CONTROL OF SUBTALAR MOTION
WITH THE USE OF SKI-BOOT FOOTBEDS

By

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B.A., York University, 1986

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF PHYSICAL EDUCATION

in

THE FACULTY OF GRADUATE STUDIES
(School of Physical Education)

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

JUNE, 1990

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June 20, 1990

ABSTRACT

Research shows that up to 80% of recreational skiers have lower limb alignments which can impede their ability to turn their skis properly (Subotnick, 1982). The most difficult of these alignment problems to control within a ski-boot is the varus alignment of the subtalar joint (Macintyre and Matheson, 1988). The use of custom molded footbeds made specifically for use inside of ski boots has been suggested as one method of compensating for a varus aligned foot. This study compared the effectiveness of one brand of custom molded ski boot footbed with that of a non-custom insole in controlling the motions of the lower limb associated with subtalar varus. Specifically these motions were those of the rearfoot and the navicular tubercle, along with the alignment of the tibial tuberosity with respect to the mid-line of the ski boot. In addition, subjects were given the opportunity to assess their subjective feelings of edge control, pain, and fatigue while skiing with both the custom molded footbeds and non-custom insoles.

The subject group for this study consisted of 13 advanced level adult skiers who demonstrated more than three degrees of subtalar varus when non-weight bearing. Each subject received a pair of custom molded ski boot footbeds at the beginning of the study.

Ski boots that had been cut away at the rear and the medial side were used in the laboratory in order to observe the motions of the navicular tubercle and the rearfoot as

the subject transferred their weight in a simulated skiing motion.

The right and left navicular tubercle, tibial tubercle, and the insertion of the Achilles at the calcaneus of each subject were located by palpation and marked. After sufficient practice of the weight transfer motion, two trials of each landmark were photographed using 35mm slide film. The subjects were first photographed while using the non-custom insoles and again using the custom molded footbeds. The slides were digitized and comparisons were made between the two types of insoles for both the start and end locations of the landmarks as well as for the ranges of motion through which the landmarks traveled.

Statistical analyses of the group results indicated that there was significantly less ($p=0.000$) navicular motion during the shift from the start to the end positions with the use of the custom molded footbeds as compared to the non-custom insoles. The rearfoot angle was significantly less at both the start ($p=0.000$) and end ($p=0.000$) positions with the use of the custom footbeds as compared to the non-custom insoles. There was no statistical difference between the amount of rearfoot motion allowed by either type of insole. The tibial tubercle was positioned significantly ($p=0.000$) closer to the mid-line of the ski boot when using the custom footbeds than with the use of the non-custom insoles. These results indicate that the custom footbeds do

maintain the subtalar joint in a more neutral position than do non-custom insoles.

During the skiing section of the study the subjects rated the custom footbeds as providing better edge control ($p=0.000$) and resulting in less fatigue ($p=0.000$) than non-custom insoles. There was no statistical significance when comparing the ratings given by the group for the level of pain experienced with the use of either type of insole. There was a statistically significant improvement ($p=0.000$) in race times for the group when using the custom footbeds as compared to the non-custom insoles.

The results of this study indicate that custom molded ski boot footbeds are able to control subtalar motion more effectively than a non-custom insole. It appears that this control of subtalar motion enhances the skiing experience by increasing edge control and reducing the amount of fatigue experienced.

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ACKNOWLEDGEMENTS

I would like to acknowledge the contributions of several people without whom this project would not have been made possible.

To my thesis and graduate advisor, Dr. Jack Taunton for his direction, enthusiasm, and encouragement as well as for his extensive network of valuable resource people.

To Dr. James Macintyre for his insight, expertise, and contributions in the area of ski research.

To Dr. David Sanderson for his expertise and devotion to his field, his uncompromising standards, and most importantly for his approachability and genuine interest in his students.

To Mr. Paul Paris who has the ability to get water from a stone in the form of time and equipment donations and whose own sacrifice of valuable time and effort was the true turning point for this project.

To my friends at U.B.C., particularly those in the Biomechanics Laboratory who kindly adopted an outsider and gave me a home base from which to operate.

Finally, to my family who support me in all that I undertake.

Support provided by Bud Ryckman/ MJD Agencies, Norvinca Inc., Paris Orthotics, John Colpitts, David Steers, and Grouse Mountain Resorts Limited is gratefully acknowledged.

Chapter 1

INTRODUCTION

Over two million Canadians participate in the sport of alpine skiing. Skiing is unique in that it is the only sport in which a lever system is rigidly attached to the body. This system consists of the ski, binding, and boot. The ski boot is the main link in transferring forces from the skier to the ski.

The ability of the skier to ride a flat ski (ie. maintaining ground contact with both edges of the ski simultaneously) without altering their natural stance is important. From this position the skier is able to pivot, edge, and pressure the ski through a carved turn with minimal leg actions. The skier whose natural stance places them on their ski edges has difficulties initiating a turn. Research indicates that up to 80% of recreational skiers have lower limb alignments which prevent them from riding a flat ski while in a natural stance (Subotnick, 1982). The most common conditions which contribute to the inability to ride a flat ski are varus alignments of the tibia and foot. This research investigated one suggested method for overcoming the problems associated with a varus alignment of the foot.

The need to compensate for imperfect leg alignments has resulted in the improvement of ski boot design. Adjustable boot cuffs can be aligned to approximate the angle of the

tibia while allowing the base of the boot to remain level. The skier with all but the most severe amounts of tibia vara is thus able to ride a flat ski.

Forefoot and rearfoot varus typically result in excessive pronation during weight bearing. Excessive pronation is identified by the accompanied increase of tibial rotation, a decreased ability to reduce the transmission of shock up the leg, and difficulty in resupinating during unweighting. Excessive pronation is a difficult condition to correct within a ski boot. The nature of the modern ski boot is such that the rigid plastic shell and tight fit can increase the amount of pronation experienced by most skiers by causing the longitudinal arch to flatten. The manufacturers of custom molded ski boot footbeds claim that these devices can maintain the foot in a neutral position and control excess pronation thereby reducing the pain, fatigue, and edge control problems associated with excessive pronation (Peterson Tech. Manual, Superfeet Tech. Manual). To date there are no reliable data supporting these beliefs.

Statement of the Problem

This research was designed to investigate the effectiveness of one type of custom molded footbed to control rearfoot motion, navicular drop, and tibial rotation, three events associated with pronation. The focus of the study was to obtain quantitative measures of the

ability of the footbed to control motion within a ski boot in an effort to determine the mechanism of control. A second focus was the quantification of the subjective feelings of edge control, pain, and fatigue which to date have only been reported anecdotally.

Hypotheses

1. It was hypothesized that there is significantly less pronation, as measured by a) navicular drop, b) rearfoot motion, and c) tibial rotation while weight bearing with feet placed on custom footbeds than on non-custom insoles.

2. It was hypothesized that there is a significant decrease in the levels of perceived foot and leg pain with the use of a custom footbed as compared to a non-custom insole.

3. It was hypothesized that there is a significant decrease in the level of perceived foot fatigue with the use of a custom footbed as compared to a non-custom insole.

4. It was hypothesized that there is a significant increase in the level of perceived edge control with the use of a custom footbed as compared to a non-custom insole.

5. It was hypothesized that the increased level of edge control would result in improved performance on a timed race course.

Significance of the Study

This study served to test the manufacturers claims as to the effectiveness of custom molded footbeds in controlling the events associated with pronation and improving skiing ability and enjoyment. It was the intention of this study to develop a method for quantitative assessment of motion within a ski boot in order to determine the effectiveness of ski boot footbeds.

Definition of Terms

Forefoot Varus. Medial border of the foot is raised at the metatarsal heads while in a non-weight bearing position (Root et al., 1971).

Subtalar Varus. Medial border of the foot is raised at the heel while in a non-weight bearing position (Root et al., 1971).

Pronation. Position described by ankle eversion, abduction, and dorsiflexion; internal rotation of the tibia occurs secondary to subtalar eversion (McKenzie, Clement, and Taunton, 1985).

Navicular Drop. The forward and downward motion of the navicular tubercle that typically occurs with weight bearing.

Rearfoot Angle. The angle of insertion of the Achilles tendon at the calcaneus with respect to an imaginary line which is perpendicular to the ground.

Tibial Rotation. The alignment of the tibial tuberosity with respect to the mid-seam of the toe piece of a ski boot. The tibial tuberosity is rotated outward as the arch collapses with pronation. This rotation occurs as a result of the subtalar joint's attempts to maintain proper alignment with the tibia despite the effects of pronation.

Orthotic. Device designed to assist in biomechanical control of the lower extremity; stabilizes the joint in a neutral position (Macintyre and Matheson, 1988).

Non-custom Insole. Removeable insole found inside ski boots.

Custom Molded Ski Boot Footbed. Custom molded insole that begins as a foot shaped blank. Insoles are heated and shaped to individual foot contours while the foot is maintained by some method in a neutral position (Colpitts, 1987). The footbed used in this study was constructed of cork and molded in a non-weight bearing, neutral position by the use of suction.

Horizontal Visual Analogue Scale. A 10cm horizontal line with stops at both ends at right angles to the line. The addition of descriptive terms produces a graphic ratings scale (Scott and Huskisson, 1979).

Delimitations

Results of this study were restricted to adult, advanced level skiers who exhibited more than three degrees of subtalar varus in each foot. The results were also restricted to the one make and model of custom molded footbed tested as well as the make and model of test boot used in the laboratory. An effort was made to standardize the make and model of test boots as Schaff et al. (1987) have shown that while there is little or no variability in the flex pattern and pressure profiles of various sizes of the same boot, there is variability between boot styles and makes. The effectiveness of the footbeds was restricted to the abilities of the technicians to work with the product. Variability in construction was minimized by using only two technicians to make all the footbeds for this study.

Analysis of motion inside of the ski boots was confined to laboratory conditions. Skiing maneuvers create forces which are not easily reproduced in the lab (Schattner et al., 1985). Windowing of the ski boots minimally altered flex and support characteristics. Accuracy of the results may have been affected by these experimental conditions.

Assumptions

This research operated under the assumption that if custom molded ski boot footbeds did reduce pain and fatigue, and increase edge control they did so by reducing pronation. Although the literature speculated that this is the underlying mechanism of their effectiveness there were no reliable data available at the time of this study.

It was assumed that each subject was at a skiing level which was sufficiently high so as to allow them to accurately judge the subtle differences in edge control, pain, and fatigue experienced with the use of various types of insoles. In the laboratory it was assumed that all markers were properly positioned on their intended landmarks.

Chapter 2

REVIEW OF LITERATURE

This review is divided into five major sections:

(a) mechanics of skiing; (b) lower limb alignment and skiing; (c) orthotics, footbeds, and skiing; (d) footbed construction; (e) pain analysis.

Mechanics of Skiing

The carved parallel turn is the most essential skill of alpine skiing. Pivoting, edging, and pressure control are the three elements involved in the turn. Ankle eversion, valgus angulation of the flexed knee, and hip flexion are the motions used to pressure the inside edge of the downhill ski (Macintyre and Matheson, 1988). This pressure causes the ski to flex and carve an arc. Upon completion of the arc the skier unweights , pivots toward a new direction, and pressures the inside edge of the new downhill ski creating another arc.

While the motions of the ankle, knee, and hip during a ski turn can be easily observed, the motion of the foot within the ski boot is completely hidden from view. During the ski turn the foot is subjected to a pattern of weight shifting similar to that of normal gait (Macintyre and Matheson, 1988). The often documented walking and running pattern of supination-pronation-resupination occurs during the ski turn as the skier's weight shifts from the heel to the forefoot (Macintyre and Matheson, 1988). Because of the

locking effect of the buckled ski boot there is no true heel strike or toe-off experienced (Macintyre and Matheson, 1988). Using transducers located in the footbed and tongue of a ski boot, Medoff et al. (1985a) found the foot to go through a repetitive pattern of motion beginning with a heel thrust, followed by an even distribution of forces on the heel and forefoot, and finally a push-off on the forward part of the foot. In addition it was observed that short radius slalom type turns showed a more rapid, inconsistent pattern than that observed during long radius turns (Medoff et al., 1985a).

The forces involved in causing the ski to arc during a turn are transferred from the skier through the ski boots to the ski (Medoff et al, 1985a). At the same time forces are being transferred from the snow through the boot and back up to the skier (Medoff et al, 1985a). The boot is the main link in this system of action and reaction, and as such it is of vital importance that the foot to boot fit be as close as possible (Medoff et al, 1985a). For example, the ankle eversion required to initiate a ski turn is a subtle motion. This subtle action will not be transferred to the ski if there is too much room between the foot and the boot. Instead, the force of the action is lost inside of the boot as there has been little or no contact between the foot and the boot during the motion. Exaggeration of such a motion is difficult due to the limitations of motion created by the rigid plastic shell and thick foam liner of the ski boot.

Likewise, compensation for a poor fit by tightly buckling the boots can disrupt the transmission of forces by locking the foot into a pronated position (Macintyre and Matheson, 1988).

Lower Limb Alignment and Skiing

All skiing skills originate from a neutral glide position which requires the skier to ride on both edges of their ski simultaneously while in a natural stance. This position is referred to as riding a flat ski. Riding on either of the ski's edges while gliding will predispose the skier to catching an edge on the snow, and prevent them from pivoting successfully. Subotnick (1982) found 80% of the skiers that he tested to exhibit lower limb alignments which prevented them from riding a flat ski without adjusting their natural stance. The most common alignments which can adversely affect the ability of a skier to properly ride a flat ski are tibia vara, forefoot varus, and rearfoot varus. Most people exhibit an average of two to three degrees of rearfoot or subtalar varus (James, 1979).

Macintyre and Matheson (1988) outlined the effects of varus alignments of the tibia and foot on skiing. Varus alignment of the tibia is transferred through the boot to the ski. If the boot cuff is set perpendicular to the boot base the skier with tibia vara will stand on the outside of the skis. The knees will consequently be in a varus position. Initiating a turn from this position is

difficult. Because they are locked onto their outside edges, skiers with this condition tend to jump from one turn to the next instead of carving linked turns. Aligning the boot cuff to the angle of the tibia while the base of the boot remains level allows the skier to ride a flat ski while in a natural stance.

A more difficult condition to control within the ski boot is a varus alignment of the foot. The condition may not appear until the skier assumes a functional skiing position. During weight bearing the varus aligned foot will pronate excessively. (Macintyre and Matheson, 1988)

Pronation is a combination of ankle eversion, abduction, and dorsiflexion. During running pronation is necessary for decreasing the forces experienced by the leg, but excessive pronation causes an increased amount of tibial rotation and a decreased ability to reduce shock (Nigg, 1986).

Contributing to pronation in skiers is the ankle eversion necessary for turn initiation as well as the ski boot itself. A tightly buckled boot is believed to flatten the longitudinal arch, preventing the foot from supinating after unweighting (Macintyre and Matheson, 1988).

Excessive pronation can place the skier in a position characterized by the ski tips pointing outward and the knees pointing inward. This position results in poor skiing technique and pain. The extreme valgus position of the knee required for turning from this position causes the upper body and the hips to rotate into the hill. Instead of

carving, the skier banks their turns. This results in a shifting of the center of gravity outside of the base of support and the skier falls uphill. Pain may result from the extreme rotation of the tibia at the knee which accompanies excessive pronation. Attempts to stabilize the foot by curling the toes or tightening the buckles leads to cold, cramped feet. (Macintyre and Matheson, 1988)

Orthotics, Footbeds, and Skiing

It has been suggested that the solution to the problems associated with pronation is the stabilization of the foot in a neutral position within the ski boot (Macintyre and Matheson, 1988). Running studies have shown orthotics to reduce rearfoot motion and overall pronation when used in running shoes (Clarke et al, 1984). There are various theories as to the mechanism by which orthotics reduce rearfoot motion and pronation. Smith et al. (1983) found running shoe orthotics to reduce calcaneal eversion during running and suggested that this decrease may be a significant mechanism for the reduction of symptoms by orthotics. Bates et al. (1979) found that pronation began later and ended sooner during running trials with orthotics than without the use of orthotics. In independently run studies Bates et al. (1979) and Nigg and Leuthi (1980) both found that the use of orthotics by injured runners altered the mechanics of the lower extremity enough to decrease the amount of pronation experienced to levels similar to those

experienced by non injured runners (Stacoff and Leuthi, 1986). Another study found a decrease in rearfoot motion with the increased height of the orthotic (Cavanagh, 1980).

The manufacturers of ski boot footbeds claim that their products can control pronation inside of a ski boot similarly to the control found to occur with the use of orthotics during running. In addition their literature maintains that controlling the excessive motions associated with pronation can reduce pain and fatigue, and increase edge control (Peterson Tech. Manual, Superfeet Tech. Manual).

Footbed Construction.

The primary function of any orthotic footbed is the biomechanical control of the foot (McKenzie, Clement, and Taunton, 1985). Ski boot footbed manufacturers agree with sports medicine practitioners that the ideal position of the foot is one in which the subtalar joint is neutral (McKenzie, Clement, and Taunton, 1985). Manufacturers differ on their methods of creating a footbed in which the subtalar joint is held neutral. The footbeds utilized in this study were molded with the subject in a seated position with no weight being placed on the feet (Superfeet Tech. Manual). The foot is maintained in a neutral position throughout the molding process by the technician (Superfeet Tech. Manual). Other ski boot footbeds are molded in a weight bearing position with high density foam placed under

the foot to maintain a neutral position (Peterson Tech. Manual). There are no data available comparing the successes of these two techniques in creating a footbed which can maintain the foot in a neutral position.

Footbed materials vary with manufacturer. The footbeds utilized in this study were made from cork with a non-slip, breathable top cover (Superfeet Tech. Manual). The material chosen for a footbed must be firm. A flexible footbed can collapse under the pressures associated with the ski turn (Superfeet Tech. Manual). The footbed must also withstand the pressures exerted by the buckling of the boots.

Running shoe orthotics typically end just after the metatarsal heads to allow for flexibility at the toes and reduce the chance of cramping (McKenzie, Clement, and Taunton, 1985.). This is justifiable in such orthotics as it has been shown that all the biomechanical control that takes place does so from the heel to immediately proximal to the metatarsal heads (McKenzie, Clement, and Taunton, 1985). Ski boot orthotics are full length as the manufacturers believe that this increases the stability offered by the footbed while balancing the overall support and function (Superfeet Tech. Manual). No data were available to indicate the mechanism of control in any brand of ski boot footbed.

Studies have found significant differences between the biomechanical parameters of individuals' right and left legs suggesting that there is a need to control each foot

individually (McKenzie, Clement, and Taunton 1985). All custom molded footbeds deal with each foot separately, molding one footbed at a time. This study operated under the same ideology and as such analyses were designed to look at each foot as a separate variable belonging to one subject. This allowed for the investigation of within subject variability between feet as well as between type of insole.

Pain Analysis

Unfortunately, pain is a part of many people's skiing experience. Although common, pain is a difficult parameter to define. It is a complex phenomenon encompassing the sensations evoked by tissue-damaging stimuli as well as the subject's reaction to that stimuli (Medoff et al, 1985b). Variability in response to painful stimuli has been attributed to factors such as age , gender, cultural background, previous training, and the influence of suggestion (Medoff et al, 1985b). Pain in skiing is often the result of a fall, collision, cold injury, or as it relates to this study, improperly fitted boots or tightly buckled boots.

Rating pain using descriptive scales can be approached from two directions. Sensory scales utilize words that relate to quality and intensity such as the words weak and moderate (Medoff et al, 1985b). Affective pain scales use words such as unpleasant and distressing, which relate to

the motivational and emotional variables associated with the pain experience (Medoff et al, 1985b). The sensory type of scale was chosen for this study as it utilizes terms which are more appropriate for describing the effectiveness of footbeds.

Visual analogue scales have been shown to be satisfactory measurement tools in the assessment of pain (Huskisson, 1983). According to Huskisson (1983) the greatest advantage of the visual analogue scale is the uniformity of distribution of results. The scale may consist of either a vertical or horizontal line with stops at both ends at right angles to the line (Huskisson, 1983). Both scales have proven satisfactory although it is recommended that only one of the two be used over the course of any one study in order to maintain consistency (Scott and Huskisson, 1979). The vertical scale has as a source of error the angle at which it is viewed (Dixon and Bird, 1981). Viewing angle does not affect the horizontal scale which was therefore chosen for use in this study. Further sources of error encountered when using rating scales can be a result of inadequate instructions and subject compliancy (Dixon and Bird, 1981). Some researchers feel that rating scales reflect what the subject believes they ought to feel rather than their true feelings (Dixon and Bird, 1981). The horizontal visual analogue scale was utilized in this study for the purpose of rating edge control and fatigue as well as the traditional use as a pain scale. This was done in an

effort to maintain consistency while minimizing the amount of instructions required.

Chapter 3

PROCEDURES

The primary purpose of this study was to determine quantitatively the effectiveness of custom molded ski boot footbeds in controlling the motions associated with pronation. The second purpose of the study was to quantify the subjective experiences of skiers in a controlled study.

Subjects

The study utilized a subject group of 15 advanced level adult skiers recruited through the use of posters displayed at a major university, ski shops, and local ski hills. The subjects all displayed a minimum of three degrees of subtalar varus in both feet. No subject had prior experience skiing on the brand of custom molded footbed used in the study. Prior to testing, each subject was informed as to the nature of the study and gave written consent to participate.

The laboratory section of the study was conducted using only 13 out of the original group of subjects due to attrition.

Research Design

The independent variables for both the laboratory and the skiing portions of this study were the non-custom insoles and the custom molded footbeds. The laboratory

portion of the research also looked at the right and left feet, while the skiing portion of the study controlled for short radius and long radius turns. The dependent variables for the laboratory portion of the study were navicular drop, the angle of insertion of the Achilles tendon at the calcaneus (rearfoot angle), and the alignment of the tibial tuberosity with respect to the mid-seam of the boot's toe piece. These variables were chosen as they reflected the events associated with pronation and were easily monitored in the laboratory. The dependent variables for the skiing portion of the study were level of perceived edge control, level of perceived pain, level of perceived fatigue, and race results.

The study was designed as a test/retest situation with each subject repeating the same procedures with both the custom molded footbeds and the non-custom insoles in a random order.

Laboratory Section

Initial Assessment. All subjects were assessed for subtalar varus, forefoot varus, and functional hypermobility by one investigator following the protocols outlined in Appendix A. Forefoot varus and functional hypermobility were assessed only for their presence. Subtalar varus was measured to the nearest degree and recorded in Appendix C.

Footbed Preparation. Custom molded footbeds (Superfeet brand) were prepared for each subject by one of two technicians following the protocol outlined in Appendix B.

Ski Boot Preparation. A total of five pairs of four buckle overlap design ski boots, women's sizes 6.5, 7.5, and men's sizes 8.5, 10.5, 11.5 were used in the laboratory section of this study. All of the boots were of the same make and comparable model. These boots were cut away at the rear and medial sides to allow for the observation of the insertion of the Achilles at the calcaneus and the navicular tubercle respectively. These areas of the boot shell were ground down using a belt grinder and cut open with a jigsaw. Edges were smoothed and finished by knife. The boot liners were then placed inside of the shells and the outlines of the windows were traced. Liners were removed, cut open by knife, and placed back into the boot shell. All boots were checked on test subjects to ensure a clear view of the required landmarks.

Markers were placed along the mid-seam of the toe and heel pieces of the boot as well as to the front of the medial arch window as shown in Figure 1. These marks serve as standard points of reference for later analyses.

Ski boots were labeled for size and foot on the front, rear, and medial side for easy identification during digitizing. As well, each subject was identified on the boot during their trials.

Figure 1a. Medial window of ski boot exposing the navicular tubercle.

Figure 1b. Rear window of ski boot exposing the insertion of the Achilles at the calcaneus.

Figure 1c. Front view of ski boot with tibial tuberosity.

Data Collection. The subject removed both socks and shoes and was fitted for test ski boots using a sizer provided by the boot company. All subjects were palpated and marked on both legs by one individual. The following landmarks were marked: a. Navicular tubercle; b. The attachment of the Achilles tendon to the calcaneus, a point 1.5 cm distal to the attachment site, and two more points spaced between the top of the ski boot and the popliteal space on the midline of the leg as outlined in James (1979); c. Midpoint of the tibial tuberosity.

The subject put on the right boot with the non custom insole and buckled the boot as they would for skiing. All windows were checked for an unobstructed view of the landmarks. The subject then stood on a flush mounted Kistler Model 9261-A force platform such that the mid-seam of the front and rear of the boot were aligned with the y axis of the platform and the metatarsal heads crossed the x axis. An oscilloscope was used to detect the displacement of the center of pressure on the force platform and convert this into a single vector. When the center of pressure was located on the x axis of the platform, the line on the scope representing motion in the 'y' plane was aligned with the scope's zero line. When the center of pressure is moved to the rearfoot the 'y' plane line of the scope dropped below the zero line.

The subject initially stood on the right foot only. Ski poles were used to assist in maintaining balance without supporting the load. The center of pressure was transferred to the rear of the foot. This position was deemed the "start position". The subject then transferred pressure to the metatarsal heads while maintaining heel contact with the force platform. This "end position" is confirmed on the scope by the alignment of the 'y' plane line with the zero line. These start and end positions were chosen for use in this study as they mimic the actions of unweighting and weighting during a carved parallel turn. Both the start and end positions were held for five seconds each. The subject practised moving from the start position to the end position until they could consistently match up the lines on the scope. This took a mean of 13.07 trials.

When the subject had successfully completed the practise trials, photographs were taken of the start and end positions over two trials using 35mm slide film. The navicular was photographed first, followed by the rearfoot. The subject's front lower leg was then photographed in a position in which center of pressure was neutral. The subject repeated the protocol using the right foot with the custom footbed, the left foot using the non custom insole, and the left foot using the custom footbed. A 30 cm ruler was placed beside the subject during all photographs to act as a scaling rod in later analyses.

Data Analysis. Processed slides were projected onto white paper taped to a wall. Images of the marked points on both the subject and the boot were traced onto the paper. A grid was constructed on each individual data page using the boot landmark as the origin. The distance of the anatomical landmark from the x and y axes was measured and recorded as a set of coordinates. Angles were measured by protractor. Scaling factors were calculated for each frame by measuring the image of the scaling rod. Real length coordinates were calculated by image length/scaling factor. Differences in start and end positions for all measurements were calculated and recorded.

Statistical Analysis. Laboratory data were entered into the computer program Lotus 1-2-3 where averages were calculated across the two trials for each subject in each variable. Averages were transferred to another computer program, Systat for analysis as two factor models with two levels for each factor and repeated measures on each level at a significance of 0.05. Graphs were produced using the Harvard Graphics computer program.

Skiing Section

Data Collection. Levels of perceived pain, fatigue, and edge control were assessed using horizontal visual analogue scales. Each scale consisted of 10cm horizontal line with stops at both ends, at right angles to the line. The stops were labeled "none" and "severe" for both the pain and the

fatigue scales and "none" and "total" for the edge control scales. The subjects were asked to make a mark on the lines at the point which they felt corresponded to their experiences. The visual analogue scale was chosen as it was simple enough to be administered on the hill immediately following each ski run.

On-hill ski testing took place over the course of one ski day. Subjects skied in their own ski boots. A draw was made to randomly assign each subject to one of two test groups. One group skied the first half of the day using non custom insoles while the other group used the custom molded footbeds. Although the subjects were not informed as to which of the two groups they had been assigned, the differences in feel of the two types of insoles make a truly blind study improbable.

All subjects spent two hours free skiing to adapt to whichever insole they were using. After two hours the group gathered for a set of assessment runs. These runs were skied on intermediate terrain consisting of a gradual slope, groomed conditions, and only a few small bumps. The subjects skied one run using short radius turns, and one run using long radius turns. Following each of these runs the subjects completed a visual analogue scale to assess perceived edge control during the run. After completing both runs the subjects skied two timed runs each through a race course. All times were recorded. Following the timed runs each subject completed visual analogue scales for both

pain and fatigue levels at the end of the session. The groups then changed assignments and repeated the protocol with their new footbed/insole.

Data Analysis. Visual analogue scales were measured for distance from the left stop to the subject's mark and all distances were recorded. Race times were recorded.

Statistical Analysis. Skiing data were entered into the computer program Lotus 1-2-3 where averages were calculated for each subject in each variable. Averages were transferred into the Systat computer program for analysis as one factor models with two levels and repeated measures on each level at a significance of 0.05. Graphs were produced using Harvard Graphics computer program.

Chapter 4

RESULTS AND DISCUSSION

Description of Subjects

The subject group utilized in this study consisted of 15 advanced level adult skiers who exhibited more than three degrees of subtalar varus in each foot. As indicated in Appendix C, the mean age, height, and mass of the subject group was 25.13 ± 3.96 years, 171.17 ± 5.69 cm, and 70.47 ± 7.25 kg respectively. The group exhibited an average of 5.6 ± 1.5 degrees of subtalar varus in the right foot, and 4.9 ± 1.2 degrees of subtalar varus in the left foot, a difference which was not statistically significant ($p=0.156$). The average number of years of skiing experience was 15.47 ± 3.15 years. All subjects participated in the skiing section of the study. A subgroup consisting of 13 of the original group of subjects participated in the laboratory section.

Laboratory Section

The position of the navicular tubercle, displacement of the tibial tuberosity from the center line of the boot, and rearfoot angle were monitored as they reflected the events associated with pronation and could be easily monitored in the laboratory.

Navicular Drop. As weight is transferred forward along the foot during the carving phase of the ski turn the navicular tubercle typically moves both forward and downward

in relation to its position during the unweighted phase of the turn. This navicular motion, referred to in this study as navicular drop, is similar to that experienced during walking as the foot moves from the heel strike phase through to the point just prior to toe-off. Navicular drop along both the x and y axes of the sagittal plan was calculated for each subject's right and left foot over a total of four trials. Two trials were performed using the non custom insoles and two trials used the custom molded footbeds. Location of the navicular tubercle was determined at both the start and end positions as outlined in the procedures section.

The location of the navicular tubercle on both the x and y axes for the start and end positions using both the non-custom insoles and the custom molded footbeds are summarized in Figures 2-3. The non-custom insoles are referred to as "boot" and the custom molded insoles are shown as "footbed" on all charts.

In the start position for both the right and left feet there was a statistically significant difference between the location of the navicular tubercle in both the x and y direction when comparing the boot to the footbed. The navicular was positioned both higher and farther backward when the subject was standing on the foot bed as compared to standing on the non-custom insole. This difference can be attributed to the thickness of the footbed as compared to the non-custom insole as well as to the realignment of the

Figure 2a. Navicular start/end positions, x dir., right foot

Figure 2b. Navicular start/end positions, x dir., left foot

SB - Start Boot
EB - End Boot

SF - Start Footbed
EF - End Footbed

Figure 3a. Navicular start/end positions, y dir., right foot

Figure 3b. Navicular start/end positions, y dir., left foot

SB - Start Boot
EB - End Boot

SF - Start Footbed
EF - End Footbed

foot by the footbed. There was a similar significance when comparing end positions of the navicular tubercle. The navicular was situated higher and farther back in the boot when the subject was standing in the end position on the custom footbed than it was when standing in the end position on the insole.

Figures 4-5 show the range through which the navicular tubercle moves when the subject shifts from the start to the end position. This range was determined by calculating the differences between the start and end positions of the navicular. There is a statistically significant difference in the amount of navicular motion experienced when using the two types of insoles. The custom footbeds allowed significantly less forward and downward motion than did the non-custom insoles. These findings indicate that the custom insoles changed the position of the foot and reduced the amount of motion experienced inside of the boot, specifically that navicular motion which is associated with the flattening of the arch during pronation.

It was noted that one subject displayed a slight backward and downward motion of the left navicular tubercle while using the non-custom insole. One study conducted by a boot manufacturer has shown this to be a somewhat common phenomena with the use of overlap design boots due to slippage at the heel (Walkhoff and Baumann, 1987). The subject displayed the more typical forward and downward motion when using the custom molded footbed.

Figure 4. Navicular motion in the x direction.

R - Right Foot
B - Boot

L - Left Foot
F - Footbed

Figure 5. Navicular motion in the y direction.

R - Right Foot	L - Left Foot
B - Boot	F - Footbed

There was no significant difference between the navicular motions of the right and left feet of the subject group. There was no significant interaction between type of insole and feet.

Rearfoot Angle. The angle created by the midline of the lower leg as it moves away from the perpendicular was taken as the rearfoot angle in this study. Photographs were taken of the rearfoot in the start and end positions using both non-custom insoles and custom footbeds. These angles, expressed in degrees are displayed in Figure 6. The group results comparing the rearfoot angle at the start position of the non-custom insoles to that at the start position of the custom footbeds for the right foot showed a significant difference. A statistically significant difference was also found when comparing the rearfoot angles at the end positions of the two types of insoles. In both cases the angle of the rearfoot was decreased when using the custom footbeds as compared to the angle exhibited when using the insoles. The results were the same for the left foot. This difference in angles can be attributed to the change in foot alignment brought about by the custom molded footbeds.

Neither the non-custom insole nor the custom footbed allowed any significant change in angle when moving from the start to the end position with either foot. The integrity of the boot at the rear may influence the amount of motion experienced by the rearfoot. The results indicate that

Figure 6a. Rearfoot angles at start and end, right foot.

Figure 6b. Rearfoot angles at start and end, left foot.

SB - Start Boot
 EB - End Boot

SF - Start Footbed
 EF - End Footbed

while neither type of insole allows any significant rearfoot motion, the custom footbeds maintain the leg significantly closer to the perpendicular both at the start and at the end position.

There was a significant difference found in both the start and end positions when comparing the rearfoot angles of the right foot to the left foot. Although the non-weight bearing measurements of subtalar varus taken during the initial screening process showed no significant difference between feet, added factors such as weight bearing, and knee and hip alignments could help to amplify any differences which did exist. This result is consistent with other research findings which have indicated the differences in biomechanical parameters when comparing right and left feet (McKenzie, Clement, and Taunton, 1985). This finding supports the concept of creating footbeds for each foot separately. There was no significant interaction between the type of insole and feet.

Tibial Rotation. Tibial rotation was measured by the horizontal displacement (x direction) of the tibial tubercle from a line lying perpendicular to the floor and passing through the midseam of the boot. This variable was measured in one position only. This position placed each subject on one leg at a time with weight equally distributed across the foot. The results are shown in Figure 7. A statistically significant difference was found between the positions of the tibial tuberosity when comparing the two types of

Figure 7. Tibial tubercle horizontal distance from midline.

RB - Right Boot
LB - Left Boot

RF - Right Footbed
LF - Left Footbed

insoles. The tuberosity was significantly closer to the midline when the subjects were using the custom molded footbeds. This finding was true for both the right and left feet. This result was attributed to the custom molded footbed altering the position of the foot which in turn changed the alignment of the lower limb. There was a statistically significant difference between the location of the tuberosity for the right and left feet. Separate statistical analyses performed on each type of insole alone showed that this significance occurred when using the non-custom insoles. The custom molded footbeds showed no significant difference between the position of the tibial tuberosity of the right and left feet. This result indicated that the custom molded footbeds both decreased the amount of tibial rotation and minimized the between leg differences.

Summary. The custom molded footbeds maintained the navicular tubercle in a position inside of the ski boot which was both higher and farther back as compared to the non-custom insoles at both the start and end positions. This was due to the thickness of the footbed as well as to the change in foot position brought about by the footbed. Further, the custom footbeds allowed less forward and downward motion of the navicular than did the insoles when moving from the start to the end position.

The rearfoot angle was smaller at both the start and end position when using the custom footbed as compared to

the non-custom insole. This was due to the repositioning of the foot by the footbed. There was no difference between the amount of motion that either of the types of insoles allowed when moving from the start to the end position.

The custom molded footbeds maintained the tibial tuberosity in a position closer to the mid-line than did the non-custom insoles. Again, this is due to the repositioning of the foot by the footbed.

Skiing Section

Horizontal visual analogue scales were utilized by the subjects in order to rate their experiences with edge control, pain, and fatigue while skiing. The group data from these scales are displayed in Figures 8-10.

Edge Control. The subjects gave the custom molded footbeds significantly higher marks than the non-custom insoles in the category of edge control. This was true for both the short radius and the long radius turns.

Pain. Although the subjects experienced slightly more pain with the use of the custom molded footbeds than with their own non custom insoles, the figures were not significant. The slight increase in pain was attributed to an insufficient break-in period when using the new custom footbeds. Adjustments such as buckle tightness and sock thickness with the use of any new footbed or ski boot take more time than was available during this study. It was noted that most subjects experienced less pain as they spent

more time in the custom footbeds but were instructed to complete the ratings scale based on their overall impression during the entire test period.

Fatigue. The subjects found their feet and legs to be significantly less fatigued after skiing with the custom footbeds than with the non-custom insoles.

Timed Runs. Subjects were timed for a total of four trials through a race course. The average times for the group were significantly faster when using the custom molded footbeds as compared to the non custom insoles. In addition it was noted that all subjects had equivalent or faster times when using the custom footbeds as compared to the non custom insoles. Although each subject skied the same race course all four times, the effects of learning were controlled by the division of the group into two subgroups. While half of the subjects skied their third and fourth runs using the custom footbeds, the other half of the group skied their first and second runs using the custom footbeds.

Summary. The subject group rated the custom footbeds as significantly better than the custom insoles in providing edge control for both short and long radius turns. The footbeds were also rated as causing significantly less fatigue than non-custom insoles. The subject group did not find any statistically significant differences in the level of pain experienced while using either type of insoles.

Figure 8a. Edge control ratings for short radius turns.

Figure 8b. Edge control ratings for long radius turns.

B - Boot F- Footbed

Figure 9a. Pain ratings.

Figure 9b. Fatigue ratings.

B - Boot F - Footbed

Figure 10. Race results.

B - Boot F - Footbed

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

This investigation was designed to test the hypothesis that custom molded ski boot footbeds could control the events associated with pronation more effectively than non-custom insoles. The control of pronation was tested by analyzing the related motions of various foot and lower leg landmarks. Navicular drop was monitored as it reflects the collapsing of the medial arch which accompanies the abduction and ankle eversion associated with pronation. Rearfoot angle was chosen as another indicator of abduction and ankle eversion. The location of the tibial tubercle was monitored because tibial rotation has been shown to accompany pronation. The results of the investigation showed the custom footbeds to control navicular drop and tibial rotation more effectively than the non-custom insoles. The amount of rearfoot angle at both the start and end positions was significantly changed with the use of custom footbeds even though overall motion was not affected.

It was hypothesized that custom footbeds could improve edge control, decrease pain and decrease fatigue as compared to non-custom insoles. The results of the investigation indicated that the test group felt that custom footbeds did increase edge control in both short and long radius turns, and decreased the amount of fatigue experienced. The group did not report any significant differences in the level of pain experienced. These results were based on purely

subjective analyses. Timed runs through a race course resulted in faster times for skiers when using the custom footbeds as compared to the non-custom insoles.

It was believed that maintaining the subtalar joint in a more neutral position would result in all the skiing improvements previously discussed. From the differences in landmark positions in both start and end positions when comparing the two types of insoles, it appears that the custom footbeds effectively realigned the foot within the ski boot. Because of the molding technique utilized in this study, it is assumed that the footbed does maintain the foot in a neutral position during weight bearing. In addition to the realignment of the foot, the footbed served to fill in any gaps under the foot and provide a solid, minimally compressible base of support. The combination of these two factors likely allows for the control of motion witnessed during this investigation. It is also believed to be responsible for an improved transmission of forces between the skier and the boot, resulting in better edge control and decreased effort to carve a turn.

The subjects utilized in this study exhibited more than three degrees of subtalar varus when measured in a non-weight bearing position. The effectiveness of the footbeds in controlling the motion experienced by these subjects could be thought to indicate a similar effectiveness when footbeds are used by skiers with lesser degrees of

malalignment. However, the use of this product by such skiers would not necessarily be indicated.

Conclusions

Based upon the results of this study, the following conclusions were made with regards to the hypotheses:

1.a) Custom molded footbeds controlled the navicular drop associated with pronation more effectively than non-custom insoles.

b) Custom footbeds realigned the subtalar joint so as to decrease the rearfoot angle as compared to that experienced with the use of non-custom insoles. Custom footbeds did not reduce the amount of rearfoot motion as compared to that experienced with the use of non-custom insoles.

c) Custom molded footbeds realigned the foot and lower leg so as to maintain the tibial tubercle in a position closer to center than that experienced with the use of the non-custom insole.

2. The hypothesis that custom footbeds decrease the amount of pain experienced while skiing was not supported by the findings of this study.

3. The use of custom footbeds resulted in a subjective decrease in the amount of fatigue reported by the subject group as compared to that reported with the use of the non-custom insoles.

4. The use of custom footbeds resulted in an improvement in the amount of edge control reported by the test group.

5. The use of custom footbeds resulted in improved race times for the subject group.

Recommendations

The ability of custom molded ski boot footbeds to control subtalar motion and enhance the skiing experience is supported by this study. These findings were based on the use of one style of footbed. At the present time there are other styles of custom footbed being marketed to skiers. Skiers should be aware that some of the footbeds available do not provide a solid bottom and may therefore be highly compressible, allowing more motion at the navicular with forward weight transfer. In addition, the use of different materials in the construction of the footbeds, as well as the method of molding the footbeds can alter the amount of control they provide. The consumer should be aware of the differences in the available products in order to fully benefit from the use of a custom molded footbed.

Future directions for research in this area should include laboratory testing incorporating the protocol utilized in this study for the analyses of different types of ski boot footbeds. Field research should be performed documenting injury rates among skiers using custom molded footbeds. Such investigations would be beneficial additions to the present research.

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APPENDIX A

DETERMINATION OF LOWER LIMB ALIGNMENT.

1. Leg - heel alignment (subtalar varus)
 - subject in prone position with feet extended clear of the examining table
 - mark midline of the calcaneus at intersection of Achilles tendon and at a point 1.5cm distal
 - place two additional marks on the midline of the distal 1/3 of the leg to represent the longitudinal axis of the tibia
 - place the subtalar joint in neutral position: stabilize the forefoot by applying pressure under the fourth and fifth metatarsal heads and dorsiflex until the point of resistance, then invert/evert the foot through the arc of motion until the balance point is identified
 - measure the angle between the longitudinal axis of the leg and heel using a goniometer

James (1979)

2. Forefoot - heel alignment (forefoot varus)
 - place subject in prone position with feet extended clear of the examining table
 - marks on calcaneus from the previous measurement are used as references for the heel, the plane of the metatarsal heads is used in reference to these marks
 - varus alignment is said to be present if the plane of the forefoot at the metatarsal head level is such that the medial side of the foot rises above a perpendicular plane

James (1979)

3. Functional Hypermobility
 - subject is weight bearing, standing on the floor
 - observe the movement of the great toe, the flattening of the arch/navicular drop, and tibial rotation/knee valgus with weight bearing

APPENDIX B

FOOTBED MOLDING PROCEDURE.

1. Rear/Midfoot Molding

- subject is seated comfortably, shoes and socks off
- position the "3/4thotics" on the heating paddles, and inside the oven (160 °C) for approx. 10min.; position the blanks above the oven to pick up ambient heat
- while positioning the 3/4thotic on the molding cap, insert the rear part of the blank into the oven to warm slightly before positioning the blank on the 3/4thotic (max. time in oven is 20 sec, this ensures proper bonding of the blank and the 3/4thotic)
- remove 3/4thotic from spatula by tapping against the bench
- center the 3/4thotic and blank flanges flush with the flanges of the molding cap
- tack all edges together
- center the parts against the bottom of the foot and gently slide the heel of the foot into the heel cup
- fasten the retaining strap
- check that the heel is in the back of the skithotic, the long axis of the foot and the skithotic are in alignment with the cap, and the skithotic and the cap are perpendicular to the long axis of the leg
- slip on the plastic sock, pull up from heel, and secure with ankle cinch band
- turn on vacuum pump.
- as air evacuates, gently hold down the first metatarsal head
- position the foot in a locked, neutral position (as described in James 1979 - see Appendix A)
- have subject step down on the other foot and slowly put the down the 'orthotic' foot just to the point of contact with the ground - no weight
- turn off the vacuum
- subject flexes both knees forward slightly, gently transfers weight to both feet equally - maintain neutral, locked position
- turn vacuum back on, have the subject lift the foot again and sit down for 30 seconds
- allow parts to cool for 2 min before separating the footbed from the molding cap

2. Forefoot Molding

- position footbeds about half way into the oven for 3 min
- do not heat more than 3-4cm beyond the leading edge of the 3/4thotic so as not to soften the medial arch or cuboid areas
- position the skithotic and molding cap squarely on the foot with an insulation pad placed between the foot and footbed
- have subject step down on the other foot and bring footbed foot down to the point of contacting the ground - no weight

- check that heel is in position, ball of foot and medial edges of footbed and molding cap are all flush
- gather toes together as they would be in a ski boot
- hold toes and forefoot down, gently lift the heel with the other hand
- have subject transfer all the weight to the footbed and hold for 5 seconds
- transfer weight back to the other foot and lower the heel slowly without weight - guide the heel until contact is made
- gently push toes down with the palm of your hand top help increase definition
- push down on the first metatarsal head while the rearfoot remains neutral - without weight

3. Finishing the Footbeds

- use ski boot's standard insole to trace length and shape onto footbed - trim back, leaving footbed slightly longer than the insole (leave even longer for rear entry boots)
- use a wire-brush wheel to grind off excess cork in the arch area
- use the edge of a stone wheel to cut back any other excess and to leave a smooth finish
- keep the flange edge thin, but no less than 1mm
- keep the heel cup as vertical as possible
- fit the footbed into the boot, trim if necessary

Superfeet Technical Manual(1983)

APPENDIX C

GENERAL DESCRIPTIVE DATA FOR ALL SUBJECTS

Table C-1
General Descriptive Data for all Subjects

Age(yrs)	Height(cm)	Weight(kg)	Skiing(yrs)	SV	
				R	L
28	170	70.4	20	6	5
24	170	76.4	16	7	8
21	177.5	81.8	12	4	4
23	162.5	61.4	13	5	4
27	175	77.3	15	5	6
24	177.5	65.9	18	9	4
18	180	70.4	12	6	4
23	175	80.4	10	5	4
36	177.5	79.5	21	8	6
23	167.5	61.4	14	4	6
23	172.5	68.2	17	7	5
25	162.5	56.8	16	4	3
28	167.5	65.9	15	5	4
28	170	70.45	20	5	6
26	162.5	70.9	13	4	5
Avg.	25.13	171.17	70.48	15.47	5.6/4.9
S.D.	3.96	5.69	7.25	3.16	1.5/1.2

SV - Subtalar Varus (Right/Left)

APPENDIX D

COMPLETE NAVICULAR DATA.

Table D-1

Right Foot - Location of Navicular(cm), Average of 2 Trials

	SBX	SFX	EBX	EFX	SBY	SFY	EBY	EFY
	9.595	9.6	9.035	9.28	7.38	7.79	6.825	6.825
	9.225	9.29	8.0	9.135	6.39	7.125	5.715	7.11
	7.335	8.125	6.56	7.975	6.385	7.79	5.91	7.73
	8.465	8.575	7.855	8.42	6.21	6.70	5.485	6.595
	8.225	10.71	7.275	10.39	6.455	7.16	6.075	7.045
	8.81	9.635	8.165	9.26	6.325	6.84	6.16	6.83
	7.695	7.855	7.405	7.83	7.51	7.935	7.06	7.64
	8.03	8.1	7.08	7.965	6.89	7.48	6.415	7.45
	8.565	8.595	7.66	8.42	6.625	7.385	6.105	7.34
	7.8	7.84	6.84	7.715	5.62	6.765	5.21	6.745
	8.46	9.52	7.675	9.33	5.515	7.75	5.09	7.545
	8.01	8.06	7.07	7.865	6.36	7.325	5.825	7.26
	8.36	8.74	7.575	8.495	6.51	7.03	6.17	6.925
Mean	8.352	8.819	7.553	8.622	6.475	7.313	6.003	7.157
SD	0.619	0.837	0.642	0.801	0.567	0.419	0.569	0.367

SBX - Start, boot, x axis
 EBX - End, boot, x axis
 SBY - Start, boot, y axis
 EBY - End, boot, y axis

SFX - Start, footbed, x axis
 EFX - End, footbed, x axis
 SFY - Start, footbed, y axis
 EFY - End, footbed, y axis

Table D-2

Left Foot - Location of Navicular(cm), Average of Two Trials

	SBX	SFX	EBX	EFX	SBY	SFY	EBY	EFY
	8.385	8.78	7.475	8.51	6.89	7.535	6.59	7.51
	8.43	8.61	7.91	8.37	5.93	6.83	5.295	6.77
	8.11	8.35	7.50	8.04	6.255	6.995	5.54	6.935
	8.765	9.22	8.24	9.06	6.105	6.62	5.68	6.425
	9.075	9.57	8.475	9.495	7.145	7.67	6.77	7.56
	9.535	10.435	8.64	10.245	7.085	7.77	6.915	7.74
	8.895	8.96	8.06	8.865	7.225	7.86	7.005	7.75
	7.23	7.51	6.41	7.38	7.125	7.79	6.56	7.62
	8.26	8.41	7.415	8.245	6.735	7.665	6.235	7.56
	6.665	7.59	7.205	7.475	5.79	6.845	5.45	6.80
	7.55	7.6	6.695	7.36	6.695	6.69	5.99	6.62
	7.28	7.625	6.485	7.565	6.845	7.56	6.3	7.41
	7.675	8.03	7.515	7.68	5.615	6.54	5.345	6.495
Mean	8.143	8.515	7.540	8.253	6.572	7.259	6.129	7.169
SD	0.829	0.882	0.720	1.000	0.563	0.507	0.617	0.501

SBX - Start, boot, x axis
 EBX - End, boot, x axis
 SBY - Start, boot, y axis
 EBY - End, boot, y axis

SFX - Start, footbed, x axis
 EFX - End, footbed, x axis
 SFY - Start, footbed, y axis
 EFY - End, footbed, y axis

Table D-3
Navicular Range of Motion, Average of Two Trials

	RIGHT				LEFT			
	Boot		Footbed		Boot		Footbed	
	(x	y)	(x	y)	(x	y)	(x	y)
	.56	.55	.32	.085	.91	.3	.27	.025
1.225	.675	.155	.015	.52	.635	.24	.12	
.77	.475	.15	.06	.61	.715	.31	.06	
.71	.725	.155	.105	.525	.425	.16	.195	
.95	.38	.32	.115	.6	.375	.075	.11	
.645	.165	.375	.01	.895	.17	.19	.03	
.29	.45	.025	.295	.835	.22	.095	.11	
.95	.475	.135	.03	.82	.565	.13	.17	
.905	.52	.175	.045	.845	.5	.165	.105	
.91	.41	.125	.02	.54	.34	.115	.045	
.785	.425	.19	.205	.855	.705	.24	.07	
.94	.535	.15	.065	.795	.545	.06	.15	
.785	.34	.245	.105	.655	.27	.35	.045	
Mean	.802	.472	.194	.089	.723	.443	.185	.095
SD	.227	.143	.096	.082	.150	.182	.092	.055

Table D-4
Analysis of Variance - Right Foot, Location of Navicular

Source	Sums of Squares	Mean Squares	DF	F Ratio	P
SBX vs SFX	1.417	1.417	1	5.701	0.034
Error	2.983	0.249	12		
EBX vs EFX	7.415	7.415	1	28.400	0.000
Error	3.133	0.261	12		
SBY vs SFY	4.570	4.570	1	34.710	0.000
Error	3.133	0.261	12		
EBY vs EFY	8.648	8.648	1	45.822	0.000
Error	2.265	0.189	12		

SBX - Start, boot, x axis
 EBX - End, boot, x axis
 SBY - Start, boot, y axis
 EBY - End, boot, y axis

SFX - Start, footbed, x axis
 EFX - End, footbed, x axis
 SFY - Start, footbed, y axis
 EFY - End, footbed, y axis

Table D-5
Analysis of Variance - Left Foot, Location of Navicular

Source	Sums of Squares	Mean Squares	DF	F Ratio	P
SBX vs SFX	0.899	0.899	1	23.503	0.000
Error	0.459	0.038	12		
EBX vs EFX	3.302	3.302	1	37.972	0.000
Error	1.043	0.087	12		
SBY vs SFY	3.067	3.067	1	87.660	0.000
Error	0.420	0.035	12		
EBY vs EFY	7.030	7.030	1	173.012	0.000
Error	0.488	0.041	12		

SBX - Start, boot, x axis
 EBX - End, boot, x axis
 SBY - Start, boot, y axis
 EBY - End, boot, y axis

SFX - Start, footbed, x axis
 EFX - End, footbed, x axis
 SFY - Start, footbed, y axis
 EFY - End, footbed, y axis

Table D-6
Analysis of Variance - Range of Motion, X Direction, Boot vs
Footbed

Source	Sums of Squares	Mean Squares	DF	F Ratio	P
Within Subjects					
R vs L	0.025	0.025	1	0.877	0.368
Error	0.345	0.029	12		
B vs F	4.278	4.278	1	292.314	0.000
Error	0.176	0.015	12		
Interaction	0.016	0.016	1	0.506	0.491
Error	0.374	0.031	12		

Table D-7
Analysis of Variance - Range of Motion, Y Direction, Boot vs
Footbed

Source	Sums of Squares	Mean Squares	DF	F Ratio	P
Within Subjects					
R vs L	0.002	0.002	1	0.158	0.698
Error	0.119	0.010	12		
B vs F	1.737	1.737	1	91.227	0.000
Error	0.229	0.019	12		
Interaction	0.004	0.004	1	0.405	0.537
Error	0.113	0.009	12		

APPENDIX E

COMPLETE REARFOOT DATA.

Table E-1
Rearfoot Angle, Average of Two Trials

	RBS	RBE	RFS	RFE	LBS	LBE	LFS	LFE
	6.75	6.0	3.5	3.0	4.0	3.5	1.25	1.0
	5.5	5.25	4.25	4.25	2.5	2.0	1.5	1.25
	5.75	5.5	3.0	2.75	3.75	3.5	2.0	2.0
	4.25	3.5	3.5	2.25	5.75	5.5	3.0	3.5
	8.5	8.75	4.5	4.75	4.25	4.0	1.5	1.75
	7.5	7.5	3.5	3.0	3.0	2.75	1.75	2.0
	6.5	5.75	3.0	2.25	5.5	5.25	2.0	1.5
	3.0	4.5	2.75	4.0	5.75	4.25	1.0	0.5
	6.25	4.5	3.5	3.75	4.0	3.25	1.625	1.25
	7.0	5.5	4.25	3.5	4.0	2.75	1.5	1.5
	5.0	4.25	3.25	3.0	3.75	3.25	1.5	1.25
	5.75	6.0	3.25	2.75	5.25	5.0	1.5	1.0
	4.25	3.5	2.0	1.25	4.25	4.0	1.0	1.0
Mean	5.846	5.423	3.404	3.115	4.288	3.769	1.625	1.500
SD	1.488	1.491	0.673	0.939	1.015	1.038	0.515	0.736

RBS - Right, boot, start
 RBE - Right, boot, end
 LBS - Left, boot, start
 LBE - Left, boot, end

RFS - Right, footbed, start
 RFE - Right, footbed, end
 LFS - Left, footbed, start
 LFE - Left, footbed, end

Table E-2
Analysis of Variance - Rearfoot Angle, Start Position, Boot
vs Footbed

Source	Sums of Squares	Mean Squares	DF	F Ratio	P
Within Subjects					
R vs L	36.181	36.181	1	21.612	0.001
Error	20.089	1.674	12		
B vs F	84.724	84.724	1	187.557	0.000
Error	5.421	0.452	12		
Interaction	0.159	0.159	1	0.197	0.665
Error	9.704	0.809	12		

Table E-3
Analysis of Variance - Rearfoot Angle, End Position, Boot vs Footbed

Source	Sum of Squares	Mean Squares	DF	F Ratio	P
Within Subjects					
R vs L	34.736	34.736	1	16.832	0.001
Error	24.764	2.064	12		
B vs F	68.082	68.082	1	91.608	0.000
Error	8.918	0.743	12		
Interaction	0.005	0.005	1	0.007	0.936
Error	8.495	0.708	12		

APPENDIX F

COMPLETE TIBIAL TUBEROSITY DATA.

Table F-1

Displacement of the Tibial Tuberosity From Center, Average of Two Trials

	RBX	RFX	LBX	LFX
	2.33	1.315	1.85	0.38
	1.405	0.98	0.95	0.645
	1.53	1.285	1.22	0.88
	2.46	1.185	2.065	2.39
	2.235	1.345	1.205	0.8
	2.305	2.025	1.25	0.3
	2.67	1.72	2.605	1.72
	1.835	1.355	2.185	1.61
	2.97	1.215	2.29	0.78
	2.625	1.545	1.74	0.935
	2.06	2.355	1.97	1.69
	1.38	0.815	1.8	0.95
	3.13	1.035	3.05	1.095
Mean	2.226	1.398	1.860	1.090
SD	0.567	0.427	0.604	0.599

RBX - Right, boot, x dir.
LBX - Left, boot, x dir.

RFX - Right, footbed, x dir.
LFX - Left, footbed, x dir.

Table F-2
Analysis of Variance - Tibial Rotation, Displacement in the
X Direction, Boot vs Footbed

Source	Sum of Squares	Mean Squares	DF	F Ratio	P
Within Subjects					
R vs L	1.474	1.474	1	5.513	0.037
Error	3.208	0.267	12		
B vs F	8.292	8.292	1	26.405	0.000
Error	3.768	0.314	12		
Interaction	0.011	0.011	1	0.131	0.724
Error	1.003	0.084	12		

RBX - Right, boot, x dir.
 LBX - Left, boot, x dir.

RFX - Right, footbed, x dir.
 LFX - Left, footbed, x dir.

APPENDIX G

COMPLETE RATINGS DATA.

Table G-1
Subjective Ratings Out of 100 for Edge Control, Pain, and Fatigue

	LRF	LRB	SRF	SRB	PF	PB	FF	FB
	76	40	81	31	11	31	10	40
	66	32	70	39	59	44	31	43
	53	21	53	23	62	43	25	44
	72	39	66	31	58	50	55	64
	72	42	81	44	40	30	28	40
	83	27	98	30	75	75	63	84
	58	84	79	77	46	3	2	11
	73	44	79	41	53	37	24	70
	62	41	62	35	18	40	24	58
	83	68	89	62	33	27	61	62
	73	46	69	57	33	42	34	49
	48	65	66	65	41	59	70	56
	90	59	74	64	43	66	24	27
	85	56	78	46	24	22	29	31
	85	65	74	61	60	33	53	52
Mean	71.9	48.6	74.6	47.1	43.7	40.13	35.5	48.7
SD	12.5	17.2	11.1	16.2	17.9	17.9	20.1	18.3

LRF - Long radius, footbed
 SRF - Short radius, footbed
 PF - Pain, footbed
 FF - Fatigue, footbed

LRB - Long radius, boot
 SRB - Short radius, boot
 PB - Pain, boot
 FB - Fatigue, boot

Table G-2

Analysis of Variance - Ratings for Edge Control, Pain, and Fatigue, Boot vs. Footbed

Source	Sum of Squares	Mean Squares	DF	F Ratio	P
Within Subjects					
LRF vs LRB	4083.333	4083.333	1	19.587	0.001
Error	2918.667	208.476	14		
SRF vs SRB	5685.633	5685.633	1	34.975	0.000
Error	2275.867	162.562	14		
PF vs PB	97.200	97.200	1	0.519	0.483
Error	2623.800	187.414	14		
FF vs FB	1306.800	1306.800	1	11.271	0.005
Error	1623.200	115.943	14		

LRF - Long radius, footbed
 SRF - Short radius, footbed
 PF - Pain, footbed
 FF - Fatigue, footbed

LRB - Long radius, boot
 SRB - Short radius, boot
 PB - Pain, boot
 FB - Fatigue, boot

APPENDIX H

COMPLETE RACE DATA.

Table H-1
Race Results, Average of Two Runs

	Footbed	Boot
	17.145	17.45
	17.19	17.47
	16.115	16.735
	17.5	17.785
	17.685	17.99
	18.585	18.585
	20.235	20.535
	19.55	19.78
	18.315	18.7
	17.32	17.45
	16.4	16.905
	16.365	16.65
	18.435	18.73
	17.39	17.645
	18.21	18.485
Mean	17.763	18.060
SD	1.327	1.202

Table H-2
Analysis of Variance - Race Results, Boot vs Footbed

Source	Sum of Squares	Mean Squares	DF	F Ratio	P
Within Subjects					
B vs F	0.662	0.662	1	66.420	0.000
Error	0.139	0.010	14		