A Kinematic Description of the Ankle During the Acceleration Phase of Forward Skating

by

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A Thesis Submitted to
The Faculty of Graduate Studies and Research
in Partial Fulfillment of the Requirements
for the Degree Master of Arts (Education)

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Montreal, Quebec, Canada

August, 1986

ISBN 0-315-38320-8

Short title of thesis:

Kinematics of the ankle during skating acceleration

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ABSTRACT

The purpose of this study was to document the kinematic pattern of the ankle in a forward skating acceleration task. The second major concern was to assess the effect of removing the ankle support normally provided by hockey skates on this pattern. Two male advanced level hockey players were filmed on the fourth stride of a maximal intensity acceleration by two LOCAM cameras operating at 100 fr/s. Cameras were placed to give sagittal and frontal plane views with respect to the skate blade during ice contact. Subjects underwent 10 trials in each of two skate conditions: a conventional hockey skate, and an identical skate with all ankle restriction removed.

Analysis revealed dorsiflexion upon touchdown, with pronation and further dorsiflexion occurring during contact. Maximum values of pronation and dorsiflexion were reached just before the heel of the skate blade left the ice. The heel-off to toe-off phase was characterized by large plantar flexion and supination velocities. The ranges of motion as well as the angular velocities at the ankle in both planes were greater for the test skate condition. It was apparent that important forward impulse occurred as a result of ankle flexion. The ankle support inherent in hockey skates appeared to reduce this impulse. Results were discussed in terms of a biomechanical model of skating.

RESUME

La présente étude visait dans un premier temps à documenter le pattern cinétique de la cheville lors d'un mouvement d'accélération avant sur patin à glace. Dans un deuxième temps l'élément du support du patin a été enlève afin d'évaluer les conséquences de l'absence de soutien sur le pattern cinétique obtenu. Deux joueurs de hockey de niveau avancé ont été filmé à l'aide de deux caméras LOCAM reglées à une vitesse de 100 fr/s, lors de la quatriéme foulée d'une accélération d'intensité maximale. Les caméras étaient placées de façon à obtenir une vue des plans saggitale et frontale de la lame du patin lors du contact avec la patinoire. Les sujets ont été soumis à une série de 10 essais pour chacune des deux conditions experimentales, avec ou sans support de cheville. Les résultats de l'analyse cinématographique révèlent un pattern de flexion dorsale en phase initiale de contact avec la surface glacée, associé à une pronation et une flexion dorsale accentuées au moment de contact. Les valeurs maximales de pronation et de flexion dorsale ont été observées immédiatement avant l'élévation du talon de la lame du patin. La période entre l'élévation du talon de la lame de patin et l'élévation de la partie antérieure proximale du patin se caratérise par des vitesses de flexion plantaire et de supination importantes. Des amplitudes de mouvements et des vélocités angulaires de la cheville plus importantes ont été observées lors des essais effectués avec le patin modifié. Il apparaît évident qu'une impulsion antérieure importante survienne en réponse à la flexion de la cheville. Il semble que l'insertion d'un support de cheville dans la chaussure du patin de hockey provoque une diminution de l'impulsion antérieure. Un modèle biomécanique du patinage sur glace est présenté à partir des résultats obtenus.

ACKNOWLEDGEMENTS

In the pursuit of this project I have been extremely fortunate in being able to rely on a group of very helpful and capable individuals. A heartfelt 'thanks' is extended to the members of the McGill Physical Education faculty and to my fellow biomechanics students for their support and their willingness to take time to share their expertise.

I would like to acknowledge the contributions of the following individuals to this project. Marc Gélinas, who handled the cameras, must be given credit for the excellent film data collected. The invaluable assistance and advice of Heidi Sveistrup, George Vagenas, and Gary Currie were instrumental in the smooth and efficient running of the experiment. Bob Beaulac was responsible for many of the organizational details of the project and also aided in the data collection. Tim Gallivan was of enormous help in the digitization and analysis of the data. The abstract was translated by Dr. Hélène Perrault and Marc Gélinas.

Particular gratitude is extended to Dr. T.B. Hoshizaki, whose expertise, encouragement, and unwaning interest in the project made the research experience a most enjoyable one for me.

Financial support was provided by Warrington Inc., the McGill Department of Physical Education, and the McGill Computer Center.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The ability to accelerate very quickly from a state of low velocity is one of the most important, fundamental skills of a hockey player. The necessity of this skill becomes apparent when one considers the nature of the game and the physical boundaries of the surface on which it is played. In a game in which plays develop with split-second timing, even a slight advantage in this area can make the difference between winning and losing.

In hockey coaching manuals, the need for full extension of the hip, knee, and ankle in effective acceleration is stressed (Wild, 1971; Can-Am Hockey Group, 1973; Watt, 1973; Hockey Canada, 1975; Stamm, Fischler, & Freidman, 1982). However, extension of the ankle may be compromised by the type of hockey boot worn by the skater. The development of the restrictive hockey boot, and in particular the achilles tendon guard, has evolved from the need for protection, and the need of young skaters for ankle support, without any concomitant assessment of the effect of the boot on kinematic skating pattern or skating performance. Other types of skates, such as speed skates and bandi skates (used in a game which has demands similar to hockey), leave the ankle free from restriction. It is very possible that the present hockey skate inhibits skating performance.

1.1 Nature and Scope of the Study

Skating differs fundamentally from other means of bipedal locomotion in three primary aspects. First, horizontal ground reaction forces are elicited perpendicular to the direction of the foot, necessitating outward rotation of the thigh before a forward directed impulse can be applied. Secondly, the foot through which the force is being applied is moving (gliding) relative to the ice surface. In addition to these concerns, the skate blade offers an extremely narrow base of support resulting in a very effective mechanical advantage for forces rotating the skate about an axis along the blade.

With virtually all external force in skating propulsion acting through the skate blade, it should be readily apparent that the position and angle of the blade relative to the ice, and the transmission of forces to the blade, are of fundamental importance to skating. The function of the ankle in this regard is critical. However, the manner in which the ankle controls the direction and timing of force application, as well as the ankle's effect on total impulse, are aspects of skating which are presently very poorly understood.

Motion at the ankle takes place at two joints (Wells & Luttgens, 1976). The ankle proper is a hinge joint formed by the articulation of the talus with the malleoli of the tibia and the fibula. The sub-talar joint is formed by the articulation of the talus with the calcaneus. This non-axial joint permits limited gliding between the articulating surfaces. Together, these two joints produce four movements in two planes: plantar -

dorsal flexion in the sagittal plane and supination - pronation in the frontal plane. The range of motion for each action is a reflection of joint structure, soft tissue characteristics such as ligaments, and muscular activity. The factors influencing ankle movement interact with the support characteristics of the skate to yield the resulting kinematic pattern for the skater.

It is mechanically sound to expect that energy provided to the athlete is maximized when the torque-producing musculature of the hip, knee, and ankle can act through as large a range of motion as possible. Page (1975) and McCaw (1984) related maximal skating velocity to range of motion at the knee and hip. However, McCaw (1984) indicated that elite skaters had smaller ankle displacements than intermediate or novice skaters. McCaw did not complete his analysis of the ankle results, noting that his experiment was not designed to provide data on the kinematics of the ankle.

Excess pronation during lower limb extension can effectively absorb a great deal of the energy provided by the hip and knee extensors. This is considered a common and often severe problem with young, beginning skaters (Hunter, Schuberth, & McCrea, 1981). However, some pronation may be necessary in order to set the blade in the ice at an appropriate angle to elicit a horizontal ice reaction force early in the propulsive phase of the skating stride, when forward lean of the skater is very small. It is also possible that supination of the ankle adds impulse to the skater later in the stride; if so, early pronation increases the range of motion for this action and may even serve to store energy in the muscles and ligaments. Film of advanced skaters (Hoshizaki, 1985) indicated that pronation was occurring during the fourth stride in an acceleration task. Little is known about the degree of importance of pronation and the effect of boot restriction on this action.

A number of studies (Marino & Dillman, 1978; Marino, 1983; Greer & Dillman, 1984; McCaw, 1984) have used high-speed cinematography to measure variables reflecting the lower limb kinematic pattern, but none of these have been directed at examining ankle movement. A major problem with the design of these studies, as far as the ankle is concerned, is that filming takes place in the sagittal plane, while joint motion of the lower limb takes place in oblique planes. Measurement error increases with increasingly distal joints, with ankle measurements being particularly affected. Documenting total body parameters necessitates a relatively large camera-to-subject distance, limiting the precision of ankle kinematic measurement.

1.2 Purpose of the Study

The purpose of this study was to document the kinematic pattern of the ankle joint during the acceleration phase of forward skating. The second concern of this investigation was to compare the effect (on kinematic pattern) of a skate which was designed to support the ankle range of motion of a skater with an identical skate that was designed to allow the ankle freedom of movement.

1.3 Statistical Hypotheses

Each of the following hypotheses compares a skater wearing the test skate (with little ankle support) to the same skater wearing a conventional skate.

1. There will be no significant differences in MINIMUM ANKLE ANGLE IN THE SAGITTAL PLANE (dorsiflexion).
2. There will be no significant differences in PLANTAR FLEXION ANGLE AT TOE OFF.
3. There will be no significant differences in MAXIMUM PLANTAR FLEXION VELOCITY.
4. There will be no significant differences in MINIMUM ANKLE ANGLE IN THE FRONTAL PLANE (maximum pronation).
5. There will be no significant differences in MAXIMUM SUPINATION VELOCITY.

Evaluation of these hypotheses necessitates a quantitative description of ankle kinematics. Therefore, although the hypotheses deal with what has been labelled a 'secondary concern' of the study (that is, an assessment of the effect of ankle support on the kinematic pattern), the primary purpose of the study will be served.

1.4 Limitations and Delimitations

The limitations of this study are:

1. Movement of the foot within the skate boot will cause an error in the measurement of pronation, since the back of the

boot is representing the calcaneus segment. This error was minimized in this study by using only a professionally fitted and high quality molded skate boot.

2. Each trial is assumed to have been a maximal effort.
3. Subjects did not carry a hockey stick.

The following delimitations apply to this study:

1. Only the Micron Medalic skate was used.
2. Only the 4th stride in the acceleration task was analyzed.
3. Results apply to each subject individually, and they cannot be assumed to be representative of any particular population of skaters.

1.5 Definitons and Abbreviations

The following definitions and abbreviations will be used in this study:

SPATIAL-TEMPORAL COMPONENTS

Skating stride : The unit of movement in skating between contralateral foot touchdowns. A right stride begins with right foot touchdown and ends with left foot touchdown. It is one-half of a skating cycle, which commences with touchdown of one foot and terminates with the subsequent touchdown of the same foot.

Touchdown (TD) : That moment during a skating stride when the skate first makes contact with the ice.

Heel-off (HO) : That moment during a skating stride when the posterior end of the skate blade is lifted off the ice.

Toe-off (TO) : That moment during a skating stride when the skate blade leaves the ice.

Contact Time (CT) : The duration in time from TD to TO of the same skate (seconds).

Stride Time (ST) : The duration of one stride (seconds).

Stride Rate (SR) : The reciprocal of stride time (/s).

Single Support Time (SST) : The time during a stride when only one blade is in ice contact (seconds).

Double Support Time (DST) : The time during a stride when both blades are in ice contact (seconds).

Stride Length (SL) : The distance covered by the skater in the sagittal plane during one stride. It was measured as the distance between heel positions at successive TDs (meters).

ANGLE DEFINITIONS

*Note that in the following 'lateral' and 'posterior' are considered with respect to the foot.

Ankle Flexion Angle : Measure of the angle between foot and shank as seen by the lateral camera (degrees). Angle is formed by the 5th metatarsal-phalangeal joint, lateral malleolus, and the tibia-femur joint.

Ankle Pronation Angle : Measure of the angle between the posterior midline of the leg and a line on the boot in the same plane as the skate blade, measured laterally (degrees).

Angle of Propulsion : The angle between the desired direction of the skater's motion and the direction of the skate blade during propulsion (degrees).

Blade Angle : Angle between the normal to the ice surface and the vertical axis of the skate blade (zero degrees when standing).

CHAPTER II

REVIEW OF LITERATURE

Although a number of studies have addressed the problem of identifying the biomechanical factors which contribute to skating acceleration performance, none of them have dealt with the function of the ankle. In this chapter the importance of ankle motion to skating performance will be argued. In particular, the relationships of plantar flexion, dorsal flexion, and ankle pronation to forward impulse in the skating stride and the possible but unknown effects of ankle support on these components will be discussed.

Hockey skating coaches generally insist that proper skating acceleration is characterized by maximum extension of the hip, knee, and ankle joints of the lower limb (Wild, 1971; Can-Am Hockey Group, 1973; Hockey Canada, 1975; Marcotte, 1978; Stamm et al, 1982). Page (1975) found correlations between maximal velocity of hockey players and both knee flexion and knee extension. McCaw (1984) studied novice, intermediate, and elite level skaters and found that higher ability levels registered greater ranges of angular motion at both the hip and the knee when skating at maximal velocity. Significantly, the greater range of motion resulted primarily from greater joint flexion prior to extension. None of the ability levels exhibited full knee extension, in contrast to the expectations of coaches. These results are consistent with studies of running (Mann &

Hagy, 1980) and the diagonal stride in cross country skiing (Gagnon, 1980) which demonstrated that larger ranges of motion at both the hip and the knee corresponded to an increased speed. These increased ranges of motion with speed resulted primarily from greater degrees of joint flexion prior to propulsion. Mann & Hagy (1980) noted greater dorsiflexion when subjects switched from running to sprinting, and Sykes (1975) measured increases of the order of 10° for both plantar flexion and dorsiflexion for an elite runner changing speeds from 6,4 to 8,9 m/s.

The increase in range of motion with speed is to be expected since the distance through which each of the extensor groups exerts force is important in determining the body's kinetic energy at the end of propulsion (Hay, 1978). Mann & Hagy (1980) point out that an additional benefit of increased hip and knee flexion as well as ankle dorsiflexion is the lowering of the center of mass of the body. The result is that the center of mass is more optimally placed for the application of forward horizontal force once it is ahead of the ground support foot.

McCaw (1984) measured ankle angles of novice, intermediate, and elite skaters at maximal velocity with a camera filming motion in the sagittal plane. The experiment was designed to measure total body parameters; the large field of view required, combined with the three dimensional nature of the motion involving lateral rotation of the hip and hip abduction, make both the reliability and validity of the ankle measurement results questionable. Results showed an increase in the degree of maximal dorsiflexion with skating ability, as expected. However, plantar flexion values at takeoff were not large, and decreased considerably as skating ability increased, to the extent that the elite skaters had a smaller ankle range of motion than the novice skaters did. The range of motion was less than 20° for all three groups. This result is contrary to the subjective description of ankle action presented in the general coaching literature cited earlier, which emphasizes ankle plantar flexion. McCaw suspected that his measurements were in error because of the three dimensional nature of lower limb extension, and suggested that his results were more a reflection of greater lateral hip rotation with the superior ability levels than decreased plantar flexion.

The importance of ankle extension in gait has been a subject of several studies. Mann & Sprague (1980) and Mann (1981) measured joint moments in the lower limb during sprinting. Their results indicate that a large impulse is provided by the ankle extensors during pushoff (not to mention a large eccentric braking impulse upon landing). In fact, the data show that ankle extension provided more impulse during the last quarter of contact time than knee extension during that period. In an EMG study, Mann & Hagy (1980) found that the posterior calf muscle was active right up until toe-off in sprinting, but activity stopped shortly after plantar flexion commenced in running. This implies that ankle extension is of increasing importance as running speed increases, particularly in the final portions of ground support. As far as energy production capability is concerned, Winter (1983) found that peak power generation, a reflection of both joint moment of force and angular velocity, was greater at the ankle during walking than at the hip or the knee.

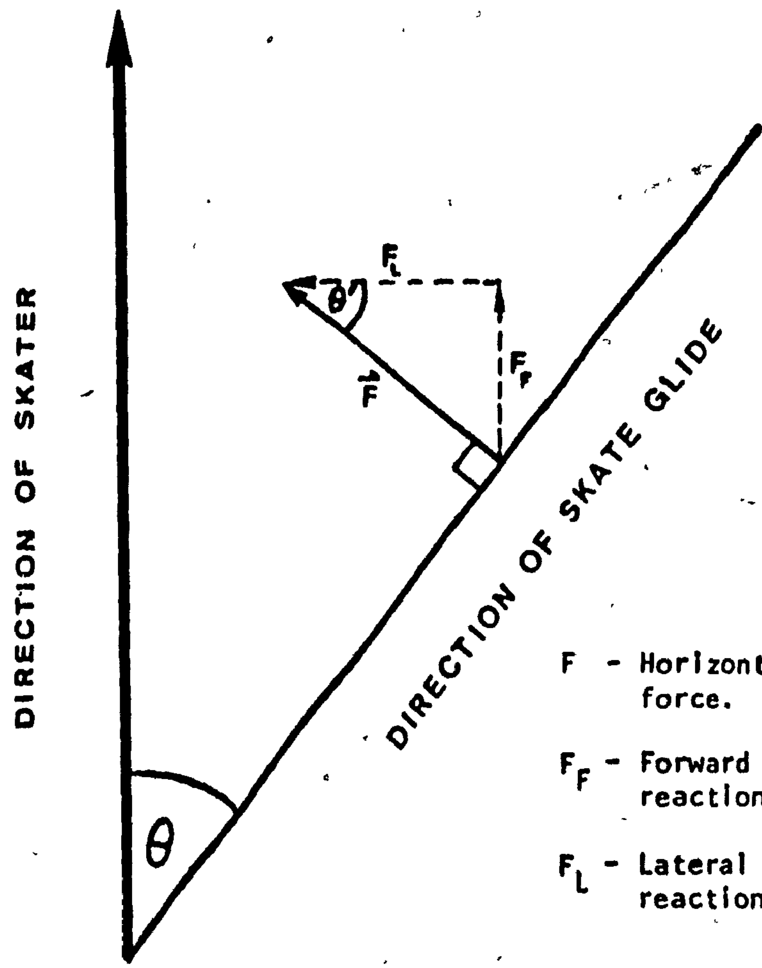
The applicability of these results to skating is questionable. Van Ingen Schenau & Bakker (1980) have developed a biomechanical model of speed skating in which no plantar flexion occurs. Apparently, speed skaters are coached to avoid plantar flexion during the pushoff. The reason for this is as follows: While lateral impulse is being provided through extensions of the hip and knee, the skate is sliding in the direction of the blade. Plantar flexion involves pushing the front end of the skate against a fixed point on the ice, and above a certain speed retroflexion of the hip and plantar flexion of the ankle will move the blade tip backward relative to the skater at a speed slower than that of the skater relative to the ice. The result will be a braking rather than a positive impulse. The authors point out that plantar flexion is a particular problem with beginners because of the confusion of skating technique with the more familiar techniques of pushoff in walking or running.

This may explain McCaw's (1984) data which indicated a trend to less plantar flexion with the more advanced skaters. However, it directly contradicts the description of proper ankle action presented in the hockey coaching literature. Furthermore, the movement pattern of hockey power skating is quite different from that of speed skating (Marino & Weese, 1979). Finally, the reason for eliminating plantar flexion action was related to the speed of the skater relative to the ice, which for speed skaters can surpass 14 m/s (Kuhlow, 1974). McCaw's subjects had mean maximal velocities which ranged from 6,9 m/s for his novice group to 9,2 m/s for his elite group, considerably less than the velocity of speed skaters. It must also be remembered that maximal velocity data has limited applicability to the type of skating which occurs in hockey, which consists primarily of short duration, high intensity accelerations at relatively low velocities (Dillman, Stockholm, & Greer, 1984). These authors filmed 22 advanced level hockey players for 13,5 second sequences in a game situation and found mean peak velocities of only 5,01 m/s. Ranges and standard deviations were not presented.

Consideration of the dynamics of the skating stride is helpful in elucidating the role of the ankle in forward propulsion. During the skating step, forces acting on the center of mass are elicited through the reaction force of the ice on the skate blade. Considering that the coefficient of dynamic friction between ice and skate blade is 0,02 and forces applied by the skater against the ice are typically less than 2000 N (Roy, 1978), it is clear that horizontal propulsive forces along the direction of the skate blade cannot be greater than about 40 N. Since the horizontal force on the skater may be 20 times this amount, almost all of this force must be in a direction perpendicular to the blade.

Skating therefore requires rotation at the thigh so that a large component of this perpendicular force will propel the skater in the desired direction of motion. This angle of propulsion (the angle of rotation of the skate blade relative to the direction of motion) was found by Marino (1983) to have a mean value of 40,5 degrees for a group of 69 skaters of various ability levels over the first three strides of a maximal acceleration task. An overhead camera was used to obtain the data. This value implies that the impulse given to the skater in the lateral direction was greater than that in the forward direction (by a factor of 1/tan 40,5 ; see Fig. 1). This is contrary to the visual impression noted by Marino that the legs tended to extend straight back from the hip during the first several strides. Lariviere (1968) used a technique of painting the ice imprint left by the skater to determine the angle of propulsion for a heterogeneous group of 18 hockey players. He found the mean angles of propulsion for the start and the first three strides to be 68°, 59°, 44,5°, and 34,8°.

Roy (1978) used a force plate embedded in a synthetic skating surface to measure force production from 8 highly skilled hockey players performing three types of starts. Measurements were also taken for a regular stride. A definition or description of the term 'regular stride' was not given. Mean forward impulse decreased from 170 N-s (front start) to 88 N-s on the second step, while lateral impulse increased from 33 N-s to 50 N-s. For a regular stride, the forward impulse was 69 N-s and the lateral impulse was 56 N-s. These numbers imply a decreasing angle of propulsion as the skater accelerated (tan



F - Horizontal ice reaction force.

F_F - Forward component of ice reaction force.

F_L - Lateral component of ice reaction force.

FIGURE 1. Depiction of horizontal ice reaction force on skater. The skater is skating toward the top of the page, and the angle of propulsion is θ. The ratio of the forward force F_F to the lateral force F_L is tan θ', and it can be shown geometrically that $\theta' = \theta$.

theta decreased - see Fig. 1), combined with a decreasing magnitude of force application as velocity increased. What is particularly interesting about these numbers is that the forward impulse is consistently larger than the lateral impulse, implying that the greater part of the skater's propulsion occurs when the angle of propulsion is considerably larger than expected (greater than 45°).

Inspection of a force vs time graph for the regular stride presented in the Roy (1978) study is illuminating. This graph is reproduced in Fig. 2. The ratio of forward:lateral force remains less than 1 for more than two thirds of the total propulsion time (indicating an angle of propulsion less than 45 degrees during this portion), yet it increases steadily. During the last quarter of the propulsion phase the ratio suddenly increases to as high as 1,5 and remains high as lateral force drops off and forward force increases. These results may be interpreted as depicting a gradual and then sudden increase in the angle of propulsion. The sudden increase could very well correspond with the time when the skater's center of pressure against the ice moves forward to the anterior end of the skate blade. With less blade surface on the ice, the skater is able to pivot on the skate blade through further lateral rotation at the hip, increasing the angle of propulsion during the final moments of ice contact as the skater digs the toe of the blade into the ice and pushes back. The implications of this phenomenon are considerable. The data presented by Roy demonstrate that over 1/2 of the forward impulse takes place

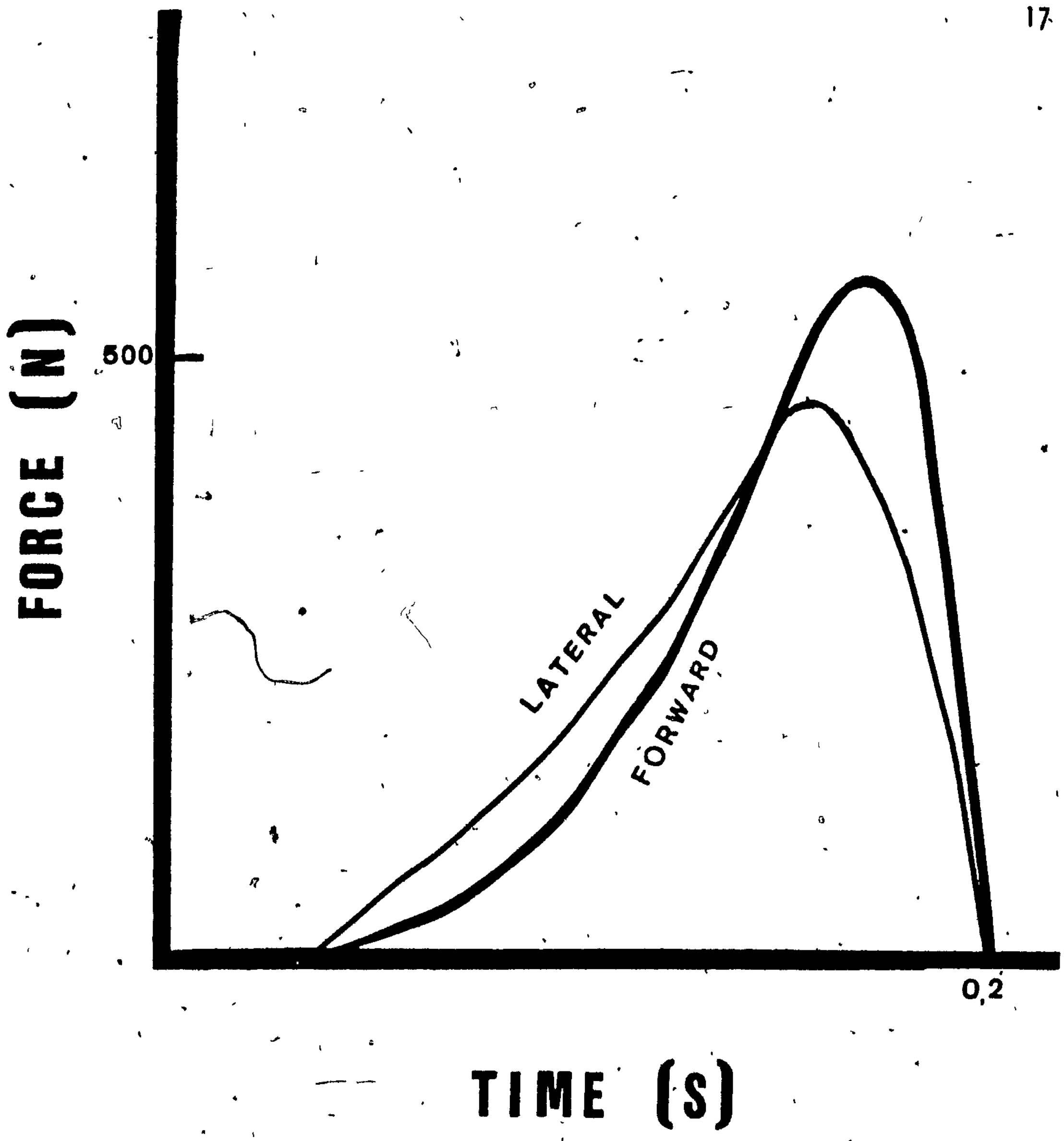


FIGURE 2. Forward and lateral components of horizontal ice reaction force during a 'regular' skating stride. From Roy (1978).

during the final quarter of propulsion, during which the angle of propulsion increases significantly. This corresponds to the time that 'toe push' or 'heel snap' (plantar flexion) would take place, as expounded by skating coaches (Wild, 1971; Hockey Canada, 1975; Marcotte, 1978; Stamm et al, 1982).

The reason there is a large horizontal impulse from this portion of the skating stride is that the center of mass is well ahead of the point of force application on the ice, creating a good angle for horizontal propulsion. An easily measured variable which is reflective of this angle at the end of double support is 'angle of takeoff', being the measurement of the angle above the horizontal of a line joining the skate tip to the hip at toe off. Multiple regression models of skating acceleration have shown that the angle of takeoff is a key element contributing to performance (Marino & Dillman, 1978; Marino, 1983; Greer & Dillman, 1984). In other words, these studies imply that one of the primary skills that differentiates an elite skater from a good skater is the former's ability to position his center of mass further ahead of his propulsive skate during the last moments of double support so that this 'toe push' drives him forward rather than vertically. This results in a more effective application of force for horizontal acceleration.

It would appear from the above research that the very last portion of contact is an important time for force application because a) the center of mass is optimally placed for horizontal propulsion, and b) the angle of propulsion is greater. Plantar flexion could be an important source of impulse at this time, particularly if skating velocity is not high. However, the design of the skate boot used in hockey may restrict plantar flexion. If so, then the limitation of this motion would result in a decreased production of horizontal impulse.

More dynamic data of the type found in the gait literature is needed, however the nature of the sport and the surface on which it is played make the determination of ground reaction forces difficult to obtain. Lamontagne, Gagnon, and Doré (1983) and Gagnon, Doré, and Lamontagne (1983) utilized strain gauges fixed to the frame of the skate blade to measure forces in combination with a three dimensional cinematographical analysis for the determination of skate angles. They analyzed the two-legged stop in hockey and obtained what they termed good results. Their research technique has yet to be corroborated. In addition, there has been no recently published research employing the experimental technique of Roy (1978) cited earlier, who embedded a force platform into a synthetic ice surface. Apparently, the technical difficulties associated with obtaining good data using these procedures are greater than what one would expect based upon the published literature.

Ankle pronation plays a very different role in skating as opposed to running. The skate blade offers a very narrow base of support located approximately 15 to 20 cm distal to the subtalar joint, resulting in a large mechanical advantage for rotation around the subtalar joint in the frontal plane. Extensive pronation can easily result upon weight bearing combined with the forces of leg extension. This has been said to cause improper alignment of the lower limb segments in the frontal plane, resulting in instability, loss of force production, and poor blade edge control (Hunter et al, 1981; Gazdig, 1983). This is thought to be a particularly serious problem with many young, beginning skaters. Skate manufacturers have responded to this situation by producing skates with a great deal of ankle support in an attempt to control eversion of the foot. As the skater matures, the problem becomes much less serious. Soft tissue maturation on the lateral side of the foot, development of the sustentaculum tali and navicular on the medial side, inversion of the functional position of the heel with skeletal maturity, decreased ligamentous laxity, and increased muscular development and central nervous system maturity are all physical growth factors which decrease the tendency of the ankle to evert due to torque about the skate blade (Hunter et al, 1981). As a result, mature, skilled players require less ankle support provided by the skate.

High speed film of advanced ability university-aged skaters taken with a camera placed directly posterior to the direction of the skate blade during the fourth stride of an acceleration from a stop revealed that significant pronation (of the order of 10° but highly variable) was taking place during propulsion (Hoshizaki, 1985). The anatomical compensation of the skate (a high quality model) may have been insufficient even for advanced skaters. Another possibility is that the pronation which did exist was an integral part of the skater's kinematic pattern.

Controlled pronation may be desirable for two reasons. First of all, it increases the blade angle (the tilt of the skate blade from the vertical), and this may be necessary to give the skate sufficient 'bite' into the ice early in propulsion when there is not a great deal of horizontal displacement between the skater's center of mass and the skate. Secondly, ankle movement in the frontal plane may be a source of impulse for the skater. The blade to ankle distance provides a lever arm in the frontal plane analogous to the lever arm provided by the toe to ankle distance in the sagittal plane. The return to anatomical position from a state of pronation late in the propulsive phase would provide force at a time when the center of mass is in a favourable position for the application of forward horizontal impulse. If this is the case, then the purpose of pronation would be to increase the range of motion for this supination action, as well as to store energy in the musculature and ligaments for recovery late in the propulsive phase. The skates presently employed by elite hockey players may hinder this action as a result of the ankle support provided. To date there is no research recorded in the literature studying the effects of pronation in skating.

In summary, a great deal of confusion exists regarding the role of the ankle in skating. Coaches generally insist that full extension of the joints of the lower limb, including a final push at the ankle, is an important criterion for effective skating, yet skates are designed with ankle protection and ankle support systems which limit the range of motion. Studies of the kinematics of skating, sprinting, and cross country skiing have supported the logical expectation that greater range of motion of lower limb joints is associated with greater velocities, although the increases in range of motion resulted primarily from greater flexion rather than extension (Page, 1975; Gagnon, 1980; Mann & Hagy, 1980; McCaw, 1984). Ankle plantar flexion has been shown to be an important source of energy and impulse in gait, particularly sprinting, with evidence presented indicating that it may contribute significantly to forward impulse in skating (Roy, 1978; Mann & Sprague, 1980; Mann, 1981; Winter, 1983). However, some questionable data has been obtained indicating that plantar flexion occurs only to a very small extent in skating, and that advanced level skaters actually undergo less plantar flexion than novice skaters (McCaw, 1984). It has been argued that plantar flexion is detrimental to performance at very high speeds (van Ingen Schenau & Bakker, 1980). Regarding frontal plane motion, pronation generally connotes poor performance (Hunter et al, 1981), hence the development of ankle support systems in skates to limit eversion. However, research has demonstrated that even advanced level skaters wearing high quality skates undergo pronation in the order of 10° (Hoshizaki, 1985).

In light of this confusion, and considering that the equipment used has a direct bearing on the phenomena reported, a study which seeks to quantify the kinematic pattern at the ankle, as well as to document the effect of skate boot support on this pattern, seems warranted.

CHAPTER III

METHODOLOGY

This chapter contains the following headings: 1) Subjects, 2) Cinematographical Procedures, 3) Conditions, 4) Testing Procedures, and 5) Treatment of Data. The methodology utilized in this study was accepted by an Ethical Review Committee of the McGill University Faculty of Graduate Studies and Research.

3.1 Subjects

A group of seven junior and college level hockey players between the ages of 18 and 25 volunteered to participate in a study of advanced level skating performance sponsored by Warrington Inc. The two players who received the best scores in forward skating acceleration performance were chosen as subjects for this study. These subjects were both highly skilled and experienced, ensuring that a mature skating technique would be examined. General information regarding the two subjects is presented in Table 1. A consent form (Appendix A) was read and signed by both subjects, acknowledging that the testing procedures and the subjects' options had been fully explained to them and were understood.

TABLE 1

Subject Description

Subject	Age	Height (cm)	Mass (kg)	Skate Size	Position	Level of Play
1	19	175	70,5	7 1/2 reg	forward	junior major
2	22	168	62,7	7 1/2 reg	forward	junior

3.2 Cinematographical Procedures

The experimental setup is illustrated in Fig. 3. Two 16 mm Red Lake Locam cameras operating at 100 fr/s filmed the subjects from orthogonal axis planes. Preliminary testing established where and at what angle each subject placed his skate on the fourth stride. The starting position of each skater was adjusted so that they would both set their right skate down at the same point on the ice for the fourth contact period. The angle of propulsion was measured to be close to 32° for both skaters. Camera #1 was located directly behind and in line with the skate blade in this position; camera #2 was aligned perpendicular to the skate blade and slightly anterior to the touchdown point so that the skater moved across the field of view during the stride. Camera #1 recorded pronation and was located so that the complete lower limb was in the field of view throughout contact; camera #2 recorded plantar and dorsal flexion at the ankle and was located so that the whole body was in the field of view throughout contact.

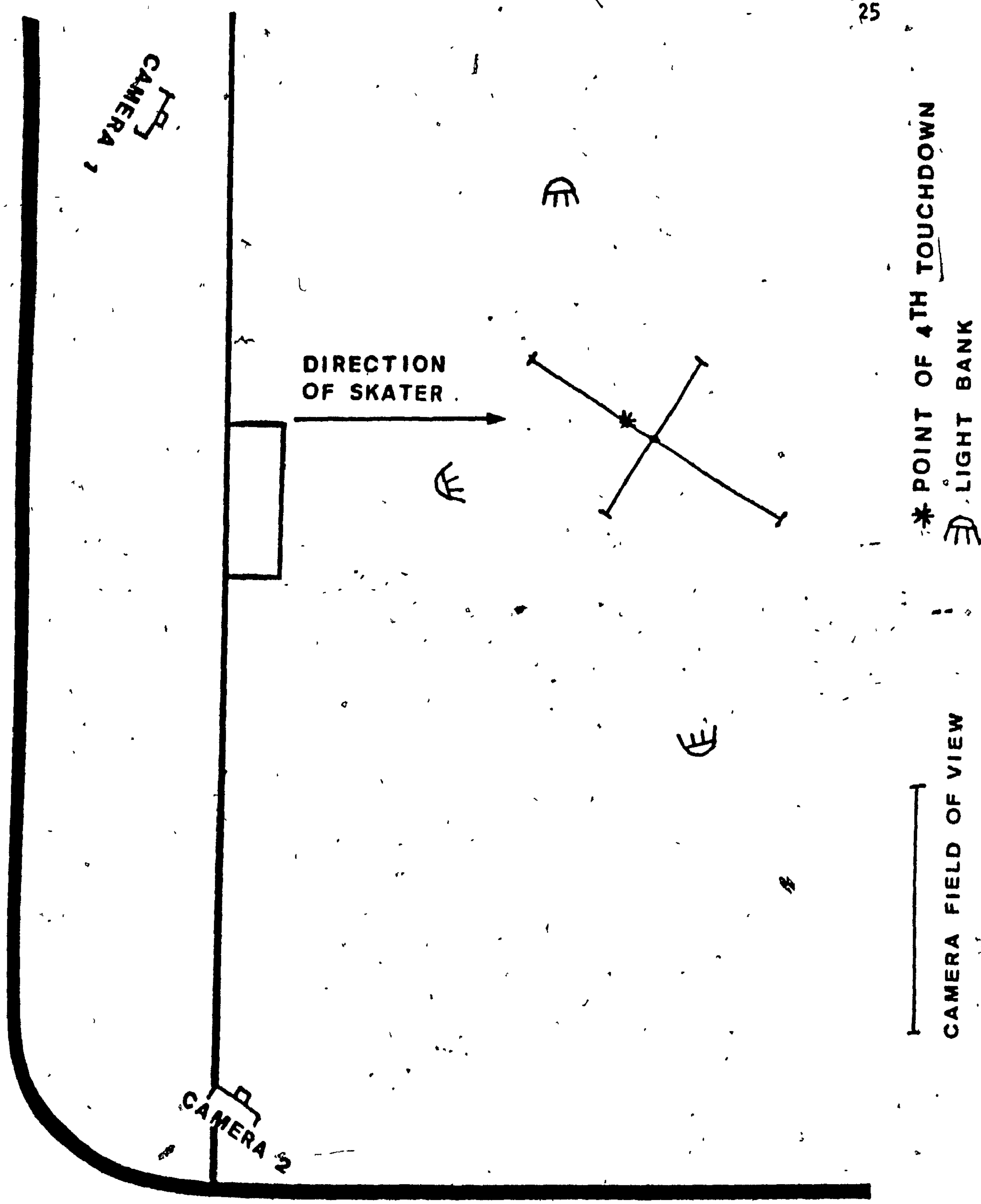


FIGURE 3. Diagram of experimental setup.

The distance between the film and the point at the center of the action was 9,70 m for camera #1 and 13,05 m for camera #2. The ground to lens heights were 72,5 cm and 78,5 cm respectively. In all trials, the subjects' motion during the fourth contact period remained within the fields of view of the cameras. A reference grid was digitized at both ends of the field of view in which analysis was to be done in order to confirm that lens distortion and parallax were not measurable error factors. Intrasubject variation in location and angle of the fourth ice contact resulted in less than one half degree of joint angular measurement error.

Three 1000 W light banks were arranged around the periphery of the filming area, and a light meter was used to determine the appropriate f-stop. Exposure time was 1/250 s, necessitating a shutter opening of 115 degrees. A coordinate reference grid was filmed in the field of view of each camera in order to facilitate the transformation of digitized data into real data. An internal timing light generator produced white dots on the border of the film representating 1/100 s intervals, allowing for the determination of actual film speed.

Subjects were filmed in shorts, and did not carry a hockey stick. The following anatomical landmarks were highlighted on each subject to allow for consistent digitization of film data: lateral border of the fifth metatarsal-phalangeal joint, lateral heel, lateral malleolus, lateral border of the femur-tibia joint, and greater trochanter. For the posterior view, a thick black line was drawn on the skin of the subject from the middle of the knee to the top of the skate delineating the leg segment. A line was drawn on the skate along the vertical axis of the skate blade aligning with the above line at 180 degrees when the subject was standing. The locations of the talus-calcaneous joint and the center of the back of the knee were marked along these lines. The purpose of the lines was to aid in the location of the joints when the actual markers were blocked from sight by the subject's left skate. A marker was also placed at the middle of the posterior thigh, just distal to the gluteal crease. Steps were taken to eliminate systematic error resulting from slight differences of marker location on the skates.

Numbers identifying the subject, condition, and trial were in the field of view of each camera. Cameras were started about one second before the subject moved in order to assure that they were up to speed when he entered the field of view.

3.3 Conditions

Two pairs of skates served as the independant variable for this experiment: the Micron Medalic, a molded plastic skate of high quality, and a test skate provided by the Micron manufacturers. This test skate was identical to the Medalic in every respect except that it gave no support above the talus. Both skates were professionally fitted and were broken in with more than seven hours of skating, and both were subject to identical sharpening procedures immediately before testing.

Conditions will be referred to as 'test skate' and

'Medalic' in the remainder of this paper.

3.4 Testing Procedures

Subjects used a front standing start from a starting point slightly in front of the goal crease. They were told to skate as quickly as possible past the center ice line, where 4 timers with stopwatches were located. The distance was 24,4 m. They were informed of their times, as well as the times of the other subject, after each trial. The skaters underwent at least 10 timed practice trials for each condition during the week prior to testing.

Ss were in the fields of view of the cameras during the fourth stride. This stride was chosen for analysis for the following reasons: a) The subject is undergoing high acceleration throughout this stride (Marino, 1979) and therefore large reactive forces are continuously acting on the skate. b) The velocities involved at this point (Marino, 1979) are very typical of velocities occurring during actual hockey games (Dillman et al, 1984), therefore maximizing the specificity of the test. c) Position of TD is consistent at this point. This, combined with the relatively small velocities involved, allowed the cameras to be placed much closer to the event than would be possible at higher velocities to assure capture of the complete stride on film.

Subjects wore one pair of skates for the first 5 trials, the second pair for the next 10 trials, and the first pair again for the last 5 trials. The order of skate testing was different for each subject. An appropriate warmup and stretching period was provided before the first trial, with a minimum of 3 minutes of rest and easy skating allowed between trials.

The subjects appeared to be highly motivated and competitive during the experiment. A great deal of attention was paid to their own and each other's times. Both subjects said that fatigue was not a factor and that they were well rested for all trials.

Deterioration of the ice surface occurred over the course of the experiment, although the subjects indicated that it was not enough to affect performance. Repair of the deeper cuts in the ice was accomplished during the time that the subjects were changing skates.

3.5 Treatment of Data

Each film frame of the trial, beginning 9 frames before TD until 9 frames after TO, was displayed on a Summagraphics digitizing board. The digitizer was connected on-line to the McGill mainframe computer, and x,y locations of the anatomical landmarks were recorded in a MUSIC (McGill University System for Interactive Computing) library file. A WATFIV program adjusted each frame to a common x,y origin, thereby compensating for any movement of the projected image as the film advanced. The data were then fed as input into the McGill Biomechanics Laboratory's kinematic analysis programs which determined the joint angles involved. Filtering was done with a low-pass, recursive digital filter with a cutoff frequency of 9,0 hz for the lateral view and 12,0 hz for the posterior view (Winter, 1979; Wood, 1982). Instantaneous velocities were determined using the technique of finite differences.

3.5.1 Statistical Analysis. The research design was a repeated measures multivariate design with one factor and two levels. Analysis was replicated independently for each of the two subjects, i.e. the experiment was done twice.

The scores from the trials for one condition serve as a sample of the "population of scores" for that condition and that particular subject. Similarly, the scores for the other condition serve as a sample of scores from the "population of scores" for the second condition and the same subject. The statistical test determined the likelihood that the 2 samples came from populations with the same means. Student's t-test was used to detect statistical significance at the 0,05 alpha level.

CHAPTER IV

RESULTS

The purpose of this study was to document the kinematic patterns of the ankle joint during the fourth contact period of a maximal intensity forward acceleration task, and to assess the effect on this pattern of removing the ankle support normally provided by hockey skates. Results are presented in this chapter under the following headings: spatial - temporal characteristics, sagittal plane kinematics, frontal plane kinematics, and other observations.

4.1 Spatial-Temporal Characteristics

A number of space-time variables were measured in order to delimit various phases of the fourth stride and to allow comparisons to be made with other studies. These variables are summarized in Table 2.

Contact time (time of ice contact of right skate) lasted for just over one quarter of a second, with about 20% of this time spent in the heel-off to toe-off (HO-TO) phase. Differences between conditions (skates) were not significant, although there was a tendency to slightly larger HO-TO times with the test skate. Stride time (right skate touchdown to left skate touchdown) was about one quarter of a second, with double support time (time from right touchdown until left toe-off)

TABLE 2

Spatial-Temporal Characteristics of the 4th Stride
(times given in 1/100 s)

VARIABLE	SUBJECT	SKATE	MEAN	STD DEV	
Contact Time	1	test	26,0	2,6	
		Medalic	28,0	1,7	
	2	test	28,4	1,2	
		Medalic	27,5	1,9	
HO - TO Time	1	test	4,9	0,99	
		Medalic	4,6	0,84	
	2	test	6,0	1,05	
		Medalic	5,3	0,68	
Double Support Time	1	test	1,5	1,27	
		Medalic	1,9	1,37	
	2	test	1,7	0,48	
		Medalic	0,8	0,92	
Stride Length	1	test	1,38 m	0,13	
		Medalic	1,55 m	0,07	*
	2	test	1,55 m	0,09	
		Medalic	1,56 m	0,11	
Stride Time	1	test	24,2	2,2	
		Medalic	25,3	0,9	
	2	test	25,8	0,6	
		Medalic	25,2	1,1	
SL/ST	1	test	5,73 m/s	0,42	
		Medalic	6,13 m/s	0,33	*
	2	test	6,00 m/s	0,26	
		Medalic	6,20 m/s	0,28	
Performance Time	1	test	3,36 s	0,10	
		Medalic	3,34 s	0,05	
	2	test	3,50 s	0,06	
		Medalic	3,49 s	0,05	

* $p < .05$

being less than 0,02 s. Some trials were characterized by a very short flight phase.

Stride length (measured from right touchdown to left touchdown) was 1,55 m, resulting in an average velocity (determined by SL/ST) of just over 6 m/s. Subject 1 had a shorter stride length with the test skate and a correspondingly slower velocity with this condition.

Performance time refers to the time for the skater to complete the acceleration task, that is, the time from the first overt movement until the skater crossed center ice (a distance of 24,4 m). Differences between conditions (skates) were not significant for either subject.

4.2 Sagittal Plane Kinematics

Although skating coaches generally argue that a powerful extension at the ankle is an important action in effective skating (Wild, 1971; Hockey Canada, 1975; Marcotte, 1978; Stamm et al, 1982), the existance of this action has been brought into question (van Ingen Schenau & Bakker, 1980; McCaw, 1984). If impulse is provided to the skater by ankle plantar flexion, then it is likely that the hockey skate boot hinders the transmission of this impulse.

This section describes the kinematic pattern of dorsal and plantar flexion during the fourth contact period of a maximal intensity acceleration, and compares the results obtained with a conventional skate (the Medalic) with those obtained with a test skate, identical to the Medalic except that no support was given to the ankle above the talus. The ankle angle was measured as the angle formed by markers on the skate corresponding to the lateral border of the fifth metatarsal-phalangeal joint and the lateral malleolus, and a marker on the knee of the subject indicating the lateral border of the femur-tibia joint. The angle so formed measures 115° to 120° when the subject is standing in skates.

4.2.1 Conventional Skate Kinematic Pattern

A graph of the ankle angle as a function of normalized contact time for a representative trial is presented in Fig. 4. The pattern is a typical one, and it was generated consistently by both subjects. The skater made ice contact in a state of dorsiflexion, and the degree of dorsiflexion increased steadily (decreasing angle) by about 10° over the first 60% of contact time. At this point a sudden increase of about 4 or 5° of dorsal flexion occurred over about 10% of contact time, followed by rapid plantar flexion for the remainder of the contact period. The angles at takeoff (TO) for almost all of the trials for one subject and many of the trials for the other subject were less than the ankle angle formed when the subject was standing in skates. The time of maximal dorsiflexion was generally found to be between 65% and 80% of contact time, and occurred just prior to the visible lifting of the posterior end of the skate blade off the ice (heel off, HO).

The ankle angle data is summarized in Table 3. Mean minimum and maximum angles were 81,6° and 107,7° for subject 1, giving a range of motion of 26,1°. Corresponding numbers for

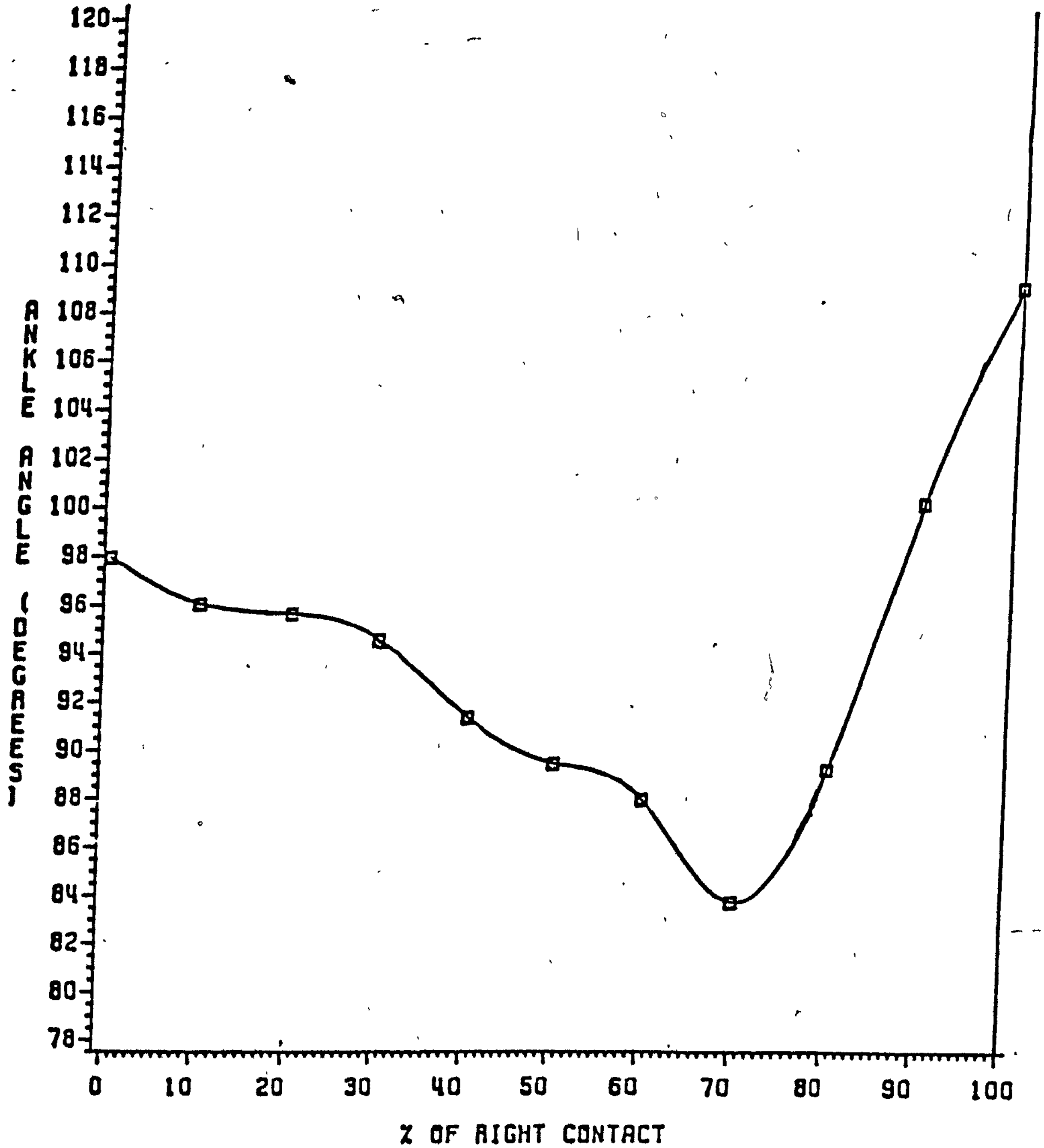


FIGURE 4. Dorsal - plantar flexion displacement curve for a typical trial.

TABLE 3

Dorsal-Plantar Flexion Statistical Summary
(angles measured in degrees, velocity in rad/s)

Variable	Subject	Mean	Std Dev
Minimum Ankle Angle (Maximum Dorsiflexion)	1 2	81,6 85,1	2,6 4,4
Ankle Angle at TO	1 2	107,7 115,5	5,5 4,4
Range of Motion	1 2	26,1 30,4	5,2 6,2
Maximum Angular Velocity	1 2	9,8 11,0	2,1 2,1

subject 2 were 85,1° and 115,5°, giving a range of motion of 30,4°. Maximum angular velocities reached during the HO-TO portion of contact were 9,8 rad/s and 11,0 rad/s.

4.2.2 Comparison of Conditions

Figure 5 superimposes the graph of ankle angle in the sagittal plane for a representative trial with the test skate upon the graph shown in Fig. 4 for a typical trial with the conventional skate. Both skate conditions resulted in a similar pattern of generally increasing dorsal flexion for about the first 60% of contact, followed by a sharp decrease in angle and then rapid plantar flexion. The most distinguishing characteristic between the conditions was the steepness of the curve (indicating higher velocity) in the HO-TO region for the test skate.

Hypotheses 1 and 2 concerned statistical differences between conditions for maximum dorsiflexion and maximum plantar flexion during contact, and hypothesis 3 was established in order to compare conditions for maximal angular velocity. Analysis of these hypotheses, along with range of motion data, is presented in Table 4.

The data demonstrate that plantar flexion values at TO were larger for the test skate condition than for the conventional skate. Differences were statistically significant at the ,01 alpha level for subject 1. The mean plantar flexion angles were close to 119° for both subjects wearing the test skate. Dorsiflexion values were not different between conditions for subject 2, but subject 1 underwent significantly less

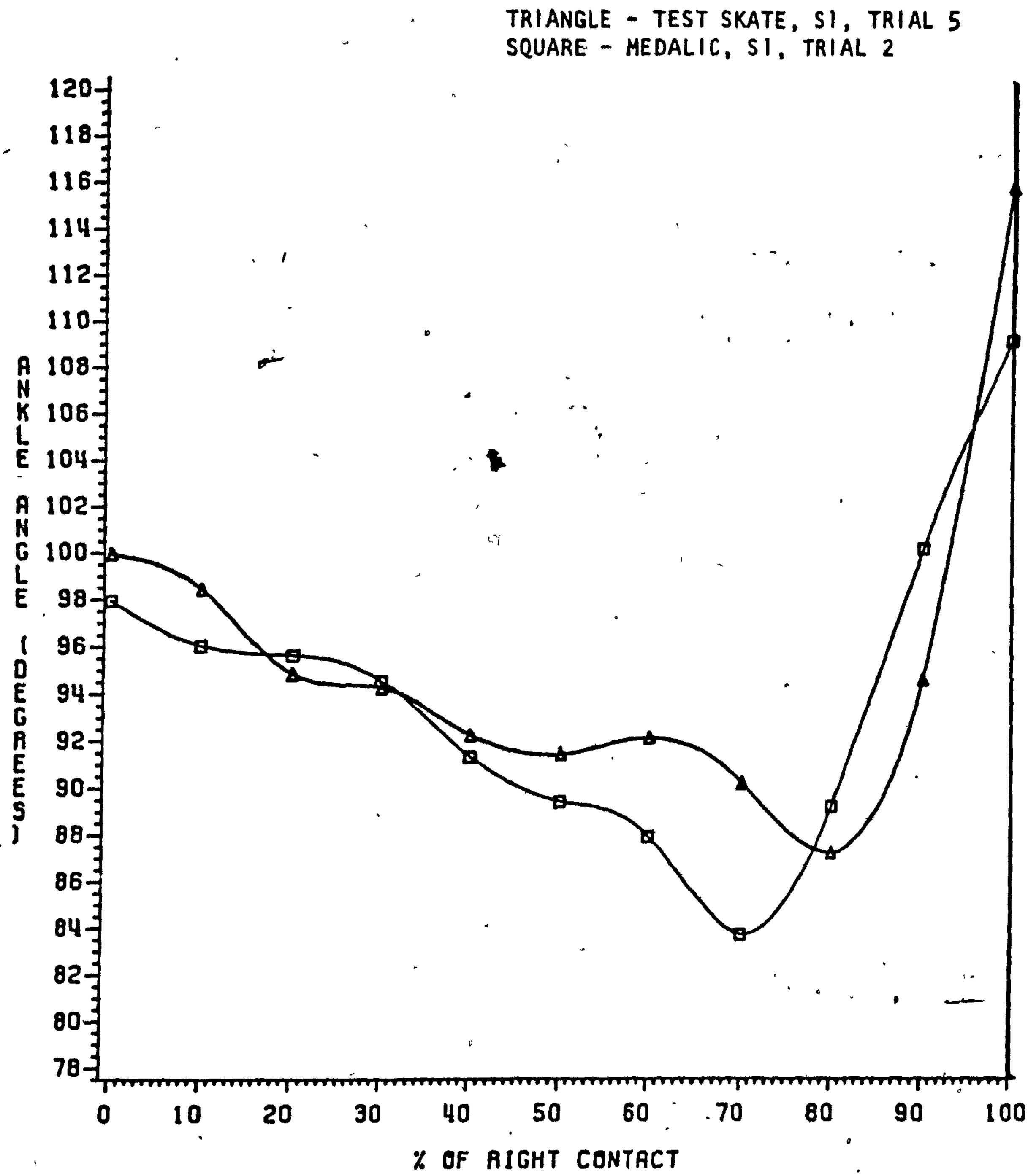


FIGURE 5. Comparison of dorsal - plantar flexion displacement curves for conventional skate and test skate.

TABLE 4

Dorsal-Plantar Flexion: Comparison of Conditions
(angles measured in degrees; velocity in rad/s)

Variable	Subject	Skate	Mean	Std Dev	T	Alpha
Minimum Ankle Angle	1	test	85,5	4,4		
		Medalic	81,6	2,6	2,40	,027 *
(Maximum dorsi-flexion)	2	test	84,0	2,9		
		Medalic	85,1	4,4	-0,68	,506
Ankle Angle at TO	1	test	118,8	4,4		
		Medalic	107,7	5,5	4,99	,000 *
	2	test	119,6	6,5		
		Medalic	115,5	4,4	1,64	,119
Range of Motion	1	test	33,3	3,7		
		Medalic	26,1	5,2	3,40	,003 *
	2	test	35,6	6,8		
		Medalic	30,4	6,2	1,69	,108
Maximum Angular Velocity	1	test	12,1	1,4		
		Medalic	9,8	2,1	2,87	,010 *
	2	test	12,3	2,6		
		Medalic	11,0	2,1	1,23	,235

* p < ,05

dorsiflexion in the test skate condition. This was an unexpected result.

Greater plantar flexion maximal velocities occurred with the test skate than with the conventional skate. Differences were statistically significant at the ,01 alpha level for subject 1. Both subjects reached mean maximal velocities of more than 12 rad/s. The greater velocities corresponded to larger angular displacements during the HO-TO phase, without an increase in time for this phase. The ankle range of motion increased by 7,2° for subject 1 and 5,2° for subject 2 when the test skate was used. This increase was statistically significant at the ,01 alpha level for subject 1.

4.3 Frontal Plane Kinematics

Ankle support systems in skates have been designed to limit pronation, which has generally been considered a fault in skating (Hunter et al, 1981; Gazdig, 1983). However, even advanced level skaters wearing high quality skates undergo some pronation (Hoshizaki, 1985). It is possible that ankle action in the frontal plane may assist in setting the blade into the ice and in providing forward impulse, but this aspect of skating has not been studied.

This section describes the kinematic pattern of pronation and supination during the fourth contact period of a maximal intensity forward acceleration task, and compares the results obtained with a conventional skate (the Medalic) and those obtained with a test skate, identical to the Medalic except that no ankle support was provided. The ankle angle was measured as the angle between the posterior midline of the leg and a line on the boot in the same plane as the skate blade, measured laterally. A mark on the skate at the level of the talus served as the vertex for the angle. The ankle angle measured 180° when the subject was standing. Decreasing angles correspond to pronation; increasing angles correspond to supination.

4.3.1 Conventional Skate Kinematic Pattern

Considerable intertrial variation was apparent in the pronation-supination patterns exhibited by the subjects. However, certain general characteristics were consistent and are represented in Fig. 6, which displays a graph of the mean values of frontal plane ankle angle for one of the subjects. Similar kinematic characteristics were observed with the other subject. Generally, the skater would contact the ice in a position of very slight pronation, and pronation would increase steadily by about 8 to 10° during the first 50% of contact time. After this, the pronation angle remained fairly constant until the time of heel-off (HO), with the heel-off to toe-off (HO-TO) phase characterized by rapid supination.

Frontal plane ankle angle data is summarized in Table 5. The minimum angles (maximum pronation) reached by the two subjects were 166,9° and 171,6° while both subjects had mean angles at TO very close to the neutral position of 180°. The ranges of motion were 13,2° for subject 1 and 8,2° for subject 2. Maximum supination velocities during the HO-TO phase were 5,9 rad/s for subject 1 and 4,8 rad/s for subject 2.

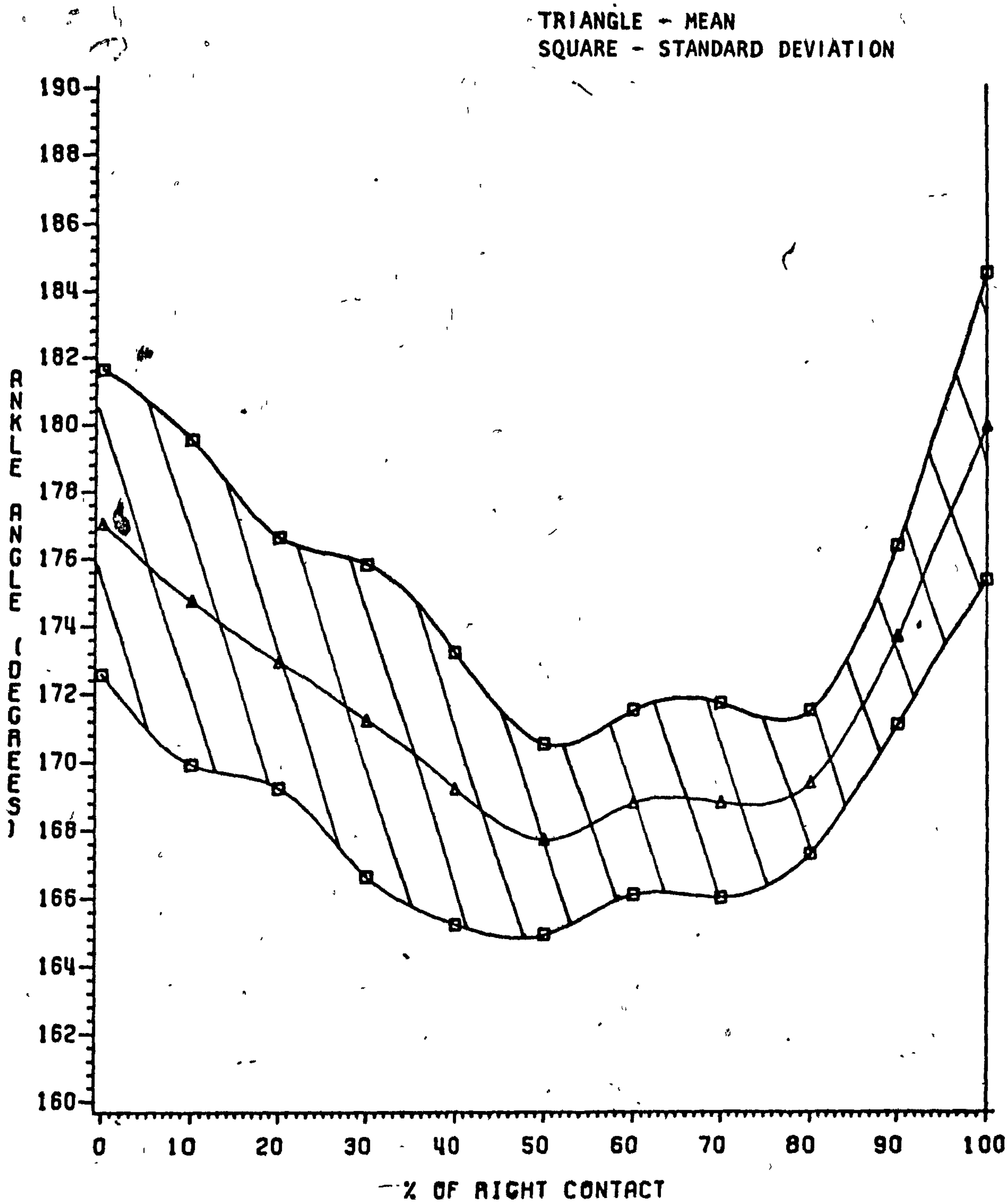


FIGURE 6. Mean pronation-supination displacement curve for Subject 1, with standard deviation.

TABLE 5

Pronation-Supination Statistical Summary
(angles measured in degrees, velocities in rad/s)

Variable	Subject	Mean	Std Dev
Minimum Ankle Angle (Maximum Pronation)	1	166,9	2,3
	2	171,6	3,4
Ankle Angle at TO	1	180,1	4,6
	2	179,8	4,1
Range of Motion	1	13,2	5,1
	2	8,2	3,9
Maximum Angular Velocity	1	5,9	1,9
	2	4,8	2,6

4.3.2 Comparison of Conditions

Figure 7 compares mean values of pronation as a function of normalized contact time for the two conditions for one of the subjects. The removal of ankle support did not result in any noteworthy differences in the pronation pattern until the time of heel off, except that the degree of pronation reached was greater in the test skate condition. The test skate condition resulted in greater supination at toe-off as well. Figure 7 shows that angular velocities reached were greater in the HO-TO phase of contact as the ankle in the test skate condition underwent larger displacement during a similar time period.

Hypotheses 4 and 5 were designed to compare the degrees of maximum pronation and the maximum supination velocities reached under each condition. The evaluation of these hypotheses, along with other frontal plane angle data, is presented in Table 6. Both subjects demonstrated greater pronation with the test skate, although for subject 1 the difference was only 1,5°, not statistically significant. Subject 2 underwent 3,8° more pronation, which was significant at the ,05 alpha level. Supination velocities were greater with the test skate, increasing from 5,9 to 8,1 rad/s for subject 1 and from 4,8 to 8,6 rad/s for subject 2. Differences were statistically significant at the ,05 alpha level for subject 2. Supination angles at TO increased by about 3° for both subjects, so that the range of motion increased from 13,2° to 17,9° for subject 1 and from 8,2° to 14,8° for subject 2.

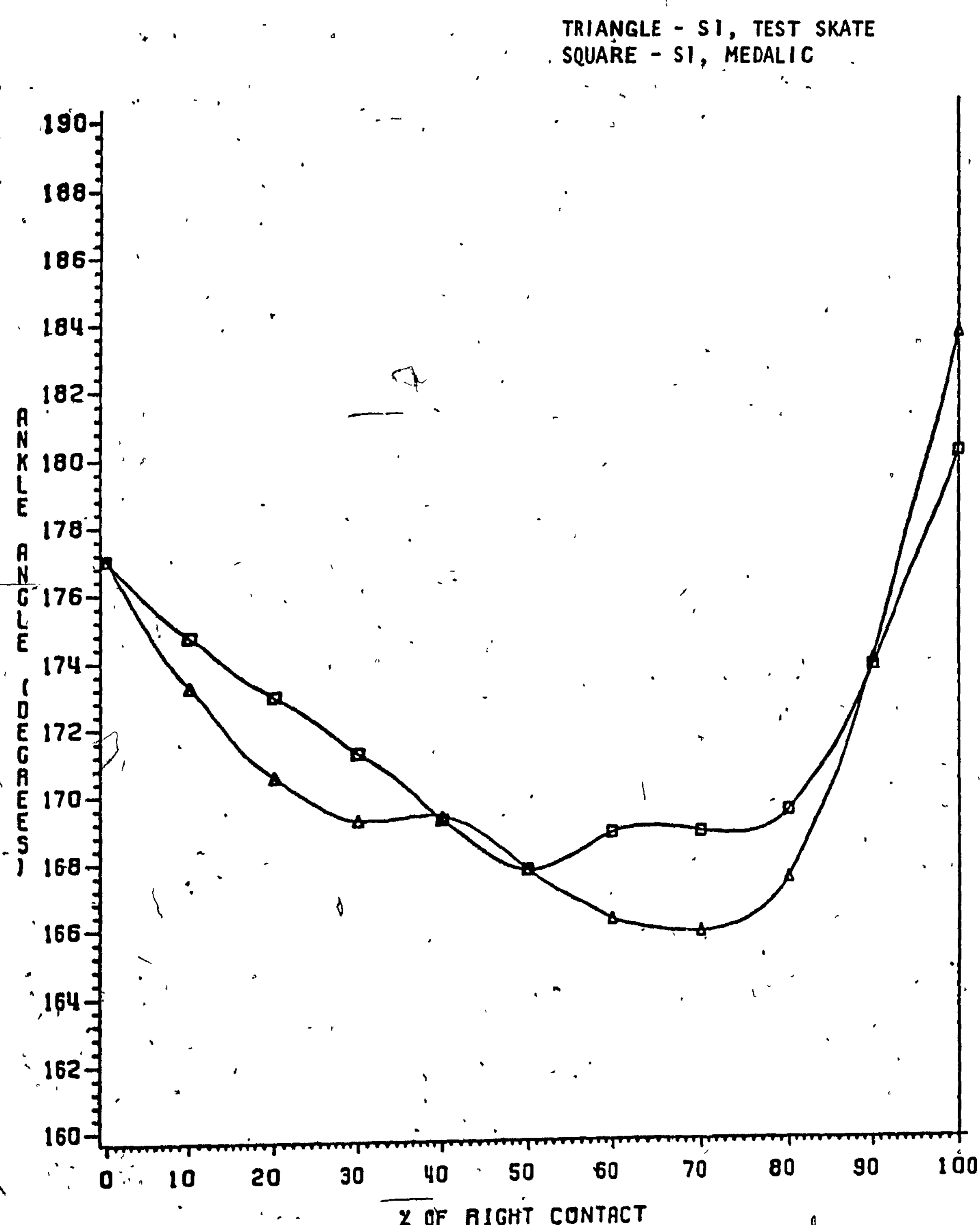


FIGURE 7. Comparison of pronation-supination displacement curves for conventional skate and test skate.

TABLE 6

Pronation-Supination: Comparison of Conditions
(angles measured in degrees; velocity in rad/s)

Variable	Subject	Skate	Mean	Std Dev	T	Alpha
Minimum Ankle Angle	1	test	165,4	3,3		
		Medalic	166,9	2,3	-1,11	,280
(Maximum Pronation)	2	test	167,8	3,0		
		Medalic	171,6	3,4	-2,70	,015 *
Ankle Angle at TO	1	test	183,3	6,4		
		Medalic	180,1	4,7	1,33	,200
	2	test	182,6	3,3		
		Medalic	179,8	4,1	1,73	,100
Range of Motion	1	test	17,9	8,3		
		Medalic	13,2	5,4	1,51	,148
	2	test	14,8	5,3		
		Medalic	8,2	4,1	3,16	,005 *
Maximum Angular Velocity	1	test	8,14	3,80		
		Medalic	5,89	1,90	1,67	,112
	2	test	8,57	4,14		
		Medalic	4,80	2,55	2,46	,024 *

* $p < ,05$

4.4 Other Observations

In the course of analysis, certain observations were made which were deemed relevant to the interpretation of the data, and therefore are presented here.

4.4.1 Minimum Skate Velocity

It was observed that the speed of glide of the skate decreased to a much smaller value than would be expected considering the low coefficient of dynamic friction involved, particularly during the HO-TO portion of contact. This corresponds to the portion of the stride when coaches emphasize a push of the toe against the ice, and the time of a sharply increasing forward to lateral force ratio (Roy, 1978). Furthermore, the minimum velocity reached in the test skate condition tended to be considerably less than that reached with the conventional skate. Fig.8 presents skate velocity over the last third of contact time for a representative trial in each condition. The velocity was that of the marker placed on the skate laterally to the fifth metatarsal phalangeal joint, resulting in a certain amount of additional velocity incorporated into that of the skate near the end of contact as the marker rotated over the anterior end of the blade. However, even with that complication, it is clear that the minimum velocity of the test skate was less than that of the conventional skate.

The minimum velocity of the toe marker was determined for each of the trials and the statistical summary is presented in Table 7. The mean minimum velocities reached by the test skate

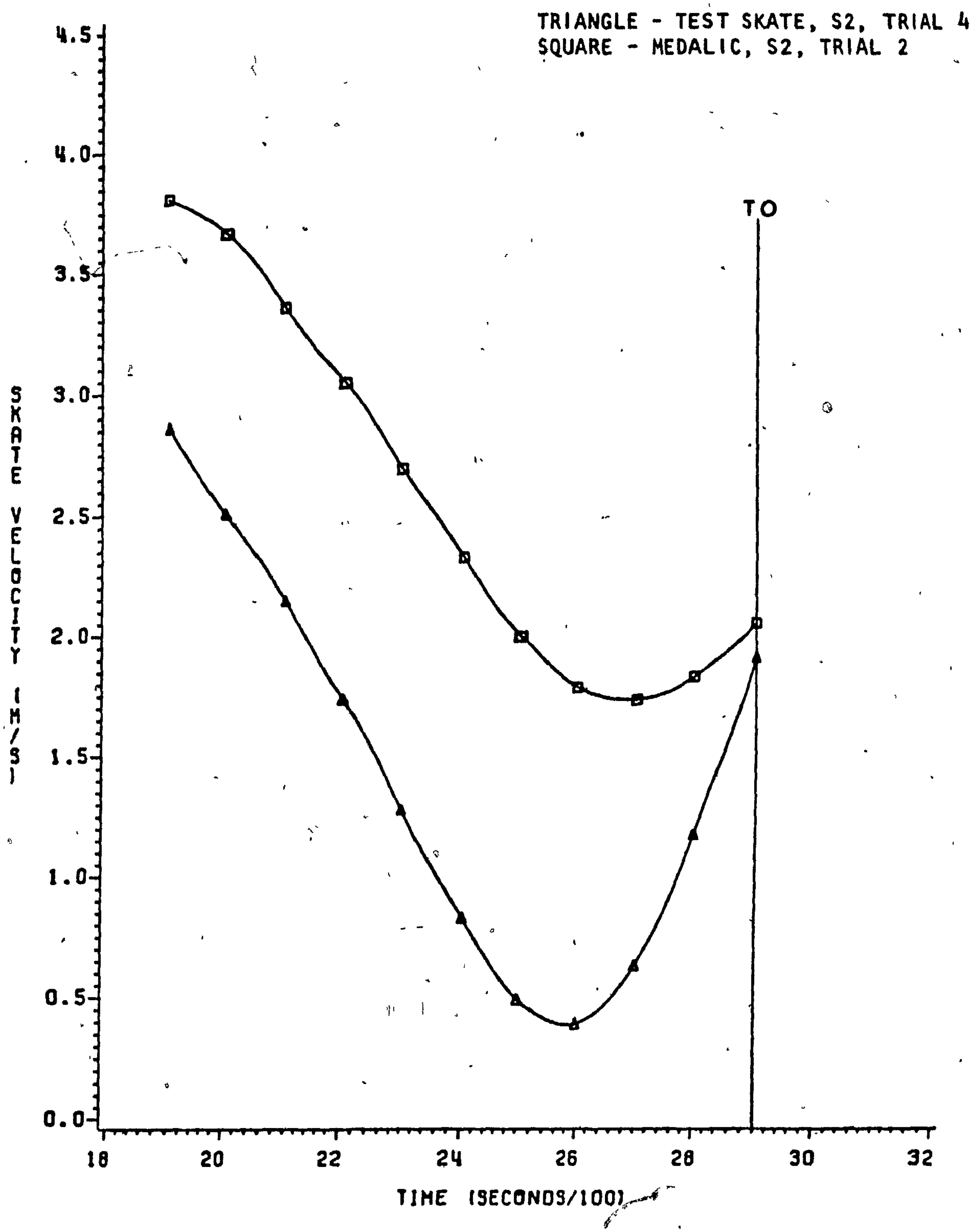


FIGURE 8. Linear skate velocity near end of contact: comparison of conditions.

and by the conventional skate were 0,23 m/s and 0,97 m/s respectively for subject 1, and 0,37 m/s and 0,72 m/s respectively for subject 2.

TABLE 7

Minimum Linear Skate Velocity: Comparison of Conditions
(velocity in m/s)

Variable	Subject	Skate	Mean	Std Dev
Minimum Skate Velocity	1	test	0,23	0,59
		Medalic	0,97	0,54
	2	test	0,37	0,53
		Medalic	0,72	0,71

4.4.2 Blade Contact With the Ice

The portion of the blade in contact with the ice could be discerned from the laterally positioned camera. The subject typically contacted the ice at a point about 4/5 the way from the posterior end towards the anterior end. The next frame of film (1/100 s later) would find the skater on the posterior portion of the blade. He would then rock forward to about midblade and then settle with his weight about 1/3 to 1/2 the way from the back to the front. This initial rocking took about 4/100 s. Beginning at around 50% of contact time, the skater gradually moved forward on the edge of his skate until at the time of HO (about 80% of contact) the part of the blade under the metatarsal condyles was on the ice.

The posterior camera clearly showed an increase in angle of propulsion during the last 25% of contact time. During this portion of the stride the long dimension of the skate blade, invisible for most of contact time, gradually came into view as the skater pivoted slightly on the anterior region of his skate blade.

These observations correspond to the instruction of coaches to start the push at the heel of the blade and finish at the toe of the blade (Hockey Canada, 1975; Stamm et al, 1982), and verify previous observations that the angle of propulsion increases at HO (Hoshizaki, 1985).

CHAPTER V

DISCUSSION

The purpose of this study was to document the kinematic pattern at the ankle during the acceleration phase of forward skating, and to assess the effect of removing the ankle support system normally provided by hockey skates on this pattern. Two subjects were filmed from orthogonal directions on the fourth contact period with the ice during an acceleration task while wearing regular hockey skates and while wearing a special test skate which afforded no support above the talus. In this chapter, the results of this study will be discussed in three sections. First of all, the results will be interpreted in terms of a biomechanical model of the skating acceleration task. Following this, the effect of the intervention (removal of ankle support) on total body parameters will be considered. Finally, comparisons will be made between the data collected in this study and those reported elsewhere in the literature.

5.1 Biomechanical Model

In a skating acceleration task, the goal is to increase speed as quickly as possible. Within a fixed amount of time for a particular stride, the skater strives to maximize the forward horizontal impulse received from the ice, within the constraints of the skating pattern. This forward impulse depends on the magnitude and direction of the ice reaction force, as well as the time during the stride that the force is applied.

Unlike other forms of bipedal locomotion, the ice reaction force occurs in a perpendicular direction to the skate blade only, since the frictional force along the skate blade is negligible (Roy, 1978; van Ingen Schenau & Bakker, 1980). As a result, the skate blade must be angled away from the desired direction of motion by an angle theta (the angle of propulsion). The component of horizontal force F which drives the skater forward is given by F(sin theta) (see Fig. 1), and this component increases as theta increases.

Another element of skating which differentiates it from such locomotor activities as running and the diagonal stride in cross country skiing is that the foot through which the ice reaction force is acting is gliding along the surface. In other words, while extension of the lower limb joints accelerates the center of mass of the body away from the foot, there exists an additional relative velocity of the center of mass to the skate by virtue of the fact that the skate and the skater are moving in different directions. This relative velocity is given by v(sin theta), where v is the center of mass velocity at the beginning of propulsion. As the relative velocity increases, lower limb extension takes place more rapidly. Since the force of muscular contraction decreases as the speed of contraction increases (Winter, 1979), the result is a decreased force exerted against the ice by the skater.

As the skater gains speed, the angle of propulsion is decreased, so that the relative velocity of the skater with respect to the skate remains small. This limits the rate of leg extension, thereby enabling the skater to continue exerting large forces against the ice. There is a tradeoff here; decreasing the angle of propulsion results in an increased magnitude of force, but the fraction of the force in the forward direction decreases.

A typical pattern of skate cuts left in the ice by the blades of an accelerating skater is represented in Figure 9a. Note that as speed is gained, the stride length increases and the angle of propulsion decreases. Also note that at higher velocities the outward rotation of the thigh which establishes the angle of propulsion is preceeded by the 'single support glide phase' (Marino & Weese, 1979). This non-propulsive glide has been shown to be negligable or non-existent during the first several strides of an acceleration task (Marino, 1979).

A skate cut during early acceleration is depicted more closely in Figure 9b. For purposes of this model, the period of ice contact can be divided into two phases: the time from touchdown until the heel of the skate blade is lifted off the ice (TD-HO), and the time from heel off until the toe of the skate blade leaves the ice (HO-TO).

During TD-HO, when the blade is flat on the ice, large forces are applied to the ice through hip and knee extensions. The role of the ankle during this phase is to optimize the application of these forces, and to limit the retardation of the skate's glide. In the frontal plane, a stable ankle prevents the large hip and knee extension forces from being dissipated in

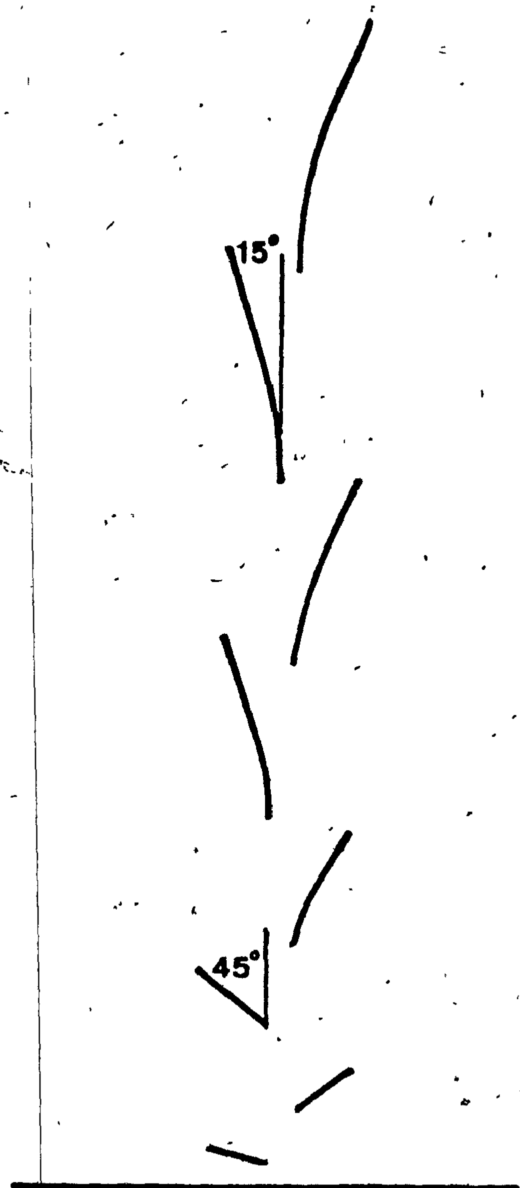


FIGURE 9a. Pattern of skate cuts from an accelerating skater.

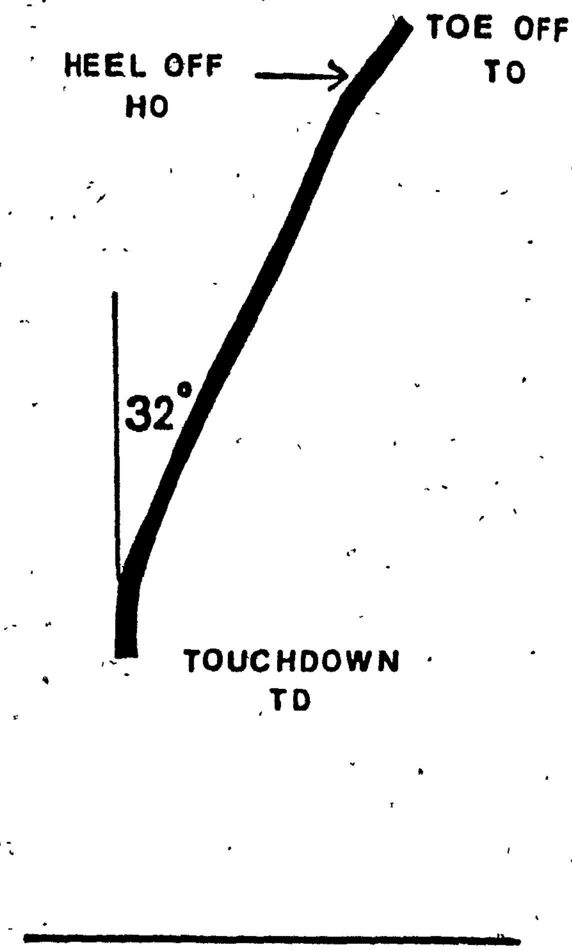


FIGURE 9b. Skate cut from the fourth ice contact.

stretching the ligaments and tendons of the ankle and bending the skate boot. Excess pronation limits propulsion because of improper alignment of the foot and leg in the frontal plane (Hunter et al, 1981).

The subjects in this study showed a smooth, controlled increase in pronation over the first 50% of contact time (Figs. 6 and 7). If pronation was controlled only by ligament structure and skate support, then a rapid increase in pronation upon weight bearing at touchdown would be expected. The fact that this didn't happen, even with the skate which provided no lateral support, is evidence that the pronation taking place was under muscular control and that the forces produced during leg extension were not dissipated in collapsing the ankle joint. This also indicates that the purpose of pronation is not to increase the blade angle (tilt of the blade from the vertical) early in propulsion. It had been suggested by the author that this action might be necessary to provide sufficient 'bite' of the skate into the ice. The reason for the limited pronation which does occur seems to be to provide a range of motion for supination at the end of the contact period, and perhaps to store some energy in the musculature and ligaments for recovery during this supination action.

In the sagittal plane, dorsal flexion serves to lower the body's center of mass and thereby increases the component of the ice reaction force vector in the horizontal direction (Mann & Hagy, 1980). In this study the subjects made ice contact in a state of dorsiflexion and increased the degree of dorsiflexion throughout the TD-HO phase (Figs. 4 and 5). The increase in dorsiflexion serves to keep the blade flat on the ice while the skater's center of mass moves forward relative to the skate. Keeping the blade flat on the ice, with the application of force well back from the front of the blade, minimizes the frictional force on the blade (van Ingen Schenau & Bakker, 1980) and gives the skater better control over the skate's glide. Perhaps the observation in this study that the skater's center of pressure began to move forward on the blade after about 50% of contact time is an indication of the limitation of dorsal flexion allowed by the skate.

Use of the test skate did not increase the degree of dorsal flexion reached by the skaters. In fact, subject 1 underwent significantly less dorsal flexion with this skate compared to the conventional skate. It should be noted that the lacing systems and the tongues were identical in both skates and it appears to be these areas which establish the limits of dorsal flexion motion. The manner in which the skaters tied their skates was not controlled; perhaps subject 1 tied his skates tighter in the test skate condition in order to compensate for the perceived laxity of the skate boot. This might explain his decreased dorsiflexion action with this skate.

Another purpose for dorsiflexion during the TD-HO phase is to increase the range of motion for the upcoming plantar flexion in the HO-TO phase. This function was clearly apparent in the data from this study (Figs. 4 and 5). The sudden increase in dorsal flexion just prior to HO may have served to activate the musculature in preparation for the following contraction of the plantar flexors.

Once heel-off occurs, an accelerating skater pivots on the anterior portion of the skate blade through further lateral rotation of the hip. This action increases the angle of propulsion, as the graph from Roy (1978) (Fig. 2) suggests. In this study, HO occurred about 80% of the way through total contact time on the fourth stride. The increase in angle of propulsion was apparent on the film taken with the posterior camera. The advantage of this movement is that, as was pointed out earlier, an increase in the angle of propulsion results in an increase in the component of the ice reaction force in the forward direction. Furthermore, the ice cut becomes very deep at this point due to the pressure exerted by the small blade surface on the ice, and this likely increases the frictional force available to the skater. As a result, the skater does not have to push perpendicular to the skate cut; a much more rearward directed force is possible. This corresponds to the visual impression noted by Marino (1979) that accelerating skaters appeared to extend straight back from the hip during the first few strides.

Forward impulse is enhanced during the HO-TO phase through plantar flexion and supination. This corresponds to the time in the stride at which skating coaches emphasize maximum ankle extension (Hockey Canada, 1975; Marcotte, 1978). In studies of sprinting, Mann & Sprague (1980) and Mann (1981) have shown that plantar flexion during this phase contributes significantly to forward impulse. High plantar flexion and supination velocities during the HO-TO phase were apparent for the subjects in this study, as depicted in Figs. 4 - 7. Surprisingly, in the conventional skate condition, the subjects usually did not plantar flex as far as a neutral standing position (115° to 120°), suggesting that, despite the emphasis in the coaching literature, even these advanced level subjects were not extending fully at the ankle. Apparently, following a forceful muscular contraction of the plantar flexors around the time of HO which rapidly increased the ankle angular velocity, the impulse provided by the ankle decreased considerably. In the test skate condition, the greater plantar flexion velocity and displacement imply that more impulse occurred in this case.

These interpretations are supported by observations of the linear skate velocity near the end of the contact period (Fig. 8, Table 7). The HO-TO action consists of pushing the toe of the skate back away from the skater's motion. This action slows down the speed of the skate, and the magnitude of the velocity decrease is an indication of this rearward push. The velocity decrease illustrated in Fig. 8 indicates that the skater was pushing back against the ice during this phase, and this backward push appears to be larger in the test skate condition. Thus it appears that the test skate condition resulted in more of a forward impulse during the HO-TO phase.

The small absolute velocity of the skate at the end of the contact period makes the increase in the angle of propulsion difficult to discern from an ice cut left in the ice. From the graph in Fig. 8, it can be estimated that the skate travels less than one skate-length during the short HO-TO phase.

As an accelerating skater gains speed, the ankle extends more quickly, and the musculature is less capable of exerting force against the ice (Winter, 1979). Eventually, the skater reaches a speed when he or she cannot push back against the ice as quickly as the ice itself is moving away relative to the skater. The toe of the blade will 'catch' in the ice, and a braking rather than a positive impulse will be applied (van Ingen Schenau & Bakker, 1980). In short, the ankle plantar flexion and supination which occur during the HO-TO phase have a decreasing importance as the skater picks up speed, and a point is reached when they can actually be detrimental to the skater. However, hockey skating generally involves intense accelerations at relatively low velocities (Dillman et al, 1984), and ankle plantar flexion and supination should be regarded as important skating components.

The HO-TO impulse is important not only because the angle of propulsion is greater during this phase, but also because the lean of the skater in the frontal plane is greatest at this time. During the course of the stride, the skater's center of mass moves away from the skate because the skate and the center of mass are moving in different directions. The ice reaction force is directed approximately from the skate to the center of mass. The angle of lean in the frontal plane is defined as phi, the angle that this vector makes with the vertical, and the horizontal component of the ice reaction force F is given by

F(sin phi) (see Fig. 10). Phi increases as the center of mass moves away from the skate along the z axis during the course of the stride. As noted by Mann & Hagy (1980), increased dorsiflexion, as well as increased hip and knee flexion, lower the center of mass along the y axis, and this also serves to increase phi. The resulting forward horizontal component of the ice reaction force (the desirable component as far as the skater is concerned) is given by F(sin phi)(sin theta), where theta is the angle of propulsion.

The following is a summary of the role of the ankle in the acceleration phase of forward skating, as suggested by the preceeding model and supported by the data from this study. During the TD-HO phase, the ankle must be stable in the frontal plane to allow transmission to the ice of the forces resulting from hip and knee extension without dissipation. Some controlled pronation does occur in order to increase the range of motion for later supination and possibly to store energy in the ligaments and musculature. In the sagittal plane, the skater touches down in a state of dorsal flexion, and the degree of dorsal flexion increases as the skater strives to keep the blade flat on the ice while he or she moves forward relative to the skate. The dorsal flexion also serves to lower the center of mass, thereby increasing the angle of lean early in the stride, and it increases the range of motion for later plantar flexion. A sudden increase in dorsiflexion occurs just prior to HO, possibly to activate the plantar flexion musculature.

As the heel comes off the ice, the skater turns the skate

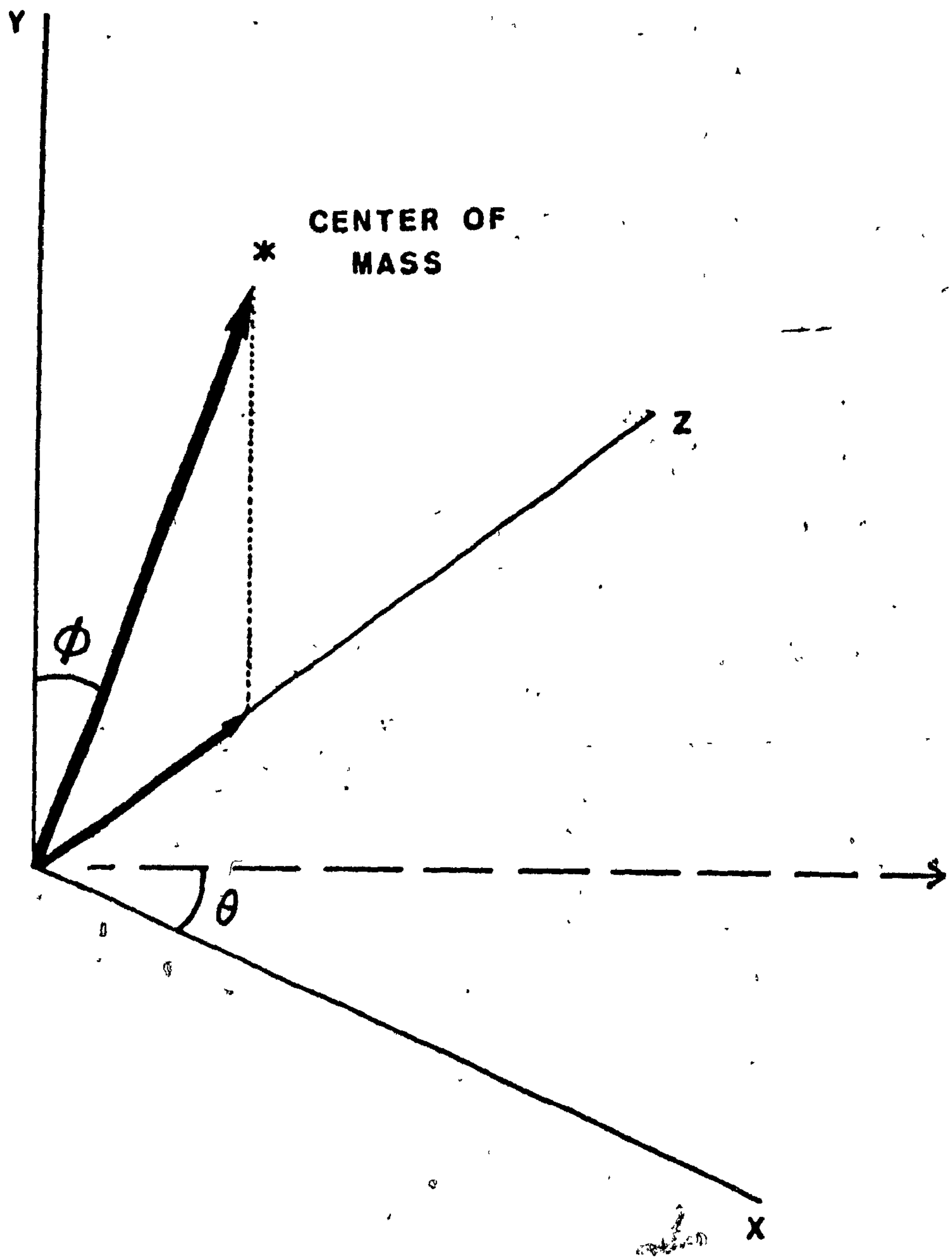


FIGURE 10. Three dimensional representation of the ice reaction force vector F. The origin is the skate; the x axis gives the direction of the skate's glide. The desired direction of motion of the skater is to the right. The horizontal component of the ice reaction force is along the z axis.

outward, increasing the angle of propulsion. This greater angle of propulsion, combined with the large angle of lean at the end of the contact period, makes the ice reaction force during the HO-TO phase very effective in providing forward impulse. A great deal of this ice reaction force comes from ankle flexion in both the frontal and sagittal planes, primarily from plantar flexion.

5.2 Total Body Parameters

Several variables were measured for descriptive purposes in order to assess any differences in total body motion brought about by the experimental intervention. These variables included the change in trochanter velocity during the HO-TO phase, and body lean measurements in the frontal plane. The statistical summary for these variables is presented in Appendix B (Tables B1 and B2).

According to the model presented in section 5.1, there should be no acceleration of the center of mass with respect to the skate in the sagittal plane of the skate during the HO-TO phase, since the ice reaction force is perpendicular to this plane (although, in reality, some acceleration will occur because of gravitational torque when the center of mass is not vertically over the skate in this plane). However, at the time of HO, the angle of propulsion increases so that the ice reaction force is no longer perpendicular to the plane of motion seen by the laterally located camera. As a result, some acceleration of the center of mass should be apparent in the film taken with this camera. Furthermore, the degree of velocity change in the plane of motion filmed by the lateral camera should correspond with the forward directed impulse during the HO-TO phase. With this in mind, the velocity of the greater trochanter was determined at the times of HO and TO. The trochanter was considered to be an adequate representation of the center of mass for the purpose of comparison between conditions.

The trochanter velocity of subject 1 was found to increase by 0,37 m/s with the conventional skate and 0,60 m/s with the test skate during the HO-TO phase, while the corresponding numbers for subject 2 were 0,61 m/s and 1,04 m/s. A great deal of intertrial variation was evident with all measurements. However, despite the shortcomings of these data, it was apparent that a considerable increase in velocity took place during the brief HO-TO time interval. There was a definite tendency for greater HO-TO impulse to occur in the test skate condition. These results are consistent with and supportive of the proposed model.

The model pointed to the importance of body lean in the frontal plane as an important factor in maximizing horizontal impulse. A measurement representing this lean was made by determining the angle formed with the vertical by a line joining the skate blade and a marker placed at the center of the posterior thigh, just distal to the gluteal crease. This measurement was made at the time of HO. An unexpected and substantial decrease in the angle of lean was observed in the test skate condition for both subjects. With the removal of the ankle support provided in the conventional skate, the lean of subject 1 decreased from 29,0° to 24,9°, while that of subject 2 decreased from 27,1° to 22,4°. Because of the importance of this factor, it was decided to run a statistical test, and the difference was found to be significant at the ,05 alpha level for each subject.

These results imply that the removal of ankle support made the subjects less willing to lean in the frontal plane and push themselves laterally. Although the removal of medial ankle support did not appear to seriously alter the skaters' ability to control pronation, it clearly hindered their ability to apply force in the lateral direction. The question is raised as to whether or not the 7 hours provided in this study for the subjects to accustom themselves to skating without ankle support was sufficient. This cannot be answered in the context of the present study. What is clear is that the skaters changed their skating strategy, relying less on the lateral ice reaction force during the TD-HO phase and taking advantage of the greater range of motion afforded by the test skate to achieve greater impulse during the HO-TO phase. These alterations apparently balanced out for the skaters; it will be recalled that the acceleration performance scores were not different for the two conditions (Table 2).

5.3 Comparison With Other Studies

McCaw (1984) measured ankle angles for novice, intermediate, and elite level skaters at maximal velocity as filmed by a camera perpendicular to the plane of the skater's motion. McCaw used the lateral heel of the skate boot as the vertex for his ankle angle while the present study used the lateral malleolus. The difference has been estimated by the author as being about 25°. For comparitive purposes, this number was added to McCaw's results.

McCaw's elite subjects reached a minimum ankle angle of 82°; results in the present study varied from 81,6° to 85,5°. This corroboration suggests that McCaw's data were correct. His novice subjects had a mean minimum angle of 89°, indicating that they underwent less dorsiflexion. In the model presented earlier, it was seen that dorsiflexion lowers the center of mass, allowing for more effective utilization of the ice reaction force, as well as increasing the range of motion. However, the elites in McCaw's study had a smaller range of motion than the novices, reaching a toe-off plantar flexion value of only 97° compared to the novices' 109°. It was this unexpected result, and the fact that the plantar flexion values at TO were so low, which led McCaw to consider his data to be confounded by the three dimensional nature of the skating motion and therefore suspect. The degree of error inherent in his measurements cannot be established at this time, but his results are consistent with the model presented in section 5.1 of this study. The model indicated that plantar flexion would have decreasing benefit as the skater gained speed and would be detrimental at very high speeds. Perhaps McCaw's elite subjects had learned through their skating experience to limit plantar flexion at high speeds.

There have been no studies in the literature which have measured pronation angles while skating. Bates, Osternig, Mason, & James (1978) measured frontal plane ankle angles for runners, and determined that the maximum degree of pronation reached during ground contact was typically between 5 and 10°, slightly less than the values found in skating. Runners typically reached a supination angle of 20° at TO, while the tendency of skaters to supinate beyond the neutral position was minimal. The reason for this is simple: while runners can achieve impulse with positive supination, the lever action involved in skating becomes negligible beyond the neutral position.

Angles of propulsion for accelerating skaters have been measured by Lariviere (1968) and Marino (1983). Both authors used a heterogeneous sample of hockey players. Lariviere measured a mean starting angle of 68° followed by 59°, 44,5°, and 34,8° for the first three contact periods, while Marino found the average for the first three contacts to be 40,5°. Both sets of data are consistent with the 32° noted for the subjects in this study for the fourth contact period, and the decreasing angle of propulsion is to be expected based upon the model presented earlier.

Measurements of stride rate and velocity are consistent with those reported in the literature for advanced to elite accelerating skaters. Greer & Dillman (1984) reported the instantaneous velocity of elite skaters at the 6 m mark of an acceleration task to be 7,0 m/s, while the skaters in this study were travelling at 6,1 m/s, as estimated by SL/ST, at about the 5 m mark (the approximate midpoint of the fourth stride). Greer & Dillman measured a stride rate of 4,02 /s; at the fourth stride in this study the mean rate was 3,98 /s.

The corroboration between this study and other studies in the literature suggests that the kinematic pattern described in this study is typical of advanced level skaters.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Very little scientific research has focussed upon the role of the ankle in power skating. A review of the literature indicated a great deal of confusion regarding its function. The purpose of this study was to quantitatively document the kinematic pattern of the ankle in a maximum intensity skating acceleration task. The second major concern of the study was to assess the effect of removing the ankle support normally provided by hockey skates on the kinematic pattern. Hypotheses were designed to compare a conventional skate and a skate which provided no ankle support on the following criteria: maximum dorsiflexion, maximum plantar flexion, maximum pronation, and maximum plantar flexion and supination velocities.

6.1 Methodology

Two advanced level hockey players were selected as subjects based on their skating acceleration performance. The task consisted of a maximum intensity sprint from the goal area to center ice. Two Locam cameras filmed the action at 100 fps. Camera location and starting point were adjusted so that the fourth contact would be filmed. Cameras were placed so as to give orthogonal views of the lower limb and oriented with respect to the skate blade. Two pairs of skates served as the independant variable for the experiment: the Micron Medalic, a molded plastic skate, and a test skate which was identical to the Medalic in all respects except that it gave no support above the talus. Subjects underwent 10 trials with each condition. Marked anatomical landmarks were digitized and then analyzed using the McGill Biomechanics Laboratory's kinematic analysis programs. Statistical evaluation of the hypotheses was done via t-tests comparing the two conditions on the dependant variables. An alpha level of 0,05 was set as the criterion for rejection of the statistical hypotheses. The two subjects were analyzed separately.

6.2 Findings

Analysis of the data and testing of the statistical hypotheses revealed the following results:

1. The skaters touched down in a position of dorsiflexion, and dorsiflexion increased during the touchdown to heel-off (TD-HO) phase, reaching a maximum value just before heel-off. Significant differences in maximum dorsiflexion between conditions for S2 were not found, although S1 underwent significantly less dorsiflexion in the test skate condition than in the conventional skate condition.
2. Maximum plantar flexion occurred at TO. The subjects frequently failed to plantar flex as far as the neutral (standing position) ankle angle, particularly when the conventional skate was worn. Maximum plantar flexion was greater for both subjects with the test skate condition. Statistical significance was obtained for S1 but not for S2.

3. Maximum plantar flexion velocity was reached during the HO-TO phase. High velocities were reached in a very short amount of time implying large angular accelerations around the time of HO. Maximum velocity was greater when the test skate was worn than when the conventional skate was worn for both subjects. Differences between conditions were statistically significant for S1 but not for S2.
4. The subjects contacted the ice in a position of very slight pronation. Pronation increased during the TD-HO phase, reaching a maximum prior to HO. There was a greater degree of pronation in the test skate condition for both subjects. Differences were statistically significant for S2 but not for S1.
5. The subjects reached high supination velocities during the HO-TO phase, implying that large angular accelerations occurred at the time of HO. The maximum supination velocity was greater for the test skate than for the conventional skate for both subjects. Differences were statistically significant for S2 but not for S1.

The kinematic patterns were very similar for both conditions. Temporal aspects of the stride (e.g. TD-HO time and HO-TO time) were not altered by the experimental intervention. The test skate condition was characterized primarily by a greater range of motion and a higher angular velocity during the HO-TO phase than the conventional skate in both the sagittal and frontal planes.

Further analysis indicated that the linear velocity of the skate reached a smaller minimum value during the HO-TO phase for the test skate than for the Medalic, and that the angle of body lean in the frontal plane was less for the test skate condition.

Large within-subject variances occurred for all variables, hinting at a complex interrelationship among a large number of components which affect the execution of this task.

6.3 Conclusions

The limited scope of the study and the lack of consistent statistical significance preclude the ability to generalize the results with any degree of certainty. However, strong evidence has been presented in support of the following points:

1. An important and measurable amount of motion at the ankle takes place during skating acceleration in both the sagittal and frontal planes.
2. Displacement in the sagittal plane primarily consists of dorsal flexion. Skilled skaters in conventional skates do not usually plantar flex as far as the neutral (standing) ankle angle.
3. Pronation is under muscular control in skilled skaters.
4. The angle of propulsion increases during the HO to TO phase.
5. Greatest plantar flexion and supination velocities occur during the HO-TO phase. Significant forward impulse is applied to the skater's center of mass through ankle extension during this phase, which comprises the last 20% of contact time.
6. Decreasing ankle restriction results in an increased degree

of motion in all directions except dorsiflexion. Dorsiflexion appears to be limited by the lacing of the skate and the tongue.

7. Decreasing ankle restriction results in higher extension velocities during the HO-TO phase, providing a greater forward impulse during this phase than the restricted condition allows.

8. Less body lean in the frontal plane takes place when the ankle is unsupported. This results in decreased forward impulse during the TD-HO portion of contact because of a smaller horizontal component of force.

9. The connection between decreased ankle support and decreased frontal plane lean is unclear. It is suggested that without medial support the point of force application on the ice is less stable. The skater, who must also be concerned with balance, shifts his skating strategy slightly to rely more on the HO-TO phase for his forward impulse.

6.4 Implications of the Study

Pronounced dorsal flexion is a critical and characteristic element of skilled skating technique. Coaches should emphasize this aspect to their skaters. Despite the insistence in much of the coaching literature for full ankle extension, the skilled subjects in this study did not forcibly extend (plantar flex) their ankles beyond the neutral position. Coaches have apparently been unsuccessful in teaching this skill. Since it was shown that plantar flexion contributes substantially to forward impulse in early acceleration, more of an effort to teach this technique to developing skaters needs to be undertaken. In light of the strong possibility that ankle extension is detrimental to maximal velocity skating, a distinction needs to be made between acceleration skating and high velocity skating.

Evidence presented in this study suggests that the skates presently employed by elite hockey players fail to maximize skating performance because they limit plantar and dorsal flexion and limit supination. Skates designed for the type of forward acceleration that occurs in hockey should provide medial support, but allow unrestricted motion in the sagittal plane.

6.5 Suggestions for Further Research

Review of the results from this study indicates directions for several closely related research initiatives. Dorsal flexion was isolated as an important component in power skating technique. However, the experimental intervention failed to interact with this variable. A replication of the experiment, except with no dorsal flexion restriction provided by the lacing or tongue of the test skate used, should be undertaken to assess the effect of this variable on the skating impulse. Another question raised by this study is the degree of importance of the HO-TO ankle plantar flexion action as the skater gains speed, and in particular the point at which this action becomes detrimental to skating performance. There appears to be a need to assess the role of the ankle at various other points along the skater's path, both earlier and later in the acceleration task. As a final area of investigation employing a similar experimental setup, the study should be replicated with skaters of different abilities so that the process of the development of a mature skating pattern can be documented.

There is a need to study the dynamics of skating acceleration directly, rather than to infer what is happening from measured kinematic variables. The relationship between kinematic patterns and total body motion is not as well understood as it should be. The development and deployment of practical sub-ice surface force platforms or within skate force measuring devices would be of enormous assistance in providing solid insight into the question of how people skate.

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APPENDIX A

INFORMED CONSENT FORM

NAME (print): ______________________________

The study you will participate in is designed to determine the ways in which the ankle restriction inherent in regular hockey skates affects your skating stride. You will be asked to perform 20 maximum intensity accelerations: 10 wearing a regular skate and 10 wearing a specially constructed non-restricting test skate. You will perform in shorts, with contrasting markers placed on specific anatomical landmarks, and you will be filmed with a high speed camera.

You may discontinue your participation in the study at any time, simply by asking to do so. That is, you can refuse to complete one or all trials, or you may ask to have your filmed trials destroyed before analysis. You may also ask to have your results withdrawn.

It will be possible for you to see the filmed recording of your trials, and for you to see a report of the study when it is completed. AFTER THE STUDY IS COMPLETED, THE FILMED RECORDINGS OF YOUR TRIALS WILL BE MAINTAINED IN THE FILM LIBRARY OF THE BIOMECHANICS LABORATORY OF THE MCGILL UNIVERSITY DEPARTMENT OF PHYSICAL EDUCATION, TO BE USED FOR RESEARCH AND INSTRUCTIONAL PURPOSES. (IF YOU DO NOT WANT YOUR TRIALS TO BE USED FOR PURPOSES OTHER THAN THE PRESENT STUDY, DRAW A LINE THROUGH ALL CAPITALIZED LINES.)

By signing below, you are indicating that you consent to participate in the study, that you have read and understood this informed consent form, and that all your questions concerning the study have been answered.

Signature: ______________________

Date: ____________

APPENDIX B

TABLE B1

Increase in Trochanter Velocity (HO-TO), Lateral View
(velocity in m/s)

Subject	Skate	Mean	Std Dev
1	test	0,60	0,49
	Medalic	0,37	0,45
2	test	1,04	0,58
	Medalic	0,61	0,53

TABLE B2

Body Lean in the Frontal Plane
(angles in degrees)

- Measurement represents the tilt of the supporting leg with respect to the vertical at the time of HO.

Subject	Skate	Mean	Std Dev
1	test	24,9	3,9
	Medalic	29,0	2,9 *
2	test	22,4	3,9
	Medalic	27,1	5,0 *

* Difference is significant, $p < ,05$