetic fibres (acrylic, nylon, polyester, spandex, and polypropylene); and membranes (more specialized). These various sock fibres will have different water retention versus transport (wicking) ability that in turn alters their insulating capacity (Kuklane, 1999).

Various studies have been conducted to investigate the effects of sock materials; however, unequivocal outcome on foot skin temperature and on whole body thermoregulation have been reported (Gavin *et al.*, 2001; Purvis & Tunstall, 2004; House *et al.*, 2003). In addition, socks assist in minimizing shear forces that lead to blistering of skin (Sulzberger *et al.*, 1966; Bush *et al.*, 2000; Herring & Richie, 1993; Flot *et al.*, 1995; Wong *et al.*, 1998; Howarth & Rome, 1996). Various sock knits enhance the properties of the fibres by allowing shearing forces to develop within the internal fibre framework, rather than at the sock-skin interface (Herring & Richie, 1990, 1993; Allan, 1964; Jagoda *et al.*, 1981; Knapik *et al.*, 1996). Thus, given the implications of socks to the internal footwear climate comfort, the type of socks utilized in conjunction with the assessment of footwear comfort must be considered.

A final, and obvious, design feature for athletic footwear is performance. One measure of performance is energetics: here specifically referring to optimizing the energy input and return both from and to the athlete (Stefanyshyn & Nigg, 2000). For instance, properties such as cushioning and weight have been shown to have significant effects on locomotion economy (i.e. percentage of energy input resulting in observed work). Predicting the energetics of footwear is not necessarily evident given the interactions between the various material and construction parameters. For example, a change in one specific sport shoe characteristic (e. g. midsole stiffness) may affect kinematics, kinetics and/or muscle activation (Reinschmidt & Nigg, 2000). Other examples include:

a) features promoting stability typically increase the weight of the shoe, implicit the energy consumed;
b) shoe soles providing good traction are typically worn out quickly;
c) the reduction of weight usually reduces cushioning and stability;
d) added cushioning typically decreases stability, but improves protection and comfort.

Elastic energy storage and recovery in the cushioning system of athletic footwear ('energy return') is thought to be a desirable quality to enhance performance (Shorten, 1993). However, depending on the movement, energy return sometimes may occur at the inappropriate time, frequency, or location as well as in the undesired direction thereby compromising performance.

2.3 THE FOOT

2.3.1 Foot shape

The foot is a complex structure made up of 26 individual bones held together by very strong ligaments and many muscles that control its movement. The foot has two major roles: one is bearing weight, and the second one is to assist with walking. With regards to footwear, thee primary function units of a foot are hind-foot (or rear-foot), mid-foot, and fore-foot (Cavanagh, 1980). The hind-foot comprises the calcaneous and the talus. The midfoot has five short bones and the main arch, while the forefoot is made of the toes (phalanges) and the ball of the foot (metatarsals).

Measures concerning shape, dimensions and proportions (i.e. anthropometrics) of the foot are a fundamental prerequisite in determining shoe fit and comfort (Liu, 1999). However, reliable and definitive data concerning foot anthropometrics has been difficult to amass. In part, differences in methodology of foot shape measurement (e.g. variable measurement tools; varied landmark boundary conditions; lack of intra- and inter-observer reliability) used in various research studies confound the ability to pool information (Hawes & Sovak 1994). Further, the majority of the data reported in the literature on foot anthropometrics has not been referenced to an anatomically defined coordinate system (Liu *et al.*, 1999). Another factor adding to the complexity of describing foot shape is the inherent non-uniform variability of these measures within a population as well as between genders (Wunderlich & Cavanagh, 2001) and races (Hawes *et al.*, 1994) as well as across the lifespan.

Accurate techniques for measurement of three-dimensional properties of foot dimensional, shape and structural characteristics have been developed. For instance Liu *et al.* (1999) demonstrated the ability to calculate a total of 23 variables from the coordinates of 26 digitized points on a uni-lateral weight bearing foot and leg. All variables were measured with reference to an anatomically defined reference frame on the foot. The intra- and inter-tester reliability for the device and for the foot measurements were found to be high (ICC> 0.8) in most of the anthropometric variables, with the lowest intra-tester reliability of 0.57 and the lowest inter-tester reliability of 0.38. Another example of the feasibility of generating anatomically detailed reconstructions of a human foot was shown by Camacho *et al.*, (2002). Computerized topographic (CT) scanned images were processed so that surface mesh models for individual bones, the plantar soft tissue, and cartilage were generated. These models served two purposes: it formed the anatomical foundation for a future finite element model of the human foot and it objectively quantified foot shape using the relationship between the principal axes of the foot bones. Though the above findings are promising, such techniques remain impractical in the market.

2.3.2 Foot function

In addition to foot shape, footwear must facilitate proper alignment and control of the foot's skeletal structure during movement. It has been proposed that overuse injuries resulting from undue foot and leg movement could be reduced with appropriate athletic footwear as well as in combination with shoe inserts or orthotics (Nigg *et al.*, 1999; Milani & Hennig, 2000). In particular, it is believed that an excessive amount and rate of pronation of the subtalar joint in turn causes a cascade of undesirable adjustments of the proximal segments thereby increasing the injury risk to the knee, hip and intervertebal joints (Mundermann, 2004). Numerous studies have been conducted to address the prophylactic potential of footwear design in mitigating lower limb injuries. For instance, Nigg *et al.* (1998) demonstrated that the material composition of shoe inserts can change the extent of foot eversion and tibial rotation during running. In general, the soft insert construction was more restrictive, forcing all feet into a similar movement pattern, whereas the harder combinations allowed for more individual variation of foot and leg movement. Other research has found less demonstrative effects. For instance, Stacoff *et al.* (2001) used intracortical bone pins with reflective marker triads to quantify the effects of shoe sole modifications on skeletal kinematics of the calcaneous and tibia during the stance phase of running. Their results showed that the sole modifications did not change tibiocalcaneal rotations substantially and it was concluded that the tibiocalcaneal kinematics of running may be individually unique. Hence, conclusive evidence of the ability of inserts or orthotics to align the skeleton maybe be found but they are small, not systematic and associated with a substantial amount of uncertainty (Nigg *et al.*, 1999). Further they are poor predictors of increased susceptibility to movement-related injuries.

2.3.3 Foot sensation

Adding to the above noted functions, the foot may also be considered an important sensory organ (Cavanagh, 1980). The central nervous system is heavily invested into gathering proprioceptive information from the feet's numerous sensory nerve ending including sensations of touch, temperature and pain (Meh & Denislic, 1994). Proprioceptive feedback is, in part, fundamental for effective motor control of balance while standing, walking and running. Therefore, since footwear is an interface between the foot and the ground, it will modify (or filter) plantar foot sensors inputs (Nigg, 2001) as well as superimpose other stimuli about the foot's surface due to the fit of footwear wrapping or envelope. Various studies have investigated foot sensor disturbances in terms of the effect on human movement.

For instance, Nurse & Nigg (1999) determined the pressure and vibration thresholds with respect to plantar pressure distribution displayed while walking at different speeds. Significant negative correlations were found between the vibration threshold of the hallux at 125Hz and peak pressure under the hallux while walking and running and between the mean vibration threshold of 125Hz with peak force during running. Similar trends were noted at the heel, lateral arch and first metatarsal head. Thus, these results demonstrate an association between the sensory system and the dynamic response of the subject (Nigg *et al.*, 1999). In subsequent study (Nurse & Nigg, 2001), the sensory threshold was determined for the plantar surface of the foot, by reducing the sensory feedback through ice intervention. Three altered sensory states were tested: whole foot, forefoot, and rear-foot. Plantar pressure distributions and lower extremity muscle patterns were collected while walking before and after ice exposure. Their findings indicated that peak pressure and pressure-time integral were significantly higher in areas of normal sensitivity and lower at the insensate areas. Furthermore, the centre of pressure underfoot shifted away from areas of decreased sensitivity when sensory input was reduced from a portion of the foot. Muscle patterns were also significantly altered when sensory feedback was changed. More recent studies adopting similar ice immersion protocols have demonstrated altered gait due to reduction in cutaneous sensations (Eils *et al.*, 2002; Taylor *et al.* 2004).

Another form of sensory inhibition can be achieved by blocking the tibial nerve impulses through injected Lidocaine inferior and posterior to the lateral malleolus. This approach was adopted by Fiolkovski *et al.* (2005) with respect to its effect on running and hopping tasks. From the results, tactile sensation, deep pressure sensation, and abductor hallucis activity were significant decreased, as was postural stability. It was concluded that plantar sensation has an effect on regulating leg mechanics.

In contrast to these previous studies, attempts have been made to enhance sensory feedback. For example, Nurse and colleagues (2005) utilized various textured shoe inserts to determine if the sensory feedback from the feet could be altered during standing or walking. Three-dimensional kinematics and kinetics, as well as muscle EMG, were collected as subjects walked with the shoe inserts. The researchers noted that the foot was significantly more plantar flexed at heel strike with the textured inserts and small changes were also seen in muscle activation, vertical ground reaction forces and joint moments. It was assumed that the changes in gait patterns were due to a change in sensory feedback caused by the textured shoe insert.

So far, discussion has focused on touch. Also relevant to foot function (and footwear comfort) is the perception of pain. Discomfort or pain originates when special nerve endings (nociceptors) detect an unpleasant or noxious stimulus. Nociception denotes the sensor stimulation due to tissue damage and the subsequent neural pathway transmission (http://www.iasp-pain.org/meetings.html). On the other hand, pain is a subjective experience that may or may not accompany nociceptor stimuli. According to the gate control theory of pain (Melzack & Wall, 1965), cognitive and emotional factors may dramatically influence painful sensations. Pain is mediated through three psychological dimensions:

- sensory-discriminative (related to the detection of the intensity and location of the painful stimuli);
- motivational-affective (involves an evaluation of the negative connotations of the stimuli), and
- cognitive-evaluative (involves a decision making process, such as "what to do about this pain") (Whitmarsh & Alderman, 1993).

The volitional ability to control the cognitive-evaluative phase, may explain why athletes may perceive painful stimuli as less noxious than their non-athletic counterparts (Tenenbaum *et al.*, 1999). Due to the psychological component of pain perception, carefully crafted questionnaires are required to obtain pertinent and reliable estimates of an individual's pain. Attention needs also to be given to the format and protocol used to obtain subjective metrics (Price *et al.*, 1983).

2.4. PUTTING THE FOOT IN FOOTWEAR

2.4.1 Relating Pressure to Fit and Function

Methods for quantifying pressure distribution between the foot (principally plantar) and shoe are relatively new, and reliable instrumentation has only been on the market for a few years. Such devices have great potential to be applied in the study of various tasks since they provide online information that is intuitively understandable (Nigg & Herzog, 1996). The measuring elements used in pressure distribution measurements include the following: capacitance, conductance, critical light reflection, force sheet (Fuji sheet), inductive sensor, piezo-ceramic element, reflecting/polarizing sheet, rod/spring elements, and strain gauge element. The disadvantages with most systems to date reside in the fact that each transducer is connected directly with the outside, requires some adaptations to provide room for cables or holes to take the leads out at different locations (Nigg & Herzog, 1996). Pressure distribution measuring devices are currently used in several major biomechanical and clinical fields of application:

- plates measuring pressure distribution (gait analysis focused on the temporal plantar pressure distribution patterns for different foot regions, for specific foot types, to determine the centre of pressure);
- development of shoe insole devices that assess the pressure distribution between the plantar aspect of the foot and the shoe insole;
- local pressure distribution measurements in specific applications (e.g. residual stump and prosthesis of amputees);

- quantify local forces with individual sensors (usually held in place by adhesive tape).

  Pressure is defined as follows:

$$\textbf{Pressure}\ \text{(Pascal)} = \textbf{Force /Area}\ (\text{N/m}^2) \qquad (1)$$

In general, pressures can be supported or distributed in two ways (Goonetilleke, 1999): (1) uniformly, or (2) concentrated (i.e. load the "stronger" parts of the anatomical structure and shield the weaker to reduce "breakage"). The most common approach is to distribute pressures as much as possible to achieve the uniform condition. However, existing research suggest in certain cases a concentrated strategy is a better approach (e.g. shoe insoles induce localized pressure, rather than distributed pressure, supposedly creating desired sensations). Pressure distribution can be modified by passive and active cushions. Passive cushions in footwear typically are formed from synthetic materials, the most popular be ethyl vinyl acetate (EVA) foams. Active cushions are more sophisticated involving periodic pressure changes controlled by internal chip sensors. The latter currently are in the infancy on the market.

2.4.2 Relating Pressure to Comfort

Pressure, then, is one of the factors that determine comfort. Pressure occurs when two surface come into contact. The greater the contact force (and resulting reaction force), the greater the pressure. The greater the contact area, the less the pressure and vise versa. Pressure is essential for touch sensation; hence, a certain magnitude of pressure is desirable for appropriate proprioceptive sensory feedback to permit, in turn, optimal movement control. Too much pressure from footwear fitting too tight, conversely, elicits discomfort and / or pain sensation that in turn may result in tissue damages and structural deformation, as well as potential abnormal gait patterns. The question remains then: what is too much pressure?

Insight into pressure tolerance can be taken from the findings of basic integumentary studies. Early research proposed the Spatial Summation Theory stating that simultaneous stimulation of many sensory receptors is required to arouse stimulation (Hardy & Oppel, 1937). That is, the larger the area stimulated, the greater the sensory response experienced. This theory has important implications for force distribution: a force distributed over a large area may induce greater discomfort than the same force over a small area. Pressure tolerance has also been related to changes in blow flow. Skin compression too great or sustained too long can lead to potential localized necrosis. Skin blood flow changes are influenced by three factors: the ratios of bone depth; the ratios of indenter diameter to bone diameter, and percentage compression of the tissue overlying the bone. The indenter (or loading area) is a factor neglected by many and its effect on discomfort can explain perceived sensations of interface designs having concentrated loading. For instance, Goonetilleke & Eng (1994) showed that the maximum pressure tolerance (MPT) is strongly related to the probe or indenter size (the contact area of the stimulus) and the depth of penetration. Since the MPT is dependent on the contact area, it may be concluded that, at high pressure, a larger area may cause a higher level of discomfort than a smaller area when stimulated with the same pressure magnitude. Localized pressure regions may in fact prove to be less discomforting when compared to distributed pressures. However, it is not certain yet whether distributing force over a larger area increases comfort at low force values even though spatial summation theory indicates that the sensation will be higher.

The traditional thinking of distributing forces may be successful only when forces are very low or below a critical value (an F_{crit}). The advantage of smaller areas to support loads is clear when the loads are high. Hence the decision to distribute or concentrate forces really depends on the magnitude of the pressure that exceeds a critical or threshold pressure (P_{crit}) for a given surface area (Goonetilleke, 1999).

With regards to footwear, it has been suggested that for comfort, the shoe should minimize pressure between the foot and the insole (Cavanagh, 1980).

Pressure magnitudes and distribution need to be optimized such that adequate pressure is maintained between the plantar surface of the foot and the insole, and local irritations to the foot above a certain threshold value are avoided. To identify discomfort due to pressure, components of fit pressure may be deconstructed of more specific relevance. These include peak pressure, pressure gradients, and contact area metrics (Goonetilleke, 1999). In terms of plantar foot pressures, research has shown that its measurement by the components noted above, can be an effective diagnostic tool in identifying clinical problems as well as differentiating between insole materials and footwear (Chen *et al.*, 1994). It therefore follows that in-shoe pressure measurement may give valuable insight into the causes of discomfort reported by wearers. However, to date little attempt has been made to quantify comfort per se and its relationship with pressure components (Jordan & Bartlett, 1995).

Jordan and Bartlett (1995) correlated the comfort ratings with pressure distribution measured in three different shoes. Their findings suggest that the measurement of pressure distribution at the foot-shoe interface could be a useful tool in identifying the causes of discomfort in footwear. For the shoes examined in this study, overall peak plantar pressures, the pressure-time integral, and total plantar area did not appear to be linked to perceived plantar comfort. In particular, it was suggested that an increase in total plantar force may have been related to a decrease in perceived plantar comfort. Findings for the shoe upper indicated that decreased dorsal forces and pressures were related to decrease upper comfort.

Discomfort and pain thresholds of mechanical forces have been studied quite extensively. Using a pressure algometer studies have shown the female/male pain tolerance to vary in the range 0.68 to 0.80 depending on the site probed (Goonetilleke & Luximon, 2001). The acceptable in-shoe pressure was estimated to be approximately in the range of 0.2-0.4 of pressure tolerance. Thus, if pain tolerance is known, one may design a product such that the interface pressures are less than approximately 20% of the pain tolerance. The differences between men and women can also be designed-in through the aforementioned ratios.

2.5 FIT AND FUNCTION OF ICE HOCKEY SKATES

The game of ice hockey and its associated equipment have continually evolved since its origins. Both coaches and players have been initiated equipment changes in order to enhance performance, prevent injuries, and improve aesthetics. Very often, these modifications raised the technical level in which ice hockey has been played (Pearsall & Turcotte, 1998; Pearsall *et al.*, 2000). Hockey skates are used mainly to propel the player' body while his attention is focused on the puck and players. The ability to skate with optimal velocity and to be well balanced at all times is a decisive factor in the overall performance of a player. The skate boot consists of an outer covering of leather or composite material, ankle support, toe box, heel counter, rigid sloe, skate blade housing, and blade (Pearsall & Turcotte, 1998; Pearsall *et al.*, 2000).

With respect to foot and ankle injuries, there are two basic concerns with skates (Minkoff, 1994): their ability to protect the foot from lacerations and impacts (accomplished to some extent by elevating the boot adequately above the ice and by the creation of molded skate bots with various guards); and, the achievement of comfort and support, without impeding on the ankle's adequate range of motion for maximum performance.

In general, skates are involved with 3% to 5% of all injuries (Minkoff, 1994). Ankle sprains are infrequent in ice hockey by virtue of the rigidity of the skate boot. However, entrapment of the skate blade by the ice of against the boards, as the pronated ankle is abducted and externally rotated by the player's inertia, will not infrequently produce a low grade syndesmosis rupture. Fractures of the ankle are relatively uncommon but bursal enlargements over the malleoli, which have been repeatedly impacted by pucks, are common. The most commonly fractured bone is the navicular.

Malleolar bursae often result from abnormal contact pressures and shear forces that arise between the bony malleolae and the skater's boot. These may occur either medially or laterally, although medial bursae are more common (Brown *et al.*, 2000). Malleolar bursitis can significantly alter a skater's performance and, in more resistant cases, can prohibit skating altogether. Most often, the player will relate it with a recent increase in their training schedule or the purchase of a new pair of skating boots. In lacing skates, it is usual to make the distal and upper laces very tight while leaving the throat area lacing looser for flexibility. The tightness of the upper boot lacing sometime causes extensor tenosynovial reactions and even painful venous thromboses of the superficial veins.

Poorly fitting skates can lead to inflammation over the tibialis anterior and extensor hallucis longus tendon. If left untreated, this may progress and lead to chronic tendinitis. These initially present as 'lace bite' and can be treated effectively with inserts placed medial and/or lateral to the tendons at the ankle joint to relieve the pressure caused by the skater's boot (Mueller, 1993)

Hockey players wear skates with sharp blades, which make it obvious that contact with these blades would cause injuries, such as lacerations to the skin, tendons, and neurovascular structures. Injury to the anterior tibial tendon, extensor hallucis longus, extensor communis tendons, or dorsalis pedis artery, vein, and nerve are known as 'boot-top' injuries. Injuries to the tendons and neurovascular structures of the anterior ankle from a skate blade are possible due to exposure of this area, located just above the skate boot and below the plastic shin pan. However, some ice hockey players endanger themselves by leaving the skate tongue everted for greater flexibility, thus exposing the anterior surface of the ankle (Minkoff, 1994). The reason for positioning the skate tongue down is a personal choice of the player and usually is believed to improve performance or/and comfort (Simonet & Sim, 1995).

The study by Wright *el al.* (2004) supported to some extent the belief that the rigidity of the skate and the decreased impact loading while skating (as compared with running. Mahar *et al.*, 1997) offers an advantage to hockey players with regard to lower ankle injury occurrence and faster return to play compared with athletes in other sports. In terms of injury types, syndesmosis sprains represent a significant injury in hockey players with an extended time lost and, unlike in other sports, are a more common injury than lateral ankle sprains. According to them (Wright *el al.*, 2004) 'the hockey skate does not appear to provide protection from the more severe syndesmosis sprain'. Athletes, coaches, athletic trainers, and equipment designers would benefit from having more information on the specific epidemiology and mechanism producing ice hockey injuries in establishing rehabilitative regimes during recovery from lower limb injuries.

Footwear comfort is a complex, multi-faceted entity of great importance in sport and leisure activities in general, and ice hockey in particular. To be comfortable, a skate boot ought to give the right feel without causing any discomfort or pain. Fit is a fundamental selection criterion for skate boots; not surprisingly, achieving optimal fit is often a problem given the variable foot morphology within the population. Proper fitting of the foot inside the skate boot requires a good understanding of the total 3-D shape of player's foot and ankle. Typically, manufacturers use generic shoe lasts as templates for the skate boot production. These lasts represent an average model which suits a specific group of athletes. The specific design, physical properties, and skate boot construction affects, beside other variables (e.g. foot shape, alignment, sensitivity, and microclimate), the way the pressure is distributed around the foot and ankle. A certain, measurable relationship must exist between the comfort perceived by the player and the pressure exerted at the foot-boot interface, influencing the overall performance in the end.

3. METHOD

3.1 PARTICIPANTS

A total of 18 male participants voluntarily agreed to participate in this study. All subject were recreational ice hockey players (i.e. play 1 to 3 times a week, during winter season) with various levels of playing experience. Their average age was 36.9 ±12.7 years old, average height 174.7±7.1 cm, and average body mass 77.5±9.9kg (see Table 3.1).

Table 3.1: Descriptive statistics for sample group (n=18)

Participant code	Age (years)	Mass (kg)	Height (cm)
001	24	68.0	167.6
002	25	69.4	172.7
003	37	63.0	164.0
004	40	67.0	167.0
006	29	68.0	170.2
007	38	88.5	179.1
008	48	93.0	176.5
009	37	83.0	175.0
010	53	74.4	175.3
011	30	63.5	162.6
012	20	76.2	181.6
013	55	78.0	175.3
014	29	93.4	173.0
015	61	78.0	175.3
016	21	77.1	177.8
017	55	77.1	175.3
019	33	86.2	190.5
020	29	90.7	185.4
Average	**36.9**	**77.5**	**174.7**
Standard deviation	**12.7**	**9.9**	**7.1**
Minimum	20.0	63.0	162.6
Maximum	61.0	93.4	190.5

Minimum inclusion criteria were used for the sample group; specifically, this required that subjects were free of severe foot and ankle deformities, musculoskeletal and neurological disorders, and in good health. Another criteria was the skate size; that is, only subjects ranging between 7½ to 8½ (US) sizes were assessed. Each subject was verbally briefed about the study's purpose, benefits, and potential risks. More detailed explanations were given before the subject read and signed the research participation consent form (Appendix A).

3.2 EQUIPMENT

Common measuring tools were used to collect anthropometric measures of the foot and ankle. This included measuring tape, linear callipers, and framing squares to determine the dimensions of foot heights, lengths, widths, and girths.

Piezo-resistive sensing technology was used to obtain direct pressure measurements (Force Sensitive Applications, FSA, Verg Inc. Winnipeg, Manitoba). The FSA system consists of pressure sensors, interface module (logger), connecting cables, and computer software (Figure 3.1). Pressure measures were collected with 30 flexible piezo-resistive sensors (dimensions 1.2

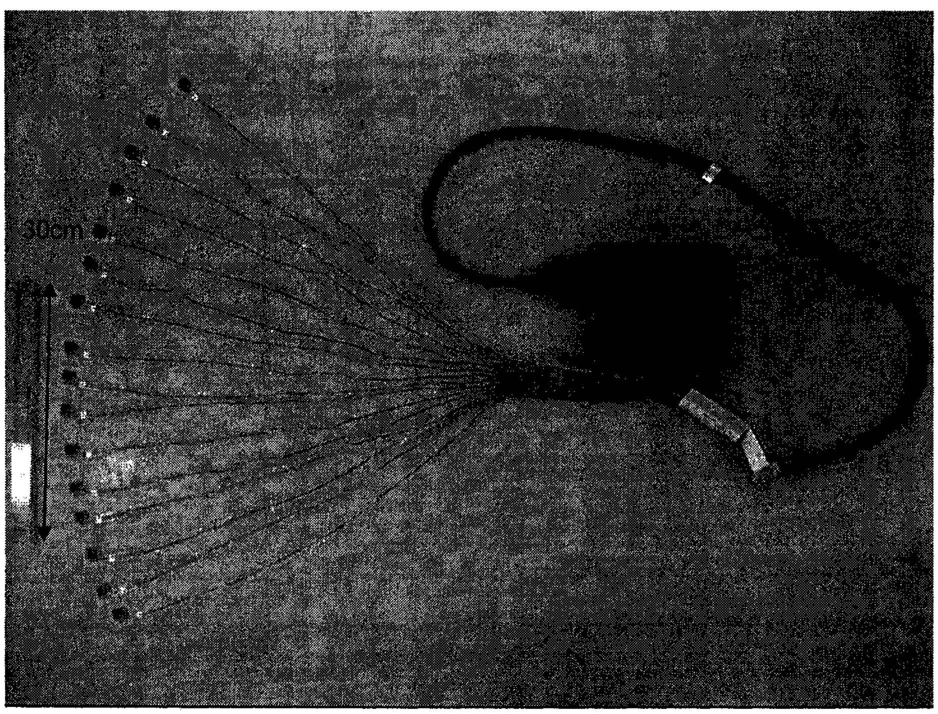


Fig. 3.1: FSA system (the interface module shown here with one of two 16 individual sensor sets)

X 0.8 X 0.2 cm), placed on skin around the foot and ankle, and connected through a customized ribbon cable to the data logger. The raw signals were recorded at a sampling rate of 5 Hz and the data were sent by a serial connection (cable and port) through and stored directly on a portable PC (IBM ThinkPad 770X, PII 250MHz, 32 RAM, 3Gb HDD, OS Win®98).

The above pressure measurement system was appropriate for this study for several reasons:

- highly accurate pressure measures up to 690 KPa with minimal hysteresis (the energy lost when loading or unloading a sensor) and creep (the tendency for the readings to steadily increase under load);
- pliable to anatomical contours with minimal signal distortion;
- low profile (2mm thick) and thin gauge wire leads;
- system portability.

3.3 FOOT ANTHROPOMETRICS

Foot lengths, heights, widths, and girths were measured for each participant (Table 3.2). Right foot and ankle dimensions were measured using a calliper, measuring tape, and framing square. All measurements were taken while the participant was in an upright standing position. The left foot rested on a 20 cm high support with the right foot supporting a majority of the body's weight.

Table 3.2: Foot and ankle anthropometrics

Foot/ankle measurements	Term	Abbreviation
Breadth	Foot breadth	FB
	Maximum heel breadth	MHB
	Inter malleolae breadth	ImB
Length	First toe length	1TL
	Metatarsale tibial length	Mt.t.L
	Metatarsale fibulare length	Mt.f.L
Height	Sphyrion fibulare height	S.f.H
	Medial malleolus height	M.t.H
Girth	Metatarsal-phalangeal joint girth	MG
	Mid-arch girth	MidG

Measurements of height (sphyrion fibulare height S.f.H, and medial malleolus M.t.H height) were all taken in a vertical plane from the standing surface to the most prominent point of the defined landmark (Figure 3.2). A sliding calliper was used to take measurements to the nearest millimetre.

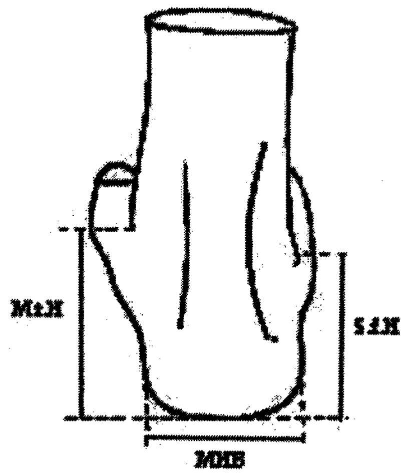


Fig 3.2: Foot heights (adapted from Hawes and Sowak, 1994)

Length measurements (Figure 3.3) were taken parallel to the long axis of the foot using the sliding calliper and recorded to the nearest millimetre. The lengths were all taken from the most posterior projecting point on the heel (the pternion) to the most prominent point of the hallux (1TL), metatarsal tibiale (Mt.t.L), and metatarsal fibulare (Mt.f.L) (Hawes and Sowak, 1994).

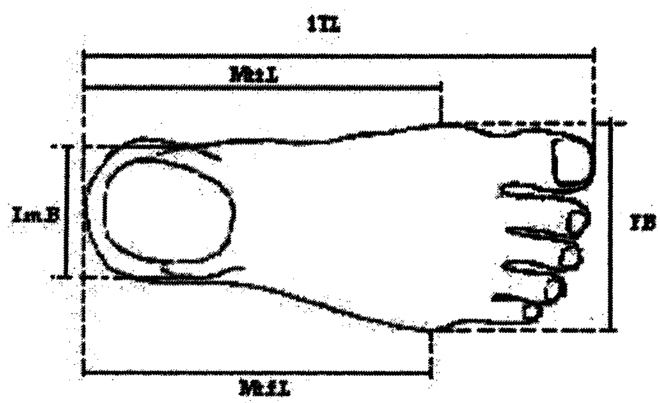


Fig.3.3: Foot lengths (adapted from Hawes and Sowak, 1994)

Breadth measurements were taken with the sliding calliper in a horizontal plane perpendicular to the long axis of the foot and rounded to the nearest millimetre. Foot breadth (FB) was measured between the metatarsale tiabiale and fibulare, maximum heel breadth (MHB) was measured with compression to the bony surface to the point of maximum heel width, and inter-malleolae breadth (ImB) with compression to the bony surface to the most prominent point.

Girth measurements (Figure 3.4) were taken using a retractable metallic measure tape and also rounded to the nearest millimetre. The metatarsal-phalangeal joint girth (MG) encompassed the metatarsal tibiale and fibulare. Mid-arch girth (MidG) was measured passing through the dorsum (Hawes and Sowak, 1994). Values were recorded for all measurements on an individual form (Appendix B).

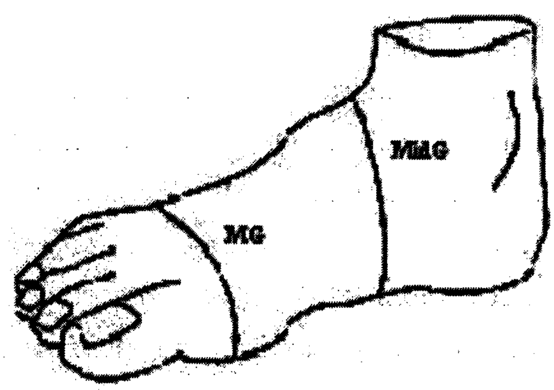


Fig.3.4: Foot girths (adapted from Hawes and Sowak, 1994)

3.4 PRESSURE SENSORS CALIBRATION

The calibration of the pressure sensors was performed prior to each data collection for each subject. Each set (n=16) of the piezo-resistive sensors were secured to an adhesive sheet, covered by a paper envelope, then inserted into air bladder "sandwich" calibration device (Tekscan, West Boston, MA, USA) that applied uniform pressure on each sensor up to 690 KPa (100 PSI). Driven by the custom designed software provided by the manufacturer (FSA Verg Inc.

Winnipeg, Manitoba), pressures were increased and decreased in a step-wise process to account for hysteresis and creep. The specific protocol sequences of applied pressures were as follows:

- null or zero pressure;
- upper pressure limit (690 KPa);
- intermediate pressure level (345 KPa);
- null or zero pressure;
- 138 KPa (20 PSI) step-wise increments up to 690 KPa;
- 138 KPa (20 PSI) step-wise decrements to zero.

The calibration process corrects for dynamic creep and hysteresis. The linearity of the sensors to both rising and falling pressures was high ($r^2 = 0.99$) over the full range (Figure 3.5; Dewan, 2004). Sensors were calibrated before each testing session.

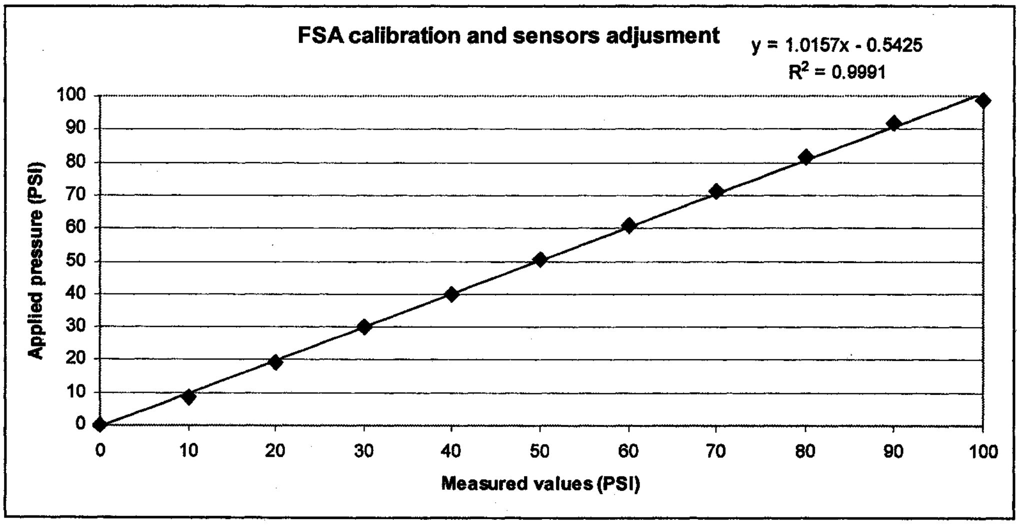
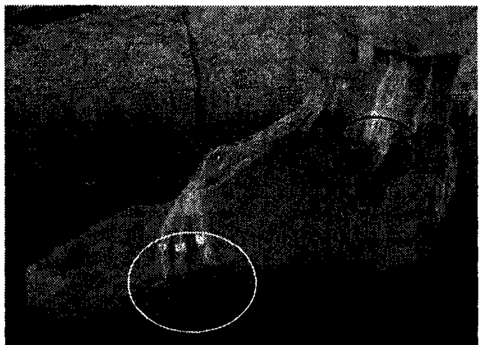


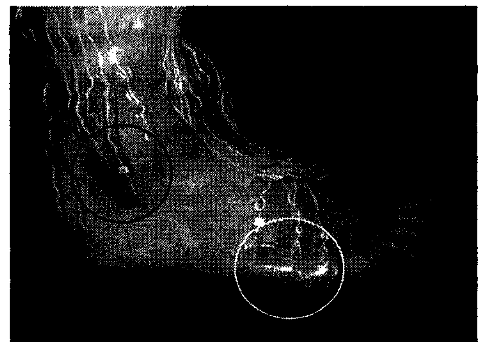
Fig 3.5: Measured pressure shows a strong relation with the applied pressure

3.5 SENSOR PLACEMENT

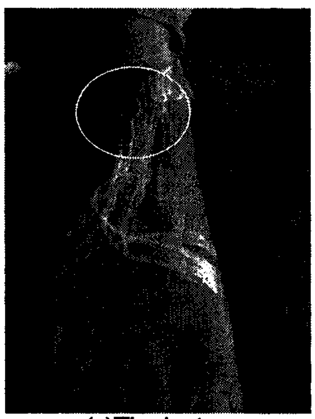
Thirty individual piezo-resistive pressure sensors were placed on predetermined areas around the foot and ankle. The subject's skin was cleaned with rubbing alcohol swabs prior to sensor placement (see Appendix C). Double sided tape (3M) was used to fix the individual sensors on the skin on predetermined areas (n=7) around the foot and ankle (Figure 3.6).



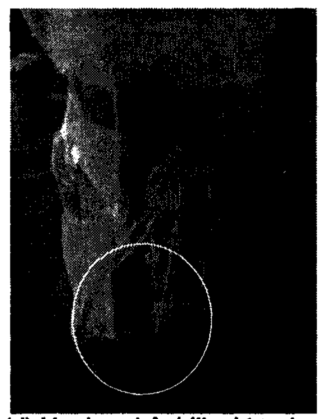
(a) Medial malleolus and 1stmetatarsal.



(b) Lateral malleolus and 5thmetatarsal.



(c)The instep



(d) Heel and Achilles' tendon

Fig 3.6: Sensors were placed in predetermined locations (a-d).

The sensors were placed at predetermined locations as follows:

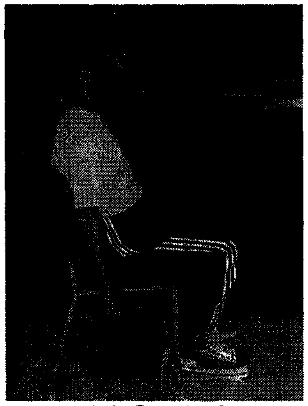
- 5 sensors on each malleolus (medial – area #1 and lateral – area #5);
- 4 sensors on the area surrounding the first metatarsal and the fifth metatarsal (areas #2 and #6);
- 5 sensors on the instep (dorsum) area (area #3);
- 2 on the Achilles' tendon (area #4);
- 5 medial-lateral on the heel (area #7).

The sensors placement on the feet was completed by the same researcher for each subject. All leads were secured to the leg with Transpore tape (3M) and elastic bandages to avoid entanglement between the cables and the subjects. The wiring from each sensor was routed proximally back along the foot surface and leg with attention to avoid bunching and crimping as well as making provision for sufficient slack to permit full range of motion (Pearsall, 2005). Once the sensors were place, a sock was slipped over the foot. All the participants were provided with the same type of socks (Kodiak, Kodiak Group Inc., Mississauga, Ontario).

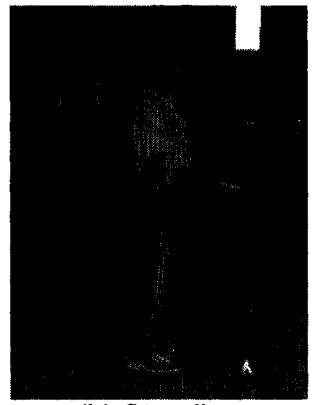
3.6 PROTOCOL

Using one skate model (Bauer-Nike Vapor XX), the participants were asked to wear first their stated skate size followed by comparison to one-half size smaller and one-half size larger (randomly chosen). While wearing the skates, six foot/ankle postures were assumed in sequence. To evaluate perception of site specific comfort and fit, an 150mm visual analog scale (VAS) scores was used similar to (Mundermann *et al.*, 2002, 2003). At the end of a test trials sequence, each subject was asked to fill out the ten items fit and comfort test questionnaire with regards to specific anatomical sites (see Appendix C). Written instructions were given to each subject to eliminate differences in assessments between subjects and sessions resulting from inconsistent verbal instructions. All testing session were done in the lab, under constant conditions. During the various tasks, subjects were positioned over a 2 x 1 m polyethylene sheet to allow the skate blade to cut in. Subjects were instructed to lace the skates with the tension they deemed sufficient to provide their accustomed fit. Each task trial consisted of a five second static measure. Measurements were taken during the following tasks:

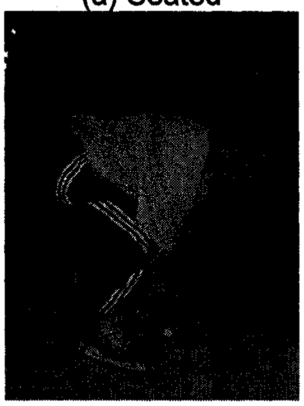
- seated (non-weight bearing)
- standing (weight-bearing),
- foot/ankle dorsi- and plantar flexion (weight-bearing);
- eversion/inversion (weight-bearing) (Figure 3.7).



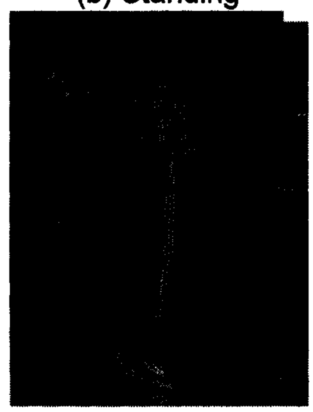
(a) Seated



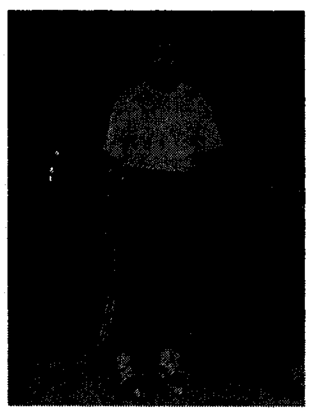
(b) Standing



(c) Dorsiflexion



(d) Plantiflexion



(e) Inversion

(f) Eversion

Fig. 3.7 The demonstrated positions and tasks required by the protocol. (a) seated; (b) standing; (c) dorsiflexion; (d) plantiflexion; (e) inversion; (f) eversion.

The whole task sequence was demonstrated to the subjects prior to commencing testing to ensure the subjects clearly understood the required action. Comments and position corrections were done also prior and during testing. Each trial sequence was repeated three times. Following execution of the six task manoeuvres, subjects were given the VAS test form to be filled out. This protocol was repeated with a + ½ size and - ½ size skate for the right foot (note: order randomized). The nominally declared size skate was worn throughout on the left foot to function, in part, as a reference during VAS evaluation.

The distance between the skate boot eye laces was measured at three different sites using a sliding calliper (Figure 3.8). First measurement (EL1) was located at the toe box edge (most distal pair), the second one (EL2) at the instep level, five pairs of eye laces proximal from EL1, and the last one (EL3) most proximal pair (boot collar).

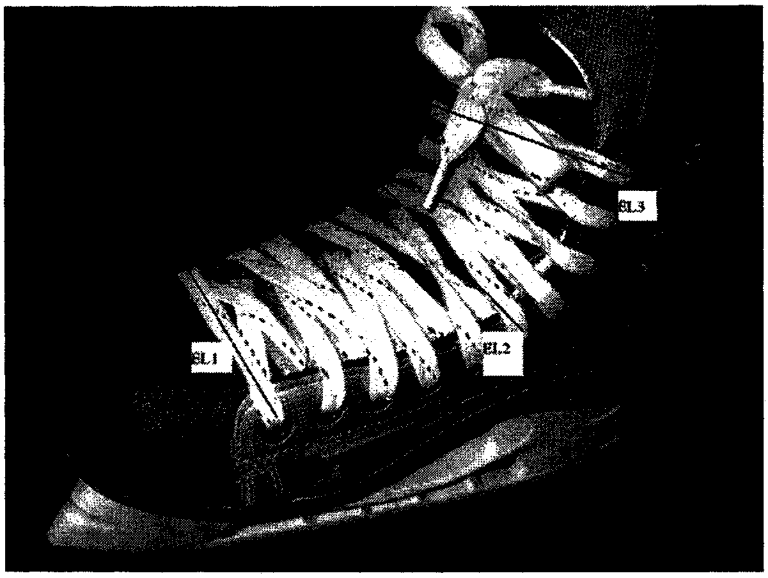


Fig.3.8 Inter-eyelets distances were measured at predetermined locations.

3.7 DATA ACQUISITION

The pressure measurements for the whole testing session were completed online using the FSA system at a sampling rate of 5 Hz. Given that task manoeuvres were performed slowly no signal aliasing occurred. After each trial, the data were saved as Excel™ spreadsheet files (*.xls) and backed-up in native (*.fsa) file format on the IBM ThinkPad 770X hard disk. Five seconds of pressure measurements per task were measured. Collection began when the participant was given the "start" signal, by pressing a pre-defined key (i.e. F3) on the portable computer keyboard, and stopped in the same manner.

3.8 DATA PROCESSING

Pressure data were organized by tasks and sensor areas within Excel spreadsheets. The average pressure per area per subject was calculated from the three repeated tests. For compatibility with the statistical analysis software, the spreadsheets were saved in accordance with STATISTICA v5.0 for MS Windows requirements (worksheet format).

3.9 RESEARCH DESIGN

Comparison of measured pressures as well as overall perceived pressure and comfort scores were performed using a repeated measures ANOVA and Tukey post-hoc tests. The level of significance was set at α =.05 for all performed statistical tests. The same approach was used for the measured distance between skate boot eyelets. Also, correlation coefficients were determined between measured pressure and perceived pressure, perceived comfort, and anthropometrics and perceived pressure and comfort. More, summary statistics were performed for foot anthropometrics.

3.9.1 Measured pressure (MP)

The experimental design involved the participants (n=18) and the following dependent and independent variables (Tables 3.3 and 3.4):

Table 3.3: The dependent variables

Dependent variable	**Levels**	**Description**	**Measurement Scale**
Measured Pressure (MP)	1	Compressive (normal) pressures from individual sensors	Numerical

Table 3.4: The independent variables

Independent variables	Levels	Description	Measurement scale
Subjects (S)	18	Recreational hockey players	Nominal
Area (A)	7	Areas around foot and ankle for sensor placement: • medial and lateral malleolae • Achilles tendon • heel (calcaneous) • instep (dorsum) • first metatarsal head • fifth metatarsal base	Nominal
Tasks (T)	6	Positions adopted by the participant: • seated • standing • dorsiflexion • plantiflexion • eversion, and • inversion	Nominal
Skate size (Sk)	3	Different skate boot sizes: regular (R), smaller (S), and larger (L)	Nominal

Data were analyzed statistically using three way repeated measure analysis of variance (ANOVA), with skate size as a repeated factor, using Statistica 5.0 software statistical application for Windows and described as:

$S_{18} \times A_7 \times T_6 \times Sk_3$ as the design model

The linear score model was:

$$x_{ijkl} = \mu + \alpha_j + \beta_k + \gamma_l + \alpha\beta_{jk} + \alpha\gamma_{jl} + \beta\gamma_{kl} + \alpha\beta\gamma_{jkl} + \varepsilon_{ijkl}$$

where:

μ = grand mean
α = effect due to placement area
β = effect due to executed tasks
γ = effect due to skate boot size
ε = error term

The factors are presented in Tables 3.5 and 3.6:

Table 3.5: Between-Subjects Factors

	Variable(s)
Area #	area1 (medial melleolus) area2 (1st metatarsal) area3 (instep) area4 (Achilles tendon) area5 (lateral malleolus) area6 (5th metatarsal) area7 (heel)
Performed task	dorsiflexion eversion inversion plantiflexion seated standing

Table 3.6: Within-Subjects Factors

Skate size	Dependent Variable
1	Regular (R)
2	Smaller (S)
3	Larger (L)

3.9.2 Overall comfort

The experimental design involved the same participants (n=18) and the following dependent and independent variables (Tables 3.7 and 3.8):

Table 3.7: The dependent variables

Dependent variable	Levels	Description	Measurement Scale
Scores (S)	1	Subjective evaluated pressure and comfort	Numerical

Table 3.8: The independent variables

Independent variables	Levels	Description	Measurement scale
Subjects (S)	18	Recreational hockey players	Nominal
Perception (P)	2	Perceived pressure (PP, in points) and perceived comfort (PC, in points) using the visual analog scale	Nominal
Skate size(Sk)	3	Different skate boot sizes: regular (R), smaller (S), and larger (L)	Nominal

For this analysis a two way repeated measure analysis of variance (ANOVA) was performed ($p<0.05$). The design symbolization model for the data set was:

$$S_{18} \times P_2 \times Sk_3$$

and the linear score model was:

$$x_{ijk} = \mu + \alpha_j + \beta_k + \alpha\beta_{jk} + \varepsilon_{ijk}$$

where:

μ = grand mean
α = effect due to overall perception
β = effect due to skate boot size
ε = error term

The factors considered for calculating the interactions between main effects and the repeated condition were the following (Tables 3.9 and 3.10)

Table 3.9: Between-Subjects Factors

Variable(s)	
Perceived comfort	PC
Perceived pressure	PP

Table 3.10: Within-Subjects Factors

Skate size	Dependent Variable	
1	Regular	R
2	Smaller	S
3	Larger	L

3.9.3 Inter-eyelets distance (ED)

For each of the tested subjects the distance between the skate boot eyelets was measured for each pair of tested skates. In the experimental design the following dependent and independent variables were used (Table 3.11)

Table 3.11: The statistical variables for inter-eyelets distance

Variable	Type	Levels	Description	Measurement Scale
Inter-eyelets distance (ED)	Dependent	1	Measured distance between skate boot eyelets	Ratio
Subjects (S)	Independent	18	Recreational hockey players	Nominal
Site (EL)	Independent	3	The predetermined sites for the inter-eyelets measurement (EL1-EL3)	Nominal
Skate size (S_k)	Independent	3	Different skate boot sizes: regular (R), smaller (S), and larger (L)	Nominal

A two-way ANOVA followed by Tukey post-hoc analysis was used to determine differences between the sites (EL1, EL2, and EL3) and skate size (S, R, L). The design model was $S_{18} \times EL_3 \times Sk_3$

and the linear score model was:

$$x_{ijk} = \mu + \alpha_j + \beta_k + \alpha\beta_{jk} + \varepsilon_{ijk}$$

where

μ = grand mean

α = effect due to measurement site

β = effect due to skate boot size

ε = error term

3.9.4 Correlations

In order to obtain regression relations between variables, correlation coefficients were calculated between measured pressure, perceived pressure, perceived comfort, and foot anthropometrics.

3.9.5 Foot anthropometrics

Foot and ankle measurements were taken from all 18 participants and recorded on individual files. Presented bellow is the summary table of all ten measured foot and ankle sites (Table 3.12)

Table 3.12: Anthropometrics summary statistics (in mm; n=18)

Foot and ankle sites	Mean	Minimum	Maximum	Std.Dev.
Foot breadth (FB)	98	92	108	4
Maximum heel breadth (MHB)	63	49	72	5
Inter malleolae breadth (ImB)	72	64	83	4
First toe length (1TL)	258	236	275	10
Metatarsale tibial length (Mt.t.L)	188	170	200	9
Metatarsale fibulare length (Mt.f.L)	162	153	172	5
Sphyrion fibulare height (S.f.H)	71	60	89	8
Medial malleolus height (M.t.H)	89	77	104	7
Metatarsal-phalangeal joint girth (MG)	250	224	270	10
Mid-arch girth (MidG)	256	235	288	13

4. RESULTS

To determine the effect of main factors (area of sensors placements, performed task, and different skate sizes) on measured pressures, an analysis of variance (ANOVA) with repeated measures (RM) was performed (α =0.05). Tukey post-hoc means comparison was selected to identify specific factor group differences. Correlation coefficients were calculated to identify the linear relationships between measured pressures, perceived pressure and perceived comfort as well as between measured pressure and anthropometrics. Differences between the skate boot eyelets distance were also analyzed. In this order, the following text will present the findings from these analyses.

4.1 MEASURED PRESSURE (MP)

The interface pressure between the hockey skate boot and the skater's foot was measured by means of individual pressure sensors placed in discreet locations around the foot and ankle regions. The grand mean of the measured pressure (MP) of all measures combined (i.e. "all factors collapsed") was 33.0 KPa (± 1.1 SE) or 4.8PSI (± 0.2 SE), which represents the average pressure value (for fit). The average pressure of sensors within a defined specific area (or anatomical regions) was calculated and used for subsequent statistical analysis.

As expected with regards to skate sizes, pressure decreased with increased skate size (Figure 4.1). RM ANOVA determined that the measured pressures were significantly different between all sizes ($p<0.05$). In general, there was greater pressure acting around the foot and ankle in a ½ size smaller skate boot compared with the regular size (36.1 to 34.2 KPa), and lesser pressure for the ½ larger size tested (28.7 KPa). One may say that the 34.2 KPa pressure value represents the numerical expression for the fit of the ice hockey skate boots.

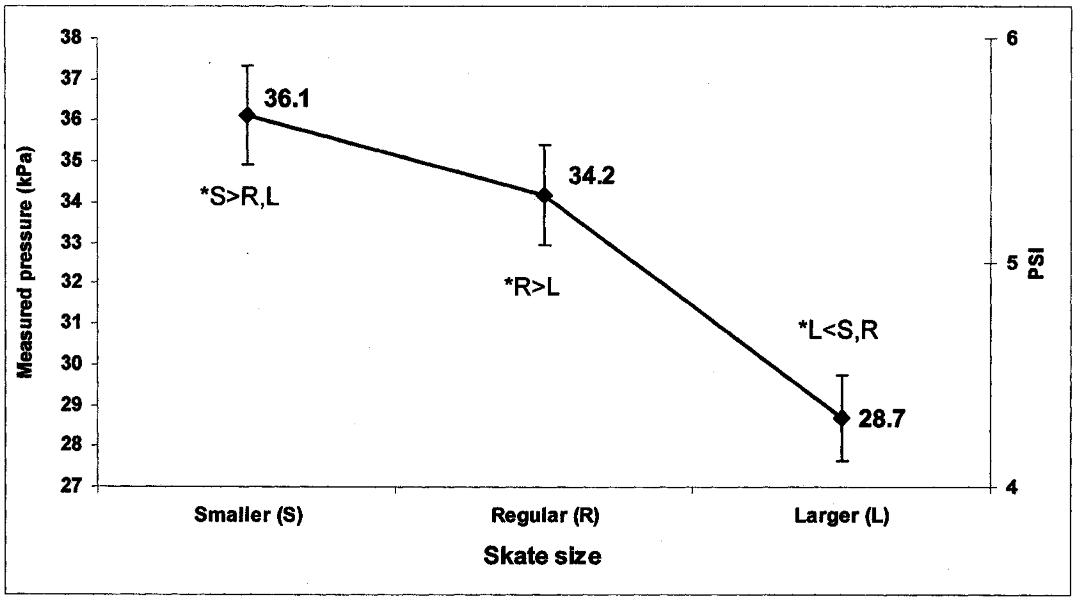


Fig.4.1: Mean pressure by skate size (* $p<0.05$)

For the area of sensor placement, substantially different pressure values were recorded on the foot-boot interface. Generally, greater values were observed around the medial malleolus and metatarsals (1st and 5th), whereas lesser pressures where seen at the Achilles tendon, heel, and lateral malleolus. The most compressed area was around the fifth metatarsal (60.5 KPa) which was significantly different from the medial malleolus (46.8 KPa), instep (38.0 KPa), and the first metatarsal (34.8 KPa) (Figure 4.2). Lesser pressures were, on the other hand, present at the Achilles tendon (8.3 KPa).

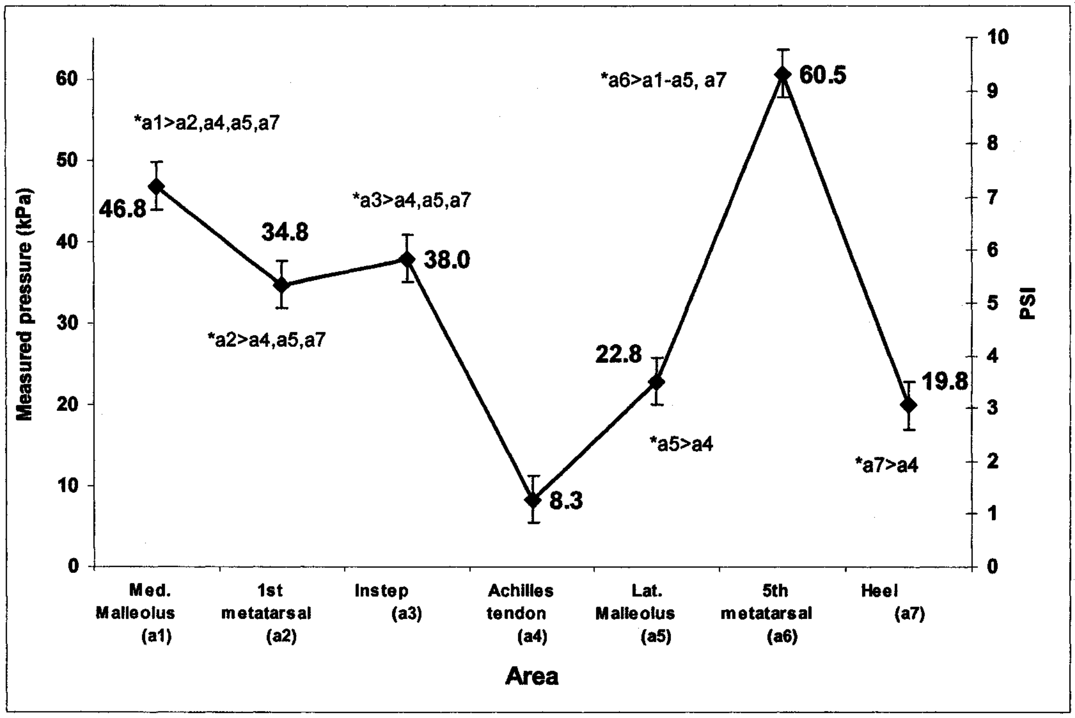


Fig.4.2: Mean pressure by area (* $p<0.05$)

With regards to the specific tasks, lowest pressure values were observed for the non-weight-bearing position (seated: 12.7 KPa). Pressures significantly increased for the weight-bearing tasks (dorsiflexion, plantiflexion, eversion, inversion; Figure 4.3). From seated to standing the mean pressures almost doubled (23.7 KPa). This change in pressure was measured around the foot and ankle and not at the plantar level, so it was only due to the medial-lateral spread of the foot and concurrent deformation of the boot upon weight-bearing. The other weight-bearing tasks elicited significantly greater mean pressures (33.6 during plantarflexion to 44.1 KPa during dorsiflexion) than during either seated and standing conditions.

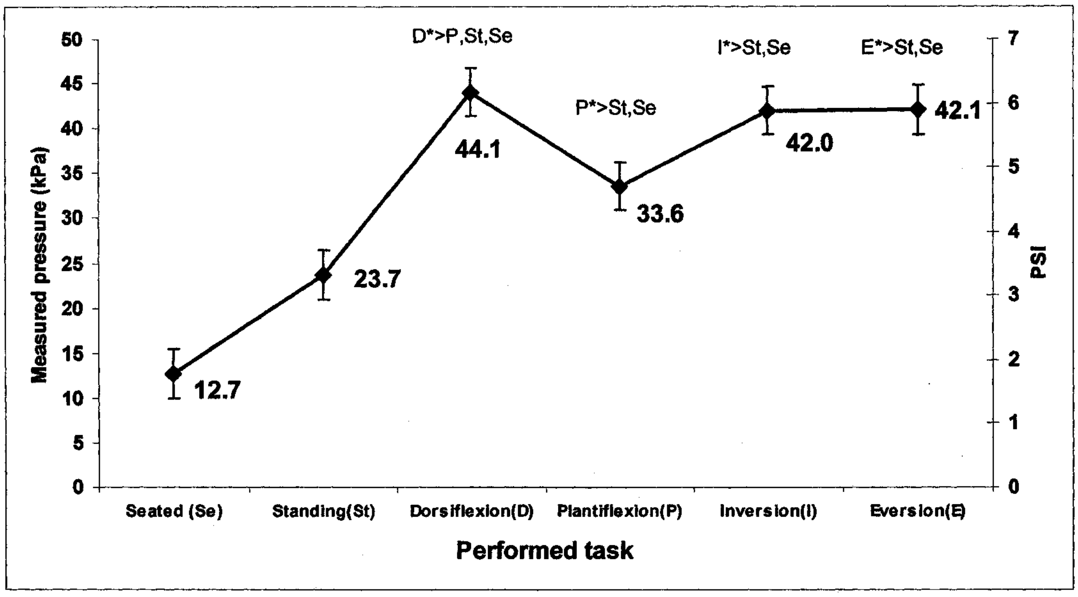


Fig.4.3: Mean pressure by tasked performed (* p<0.05)

In addition to the above findings, interactions between the three main factors (area, task, and size) were evaluated. Tests of hypotheses for both between and within-subjects effects concluded that all factors and their interactions were significant ($p<0.01$) with the exception of Size x Task ($p=.196$, in terms of Greenhouse-Geisser and Huynh-Feldt Epsilon adjustments).

For instance, significant interactions between Area x Size were observed (Figure 4.4, Table 4.1). The MPs by area were similar to the pattern presented in Figure 2. In general, higher pressures were recorded predominantly on the medial side and the fifth metatarsal on the lateral side. Within areas, significant differences ($p<0.05$) by size were seen, with greater pressure for the ½ smaller in comparison to the ½ larger sizes. As well, in some instances the pressures for regular sized skates were different from the ½ size smaller (i.e. medial malleolus and fifth metatarsal) and ½ larger (i.e. first metatarsal). No effect of size differences were detected for the areas around the Achilles tendon and lateral malleolus. In one instance, pertaining to the area around the 5th metatarsal base, the regular size pressure was greater than both smaller and larger sizes.

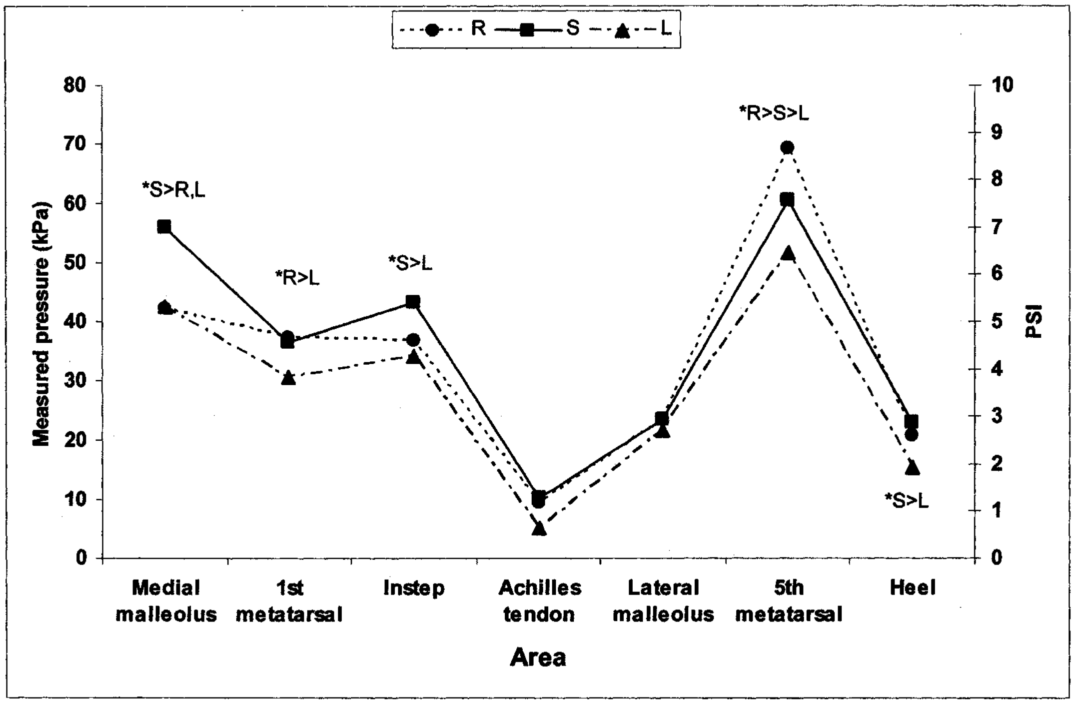


Fig.4.4: Interaction effects between sensors area and skate boot size (* p<0.05)

Table 4.1: Means and Tukey grouping for significant area and size interactions (p<0.05) by descending order

Area number	Skate size	Tukey grouping*	Mean KPa	Mean PSI
Medial malleolus	Smaller	**A**	56.0	8.1
	Regular	**B**	42.1	6.1
	Larger	**B**	42.5	6.2
First metatarsal	Regular	**A**	37.4	5.4
	Smaller	**A B**	36.4	5.3
	Larger	**B**	30.5	4.4
Instep	Smaller	**A**	43.2	6.3
	Regular	**A B**	36.8	5.3
	Larger	**B**	34.1	4.9
Fifth metatarsal	Regular	**A**	69.3	10.1
	Smaller	**B**	60.5	8.8
	Larger	**C**	51.7	7.5
Heel	Smaller	**A**	23.0	3.3
	Regular	**A B**	21.0	3.0
	Larger	**B**	15.4	2.2

(* A, B and C are significantly different groups)

A greater divergence from the general fit pattern (Figure 4.2) was recorded for the interactions between Area x Task. Some general trends were observed in measured pressures. During the tasks of eversion and dorsiflexion, the average MP for all areas was at least 20 KPa whereas in other tasks not all areas sustained high pressures at the instant task execution (Figure 4.5, Table 4.2). Minimal or zero values were measured at the Achilles tendon while seated (non-weight bearing) and during standing, inversion, plantiflexion. A noticeable tendency for almost all tasks was to mark increased or peak values around the fifth metatarsal. Most often, the MP of at least one weight bearing task was significantly different from the MP in seated position. Other task specific differences were observed for the medial malleolus, first metatarsal, instep, lateral malleolus, and the fifth metatarsal.

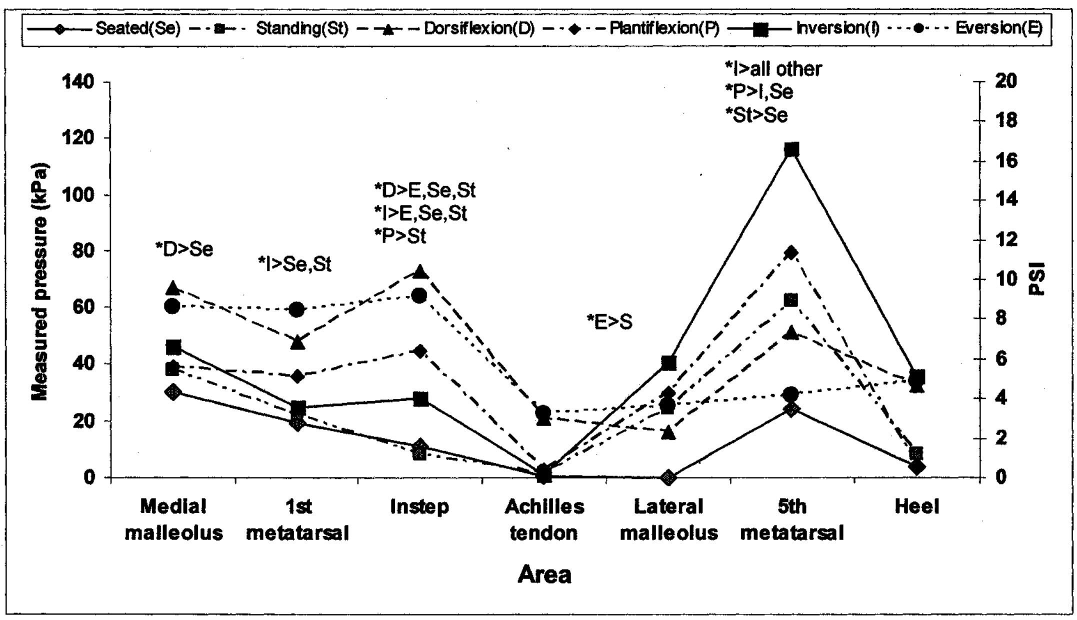


Fig.4.5: Interaction effects between sensors area and task (* p<0.05)

Table 4.2: Means and Tukey grouping for significant area and task interactions ($p<0.05$) by descending order

Area number	Task	Tukey grouping*	Mean KPa	Mean PSI
Medial malleolus	Dorsiflexion	**A**	66.6	9.7
	Eversion	**A B**	60.1	8.7
	Inversion	**A B**	46.5	6.8
	Plantiflexion	**A B**	39.0	5.7
	Standing	**A B**	38.3	5.6
	Seated	**B**	30.5	4.4
First metatarsal	Eversion	**A**	59.2	8.6
	Dorsiflexion	**A B**	47.8	6.9
	Plantiflexion	**A B**	35.6	5.2
	Inversion	**A B**	24.8	3.6
	Standing	**B**	22.3	3.2
	Seated	**B**	19.1	2.8
Instep	Dorsiflexion	**A**	72.9	10.6
	Eversion	**A**	63.8	9.3
	Plantiflexion	**A B**	44.5	6.5
	Inversion	**B C**	27.9	4.1
	Seated	**B C**	10.8	1.6
	Standing	**C**	8.3	1.2
Lateral malleolus	Inversion	**A**	41.0	6.0
	Plantiflexion	**A B**	29.8	4.3
	Eversion	**A B**	25.2	3.7
	Standing	**A B**	24.5	3.6
	Dorsiflexion	**A B**	16.1	2.3
	Seated	**C**	0.0	0.0
Fifth metatarsal	Inversion	**A**	116.4	16.9
	Plantiflexion	**B**	79.3	11.5
	Standing	**B C**	62.5	9.1
	Dorsiflexion	**B C D**	51.4	7.5
	Eversion	**C D**	29.4	4.3
	Seated	**D**	24.0	3.5

(* A, B, C and D are significantly different groups)

For Task x Size interactions, the seated (non-weight bearing) situation resulted in the lowest MPs (Figure 4.6, Table 4.3). For example, the fit pattern showed that between seated and standing, the amount of pressure around the foot and ankle increased about 1.5 times. Further, as would be expected, the ½ size smaller had the greatest MPs at the "foot-boot" interface. For all three sizes, the lowest MPs were while seated (e.g. 12.5 KPa, regular size) and the greatest MPs while in dorsiflexion (48.5 KPa, smaller size). Considering the tasks where significant differences were observed (i.e. standing, dorsiflexion, plantiflexion, and eversion), in 50 % of the cases both the ½ smaller and regular sizes exerted greater pressure than the larger size.

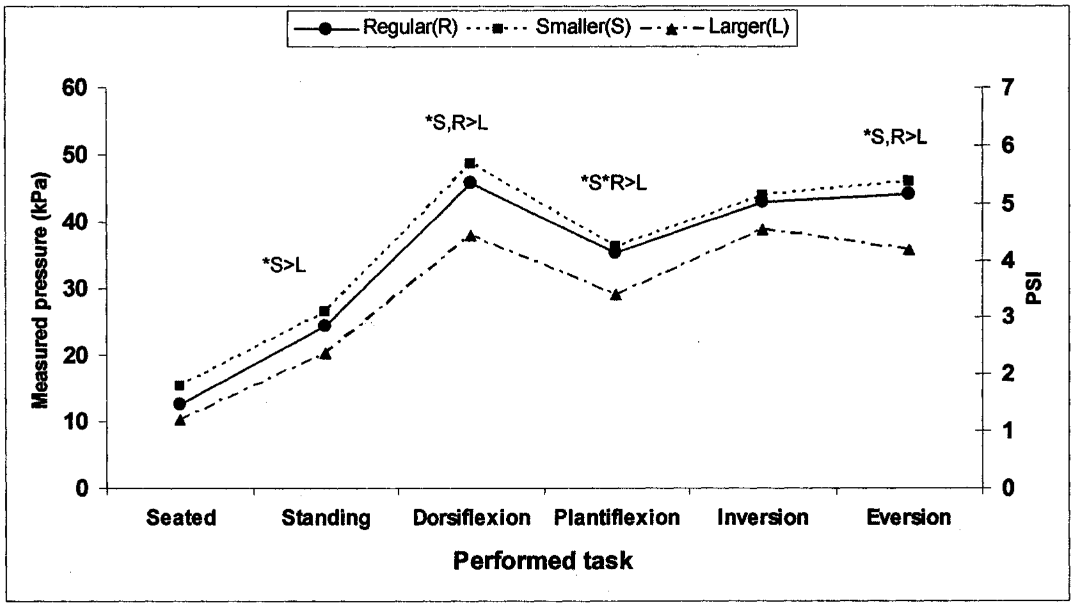


Fig.4.6: Interaction effects between the task and skate sizes (*p<0.05)

Table 4.3: Means and Tukey grouping for significant performed task and skate size interactions (p<0.05) by descending order

Task	Skate size	Tukey grouping*	Mean KPa	Mean PSI
Standing	Smaller	**A**	26.5	3.9
	Regular	**A B**	24.4	3.5
	Larger	**B**	20.1	2.9
Dorsiflexion	Smaller	**A**	48.5	7.0
	Regular	**A**	45.7	6.6
	Larger	**B**	38.0	5.5
Plantiflexion	Smaller	**A**	36.3	5.3
	Regular	**A**	35.4	5.1
	Larger	**B**	29.1	4.2
Eversion	Smaller	**A**	46.2	6.7
	Regular	**A**	44.2	6.4
	Larger	**B**	35.9	5.2

(*A and B are significantly different groups)

Further analysis identified that some multiple interactions between the three factors occurred. Specifically, significant different MPs were seen during inversion and plantarflexion tasks around the medial malleolus and fifth metatarsal (Table 4.4).

Table 4.4: Means and Tukey grouping for significant area, task, and size interactions (p<0.05) by descending order

Area #	Task	Skate size	Tukey grouping*	Mean	
				KPa	PSI
Medial malleolus	**Iversion**	Smaller	**A**	61.2	8.9
		Larger	**B**	41.0	6.0
		Regular	**B**	37.4	5.4
Fifth metatarsal	**Plantarflexion**	Regular	**A**	88.5	12.8
		Smaller	**A B**	83.8	12.1
		Larger	**B**	65.6	9.5
	Iversion	Regular	**A**	135.3	19.6
		Smaller	**B**	108.9	15.8
		Larger	**B**	105.1	15.2

(*A and B are significantly different groups)

Given the density of information presented above, it may be difficult to appreciate the observations of relevance with regards to the issue of "fit". Hence, with the goal of improving clarity, the following figures (4.7 to 4.12) will present the same information but in separated categories by task.

In the seated position (Figure 4.7), a medio-lateral pressure imbalance about the ankle was observed i.e. substantial MPs at the medial malleolus were observed (25 to 38.7 KPa) compared to the lateral malleolus (0 KPa). In order of magnitude, MPs were greatest at the medial malleolus (25 to 38.7 KPa), then followed by the 5th metatarsal (19 to 27.2 KPa), 1st metatarsal (16.1 to 22 KPa), instep (9 to 13.2 KPa), and heel (2.2 to 5.4 KPa). Minimal MPs were seen at the Achilles tendon (0.4 to 1.2 KPa) and lateral malleolus (0 KPa). A consistent size effect was evident, though not statistically significant, for all areas with greater MPs (5% to 30% above regular) for the -½ size and less MPs for the +½ size (5% to 10% below regular).

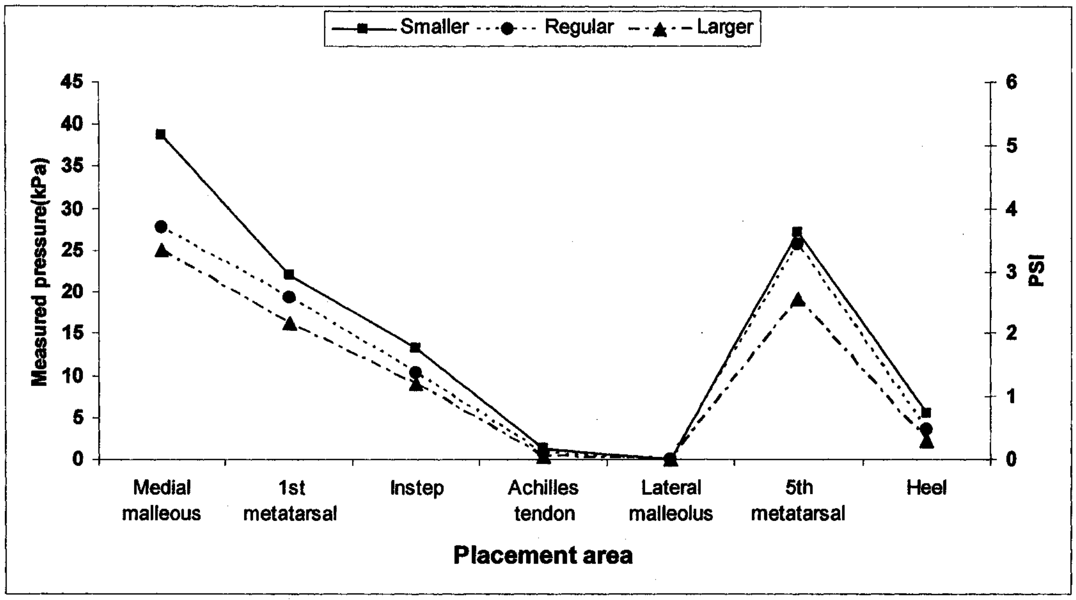


Fig.4.7: Area x Size interactions by Task: Seated.

The second task was standing. Notably, in comparison to the seated position MPs increased 2 to 3 times in order of magnitude around the lateral malleolus and 5th metatarsal while at the other areas MPs did not change substantially (Figure 4.8). Notice that size did not have a consistent effect on MPs when standing. Size did not have a statistically significant effect on MPs while standing.

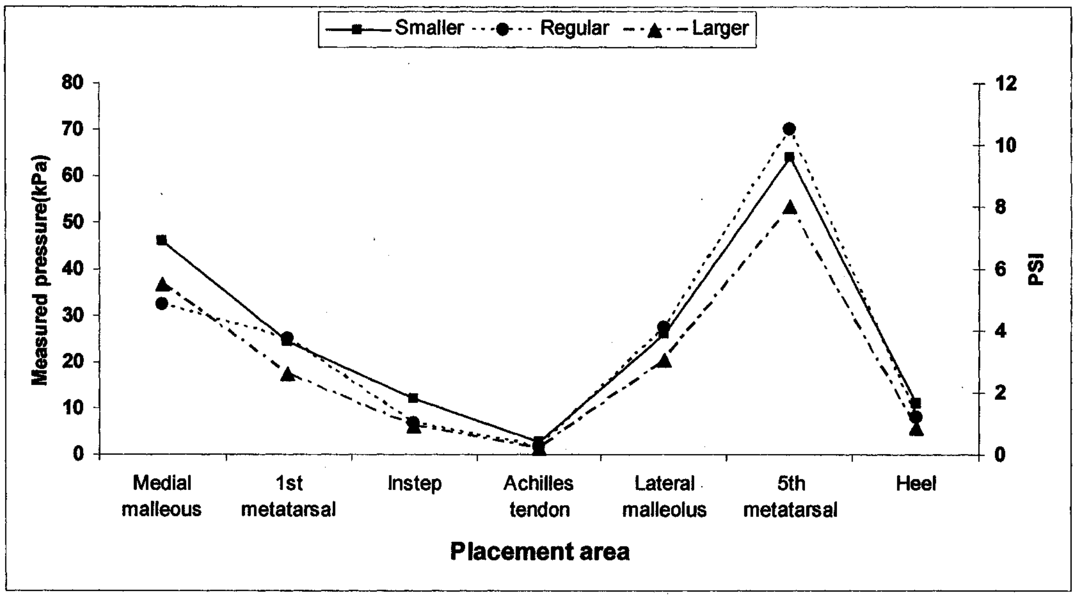


Fig.4.8: Area x Size interactions by Task: Standing.

The third task to review in the order was dorsiflexion (Figure 4.9). A change in MPs distribution pattern across areas was evident in comparison to seated and standing. In particular, MPs at the medial malleolus (61.5 to 75.1 KPa), 1st metatarsal (41.1 to 52.9 KPa), and instep (67.2 to 83.8 KPa) were 2.5 2.6, 9.3 KPa and 1.9, 2.4 to 13.7 times greater in order of magnitude, respectively. Note also the first instance of MPs at the Achilles tendon area (13.8 to 25.7 KPa) and the two fold increase in MPs magnitude at the heel. Around the ankle, MPs at the medial malleolus were 4 times greater than at the lateral malleolus. With regard to size, the MPs for the -½ size were generally greatest, except for the 1st and 5th metatarsal and the Achilles tendon. Size did not have a statistically significant effect on MPs while dorsiflexed ($p \geq 0.05$).

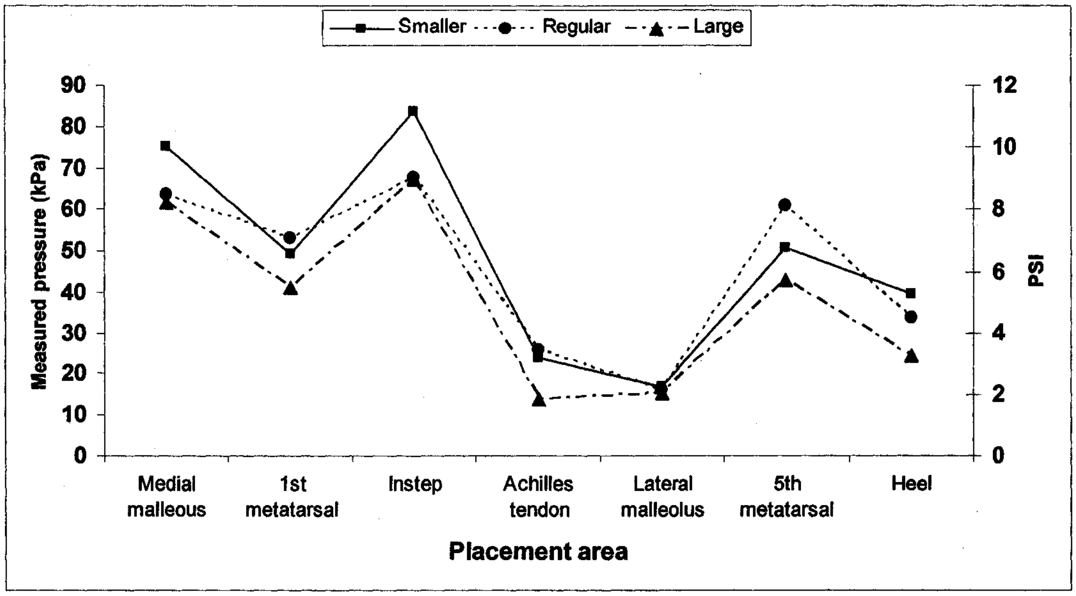


Fig.4.9: Area x Size interactions by Task: Dorsiflexion.

During plantarflexion (Figure 4.10), when compared to standing, MPs increased at the 5th and 1st metatarsals, and instep by 1.2, 1.8 and 6.6 times in order of magnitude, respectively. Again in comparison to standing, similar medial and 1.3 times greater lateral malleolae MPs were seen. In comparison with dorsiflexion, MPs were greater at the medial malleolus, 1st metatarsal, instep, Achilles tendon and heel by 10.1 to 28.1 KPa. In contrast, plantarflexion MPs were less than dorsiflexion MPs at lateral malleolus and 5th metatarsal by 11.7 to 22.9 KPa. With regards to size, the MPs for the -½ size were general greatest, except for 1st and 5th metatarsal and the lateral malleolus. In general, size did not have a statistically significant effect on MPs while plantarflexed with the noted exception of the 5th metatarsal, where MPs of the -½ size and regular size skates were significantly greater (18.2 KPa) than the +½ size.

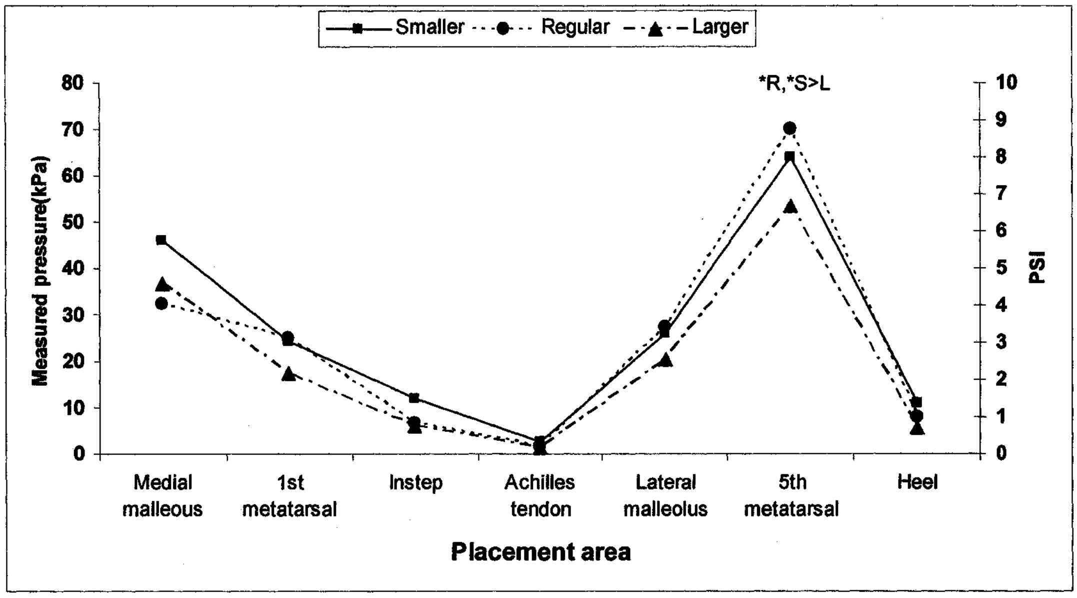


Fig.4.10: Area x Size interactions by Task: Plantarflexion. (* $p<0.05$)

Inversion (Figure 4.11) displayed a similar fit pattern as standing though the former had substantially greater MPs by 10 to 20 KPa (with the exception of the Achille tendon where MPs were below 2.7 KPa for both tasks). In some instances, MPs were substantial greater such as at the heel (plus 25.1 to 29.5 KPa), 5th metatarsal (plus 44.8 to 65.4 KPa, or 1.7 to 2.0 times larger), and lateral maleolae (1.5 to 1.9 times greater). Medial malleolus MPs were similar. With regards to size, the MPs for the -½ size were general greatest, except for the 5th metatarsal. In general, size did not have a statistically significant effect on MPs while inverted with the noted exceptions of (1) the medial malleous, where MPs of the -½ size were significantly greater (approximately 20 KPa) than the regular and +½ size, and (2) the 5th metatarsal, where MPs of the regular sized skate were significantly greater (approximately 26.3 KPa) than both the -½ and +½ sizes.

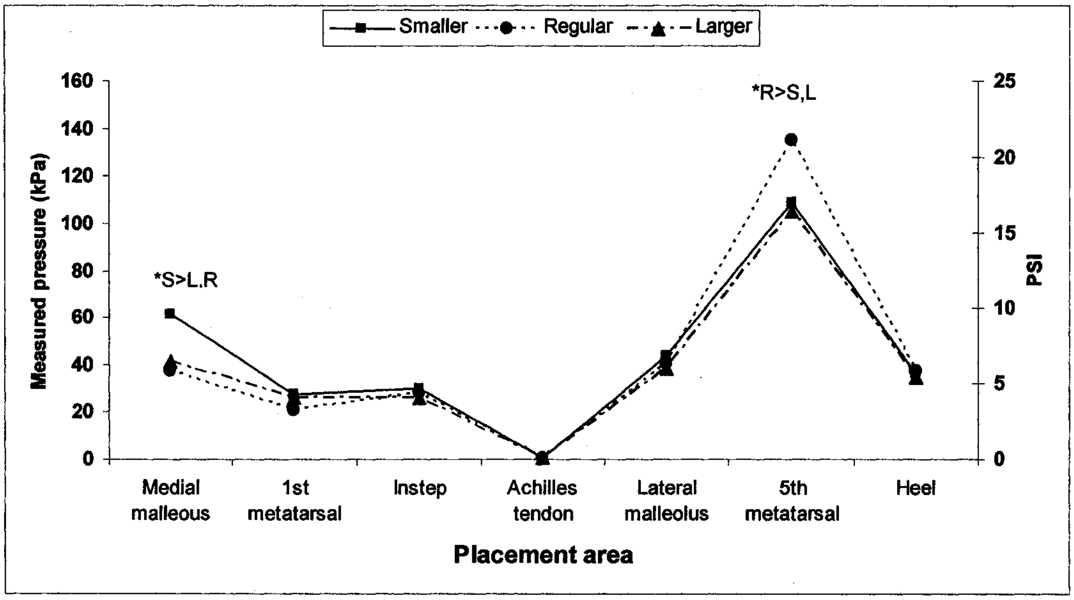


Fig.4.11: Area x Size interactions by Task: Inversion. (* $p<0.05$)

Eversion presented a similar pattern with dorsiflexion with lower MPs at the first metatarsal and lateral malleolus. Most of the higher pressure values were concentrated evenly on the medial side of the foot and ankle, while on the lateral side the pressure level was lower but also even distributed (Figure 4.12). The highest pressure value (72.6 KPa) out of all tasks was recorded at the instep, for the smaller skate boot size.

In comparison to standing, MPs increased considerably at the medial malleolus, 1st metatarsal, instep, heel as well as at the Achilles tendon by 1.5 to 16 times in order of magnitude. Medial malleolus MPs were approximately three times as large as at the lateral malleolus. In contrast, 5th metatarsal pressures were substantially lower than during standing (32.4 KPa versus 53.4 KPa). With regards to size, the MPs for the -½ size were general greatest, except for 1st and 5th metatarsal and the lateral malleolus. In general, size did not have a statistically significant effect on MPs while inverted ($p \geq 0.05$).

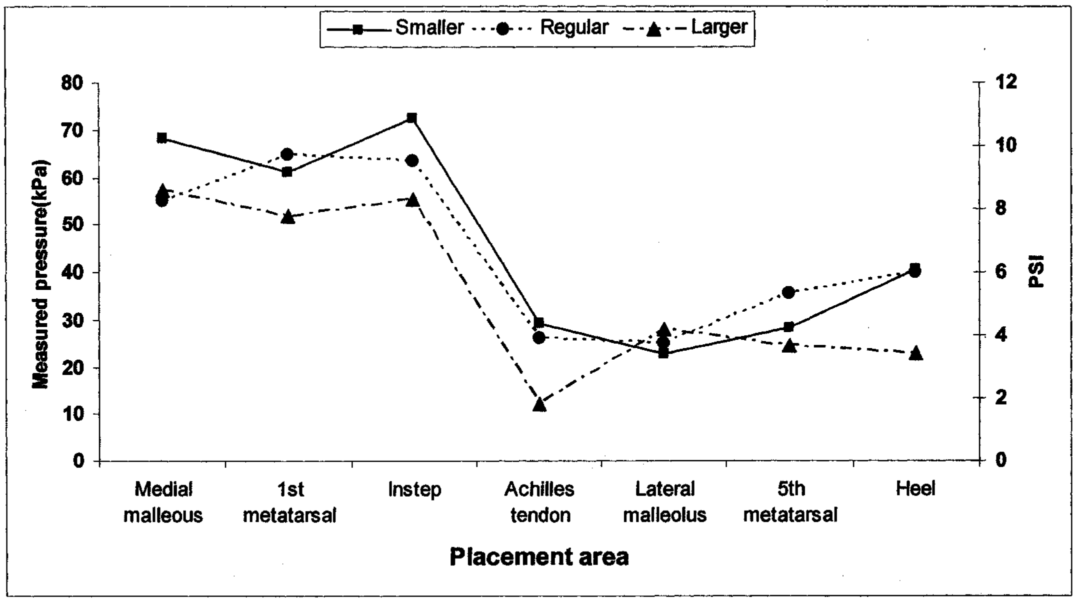


Fig.4.12: Area x Size interactions by Task: Eversion.

In summary, the fit profiles or patterns presented above describe the interactions between all factors (sensors area placement, task performed, and skate boot size). With the exception of the eversion task, there was a consistently high amount of pressure measured around (posterior) to the 5th metatarsal for the weight-bearing tasks. Sizing tended to have an inverse relationship with MP with notable exceptions during plantarflexion and inversion. Eversion presented a unique fit profile, with greatest pressures applied to medial malleolus, 1st metatarsal, and instep. Finally, the least pressure was seen at the Achilles tendon except during dorsiflexion and eversion.

4.2 PERCEIVED PRESSURE AND PERCEIVED COMFORT

A multi-univariate analysis of variance with repeated factors was performed for dependent variables of perceived pressure (PP) and perceived comfort (PC) scores obtained from the visual analog scale (VAS).

In order, the first item evaluated was the toe box. Regular size pressures were subjectively perceived of being 42.4 (out of 150; where 0 was "No pressure at all" and 150 was "The most perceived pressure") and 99.0 comfort points were attributed to the stated skate size (out of 150; where 0 was "Not comfortable at all" and 150 was "Most comfortable condition imaginable"). For both evaluations (Figure 4.13), perceived pressures and comfort, the -½ size was perceived to apply significantly more pressure at the toe box and was significantly more uncomfortable compared with the other two skate sizes (Table 4.5). Regular skate size was, on the other hand, perceived as the most comfortable, but not significantly different with the +½ larger size (97.9 comfort points).

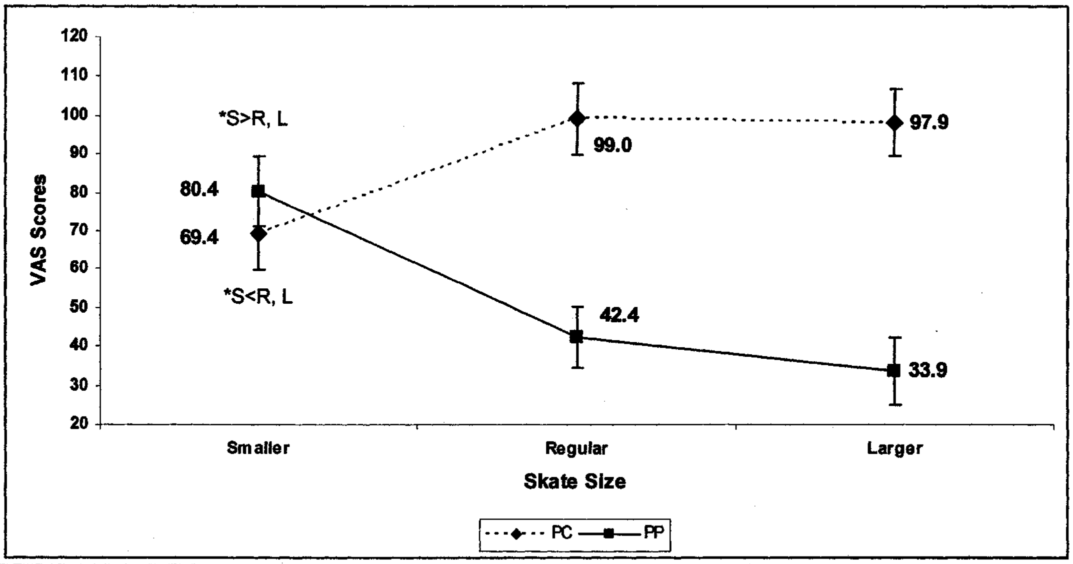


Fig.4.13: Toe box: interaction between skate sizes for the perceived pressure (PP) and perceived comfort (PC).
(*$p<0.05$)

Table 4.5: Toe box: means and Tukey grouping for significant skate boot sizes interactions (p<0.05)

Perception	Skate size	Tukey grouping*	Mean	Standard error
Perceived pressure	Smaller	A	80.4	9.1
	Regular	B	42.4	7.8
	Larger	B	33.9	8.6
Perceived comfort	Regular	A	99.0	9.4
	Larger	A	97.9	8.7
	Smaller	B	80.4	9.7

(* A and B are significantly different groups)

The next item on the questionnaire was the tendon guard. The -½ size PC was perceived to be significantly more uncomfortable (102.3±7.4) compared with the other two skate sizes rated both the same (116 comfort points). In the case of PP (Figure 4.14, Table 4.6), the least amount of pressure (31.0±5.3) was perceived in the regular skate size, with no difference compared with the +½ size (33.76.8), but significantly different with the smaller one (45.9±7.7).

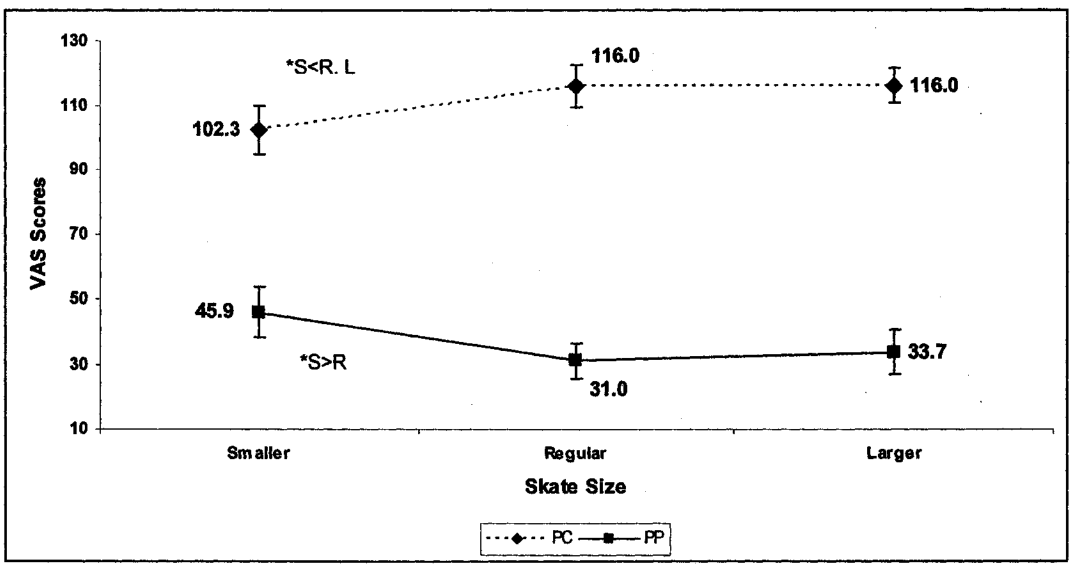


Fig.4.14: Achilles tendon ('tendon guard'): interaction between skate sizes for the perceived pressure (PP) and perceived comfort (PC).
(*p<0.05)

Table 4.6: Achilles tendon: means and Tukey grouping for significant skate boot sizes interactions ($p<0.05$)

Perception	Skate size	Tukey grouping*	Mean	Standard error
Perceived pressure	Smaller	A	45.9	7.7
	Larger	AB	33.7	6.8
	Regular	B	31.0	5.3
Perceived comfort	Larger	A	116.0	5.3
	Regular	A	116.0	6.6
	Smaller	B	102.3	7.4

(* A and B are significantly different groups)

The third reviewed item on the questionnaire was the top of the foot (dorsum of the foot). The most uncomfortable was the -½ size (85.7±8.2 PC points), followed by the regular size (95.6±7.4), and significantly different ($p<0.01$) from the larger size (100.7±7.8). Significantly increased PP magnitudes (69.4±6.8) acted on dorsum of the foot (Figure 4.15) with the -½ size compared (Table 4.7) with the other skate sizes (55.8±7.1 for regular size and 47.8±5.9 for +½ size).

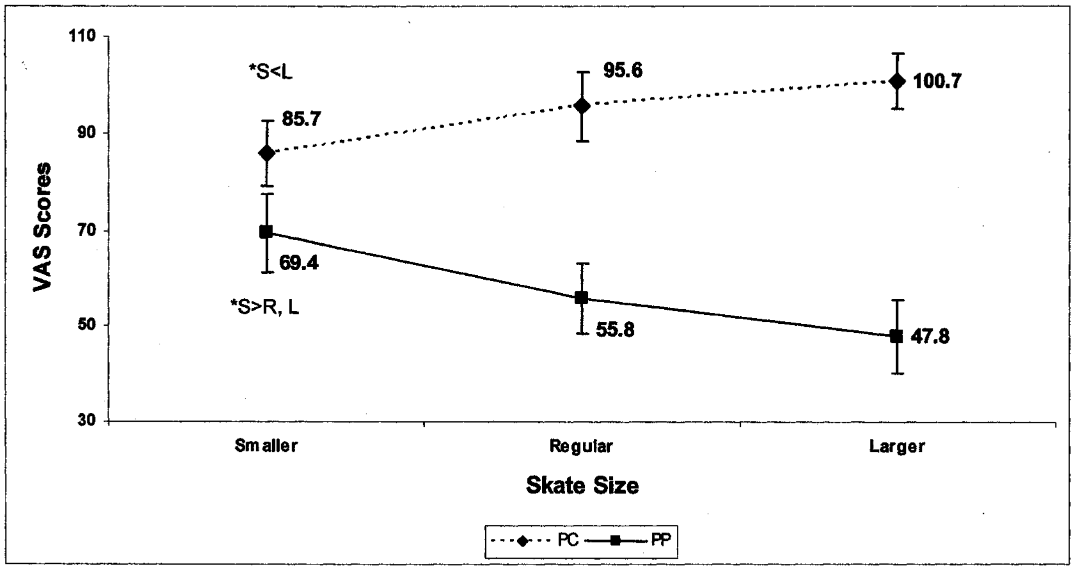


Fig.4.15: Dorsum of the foot('top of the foot'): interaction between skate sizes for the perceived pressure (PP) and perceived comfort (PC). (*$p<0.01$)

Table 4.7: Dorsum of the foot: means and Tukey grouping for significant skate boot sizes interactions (p<0.01)

Perception	Skate size	Tukey grouping*	Mean	Standard error
Perceived pressure	Smaller	A	69.4	6.8
	Regular	B	55.8	7.1
	Larger	B	47.8	5.9
Perceived comfort	Larger	A	100.7	7.8
	Regular	AB	95.6	7.4
	Smaller	A	85.7	8.2

(* A and B are significantly different groups)

The fourth item assessed was the magnitude of pressure and discomfort perceived at the tongue level ('instep', Figure 4.16). The PC was rated (Table 4.8) with 104.1±8.3 for the regular size, with the highest score for the larger size (112.1±5.8) which was significantly more comfortable than the -½ size (93.3±8.4 comfort points). The highest pressure magnitude was perceived while wearing the -½ size (56.9±8.9) significantly different than the +½ evaluated size (36.9±7.0). There was no significant difference between the latest and the stated skate size (44.5±9.0).

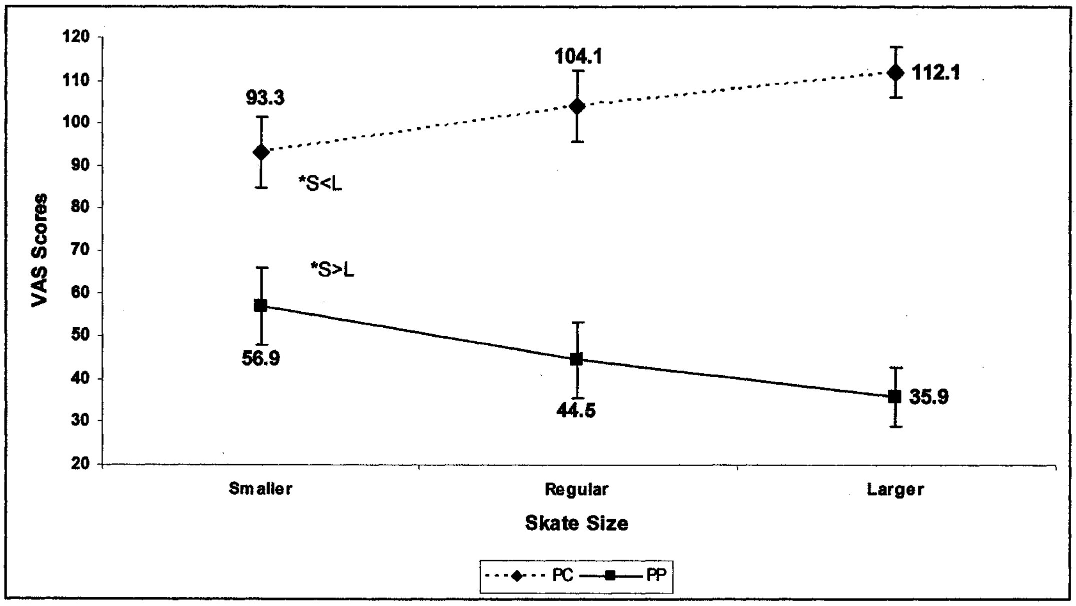


Fig.4.16: Instep ('tongue'): interaction between skate sizes for the perceived pressure (PP) and perceived comfort (PC).
(*p<0.05)

Table 4.8: Instep: means and Tukey grouping for significant skate boot sizes interactions (p<0.05)

Perception	Skate size	Tukey grouping*	Mean	Standard error
Perceived pressure	Smaller	A	56.9	8.9
	Regular	AB	44.5	9.0
	Larger	B	36.9	7.0
Perceived comfort	Larger	A	112.1	5.8
	Regular	AB	104.1	8.3
	Smaller	B	93.3	8.4

(* A and B are significantly different groups)

The fifth rated foot area (Figure 4.17) was the plantar surface ('under the foot'). Even though the +½ size was rated the most comfortable (106.3±5.2 comfort points), it was not significant different in comparison with the regular size (98.5±7.5). The least significantly comfortable was the smaller skate size (89.3 comfort points). Highest pressure magnitude (66.4±7.7) was rated on the -½ size, which was not significantly different (Table 4.9) than the regular size (61.3), but different in comparison with the larger skate size (47.2±6.2).

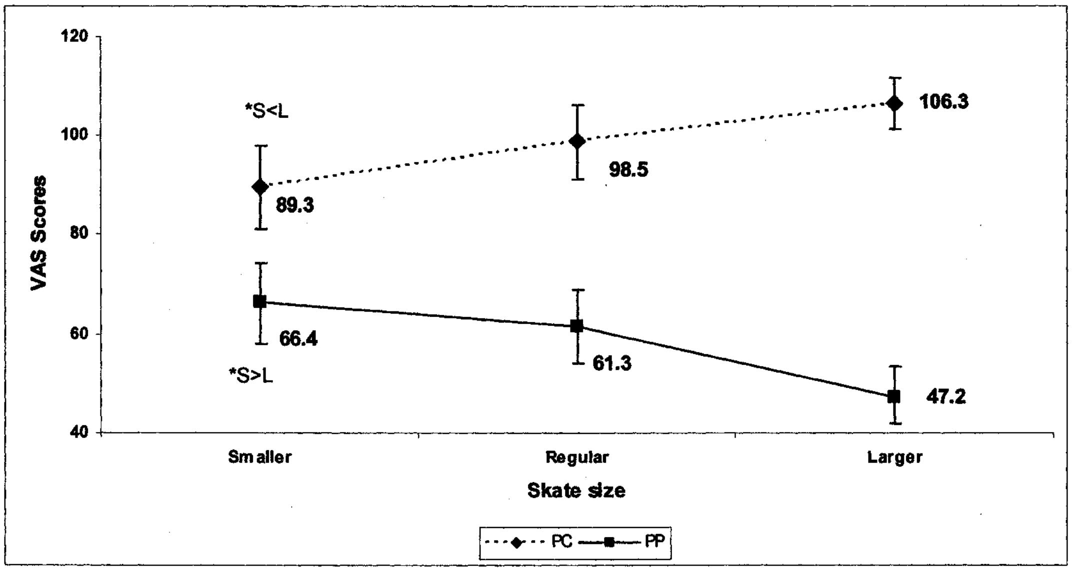


Fig.4.17: Plantar surface('under the foot'): interaction between skate sizes for the perceived pressure (PP) and perceived comfort (PC).
(*p<0.05)

Table 4.9: Plantar surface: means and Tukey grouping for significant skate boot sizes interactions ($p<0.05$)

Perception	Skate size	Tukey grouping*	Mean	Standard error
Perceived pressure	Smaller	A	66.4	7.7
	Regular	AB	61.3	7.5
	Larger	B	47.2	6.2
Perceived comfort	Larger	A	106.3	5.2
	Regular	AB	98.5	7.5
	Smaller	B	89.3	7.7

(* A and B are significantly different groups)

Next, the PP and PC scores at the medial malleolus ('inside ankle') level were assessed (Figure 4.18). The least amount of comfort points were given to the smaller skate size (76.1±9.3), followed in order by the regular (87.6±9.6), and the +½ size (98.6±7.6). More, there were significant differences (Table 4.10) between how comfortable the larger size was perceived compared with the -½ size. No differences were detected between the normal and +½ and -½ sizes. For PP, the most pressure was felt acting upon the medial malleolus while testing the -½ size (87.4±8.2) which had a significantly different magnitude compared with both, regular and +½ size (79.2±8.2 and 64.6±7.4 respectively).

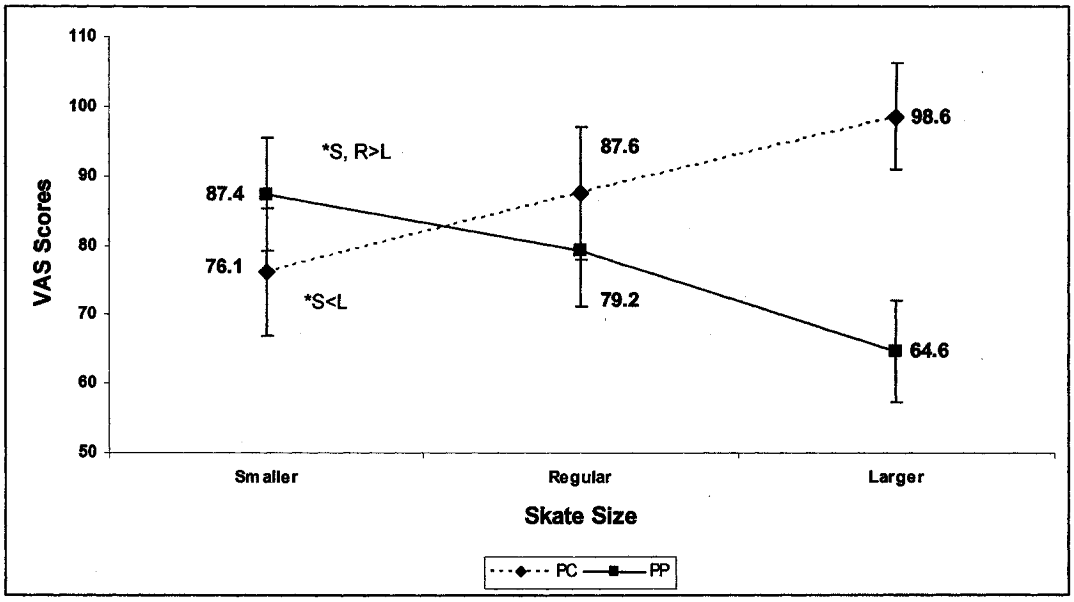


Fig.4.18: Medial malleolus ('inside ankle'): interaction between skate sizes for the perceived pressure (PP) and perceived comfort (PC). (*$p<0.05$)

Table 4.10: Medial malleolus: means and Tukey grouping for significant skate boot sizes interactions ($p<0.05$)

Perception	Skate size	Tukey grouping*	Mean	Standard error
Perceived pressure	Smaller	A	87.4	8.2
	Regular	A	79.2	8.2
	Larger	B	64.6	7.4
Perceived comfort	Larger	A	98.6	7.6
	Regular	A B	87.6	9.6
	Smaller	B	76.1	9.3

(* A and B are significantly different groups)

The seventh evaluated area around the foot and ankle was the lateral malleolus ('outside ankle'). The magnitude of discomfort (Figure 4.19) was significantly different between -½ and +½ sizes (74.3±9.5, 92.4±8.4 respectively). Even though the +½ size was evaluated the most comfortable, there was no significant differences between it and the regular skate size (84.8±10.4) regardless with comfort points (Table 4.11). Similarly, the magnitude of perceived pressure was significantly higher perceived with the -½ size (80.4±8.9) in comparison with the larger one (62.2±8.3). There was no difference calculated between the latest and the regular skate size (64.1±8.4).

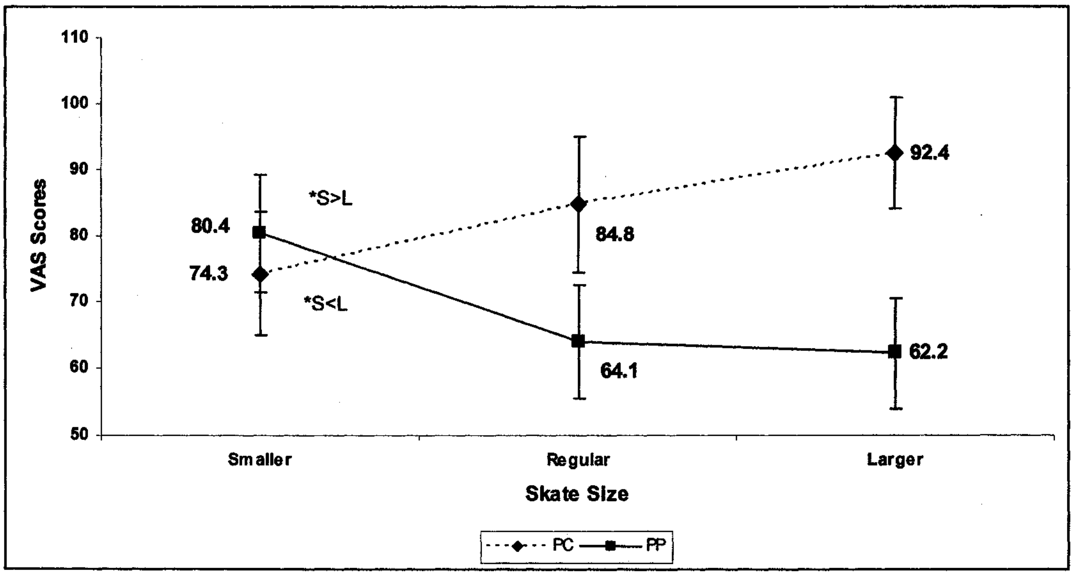


Fig.4.19: Lateral malleolus ('outside ankle'): interaction between skate sizes for the perceived pressure (PP) and perceived comfort (PC). (*$p<0.05$)

Table 4.11: Lateral malleolus: means and Tukey grouping for significant skate boot sizes interactions ($p<0.05$)

Perception	Skate size	Tukey grouping*	Mean	Standard error
Perceived pressure	Smaller	A	80.4	8.9
	Regular	AB	64.1	8.4
	Larger	B	62.2	8.3
Perceived comfort	Larger	A	92.4	8.4
	Regular	AB	84.8	10.4
	Smaller	B	74.3	9.5

(* A and B are significantly different groups)

The second last evaluated area was the inside arch (Figure 4.20). With a difference of only two comfort points, there was no subjective difference between the regular (97.2±10.2) and the larger skate sizes (99.2±9.6), but the -½ size was significantly different (87.0±10.3, $p<0.05$) than the +½ size (Table 4.12). The magnitude of perceived pressure that acted upon this foot area reached its highest value (76.0±8.4) when -½ size was tested, significantly different than regular (64.2±7.5) and +½ size (62.1±7.9).

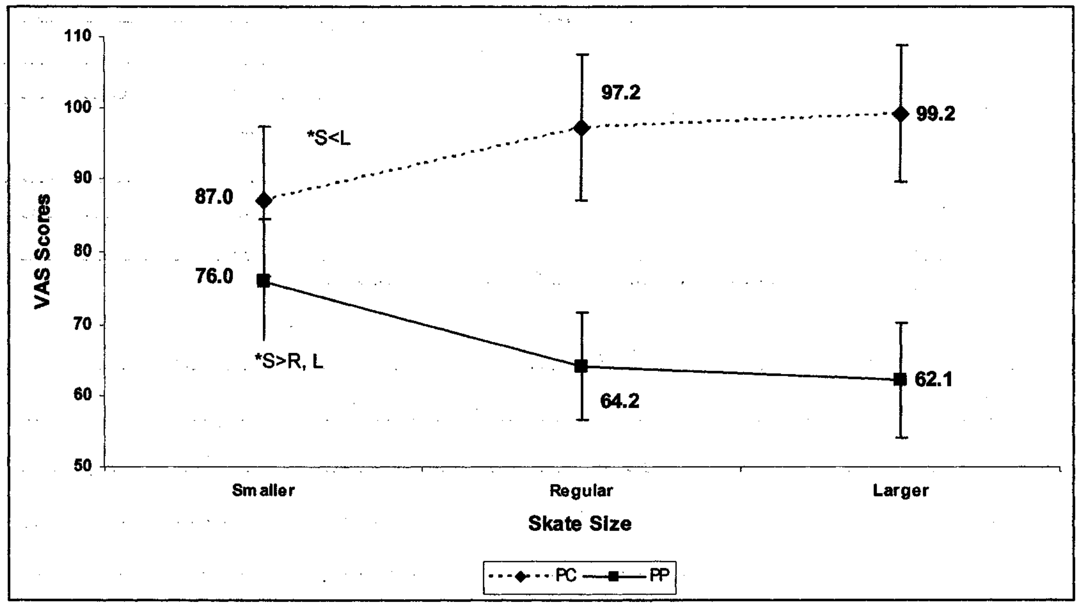


Fig.4.20: Inside arch: interaction between skate sizes for the perceived pressure (PP) and perceived comfort (PC).
(*$p<0.05$)

Table 4.12: Inside arch: means and Tukey grouping for significant skate boot sizes interactions ($p<0.05$)

Perception	Skate size	Tukey grouping*	Mean	Standard error
Perceived pressure	Smaller	A	76.0	8.4
	Regular	B	64.2	7.5
	Larger	B	62.1	7.9
Perceived comfort	Larger	A	99.2	9.6
	Regular	AB	97.2	10.2
	Smaller	B	87.0	10.3

(* A and B are significantly different groups)

The last item to review in order is overall perceived pressure and comfort. In general, the average PC score was 85.2 ± 7.0 and the average PP 69.3 ± 7.0. With regards to size, as expected, PP increased with decreasing skate where as PC increased with skate size (Figure 4.21). For the -½ size, both PP and PC, were significantly different than regular and +½ size scores.

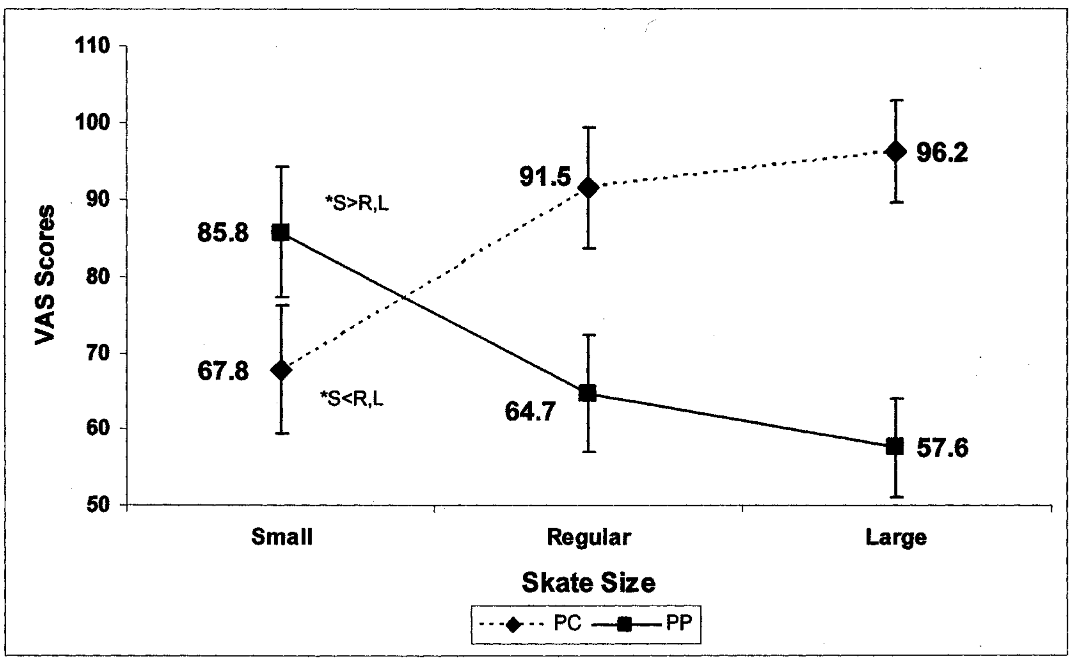


Fig.4.21: Interaction between skate sizes for the overall perceived pressure (PP) and perceived comfort (PC).
(*p<0.05)

Even though the +½ size was evaluated the most comfortable and with the least pressure around the "foot-boot" interface, the subjective ratings between +½ size and regular skate size were not different significantly (Table 4.13).

Table 4.13: Means and Tukey grouping for significant skate boot sizes interactions (p<0.05)

Perception	**Skate size**	**Tukey grouping***	**Mean**
Perceived pressure	Smaller	**A**	85.8
	Regular	**B**	64.7
	Larger	**B**	57.6
Perceived comfort	Larger	**A**	96.2
	Regular	**A**	91.5
	Smaller	**B**	67.8

(* A and B are significantly different groups)

4.3 CORRELATIONS

In order to evaluate the relationship between dependent variables, correlation coefficients were calculated. Variable relations were computed between measured pressure (MP), perceived pressure (PP) and comfort (PC), as well as between MP and foot anthropometrics. The correlation values for MP and subjective PP for performed tasks is shown in Table 4.14. The highest calculated correlation coefficient was r=0.29 (p<.001) as a weak relationship between the two variables in inversion. A weak relationship was found between MP and PC, with a small inverse relation (r = -0.14, p= 0.03).

Table 4.14 Correlation coefficients for PP and MP

PP	**r**	**r²**	**p**
Seated	0.19	0.04	<0.001
Standing	0.26	0.07	<0.001
Dorsiflexion	0.07	0.01	<0.30
Plantiflexion	0.08	0.01	<0.22
Inversion	**0.29**	0.08	<0.001
Eversion	0.00	0.00	<0.99

In Table 4.15 are presented the relations calculated between MP and PP/PC relatively to the sensors area placement. Most of the relations are weak except the ones between MP and PC. An inverse medium correlation (r=-0.30) was found at the medial malleolus level and a direct one (r=0.32) around the instep.

Table 4.15: Correlation coefficients between MP and PP and PC (n=54)

Variable	Area	r	r^2	SE	p
PP	Medial malleolus	0.08	0.01	4.75	0.57
	Instep	-0.05	0.00	4.87	0.73
	Achilles tendon	-0.16	0.02	3.88	0.25
	Lateral malleolus	--	--	4.98	--
PC	Medial malleolus	***-0.30***	0.09	5.15	0.03
	Instep	***0.32***	0.10	4.42	0.02
	Achilles tendon	-0.05	0.00	3.80	0.71
	Lateral malleolus	--	--	5.45	--

(-- data had no variance)

Strong correlation coefficient was found between the overall PP and PC with a calculated r = -0.63 (p<0.001, n=54). An inverse relationship was evident such that as PP increased around the foot and ankle, the PC decreased. With a calculated r^2=0.40, the linear equation was found to be *y=-0.5703x + 117.9* (see also Figure 4.22).

Similar, inverse correlations were found between PP and PC in the other eight areas around the foot and ankle (Table 4.16). Strong relationships were found between PP and PC around the medial and lateral malleolus (r=-0.76 and r=-0.65), inside arch, instep, toe box, and tendon guard and relatively low relationships around the plantar surface and dorsum of the foot (r=-0.40 and r=-0.33 respectively).

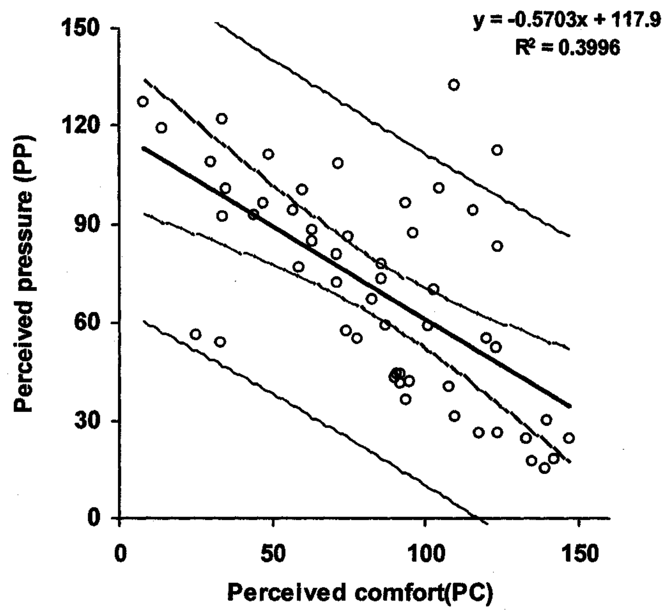


Fig.4.22: Scatter plots, regression line, and descriptive equation for the inverse relation between perceived pressure and comfort.

Table 4.16: Correlations between perceived comfort (PC) and pressure (PP) around the foot and ankle and the equations describing the linear regression (n=54)

Area	r	r^2	r^2 adjusted	SE	p	Equation
Lateral malleolus ('inside ankle")	-0.65	0.42	0.41	29.34	<0.001	y=-0.7174x+142.7
Inside arch	-0.63	0.40	0.39	32.94	<0.001	y=-0.7917x+147.841
Medial malleolus ('outside ankle')	-0.76	0.57	0.56	26.49	<0.001	y=-0.8256x+140.7089
Achilles tendon ('tendon guard')	-0.52	0.27	0.25	24.11	<0.001	y=-0.507x+130.1389
Toe box	-0.57	0.33	0.31	33.95	<0.001	y=-0.5717x+118.6342
Instep ('tongue')	-0.59	0.35	0.34	26.45	<0.001	y=-0.5358x+127.6931
Dorsum of the foot ('top of the foot')	-0.33	0.11	0.09	26.83	<0.01	y=-0.2767x+109.9581
Plantar surface ('under the foot')	-0.40	0.16	0.14	28.50	<0.01	y=-0.3986x+121.2903

Relations were analyzed between MP and foot anthropometrics. Table 4.17 displays the correlation matrix for the sensors placement area, performed task, skate boot sizes and foot anthropometrics. The highest calculated value was r= -0.17, an insignificant inverse relation between foot breadth and skate size (smaller and larger).

Table 4.17: Correlation matrix for measured pressure and foot anthropometrics

	Area	Task	R	S	L	FB	MHB	ImB	1TL	Mt.t.L	Mt.f.L	S.f.H	M.t.H	MG	MidG
Area	1.00	-0.01	0.01	-0.03	-0.03	0.00	-0.06	0.00	-0.04	-0.05	-0.02	-0.02	0.05	-0.06	-0.09
Task	-0.01	1.00	0.25	0.24	0.25	-0.04	0.01	-0.01	-0.02	-0.01	0.00	-0.02	0.00	-0.03	0.01
R	0.01	0.25	1.00	0.87	0.83	-0.15	0.05	-0.02	-0.05	-0.04	0.03	-0.01	0.04	-0.08	0.01
S	-0.03	0.24	0.87	1.00	0.89	-0.17	0.01	-0.11	-0.10	-0.09	0.03	-0.03	0.09	-0.13	-0.04
L	-0.03	0.25	0.83	0.89	1.00	-0.17	0.02	-0.09	-0.11	-0.10	0.04	-0.04	0.07	-0.12	-0.05
FB	0.00	-0.04	-0.15	-0.17	-0.17	1.00	-0.03	0.27	0.24	0.00	-0.03	0.05	0.10	0.65	-0.15
MHB	-0.06	0.01	0.05	0.01	0.02	-0.03	1.00	0.04	0.05	0.05	0.08	0.20	-0.14	0.47	0.63
ImB	0.00	-0.01	-0.02	-0.11	-0.09	0.27	0.04	1.00	0.12	0.42	-0.25	-0.30	-0.28	0.34	0.21
1TL	-0.04	-0.02	-0.05	-0.10	-0.11	0.24	0.05	0.12	1.00	0.83	0.35	0.45	0.10	0.53	0.30
Mt.t.L	-0.05	-0.01	-0.04	-0.09	-0.10	0.00	0.05	0.42	0.83	1.00	0.10	0.12	-0.20	0.35	0.31
Mt.f.L	-0.02	0.00	0.03	0.03	0.04	-0.03	0.08	-0.25	0.35	0.10	1.00	0.48	0.40	-0.11	0.05
S.f.H	-0.02	-0.02	-0.01	-0.03	-0.04	0.05	0.20	-0.30	0.45	0.12	0.48	1.00	0.61	0.29	0.19
M.t.H	0.05	0.00	0.04	0.09	0.07	0.10	-0.14	-0.28	0.10	-0.20	0.40	0.61	1.00	0.03	-0.33
MG	-0.06	-0.03	-0.08	-0.13	-0.12	0.65	0.47	0.34	0.53	0.35	-0.11	0.29	0.03	1.00	0.43
MidG	-0.09	0.01	0.01	-0.04	-0.05	-0.15	0.63	0.21	0.30	0.31	0.05	0.19	-0.33	0.43	1.00

where:

FB = Foot breadth
MHB = Maximum heel breadth
ImB = Inter malleolus breadth
1TL = First toe length
Mt.t.L = Metatarsale tibial length
Mt.f.L = Metatarsale fibulare length
S.f.H = Sphyrion fibulare height
M.t.H = Medial malleolus height
MG = Metatarsal-phalangeal joint girth
MidG = Mid-arch girth

Similarly, the relationship between the MP around the areas of sensors placement and foot and ankle measurement was assessed. Insignificant and weak correlations were found between the variables (Table 4.18). In some cases the correlation was direct (e.g. medial malleolus and its height: r=0.34, the highest coefficient) and in other indirect (e.g. lateral malleolus and foot breadth: r=-.031, 1st metatarsal and foot breadth or lateral malleolus and metatarsal-phalangeal joint girth: r=-30).

Table 4.18: Correlation coefficients between MP and foot anthropometrics (n=324)

Area	FB	MHB	ImB	1TL	Mt.t.L	Mt.f.L	S.f.H	M.t.H	MG	MidG
Medial malleolus	**-0.12**	-0.08	**-0.12**	**-0.21**	**-0.12**	**0.19**	0.02	***0.34***	**-0.21**	**-0.25**
1st metatarsal	***-0.30***	**0.13**	**-0.17**	-0.02	-0.03	**0.16**	-0.06	-0.01	**-0.17**	-0.05
Instep	**-0.19**	**0.12**	-0.03	-0.06	-0.02	-0.04	-0.04	0.06	-0.01	0.05
Achilles tendon	-0.09	0.05	-0.05	0.01	0.05	0.00	-0.10	0.04	-0.05	-0.10
Lateral malleolus	**-0.31**	**-0.27**	**-0.19**	-0.01	0.01	0.07	0.09	**0.14**	***-0.30***	**-0.28**
5th metatarsal	**-0.19**	**0.10**	-0.07	**-0.16**	**-0.15**	-0.04	-0.02	-0.09	-0.09	**0.10**
Heel	0.03	0.09	0.06	-0.09	-0.09	0.00	-0.07	0.09	-0.01	0.09

4.4 ANTHROPOMETRICS

Foot and ankle measurements were taken from all 18 participants and recorded on individual files. Simple summary statistics were calculated for the foot lengths, highs, girths, and breadths. Presented below is the summary table of all ten measured foot and ankle sites (Table 4.19):

Table 4.19: Anthropometrics summary statistics (n=18, all measurements were in millimetres)

Foot and ankle sites	Code	Mean	Minimum	Maximum	St.Dev.
Foot breadth	FB	98	92	108	4
Maximum heel breadth	MHB	63	49	72	5
Inter malleolus breadth	ImB	72	64	83	4
First toe length	1TL	258	236	275	10
Metatarsal tibial length	Mt.t.L	188	170	200	9
Metatarsal fibulare length	Mt.f.L	162	153	172	5
Sphyrion fibulare height	S.f.H	71	60	89	8
Medial malleolus height	M.t.H	89	77	104	7
Metatarsal-phalangeal joint girth	MG	250	224	270	10
Mid-arch girth	MidG	256	235	288	13

4.5 INTER-EYELETS DISTANCE

The distances between laces eyelets were obtained from the three different sites (EL1 to EL3) by direct measurement. These distances ranged from 88 to 100 mm. Eyelet lace spacing varied with site and size, though not in a uniform manner. For example, the distance between eyelets (Figure 4.23) increased from smaller to regular and larger size in the case of EL1 (toe box edge).

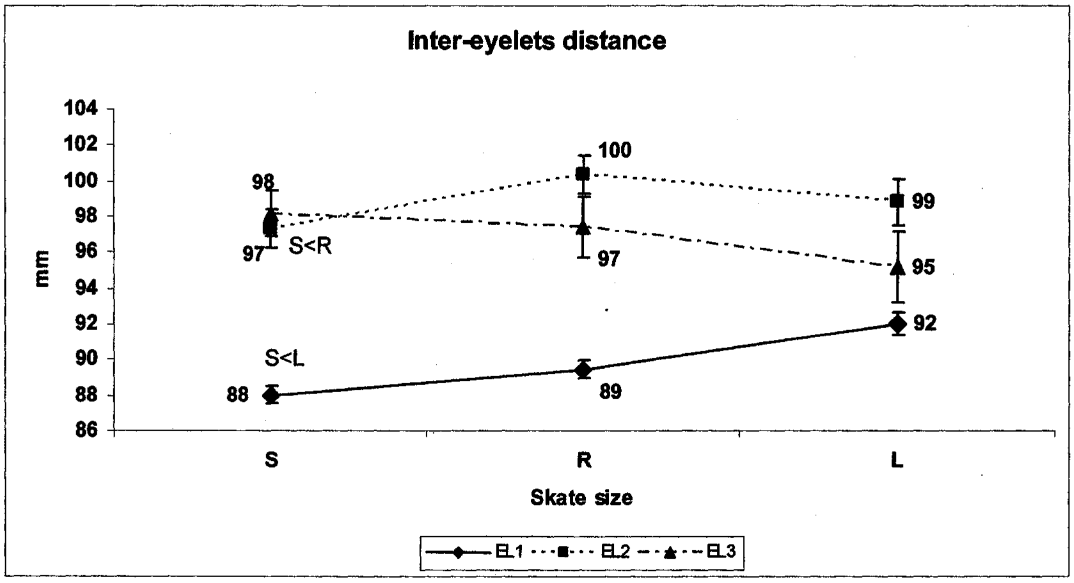


Fig.4.23: Measured distance dynamics between lace eyelets at three different levels ($p<0.05$)

At the instep level (EL2), it increased from -½ size to regular than slightly decreased (with 1mm in average) to +½ size. For EL3, the distance reduced from smaller to regular and larger size. Significant differences (Table 4.20) were found between -½ and +½ size at EL1 level ($p<0.001$), and -½ and regular size at EL2 level ($p<0.05$).

Table 4.20: Means and Tukey grouping for the inter-eyelets distance measurement by ascending order ($p<0.05$)

Site	Skate size	Distance (mm)	Tukey grouping*	SE	n
EL1	S	88	A	0.47	18
	R	89	A	0.51	18
	L	92	B	0.61	18
EL2	S	97	A	0.89	18
	L	99	A	1.04	18
	R	100	B	1.06	18
EL3	S	98	n/a	1.31	16**
	R	97	n/a	1.70	16**
	L	95	n/a	1.96	16**

(* A and B are significantly different groups; ** Participants chose not to lace up at this boot site)

5. DISCUSSION

The stated purposes of the present study were to (1) quantify the fit in ice hockey skate boots by direct measurement, (2) subjectively assess the pressure perceived and the comfort by means of a questionnaire, and (3) determine any relevant relations between foot and ankle anthropometrics with the measured pressure at foot-boot interface. The protocols and the equipment used were successful in addressing these issues.

The hypothesis that there would be significant differences in measured pressure between the skate sizes tested was found to be tenable. In general, the MPs were significantly different between all skate boot sizes ($p<0.05$). Around the foot and ankle the pressure magnitude was 36.1 KPa in the -½ size, 34.2k Pa in the regular size, and 28.7 KPa in the +½ size.

The hypothesis that there would be significant differences in MP values at the 'foot-boot' interface between sensors placement area was found to be in part true. Out of seven areas where the sensors were placed, the pressure magnitude was significantly different ($p<0.05$), ranging from 60.5 KPa at the 5th metatarsal to 8.3 KPa the Achilles' tendon. There were no significant differences ($p<0.05$) between 1st metatarsal and instep (34.8 and 38.0 KPa) and lateral malleolus and the heel (22.8 and 19.8 KPa, respectively).

The hypothesis that there would be significant differences in the pressure magnitude between tasks (non-weight and weight bearing) was tenable. The MP almost doubled from seated to standing (from 12.7 to 23.7 KPa, but not significantly different, $p\geq0.05$). All the other weight-bearing performed tasks (dorsiflexion, plantiflexion, eversion, and inversion) applied significantly more pressure at the foot-boot interface in comparison with seated and/or standing. During dorsiflexion, significantly more pressure was recorded than for all the other remaining tasks.

The hypothesis that there would be significant interactions between placement area, performed task, and skate sizes were found to be true. These interactions were mixed and are summarized as follows:

- significant interactions between area and skate size were observed. Higher pressure values were recorded predominantly on the medial side of the foot and ankle and the 5th metatarsal on the lateral side. In some instances, the pressure for -½ size was significantly different ($p<0.05$) than the regular or larger sizes, or both, regular and +½ size. Around the 5th metatarsal, the regular size pressure was greater than both -½ and +½ sizes;
- for the interaction between area and task, most often, the MP of at least one weight bearing task was significantly different ($p<0.05$) from seated. Most of the tasks marked an increase or peak values around the 5th metatarsal;
- for the performed task and skate size interactions, the non-bearing (i.e. seated) situation resulted in the lowest pressure magnitude. Considering all the tasks, in 50% of the cases, both the -½ and regular size exerted more pressure at the foot-boot interface than the +½ size;
- for the interaction between area, task, and size, significant differences ($p<0.05$) were found around the 5th metatarsal while dorsiflecting between regular and -½ size together and the +½ size and during inversion, between regular size and the smaller and larger skate sizes. Also, the -½ size was significantly higher in pressure values than regular and +½ size around the medial malleolus in inversion.

The hypothesis that perceived comfort and pressure would be affected by the skate size is tenable ($p<0.05$). For the subjectively evaluated foot areas, most often the smaller skate size was found to apply more pressure or being more uncomfortable compared with the +½ size (62.5%), regular size (6.2%), or both regular and +½ size. Regarding the overall perceived pressure and perceived comfort, the -½ size was significantly different than the regular and +½ size scores. Even though the +½ size was evaluated as the most comfortable and having the lowest pressure magnitude, the subjective ratings between +½ size and regular size were not significantly different ($p\geq0.05$). A strong, inverse relationship was evident between PP and PC around the foot and ankle. In all subjective evaluation scores, it was found that while the PP was increasing, the PC was decreasing (r from -0.65 to -0.33).

The hypothesis that there would be a strong relationship between the MP magnitude and subjectively evaluated comfort and pressure was not tenable, and the H_0 was accepted. There was no relationship between MP and PP/PC (highest value was r=0.29).

The hypothesis that there would be a relationship between foot/ankle anthropometrics and measured pressure, and foot anthropometrics and perceived pressure and comfort was found not to be true. An insignificant inverse relation (r=-0.17) was found between foot breadth and skate size (±½ size).

The hypothesis that the eyelets lace spacing varies with site and skate boot size was found to be partial true. The spacing varied with site and size, though not in a uniform manner. Significant differences were found between smaller and larger sizes at EL1 level ($p<0.001$), and -½ and regular size at EL2 level ($p<0.05$).

The following text explores in more detail the obtained results and speculates about the mechanisms acting at the foot-boot interface.

5.1 MEASURED PRESSURE

5.1.1 MP by skate sizes

Few studies have attempted to determine the fit around the foot and ankle. (Witana *et al.*, 2004; Jordan and Bartlett,1995). In the present study, each subject tested the three pairs of skates starting with their stated (reference) skate size, followed randomly by half size smaller or larger. Relatively to these procedures, the following observations should be considered:

- the objective value that describes the general "fit" of a regular sized skate boot was 34.2 KPa (overall measured pressure). This represents the first reported mechanical estimate of fit to be reported. It provides a benchmark for fit;

- despite randomized and one-way "blinded" testing order, skate size was easily distinguished by subjects. Perceived differences in fit by skate sizes were most evident for the -½ size. MPs were sensitive to and corresponded with the above. In accordance to Spatial Summation Theory (SST; Hardy & Oppel, 1937), potentially a larger skin area was stimulated. Further, increased active pressure corresponded to greater sensory response. Combined together, a greater induced discomfort was perceived;
- pressure values were collected from discrete areas around the foot and ankle. Intentionally, the plantar surface of the foot was not considered. All sensors combined, the effective area covered by the 30 sensors was approximately 30 cm^2. This represented only a small fraction of the total surface area of the foot.

5.1.2 MP by area placement

Pressure magnitudes varied substantially about the foot and ankle. Possible explanations for these include the following:

- intentional design parameters exist to shield specific areas from contact pressures; for example, about the Achilles tendon the heel counter is reinforced and its semicircular shape effectively bridges this area;
- furthermore, some areas are intentional designed to maximize contact pressures presumably to optimize fit i.e. prevent slippage between the foot and boot an thereby offer greater control in skate position and stability. For instance, high MPs were observed about the 1^{st} and 5^{th} metatarsal heads, presumably to help "lock-in" the forefoot to the boot. However, given the substantial anthropometric variation in forefoot region (compared with the relatively small variation in heel width within a selected shoe size), the right fit in this region is difficult to achieve for all people.

Correspondingly, the main complaint from the subjects was the increased amount of discomfort perceived especially around the 5th metatarsal;

- through the tension adjustment system (i.e. lacing) there is a persistent contact at the maleolae 'bony' landmarks. The larger amount of pressure on the medial malleolus compared with the lateral malleolus could be due to the observed tendency of the hockey player in adopting a pronate foot position while in weight bearing stance;
- the instep may be the most 'adjustable' interface within the skate boot upper. The increased MP may be due to the sum of the following:
- player lacing style, which has the tendency of minimizing the skate boot wobbling;
- the materials used for tongues, which is the most flexible and soft compared with all the other skate boot parts;
- the foot dorsiflexion imposed position assumed by the skate boot construction.

5.1.3 MP by performed task

At the plantar surface, it is self-evident that pressure would increase from sitting (non weight-bearing) to standing (weight-bearing). Similarly, the MPs showed clearly that, when measured around the foot and ankle, in most cases a significant increase was elicited from sitting to standing. In large part, this may be due to the medial-lateral spread of the foot and concurrent deformation of the boot upper upon weight bearing. Maximum medial-lateral foot spread occurred during dorsiflexion (44.1 KPa), followed closely by foot eversion and inversion. Plantiflexion exerted the least pressure at the foot-boot interface compared with all other weight bearing tasks.

5.1.4 MP – interaction area placement and skate sizes

As noted early, the MPs by area were similar to the pattern presented in fig.4. The intriguing aspect was why the regular size displayed higher pressure values only at the metatarsal-phalangeal joint? One explanation may reside in the degree of rigidity of the boot toe cap. The regular size can accommodate fully the forefoot; for the smaller size this happened probably only partially, losing contact with some with the sensor found more proximal. In the case of the larger size, the gap space between toe cap and forefoot was big enough to leave the forefoot loose with a reduced amount of pressure.

In a study of dorsal shoe pressures by Jordan & Bartlett (1995), they found the pressure magnitude around the dorsum of the foot of being 40 KPa (peak value, during walking). These values are pretty close to the pressure found acting upon the foot-boot interface in the present study, which was 36.8 KPa (for all tasks collapsed).

5.1.5 MP – interaction area placement and performed task

For all tasks on the medial aspect pressure values ranged between 19.1 to 66.6 KPa, while laterally the spread was from 0 KPa (lateral malleolus in seated) to 116.4 KPa (5^{th} metatarsal, in inversion). As noted above peak pressures were recorded at the 5^{th} metatarsal.

5.1.6 MP – interaction performed task and skate size

Similar patterns of pressure distribution were seen within tasks (Figure 4.6). In general, pressures were greatest for the -½ size, followed by regular size, and least for the +½ size for any given task. The MPs recorded for the -½ and regular sizes were significantly greater than the +½ sizes for more than half of tasks. Differences between the -½ and regular sizes were somewhat modified by the skater's lacing style.

5.1.7 MP – interaction by area placement, skate size and performed task

While trying different skate sizes in the shop, it would be expected that the skater will subjectively perceive discomfort at the metatarsal-phalangeal level, as long as it is rigid and un-adjustable through design (Figure 4.7). For specific tasks (i.e. dorsiflexion and eversion), approximately half the MPs were found around the 5^{th} metatarsal with the remaining half shared equally by medial malleolus, first metatarsal, and instep.

In general, dorsiflexion and eversion tasks (Figures 4.9 and 4.12) had similar fit pressure-area profiles but was quite different from the other four tasks (seated, standing, plantiflexion, and inversion). As noted previously (Figure 4.3), dorsiflexion and eversion displayed (in this order) the highest amounts of pressure.

The larger size skates consistently applied the least pressure at the foot-boot interface, with few exceptions:

- medial malleolus in standing, eversion, and inversion;
- first metatarsal in inversion, where it was slightly higher compared with the regular size;
- 5th metatarsal, where it was higher than both, -½ and regular size.

MPs for the regular size were lower compared with the -½ size skates on almost all weight bearing tasks, except during inversion, specifically around the metatarsal-phalangeal joint (1^{st} and 5^{th} metatarsals). Again, this could be due to the toe cap design, as a rigid, un-adjustable boot structure. In the case of smaller size, the forefoot cannot be accommodated 'in full' by the toe box, so that the pressure is applied distally from the sensor (area) placement. It may be pertinent for the skate boot designers to consider the following recommendations (adapted from Goonetilleke, 1999):

- identify the threshold force (or pressure) to distinguish between the experience of a positive sensation and discomfort;

- if the pressure is below a critical value (e.g. medial malleolus), it is better to distribute forces;
- if the pressure amount is closer to the maximum pressure tolerance (e.g. metatarsal-phalangeal joint), it is better to concentrate forces (preferably for a short period of time) in order to relieve discomfort.

5.2 PERCEIVED PRESSURE AND PERCEIVED COMFORT

5.2.1 Perceived pressure and comfort

All participants (n=18) were asked to evaluate, using VAS, the perceived pressure magnitude and comfort in eight areas around the foot and ankle (see Appendix D). As noted from Figures 13 to 20, most often (62.5%), the PP magnitude for the smaller skate size was significantly higher and more uncomfortable in comparison with the +½ size. For 31.3% of the scores, -½ size PP and PC scores were different from both the regular and +½ size. For 6.2%, -½ size PP and PC scores were different from the regular size only.

For each skate size the average PP scores (for the eight areas) were compared with the overall PP assessment (item #10 questionnaire). These two scores were not equivalent such that the average PP scores were less than the overall PP scores with differences of 15.4, 9.4 and 9.2 units for -½, regular and +½ sizes, respectively (Table 5.1). By area, the PP was least around the Achilles tendon area (ranked the 8th) and the most around the medial malleolus ('inside ankle'), followed by lateral malleolus ('outside ankle') and inside arch.

Table 5.1: Average ratings of overall PP and ranking of PP by area

Area	Scores			Ranks			Median
	S	R	L	S	R	L	
Toe box	80.4	42.4	33.9	2-3	7	7	**7**
Tendon guard	45.9	31.0	33.7	8	8	8	**8**
Top of the foot	69.4	55.8	47.8	5	5	4	**4-5**
Tongue	56.9	44.5	35.9	7	6	6	**6**
Under the foot	66.4	61.3	47.2	6	4	5	**4-5**
Inside ankle	87.4	79.2	64.6	1	1	1	**1**
Outside ankle	80.4	64.1	62.2	2-3	3	2	**2**
Inside arch	76.0	64.2	62.1	4	2	3	**3**
(1) Averaged	70.4	55.3	48.4				
(2) Overall PP points	85.8	64.7	57.6				
(2)-(1) Difference	**15.4**	**9.4**	**9.2**				

In the case of perceived comfort, the -½ size averaged scores were higher than the overall ratings with 16.9, the +½ size with 6.7, and the regular with only 3.0 (Table 5.2).

Table 5.2: Average rating of overall PC and ranking of PC by area

Area	Scores			Ranks			Median
	S	R	L	S	R	L	
Toe box	69.4	99	97.9	8	3	7	**6-7**
Tendon guard	102.3	116	116	1	1	1	**1**
Top of the foot	85.7	95.6	100.7	5	6	4	**4-5**
Tongue	93.3	104.1	112.1	2	2	2	**2**
Under the foot	89.3	98.5	106.3	3	4	3	**3**
Inside ankle	76.1	87.6	98.6	7	7	6	**6-7**
Outside ankle	74.3	84.8	92.4	6	8	8	**8**
Inside arch	87.0	97.2	99.2	4	5	5	**4-5**
(1) Averaged	84.7	94.5	102.9				
(2) Overall PC points	67.8	91.5	96.2				
(1)-(2) Difference	**16.9**	**3**	**6.7**				

The highest comfort scores were given to the tendon guard (Achilles tendon) area (ranked the 1st), followed by the instep ('tongue') and plantar surface ('under the foot'). The most uncomfortable was the lateral malleolus ('outside ankle') preceded by toe box/medial malleolus ('inside ankle'). This is partially in agreement with some of the findings from the MP. High pressure magnitude was measured around the 1st and the 5th metatarsal ('toe box') and medial malleolus as well as low pressure profile around the Achilles tendon ('tendon guard') area often were present. It may be concluded that in some foot and ankle areas, the comfort ratings using VAS, may have a strong relationship with the MP magnitude.

In their study, Jordan & Bartlett (1995) used a five-point interval scale for rating the PC on the plantar foot surface and dorsum of the foot. The comparison with the present study is presented in Table 5.3. The minimal difference (0.9%) between comfort points at the plantar level increases from the dorsum of the foot (5.7%) to the instep (12.4%).

Tabel 5.3: Comparison between normalized perceived comfort points around the plantar and dorsum aspect of the foot

Area	Jordan & Bartlet	Current study
Plantar comfort	64.8	65.7
Upper comfort ('top of the foot')	58	63.7
Upper comfort in lacing region ('tongue')	57	69.4

5.2.2 Overall perceived pressure and perceived comfort

With regards to skate size, as expected, perceived pressure (PP) increased with decreasing skate size (Figure 4.21). It is unclear yet why the +½ size was rated more comfortable than the regular size, even though the differences between them were not significant. Mundermann *et al.* (2002) used ten consecutive data collection sessions in order to obtain reliable subjective comfort assessment and the use of sessions 4 to 6 was recommended. The present study used only the first and only assessed condition, randomly chosen after the regular (i.e. control condition) size was initially tested. Nonetheless, comfort is a subject specific characteristic (Nigg *et al.*, 1999); that is, what is comfortable to a group of athletes may be very well uncomfortable to others (Chen *et al.*, 1994). It has to be emphasized in this context that in terms of MP (fig.1), there was a significant difference between regular size (34.2 KPa) and +½ size (28.7 KPa).

5.3 CORRELATIONS

5.3.1 Measured pressure versus perceived comfort and perceived pressure

No direct or inverse relationships were found between measured pressure and perceived pressure or comfort (Table 4.14). Jordan & Bartlett (1995) found that decreased pressure on the foot dorsum was related to decrease upper comfort. "This stresses that relationships found between perceived comfort and pressure may not be causal but could be indirect" (Jordan & Bartlett, 1995). Also, it was found that perceived plantar comfort is not related to absolute peak pressures, although it may be related to relative changes in peak plantar pressure.

5.3.2 Overall perceived comfort and pressure

The relationship between dependent variables was analyzed through correlation coefficients. Moreover, the relationship between differences in comfort and perceived pressure variables in response to skate size was determined using linear regression analysis (Figure 4.22). It was expected that, while pressure would increase around the foot and ankle (i.e. due to changes in skate size), the comfort would decrease so that an inverse, strong, relationship was detected.

5.4 FOOT ANTHROPOMETRICS

Ten foot sites dimensions were quantified for the 18 participants, similarly to prior studies, but the results may not be directly comparable because of technical variations in the measurement protocol. Some of these variations included different degrees of weight bearing, un-standardized measuring devices (cloth tape, steel tape, calliper), and/or different indirect methods used (photography, electromagnetic digitizing devices). Comparative data from most referenced of these studies (Freedman *et al.*, 1946; Hawes & Sovak, 1994; Wunderlich & Cavanagh, 2000) are presented in table 5. 4:

Table 5.4: Mean for foot variables with comparable values from referenced studies on Caucasian males (in mm)

Foot and ankle sites	Current mean	Wunderlich (2001)	Hawes (1994)	Freedman (1946)	Dahlberg (1948)
Foot breadth	98	101	99	98	Na
Maximum heel breadth	63	70	63	70	Na
Inter maleolae breadth	72	73	na	na	Na
First toe length	258	270	263	268	266
Metatarsal tibial length	188	197	193	193	200
Metatarsal fibular length	162	167	169	159	Na
Sphyrion fibular height	71	73	60	na	Na
Medial malleolus height	89	81	na	na	Na
Metatarsal-phalangeal joint girth	250	252	253	252	256
Mid-arch girth	256	262	254	258	261
n	18	293	1197	6278	8232

The differences between the current study and the other reported foot measurements ranged from -8mm (i.e medial malleolus height) to +12mm (i.e. first toe and metatarsal tibial lenght) but some limitations have to be considered:

- sample size was much larger (293 to 8232 subjects) and referred exclusively to Caucasian males. In present study only 18 participants were involved, out of which one was Asian;
- more, the participation was restricted to subjects wearing skate sizes between 7½ and 8½ US, which can explain the notable differences in length measurements.

The objectives of the previous foot anthropometric studies were to identify the diversity of measures across genders and races (Hawes *et al.*, 1994; Wunderlich & Cavanagh, 2000), to build a foot model from known measurements and their relationship (Hawes & Sovak, 1994), or to evaluate the reliability of the measurement techniques (Liu *et al.*, 1999). In the present study, a relationship between foot/ankle dimensions and MP was analyzed but no significant results were noted (i.e. the highest found r=0.17 between foot breadth and skate sizes ±½).

Of special interest were the foot breadth (FB) and metatarsal-phalangeal joint girth (MG) dimensions, considering the high MP values on the sides of the skate boot toe cap (i.e. for the first and fifth metatarsal). The (largest) differences are minimal (2 mm less for FB and 6 mm for MG) showing that the group tested may have had wider feet than the general population, as long as the inclusion criteria restricted participation by foot length (i.e. skate size). These results make it evident that, in the process of the skate boot design, if the last is to reflect the shape and proportion of the foot accurately, representative data are required.

5.5 INTER-EYELETS DISTANCE

The changes in inter-eyelet lacing distances varied with site and skate size. For EL1, the eyelets were located at the proximal edge of the skate boot toe box which, by design, is a rigid structure. This may explain the fact that the lace distance between eyelets at this level increased with skate size. The difference in lace distance (4mm) was found to be significant between -½ and +½ size.

Along the antero-posterior axis, the skate boot has a fix length. Considering that one's foot volume is also a constant inside the skate boot, the foot would deform medial-lateral and superior-inferior in order to compensate the toe flexion. It seems counterintuitive that, at the instep level, the skaters did not compensate for the pressure acting upon the tongue by loosing the lacing. This may be related to the player's preference for tighten the skates in this area or by the fact that, for the other two sizes, the eye lace distance cannot actually be reduced due to the skate boot design. The 3mm difference between the smaller and regular size was also found to be significant.

No significant differences were found between the distances at EL3 level. The distance decreased from the -½ size to regular and +½ size probably, again, due to the difficulty encountered by the skaters in having the skates laced tight around their leg imposed by the skate design.

5.6 LIMITATIONS

The present study had some limitations. Only 18 participants agreed to participate. This was due to the fact that the involvement was purely on a volunteer basis and the testing duration was long (1.5 to 2 hours). Also, only recreational players were involved; skate designers and hockey coaches will be more interested in comparative studies including elite and recreational hockey players. The results obtained described specifically only pressure magnitude and comfort and subjective pressure ratings for one skate model (Bauer-Nike 'Vapor XX'). Comparative studies between different skate boot models would reveal differences due to design and manufacturing.

The MP around the foot and ankle was expressed as the average of several pressure sensors within a specific area. For some participants, peak pressure values (689.5 KPa) were recorded during different performed tasks. An intrinsic look at the pressure values recorded individually (by each sensor) may reveal some valuable information. By knowing the "last" dimensions and the 3D pressure profile, a direct relation between peak pressure magnitude and dimensional differences at the foot-boot interface may be inferred.

5.7 CONCLUSIONS

The findings in this study suggest that the measurement of pressure distribution at the foot-boot interface could be a useful tool in identifying the causes of discomfort. Equipment fit research provides the designers with a practical and effective method for developing and manufacturing proper fitting equipment. Given the interdependency of comfort, fit, protection, and performance of the ice hockey skate, the present study answers partially the question of how to optimize the fit of a skate design for comfort. Since footwear-fit is one of the most important considerations when purchasing footwear, it has to be understood when manufacturing footwear. As a result, specific functional design criteria (comfort, injury prevention, and performance) should not be optimized independently; sport shoe manufacturers should aim to find solutions that integrate all the important functional design aspects (comfort, injury prevention, and performance).

The results obtained provide an initial understanding of ice hockey footwear fit through pressure measurement. The technology and protocol adopted were effective in discriminating between regional pressure differences as well as sensitive to foot and ankle positions. The study showed that a reasonable estimate of the mean pressure was measurable and consistent around the foot and ankle (34.2 KPa). A detailed record of the dynamic changes in fit pressure was documented with substantial shifted pressures occurring between the foot and ankle and the boot. Further, the effect of plus / minus one half boot size were also demonstrated to alter significantly the distribution and magnitudes of pressures. Taken together, the above results have revealed various aspects that contribute to "fit" around the foot and ankle. Further refinement of this investigative approach is thus warranted. Ideally a 'pressure measurement sock' should be developed that could be quickly slipped over the foot and possessing smaller spatial resolution about anatomical regions. In addition, further examination of fit with other hockey skate boots models and different populations (e.g. age, gender, performance level – recreational and elite) is necessary.

APPENDIX A

Research participation consent form

McGILL UNIVERSITY
FACULTY OF EDUCATION
RESEARCH SUBJECT CONSENT FORM

QUANTIFYING FIT IN ICE HOCKEY SKATE BOOTS

This is to state that I agree to participate in the research project entitled: "Quantifying fit in ice hockey skate boots"
And conducted by: Cristian R. Gheorghiu, Dr. David J. Pearsall
(Names of the researcher or group, researcher's supervisor (if applicable) and institution)

1. ***Purpose.*** Participation in this study consists in putting on the skate boots, lace them up, and performing simple tasks like standing and changing the foot position in inversion, eversion, flexion, and extension. You will be asked to perform this under controlled condition in the laboratory. **The risk of any type of injuries is minimal.** In order to insure your safety, the exact tasks will be explained verbally and demonstrated to you.

2. ***Procedures*** – There will be only one testing session in which you will wear the skates provided by the tester. For each task, the pressure inside your boot will be recorded using pressure mats applied on interest points to the skin of your right foot. The signals will be recorded using a portable data logger attached to your waist. The tester will monitor and assist you where needed during the testing session. After skates testing you will be asked to fill out a simple fit test questionnaire.
All nominal information collected will be protected for confidentiality by assigning an identification code to you. The code key numbers will be stored in a reference file and password protected file separate from the data set used to analyze test results. This will maintain your anonymity when data are presented in abstracts, publications or reports presented at meetings, conferences or research papers (thesis, journals, etc.)

3. ***Conditions of Participation*** – **Your participation in this study is voluntary and not mandatory.** You are free to withdraw from participating in any part or all of the study at any time.

I,____, have both read the above testing conditions and have had the testing conditions verbally explained and demonstrated to me. I understand the purpose of this study and know about the risks, benefits and inconveniences that this research project entails. I understand that I am free to withdraw at anytime from the study without any penalty or prejudice. I understand that this research will not affect my grades or evaluation of my work. I understand how confidentiality will be maintained during this research project. I understand the anticipated uses of data, especially with respect to publication, communication and dissemination of results. If I have any questions or concerns regarding the above test, I should contact Dr. David J. Pearsall, Associate Professor, Department of Kinesiology and Physical Education (room 320, Currie Memorial Gym, phone 514.398.4184 ext.0558 or e-mail: david.pearsall@mcgill.ca).

I have read the above and I understand all of the above conditions. I freely consent and voluntarily agree to participate in this study.

Name (please print) ____

Signature ________________________________ Date __________________

APPENDIX B

Foot anthropometrics measurements form

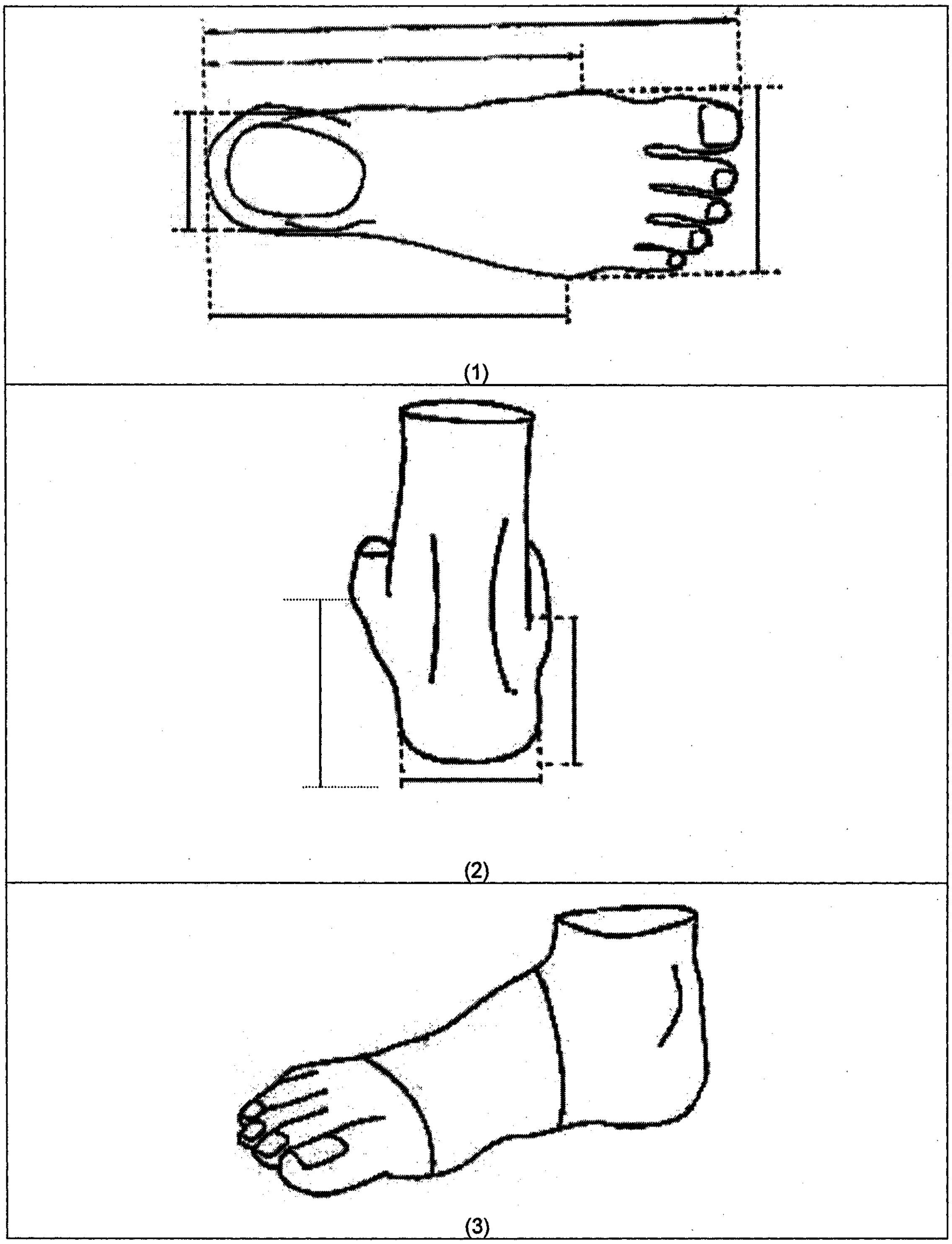
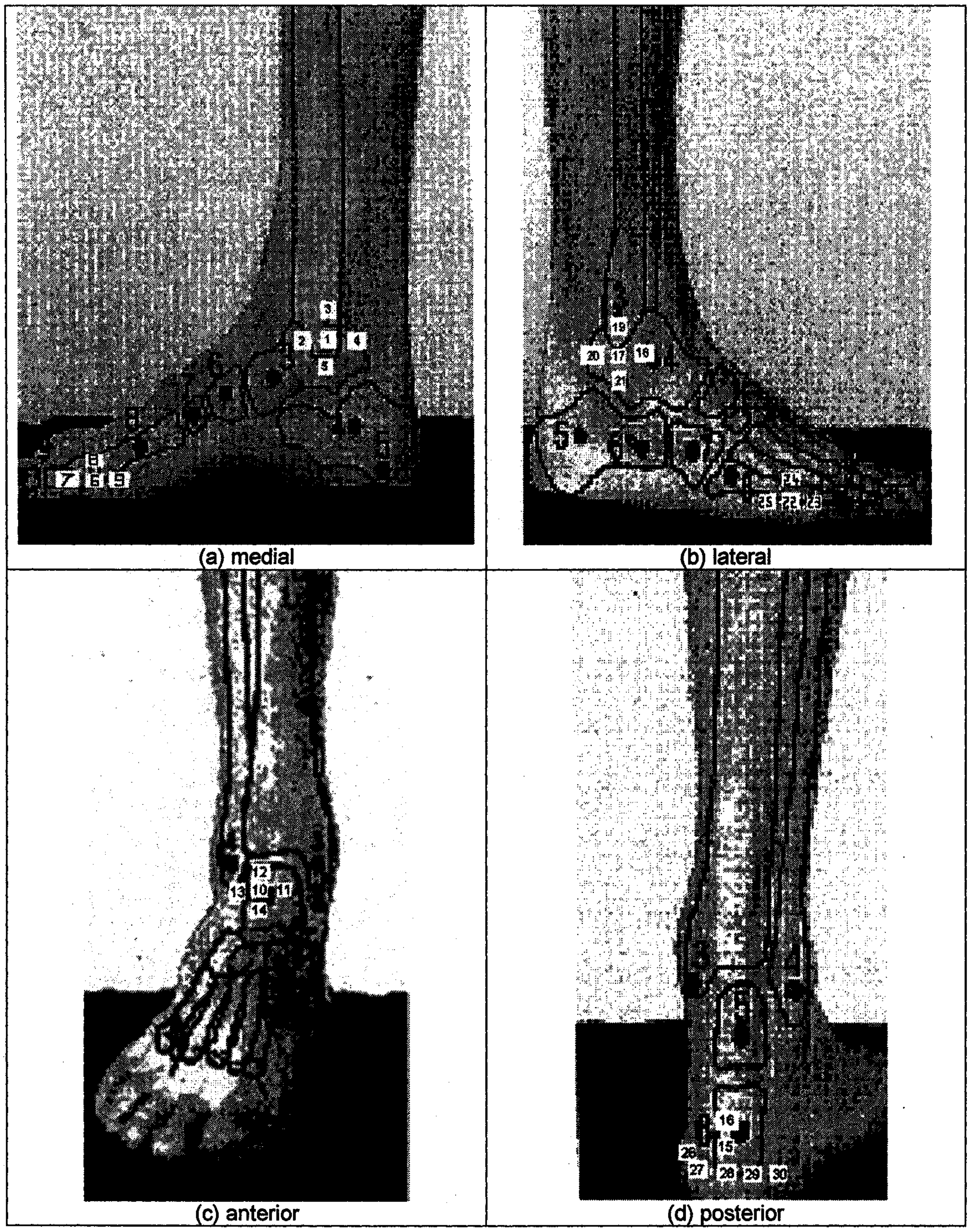


Figure B. (1) Measurement sites for foot length and breadths; (2) for heights and breaths; (3) for girths (adapted from Hawes and Sowak, 1994)

APPENDIX C

Pressure sensors placement chart



(a) medial (b) lateral (c) anterior (d) posterior

Figure C: Sensors placement chart: (a) on the medial malleolus and posterior from the first metatarsal; (b) on the lateral malleolus and posterior from the fifth metatarsal; (c) on the instep; (d) on the Achilles tendon and heel.

APPENDIX D

Visual Analog Scale: Perceptions scores of comfort and pressure

Subject's Name/Code: ________________________________

Skate code/color: ☐☐☐ ☐☐☐ ☐☐☐

Are the skates the right size? (please circle the answer) **Y | N**

Toe box

Not comfortable at all	Most comfortable condition imaginable
No pressure at all	The most perceived pressure

Tendon guard

Not comfortable at all	Most comfortable condition imaginable
No pressure at all	The most perceived pressure

Top of the foot

Not comfortable at all	Most comfortable condition imaginable
No pressure at all	The most perceived pressure

Tongue

Not comfortable at all	Most comfortable condition imaginable
No pressure at all	The most perceived pressure

Under the foot

Not comfortable at all	Most comfortable condition imaginable
No pressure at all	The most perceived pressure

Inside ankle

Not comfortable at all	Most comfortable condition imaginable
No pressure at all	The most perceived pressure

Outside ankle

Not comfortable at all	Most comfortable condition imaginable
No pressure at all	The most perceived pressure

Inside arch

Not comfortable at all	Most comfortable condition imaginable
No pressure at all	The most perceived pressure

Overall comfort

Not comfortable at all	Most comfortable condition imaginable
No pressure at all	The most perceived pressure

*** For comments, please use the back side of the page**

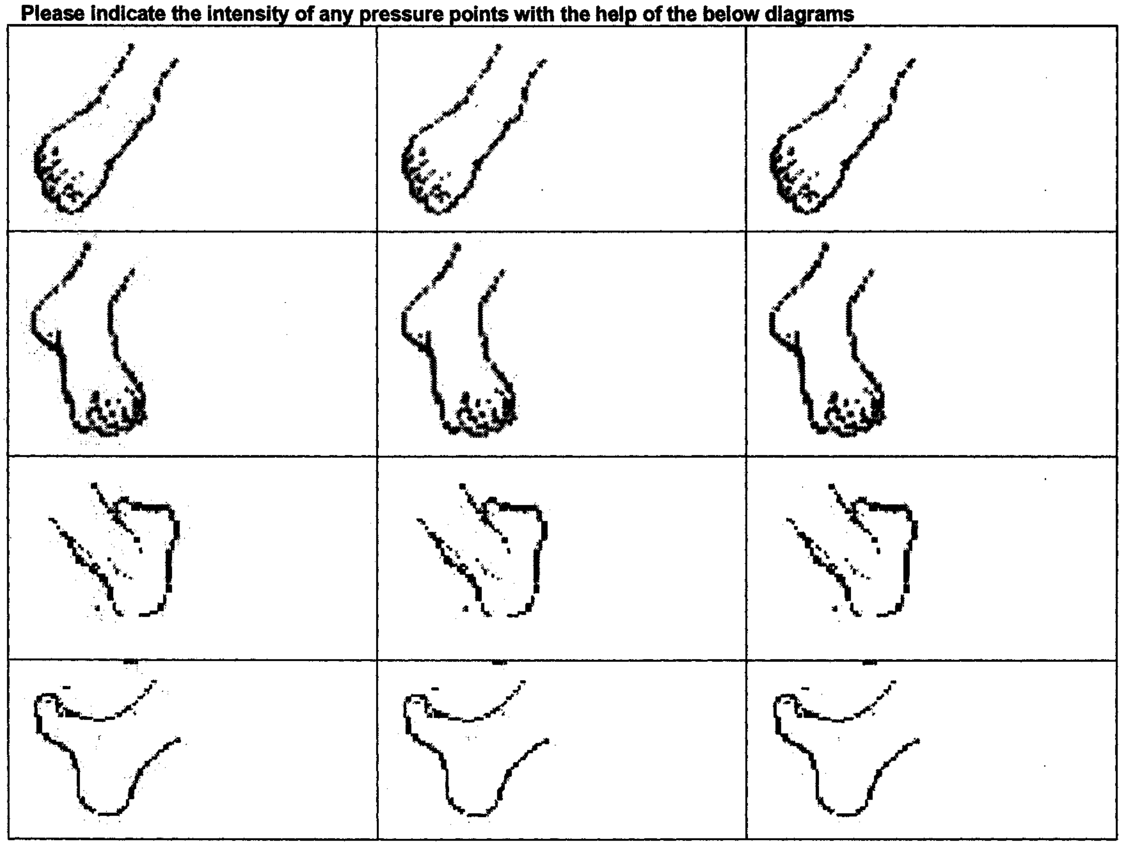
Written instructions to participant:

There are two aspects of fit for which we are interested in measuring: the comfort (i.e. how comfortable the hockey skate boot is for you), and the pressure intensity (i.e. what is the pressure magnitude). Presented are scales for measuring both aspects of fit. Although the same fit aspects may be equally comfortable, we would like you to judge these aspects independently. Please mark above the line to indicate the relative comfort of a specific hockey skate boot: the further to the right, the more comfortable the skate. Similarly, mark under the line to indicate the relative magnitude of perceived pressure: the further to the right, the most perceived pressure.

Comments:

1	2	3

Please indicate the intensity of any pressure points with the help of the below diagrams



APPENDIX E

Certificate of Ethical Acceptability and Ethics Review

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