A Biomechanical Comparison of Novice, Intermediate and Elite Ice Skaters

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ABSTRACT

The purpose of this study was to compare the basic parameters of the skating step and the kinematic pattern of the propulsive leg hip and knee among skaters of novice, intermediate and elite ability levels. 28 subjects were assigned to an ability level according to their highest level of ice hockey experience. Preliminary analysis of skating time eliminated 6 intermediate skaters from the study; the remaining 22 subjects were filmed at 100 fps as they skated three maximal velocity trials through the center ice circle. One trial of each skater was digitized. Dependent variables (Step Length (SL), Step Rate (SR), Single Support Time (SST), Double Support Time(DST), hip and knee angular displacement, peak and average angular velocity and joint coordination) were calculated from the coordinates. Further subject selection based on Horizontal Velocity (SR * SL) provided a sample of 6 elite, 6 intermediate and 5 novice skaters for comparison. Graphic and statistical analysis was used to describe trends in the dependent variables across ability level.

Analysis revealed that faster skaters utilized higher step rates; both SST and DST were shorter but DST decreased disproportionately. There were no significant differences for step length across the ability levels. Hip and knee displacement, and both peak and average angular velocity increased with skill level. The increased range of motion resulted primarily from greater joint flexion prior to extension. No differences in the relative timing of joint extension were identified. Results were discussed in relation to theories on skill development.

RESUME

L'objet de cette étude était de comparer les paramètres du pas dans le coup de patin ainsi que le programme cinématique du genou et de la hanche de la jambe propulsive chez les patineurs de niveaux novice, intermédiares et élites. 28 sujets ont été assignés à un niveau d'habileté selon le plus haut niveau de compétition atteint. Une analyse préliminaire des temps d'exécution du coup de patin a éliminé de l'étude 6 patineurs de niveau intermédiares; les 22 sujets restants ont été filmés à une vitesse de 100 photos/s, pendant qu'ils exécutaient trois essais de patinage à vélocité maximum à travers le cercle du centre de la glace. Un essai de chaque sujet a été analysé. Les variables dépendantes (longeur du pas (LP), fréquence du pas (FP), temps de support simple (TSS), temps de support double (TSD), les déplacements angulaires, vélocité angulaire moyenne et maximum, ansi que la coordination des déplacements aux articulations du genou et de la hanche) ont été calculées à partir des coordonnées obtenues du film. Une sélection additionnelle basée sur la vélocité horizontale (LP * FP) a produit un échantillon de 6 patineurs élites, 6 intermédiares et 5 novices, pour fins de comparaison. Une analyse graphique et statistique a été employée pour décrire les tendances dans les variables dépendantes, parmi les niveaux d'habileté.

L'analyse a révélé que les patineurs plus rapides ont utilisé une fréquence de pas plus élevée; les TSS et TSD étaient plus courts, cependant, le TSD avait diminué de façon disproportionnée. Il n'y avait pas de différences significatives dans la longeur du pas parmi les niveaux d'habileté. Les déplacements, ainsi que la vélocité angulaire moyenne et maximum du genou et de la hanche ont augmenté avec le niveau d'habileté. L'amplitude de mouvement accrue des articulations a résulté principalement d'une plus grande flexion avant l'extension. Aucunes différences dans la synchronisation de l'extension aux articulations ont été identifiées. Les résultats ont été discutés en relation avec les théories de développement d'habiletés.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Ice hockey is one of the most popular winter sports in Canada, with nearly 2 million participants (Canada Fitness Survey,1983). Hockey's popularity is reflected in the number of children enrolled in community hockey associations, the crowded neighborhood rinks throughout the winter, the numerous industrial leagues scheduled during the early hours of the morning, and the presence of National Hockey League teams in seven Canadian cities.

Success in ice hockey depends on an individual's mastery of the fundamental skills of the game, the most essential of these being skating. In hockey, a skilled skater possesses the characteristics of mobility, quickness and efficiency (Lariviere & Bournival,1973). In addition to improving locomotion, highly skilled technique improves the potential of a player to develop puckhandling skills (Leavitt,1979) and improves resistance to fatigue (Green,1979; Leger et al,1979). Consequently, skating ability is a major interest of players and coaches at all levels of hockey, resulting in many hours of individual and team practice devoted to the refinement of technique.

Coaches generally rely on personal experience or empirical descriptions of the skating movement pattern available in coaching manuals as a basis for instruction. Such descriptions are usually limited to the body positioning of skilled skaters, and typically identify trunk flexion and full extension of the lower limbs as optimal technique (Can-Am Group,1973; Chambers,1981; Hockey Canada,1975; Mahoney,1972; Percival,1970; Stamm et al,1982; Watt,1973; Wild,1971). While many authors state that the leg extension movements must be "hard" or "powerful", there is scant reference to the actual dynamics of leg action when skating, or how leg dynamics change as skating ability improves. Few biomechanical studies have focused on skating, and the subsequent reliance of coaches on empirical methods of instruction emphasizes the need for research in this area. The concern of this study was to investigate selected aspects of the movement pattern of skaters of varying ability levels, and to describe fundamental differences in technique between the levels.

1.1 Nature and Scope of the Study

The attainment and subsequent maintainance of high horizontal velocity in skating is dependent on an individual's ability to exert horizontal propulsive force. As in all forms of human bipedal locomotion, the propulsive force required to maintain the velocity of a skater cannot be applied constantly. Propulsive forces in skating are the result of complex lower limb movements producing force on a narrow base of support, the skate blades, resulting in reactive forces from the ice surface. Consequently, a critical problem facing novice skaters is to exert adequate horizontal forces while maintaining balance on the ice (Lariviere & Bournival,1973; Hunter et al,1981).

The leg dynamics responsible for force production have not been adequately investigated. Previous research has done little more than quantify the body position described in available coaching literature. The production of maximal propulsive force is dependent on three biomechanical principles 1) maximize the range of motion through which joints of the lower limb are extended 2) maximize the rate at which the joints of the lower limb are extended, and 3) optimize the sequencing of the extension of the joints of the lower limb. Violation of one or more of these principles is the probable cause of poor skating performance (Norman,1975), but to date there is no available analysis of skating in relation to these principles.

An accurate method of quantifying and qualifying the dynamics of a movement is to obtain high speed film recordings of performance. Analysis of the recordings allows for quantification of individual body segment and whole body kinematics during performance. Recording and comparing the performance of subjects of varying ability levels makes it possible to identify specific technique components which contribute to the inter-level performance variation. This method of analyzing human movement has previously been utilized to study other cyclical human movements such as cross-country skiing (Gagnon,1980; Donskoi,1973; Dillman et al,undated), running (Cavanagh et al,1978; Kunz and Kaufman,1981) and starting techniques in skating (Lariviere,1968; Marino & Dillman,1976; Marino,1979). Marino and Weese (1979) used a kinematic analysis of the whole body center of gravity to determine the relationship of the single and double support periods to the propulsion and glide phases of the skating cycle. Analysis of the acceleration-time curves of four elite skaters' corporeal center of gravity in relation to the single and double support periods indicated that the elite movement pattern is characterised by three functional phases, which the authors called single support glide, single support propulsion and double support propulsion. A precise demarcation point separating the glide and propulsion phases was not determined; however, the authors' evaluation of the films indicated that the transition from glide to propulsion during the single support phase was closely related to lateral hip rotation, the initial extension movements of the hip and knee of the support leg, and presumably began after the center of gravity passed in front of the support leg.

Lower limb kinematics were not quantified in Marino & Weese's study. Application of biomechanical principles to skating suggests that the primary cause of less skilled performance is poor leg action (Norman,1975). By quantifying the propulsive leg joint kinematics (hip, knee and ankle angular displacements and velocities), and the coordination pattern (initiation of joint extension and time to peak extension angular velocity) of skaters varying in ability levels, it might be possible to identify characteristics typical to an ability level.

1.2 Purpose of the Study

The purpose of this study was to compare the skating movement pattern among skaters of three distinct abililty levels: novice, intermediate and elite. Specifically, this study compared the basic spatial and temporal parameters of the skating step, and the kinematic patterns of the propulsive leg hip, knee and ankle.

1.3 Hypotheses

1. The higher skating velocity of the elite skaters to the intermediate skaters, and the intermediate skaters to the novice skaters, will be a product of a) higher step rates and b) longer step lengths.

2. The higher step rates will be a result of shorter time periods of single and double support.

3. The angular displacement of the hip, knee and ankle joints will be greater at the elite than the intermediate level, and greater at the intermediate than the novice level.

4. The peak angular velocity and the average angular velocity of the hip, knee and ankle joints will be greater for the elite than the intermediate skaters, and greater for the intermediate than the novice skaters.

5. The percentage of total step time between the start of the skating step and the initiation of hip, knee and ankle extension will be longer for the novice skaters than for the intermediate skaters, and longer for the intermediate skaters than for the elite skaters.

6. The percentage of total step time between the start of the skating step and the time of peak instantaneous hip, knee and ankle angular velocities will be longer for the novice skaters than for the intermediate skaters, and longer for the intermediate skaters than for the elite skaters.

1.4 Limitations and Delimitations

The limitations of this study were:

1. Spatial and temporal aspects of forward skating were indirectly measured from film recordings of a step, and were subject to the measurement errors characteristic of film analysis. These errors were minimized by maintaining consistent and accurate analysis techniques.

2. Only five subjects represented the novice ability level, and six subjects each of the intermediate and elite ability levels.

3. No measures were made of movement about the longitudinal axes, or in the frontal plane.

4. Each skating trial of each subject was assumed to be at maximal velocity and to be representative of their true skating pattern.

The following delimitations applied to this study:

1. Only male university students between the ages of 18-31 were used as subjects.

2. Ability levels were defined in terms of maximal skating velocity and highest level of ice hockey experience. Elite skaters were defined as members of the McGill University Varsity Hockey Club, who skated at an average velocity greater than that of the fastest intermediate skater. Novice skaters were defined as participants in the McGill University Instructional Programme's "Introduction to Ice Hockey" class, who skated at a maximal velocity less than that of the slowest intermediate skater. Intermediate skaters were defined as members of a McGill University Physical Education "B" Level intramural hockey team, who skated at a maximal velocity less than the slowest elite skater, but greater than the fastest novice skater.

3. Hockey players utilized in this study did not wear regular hockey equipment, nor did they carry a hockey stick.

Subjects wore only skates and shorts, and body landmarks were marked with tape.

4. Only one step at assumed maximal velocity was analyzed, beginning with take-off of the right foot and terminating with take-off of the left foot. No account was made for intra-individual variance in skating performance between trials.

1.5 Definitions and Abbreviations

Novice level skater: A skater who participated in the McGill University Instructional Programme's "Introduction to Ice Hockey" class. These skaters had not skated regularly in the past, and had a maximal skating velocity less than the slowest intermediate level ice skater (velocity<7.92 m/s).

Intermediate level skater: A skater who was a member of an intramural hockey team, at the faculty 'B' level. These skaters did not have experience at a high level of ice hockey competition, but had been skating and playing regularly in the past. Intermediate skaters had a maximal skating velocity between 7.93 m/s and 8.42 m/s.

Elite level skater: A skater who played on the McGill Redmen varsity hockey club, and who had extensive experience at a high level of ice hockey competition. The skater had a maximal skating velocity greater than the fastest intermediate skater (velocity 8.43 m/s).

Skating step: the analyzed unit of movement in skating, defined as the period between contralateral foot take-offs. A right step refers to a step which begins with right foot take-off and terminates with left foot take-off. A skating step is one-half of a skating stride, which refers to the period between initial take-off of one foot and its subsequent take-off.

Step Time (ST): the duration in seconds of one step.

Single Support Time (SST): the duration in seconds within a skating step between foot take-off and the subsequent return of the foot to the ice. During this time, only one foot is in contact with the ice.

Double Support Time (DST): the duration in seconds within a skating step between termination of single support time and the next foot take-off. During this time both feet are in contact with the ice.

Step Rate (SR): the number of steps completed per second, calculated as the reciprical of Step Time (SR=1/ST).

Step Length (SL): the horizontal displacement of the skater's center of gravity during one step.

Skating Velocity (SV): the average velocity of a skater during one step, calculated as the product of Step Rate and Step Length (SV=SR*SL)

Hip Angle: the measure in degrees of the angle between the thigh and a horizontal reference point. This angle is a measure of the inclination of the thigh to the horizontal, and not a measure of the posture of the hip joint.

Knee Angle: the measure in degrees of the angle between the thigh and the shank.

Ankle Angle: the measure in degrees of the angle between the shank and the foot.

Angular Displacement: the measured difference in angular position of the joint between the initiation of joint extension and the end of the step.

Angular Velocity: the quotient of angular displacement and the time difference between initiation of joint extension and the end of the step

Peak Instantaneous Velocity: the highest instantaneous angular velocity measured at the joint during the skating step.

CHAPTER II

REVIEW OF LITERATURE

Power skating, the form of ice skating used by hockey players, is a cyclical form of locomotion with a movement pattern containing characteristics of both running and cross-country skiing. Skating is similar to cross-country skiing in that both skills have a characteristic glide phase inherent in the movement pattern. However, skating differs from cross-country skiing because of the latter's reliance on the arms as a critical impulse generator(Gagnon,1980; Dillman et al,undated). Skating and running are similar because propulsive forces in both activities are exerted only through the legs, but differ due to the glide phase of skating. Skating differs from both skills because of the narrow base of support offered by the skate blades, which makes balance a critical determinant of success, and by the lower limb movement pattern, involving simultaneous hip extension, rotation and abduction, which is necessary in order to evert the skate to obtain an effective skate blade/ice surface propulsion angle (Hunter et al,1981).

The fundamental unit of movement in power skating is the stride. Various authors have equivocally used the terms "stride" and "step" to refer to the period within the movement patterns of skating, running and cross-country skiing encompassed by two consecutive contralateral foot contacts, for example from left-foot contact to right-foot contact. It would seem appropriate for all locomotion skills to adopt the convention of nomenclature proposed for running by Miller(1978), in which stride refers to consecutive ipsilateral foot contacts and step refers to consecutive contralateral foot contacts. The use of a common nomenclature would maintain consistency across forms of locomotion, facilitating comparison of the motor patterns and reducing the ambiguity in the literature.

Adopting the nomenclature of Miller(1978) to power skating in this thesis, stride refers to the period between consecutive ipsilateral foot take-offs, and step to the period between contralteral foot take-offs. When the right foot is the take-off foot, the step is referred to as a right step; alternatively, a left step refers to a step in which the left foot is the take-off foot.

In power skating, each step consists of an initial single support period, followed by a double support period. During the single support period of a right step, the body is supported on only the left foot, as the right leg is flexed and the right foot is recovered to a position in front of the left foot. Once in front of the left foot, the right foot is replaced on the ice, terminating the single support period and initiating the double support period. Figure 1 is a pictorial representation of the skating stride and its components, according to the nomenclature of Miller(1978).

FORWARD SKATING STRIDE			
LEFT STEP		RIGHT STEP	
S S RIGHT	DOUBLE SUPPORT	S S LEFT	DOUBLE SUPPORT

SS=single support

Figure 1: The components of the forward skating stride, according to the nomenclature of Miller(1978)

The majority of biomechanical studies involving maximal velocity power skating have focused on the kinematic parameters of the period between contralateral foot take-offs, which the authors have referred to as a stride. (Marino,1974; Marino,1977; Marino & Weese,1979; Hoshizaki et al,1982; Marino,1984). For purposes of consistency, all units of movement consisting of the period between contralteral foot take-offs which have been referred to as stride in the literature will be termed steps in this review.

An equation for skating exists which relates two easily measured parameters of the step, step length and step rate, to average horizontal skating velocity. This equation is derived from the fundamental equation of average velocity,

$$V = s / t \qquad (2.1)$$

where V is average velocity

s is displacement

t is time

as follows:

The displacement of a skater's center of gravity during a step is the Step Length (SL). Marino (1974) reported similar step lengths whether the displacement was measured as the change in the corporeal center of gravity between contralateral foot take-offs, or as the horizontal distance between the toes of the take-off skates at contralateral foot take-offs. When step length is substituted for displacement in equation 2.1, the equation becomes:

$$V = SL / t \qquad (2.2)$$

The time period between consecutive contralateral toe-offs is the Step Time (ST). Substituting step time for time in equation 2.2 changes the variables to:

$$V = SL / ST \qquad (2.3)$$

A measure of the number of steps completed per unit time, is obtained by taking the reciprocal of step time (1 / Step Time). This variable is referred to as Step Rate (SR). By substituting Step Rate for Step Time in equation 2.3, the fundamental equation of average velocity is redefined for skating:

$$HV = SL * SR \qquad (2.4)$$

where HV is Horizontal Skating Velocity

SL is Step Length

SR is Step Rate

Horizontal Velocity is measured in metres per second (m/s), since Step Length is measured in metres and Step Rate is measured in steps per second (steps/s).

The variables step length and step rate, and the temporal components of step rate, single support time and double support time, have been studied to establish how their relationship to velocity is affected by changes in skating velocity. The changes in skating velocity that have been investigated are conscious velocity increases made on the requests to skate at maximal, medium and slow speed (Marino,1977); involuntary velocity decreases resulting from fatigue (Hoshizaki et al,1982), and velocity increases accompanying increased age (Marino,1984).

Marino(1977) filmed 10 male college-aged skaters as they skated at a self-perceived slow and medium speed, and at their fastest speed. No description of the location of the filming area to the starting line of the trial was provided. The purpose of the study was to determine how step rate and step length varied with changes in skating velocity, and to ascertain the relationship of the single and double support periods over different skating velocities. The subjects ranged from low to high ablility. A oneway ANOVA with repeated measures followed by the Scheffe multiple comparisons test indicated that instructions to skate at different velocities did result in significant differences between the group mean velocity for the three trials (slow=12.31 ft/s(3.75 m/s); medium=20.11 ft/s(6.13 m/s); fast=22.7 ft/s(6.92m/s)). Similar statistical analyses of group means for step rate, single support time and double support time across the three conditions indicated significant differences between each of the variables for the three velocities. However, the repeated measures ANOVA on the group mean of step length was not significant. The Pearson correlation coefficent between step length and skating velocity was also not significant (r=.05), but the Pearson coefficents between skating velocity and step rate(r=+.76), single support time(r=-.74), and double support time(r=-.80) were all significant. Similar results were reported by Hoshizaki et al(1982), who investigated the influences of mass and fatigue on the relationship of step rate and step length to skating velocity. Seven college-aged skaters of advanced-intramural and varsity skill level performed the University of Ottawa on-ice anaerobic test (Reed,1978) under conditions of 0, .454 and .907 kilograms mass added at their ankles in the form of weighted belts. A skating step was analyzed from film recordings taken as the subjects skated through the center ice circle. The fatigue induced reduction in velocity was significant under each of the three conditions. Analysis of the variables step rate and step length between the non-fatigued and fatigued trial revealed that the decreased velocity was a manifestation of decreased step rate, as the step length remained essentially unchanged. The Pearson correlation coefficent was not significant between horizontal skating velocity and step length (r=+.18), but it was significant between step rate (r=+.72), and the temporal components of step rate, single support time (r=-.43) and double support time (r=-.60).

Although these results indicate a closer association between step rate and skating velocity than between step length and skating velocity, Marino's (1977) contention that "fast speed is more dependent on the number of times that force of propulsion is applied, than on the force of each propulsion, as is indicated by the length of each stride" does not fully explain the results. While no measure of the force applied to the ice was made in either study, the increased step rate probably reflects a more rapid extension of the joints of the propulsive leg, and a concomitant increase in the magnitude of the propulsive forces exerted on the ice. Both Marino(1977) and Hoshizaki et al(1982) reported decreases in single and double support time as the velocity of skating increased, but there were disproportionate decreases in double support time. Marino(1977) reported a double support decrease from .339 to .111 seconds, as opposed to single support time which decreased from .436 to .262 seconds. Hoshizaki et al(1982) reported an increase in double support time expressed as a percentage of step time from 23.4% to 28.5%, and a decrease in the percentage that is single support time from 76.6% to 71.5%, between the non-fatigued and the fatigued trial of an on-ice anaerobic test, indicating a greater change in double support time. Since double support is primarily a phase of propulsive leg extension and single support includes a phase of leg recovery and glide, the disproportionate decrease in double support time supports the contention that greater propulsive forces are exerted at faster skating velocities. The similar step length may be an artifact of changes in duration of the step, changes in exerted impulse, or both. The support foot in skating continues to glide along the ice during the step, even as the leg joints are extended to exert a propulsive force, due to the momentum inherent at the end of the previous step, and the low friction force resisiting horizontal displacement. At slow velocities characterised by low step rates, the skater has less momentum at the end of a step, but the duration of each step is increased. Conversely, the skater has greater momentum at high velocities, but the time to complete each step is decreased. Since displacement of a skater during a step is equal to the product of the skater's average velocity during the step and the step time (s=v*t), similar displacements are possible under the conditions of low velocity, long step time and high velocity, short step time. The higher forces generated by the skater in the short time of lower limb joint extension at high velocity could be great enough to produce the impulse necessary to maintain the step length.

Marino(1984) conducted a cross-sectional analysis of adolescent ice skating patterns, and reported significant correlations opposite to those presented by Marino(1977) and Hoshizaki et al(1982). For this study, the author analyzed film recordings of 104 males between the ages of 8 and 15 who were attending a summer hockey school. The filming area was set up on the far blue line of a skating path which led the skaters across the ice, and then down the length of the ice surface. Each age constituted a level in the factor age. Oneway ANOVA's were conducted on skating velocity, step length, step rate, single support and double support across age. Skating velocity increased from 4.7 m/s to 7.13 m/s between 8 and 15 years of age, with significant differences between the 8 year olds and all other age groups, and between age 9 and the 13, 14 and 15 year olds. There was no significant difference in step rate between age groups. Graphic display of the means of step length revealed a trend for increasing step length with age, and an ANOVA indicated significant differences between the 8 year olds and all other age groups, and the 9 year olds and age groups 13,14 and 15. Marino interpreted the similar step rates as an indication of mature skating pattern development by the age of 10, and attributed subsequent increases in skating velocity to changes in strength and power associated with growth and development, and to possible improvements in the coordination of lower limb joint extensions. The young skaters could be "running" on the ice, applying greater vertical than horizontal propulsive forces, maintaining a high step rate but obtaining a short step length. Expressing step length relative to the skater's stature might provide greater insight concerning the skating pattern change.

The studies cited above indicate both step rate and step length as critical determinants of skating velocity. However, it would be inappropriate to coach skaters to increase one or the other of these parameters unless the other could be maintained, or reduced only minimally, so that step velocity is increased (Hay,1978).

To provide a greater understanding of the intricate mechanics of forward skating, research must go beyond a simple description of the temporal and spatial parameters of the step. Investigations must focus on the actions of the lower limbs, which are critical for effective force production. Knowledge of the lower limb kinematic patterns of elite skaters would provide a model against which the performance of less-skilled skaters could be compared, to identify errors common to a particular skill level.

The literature available to coaches is characterised by static descriptions of the skater's body position, based on observation of skilled skaters. The skater is usually described at the end of a step, in a position of upper body flexion, support knee flexion, and full extension of the propulsive leg hip, knee and ankle. Deviations from this ideal form are then related as errors to watch for, such as skating too-erect, incomplete joint extension, or minimal support-knee flexion at the beginning of the step. Few authors realize that some of the body positioning they describe is a response to, rather than a cause of, good technique. For example, the degree of trunk flexion a skater can maintain is partially dependent on the magnitude of the horizontal component of the resultant propulsive force (Kreighbaum & Barthels,1981). As trunk flexion increases, the large upper body mass creates a destabilizing torque about the skate/ice surface axis. Unless sufficent counter-rotary torque is produced by the horizontal component of the reaction force, equilibrium maintenance is not possible. Simply extending the propulsive leg joints through a full range of motion will not create forces adequate to maintain a high skating velocity. The rate of joint extension and the coordination of the joint extensions must be optimized for high performance. Little is known concerning the action of the propulsive leg in relation to the single and double support periods of skating. Knowledge of this pattern would provide a much more valuable understanding of skating than does a simple description of the spatial and temporal parameters of the step.

Page(1975) used the descriptions of skating in the coaching literature as the basis for a study of factors which might account for observed differences in skating velocity. Two cameras, one located to the side and the other in front of the skater, recorded sagittal and frontal plane movements of fourteen subjects, who were members of either a bantam team, a university physical education class or a professional team. Each subject completed four skating trials, which consisted of skating along a 40 foot (12.2 metre) line painted on the ice. The author did not describe the parameters of the filming area, such as the location of the starting line to the 40 foot (12.2 metre) line. Time over the course was recorded by photo-electic cells. The second and fourth trial of each skater was recorded on film. Average velocity over the 40 feet (12.2 metres) was calculated, but the author did not report from which trial the calculation was made. Calculated velocites and level of hockey experience were used to categorize the adult subjects as "fast" or "slow"; categorization of the youth skaters was done by simply dividing the group at the mean velocity. Twenty-seven spatial and temporal variables were measured from the film recordings and directly from the tracings cut into the ice by the subject's skates. Page did not analyze the skating pattern in relation to the periods of single and double support. Spatial measures included joint and segment angles at the beginning and end of the step, and displacements of the skate along the ice. The author did not state whether the value for each variable was an individual trial score or the mean across trials. Step-wise multiple regression analyses were used to determine which variables best predicted skating velocity, and step-wise discriminant analyses were used to identify variables which differentiated between the "fastest" and "slowest" skaters. Three regression and three discriminant analyses were run; one on all 14 subjects, one on the six bantam skaters, and one on the 8 adult skaters. Unfortunately, when interpreting his results, Page did not consider possible correlations among the predictor variables which confounds regression and discriminant analysis interpretation, especially in cases with a low variable/subject ratio (Norusis,1983; Tatsuoka,1970). An interesting aspect of Page's results were the correlations reported. The author did not report the actual coefficents, only whether or not the coefficent was significant, and the direction (positive or negative) of the association if it was significant. An indication of the magnitude of the correlations can be obtained from a table of the correlation coefficent required for different levels of significance, such as is found in any standard statistics textbook. Using the table in the textbook by Minium (1978), it can be seen that for the group of 14 skaters, or degrees of freedom equal to 12, a coefficent of .53 was significant at the .05 level; for the group of six bantam skaters, or degrees of freedom equal to 4, a coefficent of .75 was significant; and for the group of eight adult skaters, or degrees of freedom equal to 6, a coefficent of .67 was significant. For the group of fourteen skaters and the six youth skaters, Page reported a significant positive correlation between velocity and the range of knee extension, and significant negative correlations between velocity and the angle of knee flexion prior to the initiation of knee extension and between velocity and the time duration of knee extension. Page reported the same correlations for the eight adult skaters with the exception that time of knee extension and velocity were not significantly correlated. These data suggest that both the rate and the magnitude of joint displacement are important variables influencing skating performance.

It would seem that a major limiting factor of an individual's skating velocity is their ability to rapidly extend the joints of the lower limb through a full range of motion. This skill is critical for exertion of optimial propulsive forces on the ice. It is difficult to measure skating propulsive forces directly because of logistical problems in mounting force transducers over the range of a skating step (Lamontagne et al,1983). Forces have been measured during the starting phase of forward skating using force platforms (Roy,1978; Halliwell,1977), but these studies benefitted from the stationery position of the starting skater. A new technique consisting of skate blade mounted strain gauges and 3-dimensional cinematographical techniques (Lamontagne et al,1983) has the potential to alleviate the problem in the future, but so far this technique has been applied only to ice skating stops.

The periods and the effectiveness of force application in relation to the single and double support periods of the skating step have been measured indirectly through analysis of center of gravity kinematic patterns calculated from film recordings of a skater (Marino & Weese,1979). The application of a net propulsive force by the skater was reflected by an acceleration of the center of gravity; alternatively, the center of gravity was decelerated when a net resistive force was acting on the skater. High speed film recordings at 100 fps were made in the sagittal plane for three trials of 4 highly skilled skaters as they skated at maximum velocity through a designated filming area. The author did not describe the location of the filming area in relation to the starting line of the trial. One trial was selected for analysis on the criterion that the trial occured as close as possible to the center of the filming area. Segmental end points were recorded from every second frame through the step, and were used in conjunction with Dempster's (1955) model to determine the location of the center of gravity of the body. Fifth degree polynomial curve fitting was used to smooth the horizontal displacement-time data of the center of gravity. The derivative of the resultant function was solved at .01 second increments to establish instantaneous velocity values. The velocity values were similarly smoothed and the derivative solved to determine instantaneous acceleration values at .01 second intervals. Measures were also made of step length, step rate and the single and double support periods. Analysis of the acceleration-time values indicated that the initial stage of single support was a deceleration phase, followed by an acceleration phase which continued to the end of double support. All four subjects exhibited essentially similar acceleration patterns during the step, although there was inter-subject variation in the amplitude of the acceleration. Except for one subject, the skaters reached their point of maximum acceleration during the latter stage of the single support period. The exceptional skater did not reach peak acceleration until the latter stages of double support; the authors felt that he was still trying to accelerate as he passed through the filming area. Other similarities noted by the authors in the acceleration pattern were the acceleration phase initiation near the midpoint of the single support period, and a decrease in the rate of acceleration starting early in the double support period, such that the skater was experiencing a period of near zero acceleration at the onset of the next single support period.

A striking feature of the acceleration-time curves presented by Marino and Weese was their smoothness, with all four subjects exhibiting only one minima and maxima. Investigations of cross-country skiing have identified several minima and maxima in the center of gravity velocity patterns during a step, corresponding to increases in the propulsive force applied to the ground as body segments are extended (Gagnon,1980; Komi et al,1979). The smoothness of the skating curves presented may have been influenced by the polynomial curve fitting technique used to smooth the data, or perhaps the number of times the data was smoothed, being once before each derivation. Polynomial curve fitting has a tendency to mask true oscillations in data (McLaughlin et al,1977; Pezzack et al,1977), and may have attenuated true inflections in Marino & Weese's data, providing a simplified understanding of skating kinematics (Marino,personal communication). Using a different smoothing technique, such as digital filtering might have resulted in a different and possibly more revealing interpretation of the movement (Winter et al,1974; McLaughlin et al,1977).

Although the accuracy of the curves presented by Marino & Weese may be questioned, the authors did provide scientific insight concerning the relationship of force production to the single and double support periods of skating. Their results also suggest possible biomechanical differences between skaters of different ability levels. The authors stated that the start of the single support propulsion phase coincided with the initial extension movements of the propulsive leg hip and knee, and logically followed the center of gravity coming ahead of the support foot. Since a skater's support foot continues to glide on the ice through most of the step, a more appropriate name for the initial phase of the step would be single support recovery, rather than single support glide, which might mislead a person to think that this is the only period during the step when gliding occurs. Whether skaters less skilled than the elite subjects of Marino and Weese's study are capable of initiating hip and knee extension during single support has not been studied. Powerful extension of the hip and knee during single support would require a highly developed sense of balance, an attribute noted to be lacking in novice skaters (Lariviere & Bournival,1973; Hunter et al,1981). Any prolongation of the recovery phase, resulting from a conscious or unconscious delay in the initiation of hip and knee extension, could be manifested in greater velocity fluctuations during the step. Page(1975) reported a 3.02 foot/second (.92 m/s) velocity variation during the stride for both the slowest and the second fastest skater in his study, and concluded that intra-step velocity variation was not related to skating velocity. However, the velocity of the slowest skater ranged from 16.01 to 19.03 feet/second (4.87 to 5.8 m/s) with an average velocity of 18.1 feet/second (5.52 m/s), while the velocity of the second fastest skater ranged from 32.7 to 35.72 feet/second (9.96 to 10.89 m/s), with an average velocity of 33.6 feet/second (10.24 m/s). If the ratio of average velocity to range in velocity (average velocity / maximum-minimum velocity) is calculated, it provides a dimensionless ratio indicative of the skater's efficiency (Miller,1975; Zatsiorsky,1973; Kuhlow,1975). From average velocities reported in the appendix of Page's thesis, the present investigator calculated the efficiency ratio for the slowest and the second fastest skaters as 5.97 for the slow skater, and 11.13 for the fast skater. The higher value for the faster skater indicates that he was capable of maintaining the higher velocity with less relative fluctuation in his velocity, and thus can be considered as a more efficent skater. Wickstrom(1975) has conjectured that young children learning to run may unconsciously magnify the negative horizontal force created at recovery leg foot contact as a method of maintaining velocity within manageable limits. The novice skater could conceivably delay the extension of the propulsive leg joints in a similar form of speed control, or could reduce the rate of leg extension as a result of less developed neuromotor coordination or a conscious strategy, both of which would result in greater velocity decreases.

Summary: Most previous research has focused on spatial and temporal characteristics of the skating step, especially the relationship of step length and step rate to horizontal velocity. Previous research results indicate that voluntary or involuntary decreases in skating speed by an individual are associated with reduced step rates, while step length remains essentially unchanged. The similar step lengths at different velocities are possibly a result of an interaction between changes in duration of the step affecting how far an individual glides and changes in the magnitude of the impulse exerted on the ice.

Evidence indicates that poor skating performance is a manifestation of either a limited range of joint displacement during propulsive leg extension, a reduced angular velocity of propulsive leg joint extension, a poorly coordinated pattern of propulsive leg joint extension, or some combined violation of these biomechanical principles. There are no reported measurements of propulsive leg kinematics throughout the skating step, making it difficult to identify the specific errors separating the ability levels.

Subjective evaluation of elite skaters by Marino & Weese(1979) indicates that these skaters begin hip and knee extension during the single support period of the step. Quantification of the propulsive leg joint kinematics in relation to the single and double support periods of the step of skaters of different ability levels can potentially identify patterns characteristic of the ability levels.

CHAPTER III

METHODOLOGY

The following section includes a description of subject selection and preparation, cinematographical procedures, measurement of data, and data analysis. The methodology utilized in this study was accepted by an Ethical Review Committee of the McGill University Faculty of Graduate Studies and Research (Appendix A).

3.1 Subject Selection and Preparation

Twenty-eight male volunteers were recruited, through telephone and personal solicitation, from the McGill University student body to serve as subjects in this study. Eight volunteers were members of the McGill Redmen varsity hockey club, fifteen were members of a McGill University intramural Faculty "B" hockey team, and five were participants in the McGill University Instructional Programme's "Introduction to Ice Hockey" class. Each subject was requested to appear at the McGill Winter Stadium on March 15, 1983 for data collection.

The purpose of this study was to compare skating patterns among three distinct ability levels. Ability levels were defined on the basis of highest level of ice hockey experience and maximal skating velocity. It was necessary to do a preliminary screening of the recruited subjects to ensure that the velocity criteria would be met; this applied specifically to the intermediate skaters. The screening process involved three trials of skating at maximal velocity from goal line to goal line. Timers with hand held stopwatches were positioned at each blue line; both timers started their stopwatch on the go signal, and stopped it as the skater crossed their respective blue line. The difference in these times for the three trials were averaged, and six skaters from the intermediate group whose times overlapped with either the novice or the elite level were thanked and excused from the rest of the study.

A consent form (Appendix B) was read and signed by each of the 22 subjects who remained in the study, acknowledging that the testing procedures and the subject's options had been fully explained. The subjects' age, height, mass, leg length (top of greater trochanter to floor) and years of skating experience were obtained for descriptive purposes. Subjects were asked to wear only shorts and newly sharpened skates, and the following anthropometric landmarks were marked on each subject to facilitate digitization:

1. left acromion process
2. lateral border of the left and medial border of the right elbow axes
3. styloid processes of both left and right radius and ulna
4. greater trochanter of the left femur
5. lateral border of the left and medial border of the right knee axes
6. lateral malleolus of the left fibula and medial malleolus of the right tibia
7. lateral aspect of the left and medial aspect of the right heel of the skateboot, at mid-calcaneal level

8. tuberosity of the fifth metatarsal on the left foot, and a point equidistant to the fifth metatarsal tuberosity on the right foot medial border

3.2 Cinematographical Procedures

3.2.1 Filming

All filming took place on the 61 metre (200 foot) ice surface at the McGill Winter Stadium. The center ice circle, which has a diameter of 4.6 metres (15 feet), was the designated filming area; the center of the circle is 27 metres (88.6 feet) from either goal line.

Subjects were brought onto the ice in groups of five to be filmed; the first group of five consisted of subjects who had to return to class immediately for an examination. All other subject groupings were done by random assignment.

After a suitable warm up period, each subject was asked to skate as fast as possible through the designated filming area. Subjects started from the goal line at the north end of the rink, so that the left side of the body was closest to the camera as they passed through the filming area. Subjects were instructed to maintain their velocity until the blue line opposite the starting position was reached, so that maximum velocity would be maintained through the filming area. The camera was started as the subject crossed the blue line closest to the starting position. Three trials of each subject were recorded; between each trial, the other four members of the group completed a trial, so fatigue was not a factor in the study.

3.2.2 Camera Position

A Redlake Locam camera, Model 51-003, was set up 13.18 metres (43.2 feet) from the center ice face-off circle, perpendicular to the intended line of travel. A 10mm Schneider Optik Kreuznach lens was mounted on the camera, with a lens to ground height of 1.3 metres (4.3 feet).

3.2.3 Camera Technical Data

The Locam camera was loaded with Kodak 4-X reversal film, type 7277; a film speed setting of 100 frames per second and a shutter factor of 2.5 (144 degree shutter opening) provided an exposure time of 1/250th of a second. Four 1000 watt light banks were arranged around the periphery of the circle to illuminate the area. A hand held light meter was used to measure the luminosity of the filming area; consideration of the meter reading and the shutter factor necessitated setting the f-stop at the maximal aperture of 1.8. An electrically powered LED generator, internally mounted within the camera housing, was set to flash 100 times per second. These flashes were recorded as white dots on the border of the film to facilitate the determination of actual film speed (actual film speed=number of exposed frames/elapsed time). For linear computations, a metre stick was levelled in the plane of action and filmed, then set level behind the plane of action to serve as a horizontal reference. To identify subjects and trials during film analysis, numbered markers were set up under the horizontal reference and a written record of the filming order was kept.

The exposed film was developed by the Dominion Wide Lab in Ottawa, Ontario. The lab was asked to chemically push the film 1.5 f-stops to compensate for the low light conditions in the arena.

3.3 Measurement of Data

One trial of each subject was selected for analysis, on the criterion that a complete right step was recorded in the center of the film image. Collection of data from the film was facilitated by the use of a L-W pin-registered stop-action projector, which projected the film onto a Summagraphics digitizing board. Each frame of the trial, from 15 frames before right foot take-off until 15 frames after left foot take-off, was analyzed. The L-W projector was equipped with a frame counter, which enabled accurate counting of frames exposed during a trial. A handheld cursor, connected to a Summagraphics digitizer, was used to digitize x and y coordinates of the 17 body landmarks, and the right and left end of the horizontal reference. The digitizer was hooked on-line to the McGill University mainframe computer, permitting immediate storage of the x,y coordinates in a MUSIC (McGill University System for Interactive Computing) library file.

3.3.1 Transformation of Digitized Coordinates

A Watfiv program was used to adjust each frame to a common x,y origin, to compensate for any movement of the projected image as the film was advanced. This program also reformatted the x,y coordinate file, so that it could be used as input to the McGill

Biomechanics Laboratory's kinematic analysis programs.

The raw x,y coordinates were filtered using a low-pass, recursive digital filter. The cut-off frequency was set at 4.5 Hertz (Winter et al,1974; Pezzack et al,1977; Wood,1982). The kinematic analysis programs used the filtered x,y coordinates as input in calculating the corporeal center of gravity kinematics, individual landmark kinematics, and angular kinematics of specified joints. All calculated values were both output as hardcopy and stored on disk in the MUSIC system, to be accessed for further computations, graphing and statistical analysis.

3.3.2 Center of Gravity Calculation

The kinematic analysis programs calculated the x and y coordinates of the corporeal center of gravity for each frame of the trial. Dempster's model(1955), expressing segment mass as a percent of total body mass, was modified to include the addition of the skates to the feet. Dempster's model defines the right foot as 1.42% and the left foot as 1.49% of total body mass, which in a 63 kilogram subject means the right foot has a mass of .89 kilograms and the left foot has a mass of .94 kilograms. Since a size 6.5 skate has a mass of .91 kilograms, about the same as the unskated foot, it was considered appropriate to include the skate mass in the mass distribution calculation.

To recalculate the mass distribution, it was assumed that skate mass increase was proportional to skate size increase. A 63 kilogram subject wearing a pair of size 6.5 skates has a total mass of 64.82 kilograms. Dividing the mass of the left and right foot, including the skate mass, by the total body mass provided new percentages of total body mass for the left and the right foot. The right foot percentage increased from 1.42% to 2.78%, and the left foot increased from 1.49% to 2.86%. Addition of skates to the feet did not change the mass of other body segments, so the new percentage of total body mass for each segment was calculated. Appendix C contains the segment mass distributions, indicating how the inclusion of skate mass modified Dempster's parameters.

3.3.3 Skating Step Parameters

The skating step is defined as the period between contralateral foot take-offs. This study utilized a right step as the basis for comparison among skaters of novice, intermediate and advanced ability levels.

Step length and step time were calculated between right foot take-off and left foot take-off. Two methods were used to measure step length 1) the difference between the medial marker of the right foot fifth metatarsal tuberosity at right foot take-off, and the marker of the left foot fifth metatarsal tuberosity at left foot take-off, and 2) the displacement of the corporeal center of gravity between right foot take-off and left foot take-off. These values were compared using paired t-tests; once for the whole group as one sample, and once for each ability level as a separate sample.

Step time was measured as the product of the number of frames exposed during the step and the reciprocal of actual film speed (1/actual film speed). Single and double support times were similarly calculated; single support between take-off of the right foot and touch-down of the right foot, and double support from touch-down of the right foot until take-off of the left foot.

3.3.4 Calculation of Skating Velocity

The average horizontal skating velocity of each subject during the analyzed trial was calculated as the product of step rate and step length. Step length was measured as the displacement of the corporeal center of gravity between right and left foot take-off.

The calculated skating velocities were used as the basis for final subject selection. Each subject had been previously categorized by highest level of ice hockey experience; horizontal skating velocity was used to eliminate skaters whose velocity overlapped into another ability level.

3.3.5 Angular Kinematics

Digital filtering of the digitized x,y coordinates at 4.5 Hz. provided a smoothed set of x and y coordinates to be used in the calculation of angular kinematics. Angular measures in degrees were calculated for the joints of the propulsive limb in each frame digitized. The hip angle was defined as the angle between the thigh (defined by the greater trochanter and the knee joint center) and the digitized horizontal reference point. This angle is a measure of the inclination of the thigh rather than a measure of the posture of the hip. The absolute angle of the thigh to the horizontal rather than the relative angle between the thigh and the trunk was measured so that trunk flexion and extension did not confound interpretation of hip movement. Hip extension was an increase in the angle between the thigh and horizontal; hip flexion was a decrease in the same angle. The knee angle was the relative angle between the thigh and the shank (defined by the knee joint center and the lateral malleolus); knee extension was an increase in the angle between the segments. The ankle angle was the relative angle between the shank and the foot (defined by the skate boot heel marker and the fifth metatarsal tuberosity marker); plantarflexion was an increase in the angle between the segments. A diagram of these angles is presented in Appendix D.

Measurement of the left leg's hip, knee and ankle angular displacement, angular velocity and time of extension initiation was made.

Each joint's angular displacement during the step was measured as the difference between the joint angle when extension began, referred to in this study as the joint minimum angle prior to extension, and the joint angle at take-off of the left foot. For a skater who flexed a joint during the step, the joint minimum angle was measured at the end of the period of flexion. The periods of joint flexion and extension were taken from the instantaneous angular velocity values calculated for each joint.

Two variables quantifying the rate of angular displacement were measured. Average angular velocity during the step was calculated as the quotient of the angular displacement and the time difference between the initiation of joint extension and the end of the step. Peak joint instantaneous angular velocity during the step was simply the highest value of instantaneous angular velocity calculated. Both velocity values were expressed in radians per second (1 radian = 57.3 degrees). The technique of finite differences was used to calculate instantaneous angular velocity at each sample time. The formula for instantaneous angular velocity using finite differences is:

$$\omega x_i = x_{i+1} - x_{i-1} / 2\Delta t$$

where ωx_i is the angular velocity at sample point x_i,

x_{i+1} is the joint angle at the sample point following point x_i,

x_{i-1} is the joint angle at the sample point before point x_i,

$2\Delta t$ is twice the time between sampling points

Calculations were made on the basis of $2\Delta t$ rather than Δt so that angular velocity values could be related to the actual sampling times (Winter,1979).

Curves of instantaneous angular velocity over time were plotted for each subject using SAS procedure PLOT (SAS Institute Inc,1982a). From a visual analysis of these curves, one subject's curve representative of the angular velocity pattern of each ability level was chosen and their values were plotted using SAS procedure GPLOT (SAS Institute Inc,1981). These curves were used to qualitatively compare the patterns of angular velocity between the three levels.

Coordination of the propulsive leg joint actions was quantified in two variables. The first was the relative time to joint extension initiation from take-off right, the start of the step. The second was the relative time to joint peak instantaneous angular velocity from take-off right, the start of the step. Both these variables were calculated by taking the quotient of the absolute time to the occurrence in seconds and the step time. In addition, the time at which the corporeal center of gravity was first located ahead of the toes of the left foot was noted for each subject, and indicated on their angular velocity/time curve. This variable was noted to describe the timing of the initiation of extension angular velocity at the joints in relation to when the movements would be most effective in accelerating the skater horizontally. Calculation of this variable was made by comparing the x-displacement coordinate of the left foot toe marker to the x-displacement coordinate of the corporeal center of gravity, and noting the time when the toe value was greater than that of the center of gravity.

3.4 Statistical Analysis

The use of inferential statistical techniques in biomechanics is often hindered by the low number of subjects utilised in such studies. Several factors have been responsible for the utilization of low subject numbers, including the time involved to digitize the film recording of the skill performance, and the financial expense of computer analysis. A low number of subjects makes it difficult to test for the validity of the assumptions underlying inferential statistics, including normal distribution of the sample and the homogeneity of variance between the groups. Much of the research in biomechanics has, nonetheless, utilised inferential statistics to describe the differences that exist between the groups. As long as the researcher is aware of possible violations of the underlying assumptions, and recognizes the limitations of using inferential statistics with small sample sizes, then inferential statistics provide a valuable tool in biomechanics research (Bates,1983).

The independent variable in this study was skating ability. There were three levels of ability (novice, intermediate and elite) defined by skating velocity and highest level of ice hockey experience. The dependent variables in this study were measures of the parameters of the skating step and the kinematics of the hip, knee and ankle of the propulsive leg. Specifically, these variables were:

Parameters of the skating step:

Step length
Step rate
:single support time
:double support time

Propulsive leg hip, knee and ankle kinematics:

Minimum angle prior to extension
Angle at left foot take-off
Angular displacement

Average angular velocity during the step
Peak instantaneous velocity during the step

Relative time of minimum angle prior to extension
Relative time of peak instantaneous velocity

The Statistical Analysis System (SAS) package of procedures was used to conduct the statistical analysis in this study. SAS procedures utilized were MEANS (SAS Institute Inc,1982a) to obtain descriptive statistics of the dependent variables and to conduct a paired t-test between the two methods of calculating step length, GLM (general linear method) (SAS Institute Inc,1982b) to conduct oneway analyses of variance with unequal sample sizes on the criterion variables, and CORR (SAS Institute Inc,1982a) to obtain Pearson Product Moment correlations between velocity and the dependent variables.

If the probability of the F ratio obtained with the oneway

ANOVA was less than .05, the Tukey post-hoc multiple comparison test modified for application to unequal sample sizes (Keppel, 1973) was utilized to identify which levels were significantly different. Values of the Tukey critical range were computed by hand on a Texas Instrument 55-II calculator, using the table of critical values for the Studentized Range Statisitic provided in Keppel(1973). Keppel's equation for determining the Tukey critical range for unequal sample sizes is:

$$CT_T = q\ (r_{max},\ df_{S/A})\ *\ \text{square root}\ (MS_{S/A}\ /\ s')$$

where:

- CT_T :is the Tukey Critical Range
- q :is the value for the Studentized Range Statistic
- r_{max} :is the maximum number of steps between groups
- $df_{S/A}$:are the degrees of freedom associated with the error term
- $MS_{S/A}$:is the Mean Square of the error term, taken from the printout of the Analysis of Variance
- s' :is the harmonic mean of the sample size, calculated as:

$$s' = \frac{a}{\frac{1}{s_1} + \frac{1}{s_2} + \frac{1}{s_3}}$$

a = number of groups or levels
s_1, s_2, s_3 = individual sample sizes

CHAPTER IV

RESULTS

This chapter presents the results of the study. The purpose of this study was to compare the movement pattern among skaters of novice, intermediate and elite ability levels. Results are presented within the following sections: subject description, comparison of skating step parameters, and kinematics of the propulsive leg.

4.1 Subject Description

A total of 28 subjects volunteered to participate in this study. Subjects were categorized into novice, intermediate and elite ability levels according to their highest level of hockey experience and skating velocity. Based solely on their level of hockey experience, five subjects were classified as novice, nine were classified as intermediate, and eight were classified as elite level skaters. Prior to the filming session, subjects were timed as they skated at maximal speed between the blue lines on the ice surface. Timing served to identify skaters whose maximal velocity would obviously overlap into an adjacent ability level, thus minimizing the chances of unnecessarilly filming a subject who would not be used in the comparison. Based on the mean time of three trials, six intermediate skaters were identified as having overlapping velocities, and were dropped.

The remaining 22 subjects were prepared for the filming session by marking specific anatomical landmarks with black dots on white tape.

Three trials of each subject skating at maximal velocity through the center ice circle were then recorded using high speed cinematography. After film processing, one trial of each subject was selected for analysis based on the criterion that a complete right step (from take-off of the right foot to take-off of the left foot) occurred as close as possible to the center of the film frame. Chosen trials were then projected onto an electronic digitizing tablet and landmarks were digitized for each frame of the trial, beginning 15 frames before right foot take-off until 15 frames after left foot take-off. Digitized coordinates were stored directly into a MUSIC library file, from which they were submitted to computer programs for transformation and analysis.

A point of methodological interest, not directly related to any of the hypotheses of this study, involved a comparison of two methods of calculating the skater's step length. The first method measures step length as the displacement of the corporeal center of gravity between contralateral foot take-offs, while the second involves measuring the distance between the toes of the contralateral feet at their respective take-offs. The ease of the second method makes it a preferable technique if the concern of the study is to simply investigate the temporal and spatial parameters of the step, as it reduces the number of points that must be digitized from each frame of film. While the two methods have been shown to provide similar measures of step length

(Marino,1974; Dillman,1970), no comparisons of the techniques have been made at distinct ability levels.

Table 1 presents the t-values and associated probabilities for paired t-tests conducted on the novice, the intermediate, the elite and the entire sample's mean step length calculated with both techniques.

Table 1. Comparison of two techniques for measuring step length

Level	Technique	Mean (metres)	Mean Diff. (metres)	T-value	df	p
N	C of G	2.91	0.07	1.34	4	.2504
	Toes	2.98				
I	C of G	2.68	0.02	0.29	7	.7798
	Toes	2.66				
E	C of G	2.92	0.06	1.52	7	.1713
	Toes	2.98				
All	C of G	2.83	0.03	1.11	20	.2822
	Toes	2.86				

Legend:

C of G: step displacement measured as the displacement of the center of gravity between foot take-offs

Toes : step displacement measured as the distance between toes of contralateral feet at successive take-offs

Results of the paired t-tests indicated no significant differences between the techniques of measuring step length, at any of the ability levels. However, when individual comparisons were made between the two measures (Appendix E), it was found that step length was longer when calculated as the distance between the take-off toes for fourteen subjects, for six subjects the center of gravity technique calculated a longer length, and in one subject the values were the same. Since step length is directly proportional to step velocity, this discrepancy, non-significant when analyzed from a statistical approach, magnifies and affects each subjects calculated horizontal velocity differently. When comparing results of different studies, it is necessary to be aware of this possible source of variation in calculated skating velocity.

4.1.1 Subject Classification by Velocity

Each subject's horizontal skating velocity was calculated as the product of step length and step rate. All calculations of skating velocity utilised the corporeal center of gravity technique for measuring step length. Table 2 shows the step rate, step length, step velocity and years skating experience for each of the 22 subjects. Subjects are presented in ascending order of ability level, according to highest level of hockey experience and skating velocity; the slowest novice skater is at the top of the table. Skating velocities ranged from 6.27 metres per second to 10.01 metres per second. Two intermediate subjects, 2 and 4, and two elite subjects, 16 and 18 had skating velocities which overlapped, and were not included in further analysis. These subjects are marked with an asterik on Table 2.

One intermediate subject, 3, had data which was missing digitized values. This subject was also dropped from the study.

Table 2. Step length, step rate, skating velocity and years skating experience of the 22 subjects

Ability Level	ID#	Step Length (metres)	Step Rate (steps/s)	Average Velocity (m/s)	Years Skating Experience
N	15	2.89	2.17	6.27	2
N	14	2.95	2.17	6.41	1
N	7	2.59	2.50	6.47	3
N	5	3.02	2.56	7.75	0
N	12	3.12	2.50	7.81	1
I	6	2.62	3.03	7.93	12
I	10	3.06	2.70	8.28	20
I	11	2.24	3.70	8.29	10
I	19	2.84	2.94	8.36	10
I	1	2.51	3.33	8.38	13
I	20	3.36	2.50	8.42	10
I	2*	2.33	3.88	9.02	14
I	4*	2.44	3.85	9.39	16
E	18*	2.99	2.78	8.31	17
E	16*	2.68	3.13	8.39	15
E	9	3.13	2.78	8.68	22
E	21	2.61	3.33	8.69	16
E	17	2.78	3.23	8.98	14
E	22	2.98	3.13	9.32	20
E	13	3.29	2.86	9.40	17
E	8	2.90	3.45	10.01	18

N= novice I= intermediate E= elite

* Indicates subjects dropped from the study

Note: No trial was analyzed for subject 3, intermediate.

Classification of the subjects into ability levels according to their highest level of hockey experience and skating velocity provided a sample of five novice skaters, and six skaters at each of the intermediate and elite levels. By definition, novice level skaters were slower and had less years of skating experience than intermediate level skaters, who in turn were slower and less experienced than elite level skaters. The mean skating velocity was 6.94 m/s for the novice skaters, 8.28 m/s for the intermediate skaters and 9.18 m/s for the elite skaters. Descriptive statistics of velocity and years skating experience are presented in Table 3. A oneway analysis of variance (ANOVA) for unequal sample sizes indicated significant differences between ability levels on mean skating velocity (see Table 5). A post hoc Tukey multiple comparison test showed that significant differences existed between each of the levels.

Table 3. Descriptive statistics of velocity and years skating experience for the three ability levels (Mean±S.D.)

	Novice (n=5)		Intermediate (n=6)		Elite (n=6)	
Velocity	6.94±.77		8.28±.18		9.18±.51	
	min	max	min	max	min	max
	6.27	7.81	7.93	8.42	8.68	10.01
Yrs Exp	1.40±1.14		12.50±3.89		17.83±2.61	
	min	max	min	max	min	max
	0	3	10	20	14	22

A oneway ANOVA on group means of years skating experience also indicated significant differences at greater than the .05 level, and a Tukey test showed differences between all levels. Although highest level of hockey experience and not years of skating experience was used to distinguish between abilty levels, the significant difference in years skating experience supports the distinction between ability levels.

4.1.2 Biometric Data of the Skaters

A further description of each ability level is presented in Table 4, which includes descriptive statistics of age, height, weight, and lower limb length for each ability level. Biometric data for each subject is presented in Appendix F. The ability level mean values for the biometric data were similar for height and leg length, but differed for age and mass; the elite level skaters, all members of the McGill varsity hockey team, had a mean age of 21.67 years, approximately 3 years less than either the novice (24.4 years) or the intermediate levels (24.67 years), and a mean mass of 80.32 kilograms, about 11 kilograms greater than the novice skaters, and 12 kilograms greater than the intermediate skaters.

Table 4. Descriptive statistics of biometric data by levels

Level	Variable	Mean	S.D.	Min	Max
Novice n=5	Age	24.40	2.30	21.00	26.00
	Height	1.77	.09	1.70	1.91
	Mass	68.24	9.41	56.70	81.70
	Limb length	.92	.06	.88	1.02
Intermediate n=6	Age	24.67	3.93	22.00	32.00
	Height	1.75	.07	1.67	1.85
	Mass	69.12	7.49	61.70	81.70
	Limb length	.91	.04	.85	.97
Elite n=6	Age	21.67	.82	21.00	23.00
	Height	1.75	.03	1.69	1.79
	Mass	80.32	3.13	76.70	84.40
	Limb length	.91	.03	.86	.96

UNITS:
age: years — height: metres
mass: kilograms — limb length: metres

4.2 Comparison of Skating Step Parameters

Basic statistics describing selected temporal and spatial variables of the skating step for each ability level are presented in Table 5. A summary of five oneway ANOVA's for unequal sample sizes assessing dependent variable differences among the levels are presented in Table 6. A full analysis of variance table for each variable is included in Appendix G. Alpha was set at .05 for signifigence testing.

Table 5. Descriptive statistics of the skating step for Novice, Intermediate and Elite skaters (Mean ± Standard Deviation) *=p<.05

Level	Horizontal Velocity (m/s)	Step Length (metres)	Step Rate (steps/s)	Single Support Time (s)	Double Support Time (s)
Novice	6.94**	2.91	2.38**	.29	.13**
(n=5)	.77	.20	.19	.02	.03
Intermediate	8.28* *	2.77	3.04*	.25	.08*
(n=6)	.21	.41	.44	.05	.03
Elite	9.18 **	2.95	3.13 *	.24	.08 *
(n=6)	.51	.24	.26	.02	.02

Note: Horizontal Velocity is not the exact product of Step Length and Step Rate due to decimal rounding during statistic calculation.

Table 5 demonstrates that the elite level skaters had an average skating velocity of 9.18 metres/second which was the product of the highest step rate (3.13 steps/second) and the longest step length (2.95 metres). Both the step rate (3.04 steps/second) and the step length (2.77 metres) of the intermediate skaters were lower than those of the elite skaters, although neither difference was statistically significant. When non-significant differences in the variables step length and step rate were multiplied, an average skating velocity of 8.28 m/s was obtained for the intermediate skaters, which was significantly less than that of the elite level. The average velocity of the novice skaters was 6.94 metres/second, significantly lower than either the intermediate or the elite skaters. This significant difference in velocity resulted primarily from a novice level step rate of 2.38 steps/second, which was significantly lower than either the intermediate or elite skaters' step rate. The novices' mean step length of 2.91 metres was not significantly different from either of the faster groups, but it was slightly less than the elite level and slightly longer than the intermediate level.

Differences in step rate were a result of disparity in both single and double support times between the levels. Novice skaters had single and double support times that were longer than those of the intermediate and the elite skaters by approximately .05 seconds. Only for double support time was this difference statistically significant. Although the absolute decrease in single and double support time between the novice and the elite/intermediate skaters was similar, the .05 second decrease is a greater relative percentage of double support time than of single support time. The single support time of the elite skaters was 17% shorter than the single support time of the novice skaters, while the elite skaters' double support time was 38% shorter than that of the novice skaters. The exiguous difference in step rate between intermediate and elite skaters resulted from a .01 second difference in single support time, while double support time was similar for the two levels.

Table 6. Summary of Analysis of Variance in the spatial and temporal parameters of the skating step between Novice, Intermediate and Elite level skaters

Variable	df	F ratio	p
Skating Velocity	2/14	25.57	.0001
Step Length	2/14	0.56	.5854
Step Rate	2/14	8.51	.0038
Single Support Time	2/14	3.36	.0642
Double Support Time	2/14	6.74	.0089

Note: Full ANOVA tables for these variables are located in Appendix H.

Pearson Product Moment correlation was used to determine the correlation coefficent between skating velocity and the temporal and spatial parameters of the skating step. Table 7 presents these correlations. Correlation coefficents showed a significant positive correlation between step rate and skating velocity ($r=.71$), and significant negative correlations between skating velocity and both single support time ($r=-.49$) and double support time ($r=-.74$). There was no significant correlation between skating velocity and step length.

Table 7. Correlation coefficents between skating velocity and the temporal and spatial parameters of the step

	Horizontal velocity	
	r	p
Step Length	.17	.5188
Step Rate	.71	.0014
Single Support Time	-.49	.0419
Double Support Time	-.74	.0006

r= Pearson Product Moment correlation coefficent
p= probability of r, with 16 degrees of freedom

Results presented in Tables 5, 6 and 7 suggest that different motor patterns were utilized by each ability level to attain their maximal velocity. A high step rate was utilised by the elite skaters, and they simultaneously produced the longest step length. Intermediate level skaters utilized a step rate slightly lower than the elite skaters, but at the expense of an equivalent step length. Novice skaters utilized a step length between those of the intermediate and elite skaters, but they were not capable of attaining a similar step rate.

These results support part a, but do not support part b, of the first hypothesis which stated that the higher skating velocity of the elite skaters to the intermediate skaters, and the intermediate skaters to the novice skaters, will be a product of a) higher step rates and b) longer step lengths. The faster skaters were characterised by a higher step rate, but not by a longer step length. The results also support the second hypothesis which stated that the higher step rates would be a result of shorter time periods of single and double support. Both time periods decreased, but double support time decreased disproportionately in relation to the decrease in single support time.

4.3 Kinematics of the Propulsive Leg

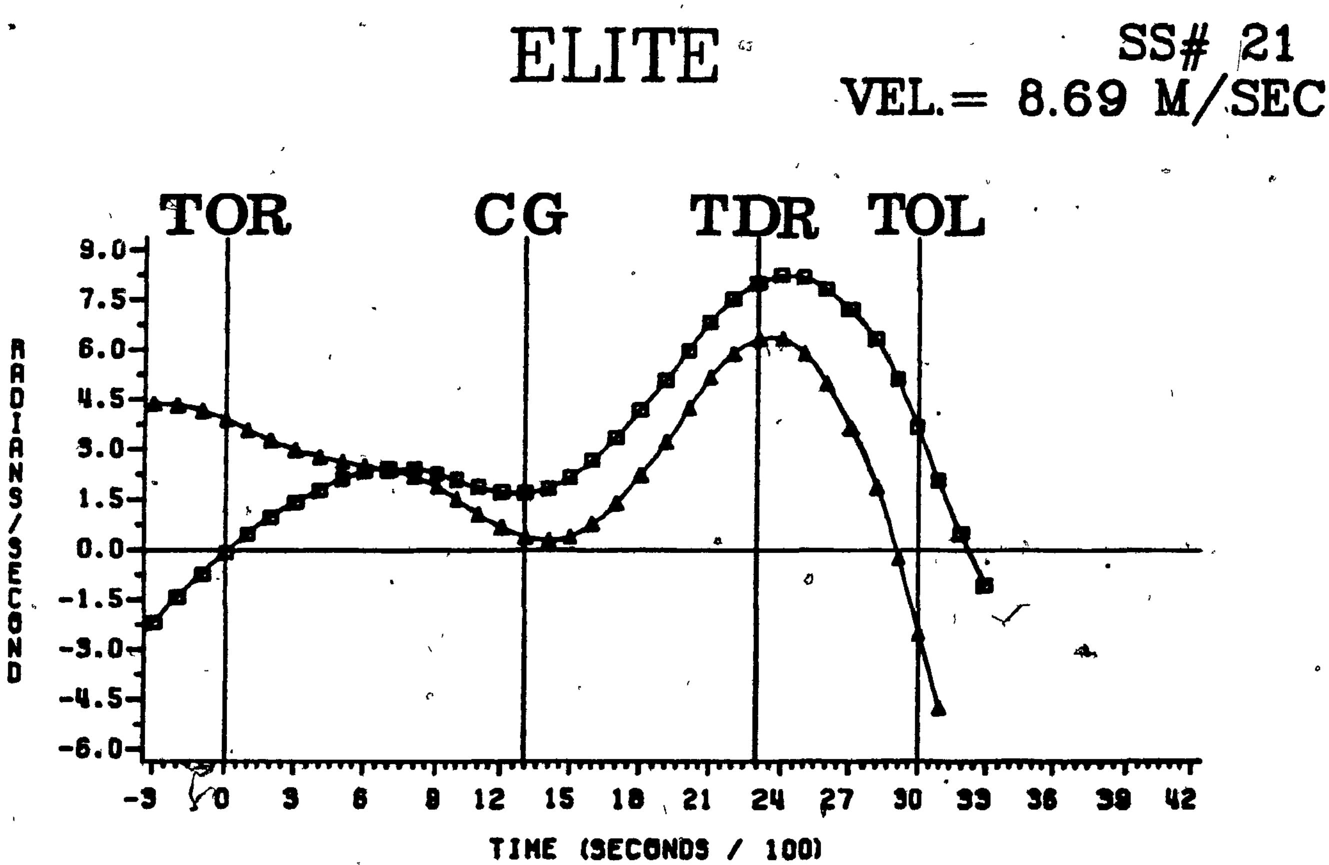
Ineffective leg action has been suggested as the probable cause of poor skating performance (Norman,1975). However, scant attention has been paid to qualifying and quantifying the leg action of skaters at any ability level in past investigations of ice skating. A primary purpose of this study was to compare the kinematic pattern of the hip, knee and ankle joints of the propulsive leg among novice, intermediate and elite level skaters.

During a right skating step, the left leg joints are displaced from a flexed position of support under the skater to a position of hip extension, knee extension and ankle plantarflexion. This study compared the angular displacement, angular velocity and the coordination of joint actions.

Measurement of the propulsive leg kinematics was confounded by lateral rotation of the leg at the hip. It is difficult to quantify the magnitude of the lateral rotation, especially when filming two-dimensionally in the sagittal plane. In the present study, no measure was made of the magnitude of the lateral rotation, and results indicate that lateral rotation might have influenced the ankle measurement to such a degree that the measure of plantarflexion is not meaningful. The measure of left ankle dorsiflexion at right foot take-off did not appear to be invalid, since the foot was parallel with the sagittal plane at this point in the step. However, measures made on skaters at all three levels indicated minimal ankle displacement during the step, such that the mean ankle angle at left foot take-off was less than 90 degrees for all three levels. Norman(1975) has suggested that one of the major faults in the leg action of poor skaters is reduced ankle plantarflexion. In the present study, novice skaters exhibited the greatest displacement, and elite skaters the least. These results strongly suggest that the true magnitude of ankle plantarflexion was masked by lateral rotation of the hip, especially among the highest level skaters. This is a reasonable suggestion when it is considered that elite skaters would be expected to demonstrate the greatest degree of lateral rotation. The measure of ankle plantarflexion during the step was not included in further formal analysis, but the table of means of the calculated values is included in Appendix H for the sake of presentation.

Although there was a degree of variability in the amplitude and phasing of the hip and knee angular velocity curves within subjects at each of the ability levels, it was possible to identify angular velocity curves that were representative of the skaters at each level.

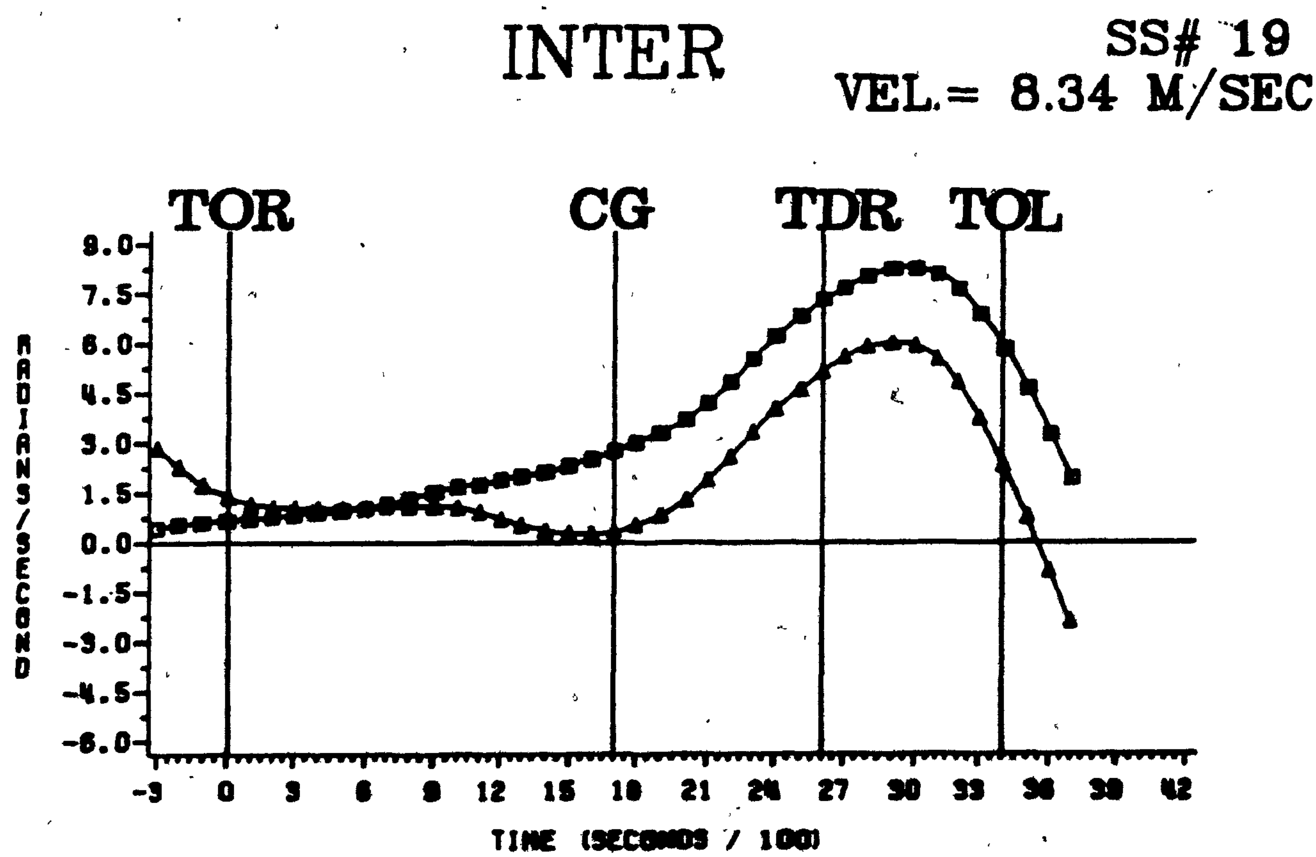
The curves representative of each level are presented in Figures 2, 3 and 4. Explanation of these curves begins with that of the elite level, to provide a benchmark for drawing comparisons to the intermediate and novice levels. Variables quantifying the leg action are presented in the text describing each level's curve. Variables are also presented in tabular format in Table 8, for hip variables, and Table 10, for knee variables. Summaries of the oneway analyses of variance for unequal sample sizes for the hip and knee variables are presented in Tables 9 and 11, respectively. Complete analysis of variance tables for each variable are located in Appendix I.



LEGEND

◘	HIP angular velocity	▲	KNEE angular velocity
TOR	Right foot take-off	TOL	Left foot take-off
CG	Time when center of gravity is in front of the support foot	TDR	Right foot touch-down

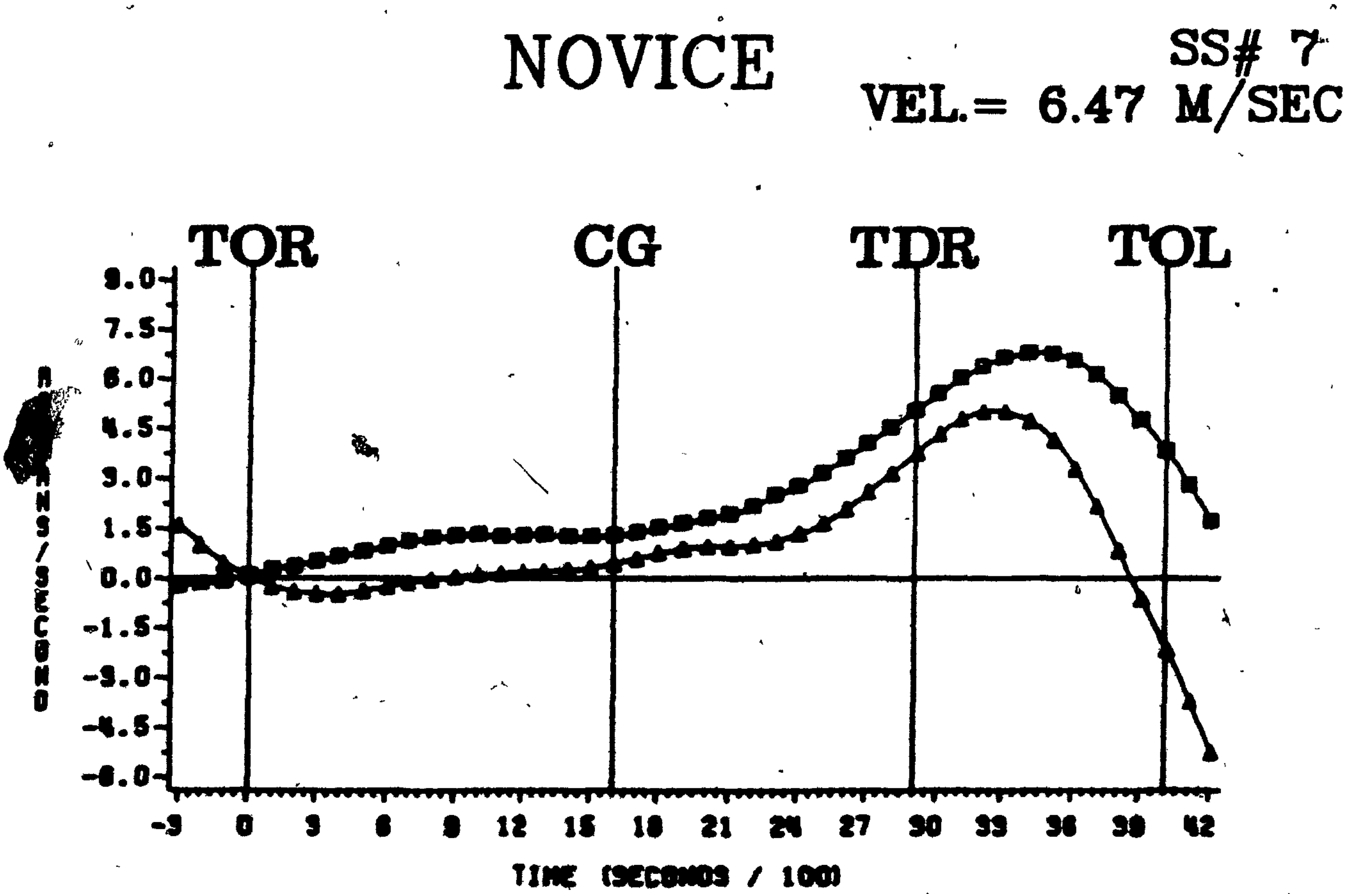
Figure 2: Angular velocity curves of the left hip and knee of an elite skater during a right step.



LEGEND

□	HIP angular velocity	▲	KNEE angular velocity
TOR	Right foot take-off	TOL	Left foot take-off
CG	Time when center of gravity is in front of the support foot	TDR	Right foot touch-down

Figure 3: Angular velocity curves of the left hip and knee of an intermediate skater during a right step.



LEGEND

■	HIP angular velocity	▲	KNEE angular velocity
TOR	Right foot take-off	TOL	Left foot take-off
CG	Time when center of gravity is in front of the support foot	TDR	Right foot touch-down

Figure 4: Angular velocity curves of the left hip and knee of a novice skater during a right step.

Table 8. Angular kinematics of the propulsive leg hip (Mean ± standard deviation)

*=p<.05

Level	Min θ	TOL θ	Δθ	Time Min θ	% ToS Min	$\bar{\omega}$	Time Peak ω	% ToS Peak	Peak ω
N	44.3 *	108.0	63.7	.02	6	2.83**	.37**	88	6.36**
(n=5)	4.5	8.4	10.1	.03	8	.62	.05	5	1.11
I	38.5	112.1	73.6	.01	4	4.03*	.30*	89	8.82*
(n=6)	4.7	8.0	6.5	.02	6	.62	.05	5	.74
E	34.0 *	109.9	75.9	.00	1	4.18 *	.28 *	86	9.15 *
(n=6)	5.3	3.8	7.5	.01	2	.49	.04	6	1.37

Legend

Min θ : Minimum hip angle prior to extension, in degrees
TOL θ : Hip angle at left foot take-off, in degrees
Δθ : Hip displacement during the step, in degrees
Time Min θ : Time to minimum hip angle from take-off right, in seconds
% ToS Min θ : Time Min θ, expressed as % of total step time
$\bar{\omega}$: Average hip angular velocity during the step, in radians per second
Time Peak ω : Time to hip peak instantaneous angular velocity from take-off right, in seconds
% ToS Peak : Time to peak ω, expressed as % of total step time
Peak ω : Hip peak instantaneous angular velocity, in radians per second

Table 9. Summary of Analysis of Variance on selected variables quantifying the kinematics of the propulsive leg hip

Variable	df	F ratio	p
Min θ	2/14	6.15	.0121
TOL θ	2/14	.48	.6267
Δθ	2/14	3.45	.0605
Time Min θ	2/14	1.08	.3675
% ToS Min θ	2/14	.90	.4284
$\bar{\omega}$	2/14	8.72	.0035
Time Peak ω	2/14	6.62	.0095
%ToS Peak	2/14	.35	.7122
Peak ω	2/14	10.19	.0019

Legend

Min θ : Minimum hip angle prior to extension, in degrees
TOL θ : Hip angle at left foot take-off, in degrees
Δθ : Hip displacement during the step, in degrees
Time Min θ : Time to minimum hip angle from take-off right, in seconds
% ToS Min θ : Time Min θ, expressed as % of total step time
$\bar{\omega}$: Average hip angular velocity during the step, in radians per second
Time Peak ω : Time to hip peak instantaneous angular velocity from take-off right, in seconds
% ToS Peak : Time to peak ω, expressed as % of total step time
Peak ω : Hip peak instantaneous angular velocity, in radians per second

Table 10. Angular kinematics of the propulsive leg knee (Mean ± standard deviation)

*=p<.05

Level	Min θ	TOL θ	Δθ	Time Min θ	% ToS Min	$\bar{\omega}$	Time Peak ω	% ToS Peak	Peak ω
N	118.4*	156.5	38.1*	.13	31	2.48	.33	78	5.57
(n=5)	13.0	6.2	17.5	.09	22	1.69	.05	5	2.31
I	114.6	153.9	39.3	.09	25	2.95	.29	86	6.29
(n=6)	5.9	4.8	6.8	.09	26	.74	.06	6	.63
E	103.6*	156.0	52.4*	.05	17	3.63	.27	85	8.16
(n=6)	6.2	8.9	12.1	.08	26	1.13	.03	4	1.90

Legend

Min θ : Minimum knee angle prior to extension, in degrees
TOL θ : Knee angle at left foot take-off, in degrees
Δθ : Knee displacement during the step, in degrees
Time Min θ : Time to minimum knee angle from take-off right, in seconds
% ToS Min θ : Time Min θ, expressed as % of total step time
$\bar{\omega}$: Average knee angular velocity during the step, in radians per second
Time Peak ω : Time to knee peak instantaneous angular velocity, in seconds
% ToS Peak : Peak ω, expressed as % of total step time
Peak ω : Knee peak instantaneous angular velocity, in radians per second

Table 11. Summary of Analysis of Variance on selected variables quantifying the kinematics of the propulsive leg knee

Variable	df	F ratio	p
Min θ	2/14	4.49	.0312
TOL θ	2/14	.24	.7876
Δθ	2/14	2.34	.1325
Time Min θ	2/14	1.05	.3767
% ToS Min θ	2/14	.43	.6572
$\bar{\omega}$	2/14	1.27	.3121
Time Peak ω	2/14	2.00	.1717
% ToS Peak	2/14	2.36	.1313
Peak ω	2/14	3.4	.0628

Legend

Min θ : Minimum knee angle prior to extension, in degrees
TOL θ : Knee angle at left foot take-off, in degrees
Δθ : Knee displacement during the step, in degrees
Time Min θ : Time to minimum knee angle from take-off right, in seconds
% ToS Min θ : Time Min θ, expressed as % of total step time
$\bar{\omega}$: Average knee angular velocity during the step, in radians per second
Time Peak ω : Time to knee peak instantaneous angular velocity, in seconds
% ToS Peak : Peak ω, expressed as % of total step time
Peak ω : Knee peak instantaneous angular velocity, in radians per second

4.3.1 Elite Level Subject

The angular velocity curves of Subject 21, presented in Figure 2, were considered representative of the elite level skaters. Subject 21 was skating at an average velocity of 8.69 m/s; this velocity was a product of a step length of 2.61 metres and a step rate of 3.33 steps/second. Single support and double support times were .23 and .07 seconds respectively. The corporeal center of gravity of subject 21 was first located anterior to the toe marker of the left foot at a time .13 seconds into the right step; this was 57% of single support time and 43% of total step time.

At right foot take-off, subject 21 was initiating left hip extension and decelerating the angular velocity of left knee extension. Left hip extension for the elite subjects was either occurring at take-off right (n=2) or was initiated within .01 seconds of right foot take-off (n=4). Mean time to initiation of left hip extension was .00 seconds after right foot take-off, or 0% of total step time. The kinematic pattern of the left hip during the right step was characterised by an acceleration in extension omega to a maximum in the initial half of single support, a slight deceleration in extension omega during which the corporeal center of gravity came ahead of the support foot toe marker, and then a rapid acceleration of extension omega for the duration of single support, peaking during the double support period. The mean peak hip extension velocity of the elite skaters was 9.15 radians per second (rads/s). Mean time to peak omega was .28 seconds, or 86% of the total step time. All elite skaters were still extending the left hip at take-off left, the designated termination point of the right step. During hip extension, the hip displaced an average of 75.9 degrees, from a minimum angle of 33.95 degrees prior to initiation of extension, to an extended angle of 109.9 degrees at left foot take-off. Elite skaters had a mean average hip angular velocity of 4.18 rads/s during the step.

The decelerating left knee extension omega evident in the angular velocity curve of subject 21 was typical of the elite skaters. Subject 9, the slowest elite subject, began to accelerate knee extension just after right foot take-off, while the five other elite subjects continued to decelerate left knee extension omega until the corporeal center of gravity was ahead of the support foot. Two subjects, 17 and 22, decreased knee extension during single support so much that the knee actually began to flex, and continued to flex until a time equal to 1/2 of total step time. Initiation of extension so late in the step by these two skaters resulted in an elite skaters' mean time to knee extension initiation of .05 seconds, or 17% of total step time. Once the corporeal center of gravity was ahead of the support foot, extension omega of the knee rapidly accelerated to peak in the double support period. Mean peak instantaneous knee extension angular velocity was 8.16 rads/s, and was reached at a mean time of .27 seconds, or 85% of total step time. Peak knee extension omega occurred prior to peak hip extension omega in all elite subjects. At take-off left, three elite subjects, including subject 21, were flexing the left knee; knee flexion was initiated soon after take-off left in the other three elite subjects. During knee extension, the knee displaced an average of 52.4 degrees, from a minimum angle of 103.6 degrees prior to initiation of extension to an extended position of 156 degrees at left foot take-off. Average knee angular velocity for the elite skaters was 3.63 rads/s during the step.

To summarize the elite subjects propulsive leg kinematic pattern, it appears that left hip and knee extension begin prior to or just after right foot take-off, the initiation of the step. In early single support, both hip and knee angular velocity decelerate to a minimum value, but accelerate very rapidly once the center of gravity is ahead of the support foot. This occurs approximately half way through the period of single support. Peak hip and knee angular velocity are reached in the double support period.

4.3.2 Intermediate Level Subject

The angular velocity curves representative of the intermediate level skaters' are those of subject 19; the curves are presented in Figure 3. This subject had an average velocity during the step of 8.34 m/s, a step length of 2.84 metres and a step rate of 2.94 steps/second. Single support and double support times were .26 and .08 seconds respectively. The corporeal center of gravity came ahead of the toe marker of the support foot .17 seconds into the step; this was 65% of single support time and 50% of total step time, later in the step than for the elite skater.

At right foot take-off, subject 19 was extending his hip and knee. While subject 19 was the only intermediate subject exibiting left hip extension prior to right foot take-off, four other intermediate skaters began hip extension within .01 second of right take-off and all intermediate subjects were extending their left hip before 0.06 seconds of single support. Mean time to initiation of hip extension was .01 seconds, or 4% of total step time. Once hip extension was initiated, subject 19 and four other intermediate skaters evidenced constant acceleration of hip extension until peak omega was attained in double support; only subject 1 displayed the decelerating hip extension coincidental with the anterior displacement of the center of gravity relative to the support foot, which was common among the elite level subjects. The intermediate skaters' mean peak hip extension angular velocity was slightly lower than that of the elite skaters, with a value of 8.82 rads/s. Peak hip omega of the intermediate skaters was attained within the double support period, at a mean absolute time of .30 seconds or 89% of step time, slightly later in the step than the elite skaters. The average hip displacement for the intermediate skaters was 73.6 degrees, from a flexed angle of 38.5 degrees prior to initiation of extension to an extended angle of 112.1 degrees at left foot take-off. The intermediate skaters did not flex the left hip as much as the elite skaters, but extended it to a greater angle. Intermediate skaters had an average hip extension omega of 4.03 rads/s during the step, slightly lower than the elite skaters. All the intermediate skaters continued to extend the hip after left foot take-off, but extension omega was decelerating.

The low knee extension omega evident in the pattern of subject 19 during the initial moments of left leg single support was typical of three intermediate level subjects. Subject 6 was actually flexing his left knee at right foot take-off, although the flexion omega was decreasing. Three other intermediate skaters were rapidly decelerating their knee extension omega at right foot take-off. The intermediate subjects tended to display a deceleration in knee extension omega prior to and continuing beyond the time when the center of gravity was displaced anterior to the toe markers of the left foot, similar to the elite skaters. Four intermediate skaters exhibited knee flexion during single support, such that intermediate skaters had a slightly longer mean time to initiation of knee extension than did the elite skaters. The value for the intermediate skaters was .09 seconds, or 25% of total step time. Subsequent to the center of gravity's displacement anterior to the support foot, knee extension was rapidly accelerated, although not as quickly as the elite skaters. Mean peak knee extension omega was 6.29 rads/s. All intermediate subjects reached peak knee omega during double support except for subject 1, who peaked in the latter part of single support. The intermediate skaters reached peak knee omega at a mean time of .29 seconds, or 86% through the step, slightly later than the elite skaters. Following peak knee omega, four of the intermediate subjects continued to extend their knee through to the end of the double support period; two subjects were flexing their left knee at left foot take-off. Average knee displacement for the intermediate skaters was 39.3 degrees, from a minimum angle of 114.6 degrees prior to initiation of extension, reached .09 seconds into the step, to an extended angle of 153.9 degrees at left foot take-off. Average knee omega during the step was 2.95 rads/s for the intermediate skaters.

All of these values were less than the elite skaters' values for the same variables.

In summary, the kinematic pattern of the left leg for the intermediate subjects differed from that of the elite subjects, although none of the differences were statistically significant. Intermediate subjects had a lower average hip omega during the step, and did not display a deceleration in hip extension commensurate with the corporeal center of gravity's displacement anterior to the support foot. The left knee pattern for the intermediate skaters displayed a deceleration about the time the center of gravity displaced anterior to the support foot, as was typical of the elite skaters, and four intermediate skaters flexed their left knee at this point of the step. The average angular velocity of the knee during the step and the peak instantaneous angular velocity were lower for the intermediate skaters than for the elite skaters. Peak instantaneous angular velocity for the intermediate subjects' hip and knee were attained slightly later in the step than were those of the elite skaters.

4.3.3 Novice Level Subject

The skater representative of the novice level was subject 7; the hip and knee angular velocity curves for this subject are presented in Figure 4. Subject 7 had an average skating velocity of 6.47 m/s, resulting from a step length of 2.59 metres and a step rate of 2.59 steps/second. Single support time was .29 seconds; double support time .11 seconds. Time for the corporeal center of gravity to displace anterior to the support foot was .16 seconds, corresponding to 55% of single support time and 40%

of total step time. These relative times were slightly shorter than the intermediate skaters', and approximately equal to the elite skaters'.

At right foot take-off, subject 7 was exhibiting a very low hip extension omega, and a slowly accelerating knee flexion. Of five novice level subjects, two were flexing and three were extending the hip at right foot take-off, and three were extending and two were flexing the knee. Mean time to initiation of hip extension was .02 seconds, or 6% of step time; mean time to initiation of knee extension was .13 seconds, or 31% of step time.

The most apparent feature of the novice skaters' curves was the reduced angular velocity of hip and knee extension, as compared to those values for the intermediate and elite skaters. Average hip and knee omegas were markedly lower among novice skaters prior to displacement of the corporeal center of gravity anterior to the support foot. Subsequent to this occurrence, extension acceleration to peak omega was also lower than in the pattern of the intermediate and elite subjects. All five novice subjects reached peak hip omega, and four reached peak knee omega, during double support. Subject 5, the exception, attained peak knee extension omega prior to the end of the single support period. Average peak hip extension omega was 6.36 rads/s, a value significantly less than that of the intermediate and the elite skaters. Time to peak hip extension angular velocity was an average of .37 seconds or 88% of total step time, a percentage of step between that of the two faster levels. The novice skaters' absolute time to peak hip extension was significantly longer than the intermediate or the elite skaters' time, but there was no significant difference when the time was expressed as a percentage of total step time. Novice skaters had a mean knee peak instantaneous angular velocity of 5.57 rads/s, lower than both faster levels. Peak instantaneous angular velocity was reached at .33 seconds, or 78% of total step time, a longer absolute time but shorter relative time than either the intermediate or the elite skaters. At left foot take-off, four of the five novice subjects were flexing their left knee, although all continued hip extension. Novice skaters had an average hip displacement of 63.7 degrees, less than either the intermediate or the elite skaters. Novice skaters had a mean minimum hip angle prior to initiation of extension of 44.26 degrees, at an average of .02 seconds into the step, and an extended hip angle of 108 degrees at left foot take-off. The minimum hip angle of the novice skaters prior to the initiation of extension was significantly less than that of the elite skaters, and less than the intermediate skaters. The hip angle at left foot take-off was lower, but not significantly lower, than both faster levels. Novice skaters had an average hip extension angular velocity of 2.83 rads/s, which was significantly less than both the intermediate and the elite skaters. Knee displacement was an average of 38.1 degrees, from a minimum angle prior to extension of 118.4 degrees, at a point .13 seconds into the step, to an extended angle of 156.5 degrees at left foot take-off. The novice skaters' minimum knee angle prior to extension was significantly less than that of the elite skaters, but only slightly lower than that of the intermediate skaters. Average knee extension omega for the novice skaters was 2.48 rads/s, which was lower, but not significantly lower, than the elite and intermediate skaters.

In summary, the propulsive leg kinematic pattern of the novice subjects showed several significant differences from those of the intermediate and elite subjects. There was little change in the angular velocity for the hip or knee of the novice skaters as the corporeal center of gravity was displaced anterior to the support foot. Both the hip and knee joint exhibited lower average angular velocity through the step, and peak instantaneous angular velocities were also lower in comparison with the two levels of faster skaters. Both joints of the novice subjects reached peak extension angular velocity during the double support period, and peak knee angular velocity tended to be reached earlier in the step, percentagewise, relative to the faster levels.

Pearson Product Moment Correlation was used to determine the relationship between horizontal skating velocity and the variables quantifying hip and knee kinematics of the propulsive leg. Coefficents and the probabililty of obtaining such a coefficent with 16 degrees of freedom are presented in Table 12 for the hip variables and Table 13 for the knee variables.

Table 12 identifies significant positive correlations ($p<.05$) between horizontal skating velocity and hip displacement during the step ($r=.71$), average hip angular velocity during the step ($r=.82$) and peak hip angular velocity during the step ($r=.87$). Significant negative correlations were found between horizontal skating velocity and the variables hip minimum angle prior to initiation of extension ($r=-.75$) and time to peak hip extension angular velocity ($r=-.68$). No significant correlations were found between horizontal skating velocity and hip angle at left foot take-off, time to minimum hip angle, percent of total step time to minimum hip angle, and percent of total step time to peak hip angular velocity.

Table 12. Correlation coefficents between horizontal velocity and selected variables quantifying the kinematics of the propulsive leg hip

	Horizontal velocity	
	r	p
Min θ	-.75	.0005
TOL θ	.28	.2841
Δθ	.71	.0014
Time Min θ	-.27	.2960
% ToS Min θ	-.22	.4025
$\bar{\omega}$	.82	.0001
Time Peak ω	-.68	.0029
% ToS Peak	.06	.8240
Peak ω	.87	.0001

r= Pearson Product Moment correlation coefficent
p= probability of r, with 16 degrees of freedom

Legend

Min θ : Minimum hip angle prior to extension, in degrees
TOL θ : Hip angle at left foot take-off, in degrees
Δθ : Hip displacement during the step, in degrees
Time Min θ : Time to minimum hip angle from take-off right, in seconds
% ToS Min θ : Time Min θ, expressed as % of total step time
$\bar{\omega}$: Average hip angular velocity during the step, in radians per second
Time Peak ω : Time to hip peak instantaneous angular velocity from take-off right, in seconds
% ToS Peak : Time to peak ω, expressed as % of total step time
Peak ω : Hip peak instantaneous angular velocity, in radians per second

Table 13 identifies significant positive correlations ($p<.05$) between horizontal skating velocity and the variables knee displacement during the step ($r=.63$), average knee extension angular velocity during the step ($r=.56$), and peak knee angular velocity during the step ($r=.76$). Significant negative correlations were found for horizontal skating velocity and minimum knee angle prior to initiation of extension ($r=-.72$) and the time to peak knee angular velocity ($r=-.55$). No significant correlations were found between horizontal skating velocity and knee angle at left foot take-off, time to minimum knee angle, percent of total step time to minimum knee angle, and percent of total step time to peak knee angular velocity.

Table 13. Correlation coefficents between horizontal velocity and selected variables quantifying the kinematics of the propulsive leg knee

	Horizontal velocity r	p
Min θ	-.72	.0014
TOL θ	.18	.4860
Δθ	.63	.0067
Time Min θ	-.39	.1247
% ToS Min θ	-.25	.3271
$\bar{\omega}$	.56	.0185
Time Peak ω	-.55	.0221
% ToS Peak	.29	.2550
Peak ω	.76	.0004

r= Pearson Product Moment correlation coefficent
p= probability of r, with 16 degrees of freedom

Legend

Min θ	: Minimum knee angle during the step, in degrees
TOL θ	: Knee angle at left foot take-off, in degrees
Δθ	: Knee displacement during the step, in degrees
Time Min θ	: Time to minimum knee angle from take-off right, in seconds
% ToS Min θ	: Time Min θ, expressed as % of total step time
$\bar{\omega}$	: Average knee angular velocity during the step, in radians per second
Time Peak ω	: Time to knee peak instantaneous angular velocity, in seconds
% ToS Peak	: Peak ω, expressed as % of total step time
Peak ω	: Knee peak instantaneous angular velocity, in radians per second

Results presented in this section of the chapter relate to hypotheses 3-6. These hypotheses stated the differences that were expected to be identified among the novice, intermediate and elite ability levels on variables measuring the joint angular displacement, joint angular velocity and the coordination of the propulsive leg joint actions. Ankle measures were not compared because of possible perspective error.

Hypothesis 3 stated that the angular displacement of the hip and knee joints would be greater at the elite than the intermediate level, and greater at the intermediate than the novice level. The hypothesis was accepted for hip displacement based on a significant positive correlation between skating velocity and hip displacement. No significant difference among group means of hip displacement was identified by the one-way ANOVA, although the means showed a trend to increase from novice to elite. The hypothesis was accepted for knee displacement based on a significant positive correlation between knee displacement and skating velocity, and the one-way ANOVA and post hoc Tukey tests indicating a significantly higher mean knee displacement for the elite skaters than for the novice skaters.

Hypothesis 4 stated that the peak instantaneous angular velocity and the average angular velocity of the hip and knee joints would be greater for the elite than the intermediate skaters, and greater for the intermediate than the novice skaters. The hypothesis for both peak instantaneous angular velocity and average angular velocity of the hip was accepted based on significant positive correlations between the variables and skating velocity, and the one-way ANOVAs and post hoc Tukey tests indicating that the elite and intermediate skaters had higher mean peak instantaneous and higher mean average angular velocities than the novice skaters. The hypothesis was accepted for peak instantaneous angular velocity and average angular velocity of the knee based on significant positive correlations between the variables and skating velocity. No significant differences were identified in the mean values for the levels, although both variables demonstrated an increasing trend from the novice to the elite level.

Hypothesis 5 stated that the percentage of total step time between the start of the skating step and the initiation of hip and knee extension will be greater for the intermediate than for the elite level, and greater for the novice than for the intermediate skaters. This hypothesis was not accepted for either the hip or the knee. Neither variable was significantly correlated with skating velocity, and there were no significant differences among the three ability levels on either variable.

Hypothesis 6 stated that the percentage of total step time between the start of the skating step and the time of hip and knee peak instantaneous angular velocity would be greater for the intermediate than for the elite level, and greater for the novice than for the intermediate level. This hypothesis was not accepted for the hip or the knee. Neither variable was significantly correlated with skating velocity, and no significant differences were found between the means of the levels.

CHAPTER V

DISCUSSION

The purpose of this study was to compare the skating movement pattern between skaters of novice, intermediate and elite ability levels. Specifically, the study compared measures of the skating step and the kinematic patterns of the hip, knee and ankle joints of the propulsive leg.

Each ability level was defined in terms of performance, (horizontal skating velocity), and highest level of ice hockey experience. Seventeen skaters, from an initial sample of 28 subjects, were used in the statistical analysis between the levels; five novice skaters and six in the intermediate and elite levels.

In this chapter, the results of the present study are discussed in relation to existing research and the significance of the results is examined.

5.1 Calculation of Step length

Evaluation of an individual's performance during bipedal locomotion requires an accurate method of measuring displacement during the basic cycle of movement. In ice skating, the basic unit of movement is the stride, a period encompassing the time between ipsilateral foot take-offs. With consideration given to the difficulty of recording a skating stride using a high speed camera under the poor light conditions available in arenas, most research on ice skating has focused on the step, which is the period between contralateral foot take-offs. Recording and analyzing one step allows an investigator to position the camera closer to the plane of action, ensuring a larger image of the skater for digitization.

Two methods have been used in the study of bipedal locomotion to measure the displacement of the subject during the step. One is to estimate the location of the subject's corporeal center of gravity for the frames in which consecutive contralateral foot take-offs occur, and then calculate the x-direction displacement. A simpler method has been to measure the distance between the toes of the take-off feet at consecutive contralateral foot take-offs; this method assumes a symmetrical body position at the toe-offs, such that a line drawn between the corporeal center of gravity and the toe marker of the take-off foot at the start of the step would be parallel to a similar line drawn at the end of the step.

In this study, paired t-tests were used to compare the two techniques. No significant difference was found between the means of the two methods for the group as a whole, as was reported previously by Marino(1974) for skating measures and Dillman(1970) for running measures, nor were the two techniques significantly different when compared between skaters of the same ability level. However, comparison of the two measures for individual subjects showed that step length was longer when calculated as the distance between the take-off toes for eleven subjects, for five subjects the center of gravity technique calculated a longer length, and in one subject the values were the same. Skating velocity is directly proportional to the length of the step, and any discrepancy in step length is magnified when it is multiplied by step rate to obtain average velocity. Although discrepancy between the methods was not significant when means were compared, the rank order of the subjects by skating velocity was dependent on the method utilized. If this study had used the distance between take-off toes as the measure of step length, different subjects would have been analyzed.

Whether the discrepancy in the methods of measuring step length is an artifact of the film analysis technique used in the study or whether it is a valid indicator of possible body position asymmetry at consecutive foot take-offs is not known. However, the results do indicate that the technique used to measure step length may indirectly determine which skaters are analyzed when subjects are selected on the basis of velocity.

5.2 Skating Velocity by Ability Level

Since skating velocity was used as one of the criteria for classifying subjects into novice, intermediate and elite levels, it was not surprising to find significant differences between the levels for maximal skating velocity. The mean velocity of the elite skaters in this study was 9.18 metres/second. This velocity was slightly higher than the mean velocity of 8.78 m/s reported for four "highly skilled" varsity hockey players by Marino(1975), and slightly lower than the average of 10.08 m/s.

for six fast adult skaters, including three professional players, reported by Page(1975).

The velocity range of intermediate skaters was more restricted by ability level definition than was that of the novice and the elite skaters, since an intermediate skater in this study had to have a velocity between the slowest elite skater and the fastest novice skater. The intermediate skaters average velocity of 8.28 m/s is similar to the 8.35 m/s average velocity of two intramural players in Page's study (1975), and slightly lower than the average velocity of 8.59 m/s reported by Hoshizaki et al(1982) for skaters from a higher level intramural team.

Very few studies have been conducted on novice skaters, and the few studies which have specifically studied skaters with limited years of skating experience have used children as subjects. Since step length is positively correlated to age (Marino,1984), and skating velocity is directly proportional to step length, inferring from children to adults can be both misleading and inaccurate. The novice skaters in this study were slower and had less years of skating experience than both the intermediate and the elite skaters, with a mean skating velocity of 6.94 m/second. This was slightly higher than the average maximal velocity of 6.91 m/second for ten skaters varying in ability from moderately low skilled to highly skilled, including five skaters rated above average in ability (Marino,1977).

Although there are not many skating studies to which velocity values can be compared, the few available are in agreement with the velocities of the present study as representative of novice, intermediate and elite skaters. Difficulty exists in comparing velocities between studies due to different techniques used to calculate velocity, and the failure of researchers to specify the exact location of the skater in relation to the starting line when velocity was calculated. Because of this latter oversight, it is impossible to know if the skaters were still accelerating from the start or were maintaining maximal velocity.

5.3 Biometric Data of the Skaters

The ability levels in this study were homogenous in regards to height and lower limb length, but the elite skaters had a greater mean mass and a younger mean age than either the intermediate or novice subjects. The greater mean mass for the elite skaters is similar to the findings of Shephard et al(1978) in a study of the anthropometric characteristics of elite pre-adolescent and adolescent hockey players. Shephard et al(1978) reported that elite 13 and 14 year old Bantam players were taller and heavier than the norms for their age group, while elite 15 and 16 year old Midget players were only heavier, not taller. Continued success and survival in elite hockey requires a stature capable of withstanding the extremely physical nature of the game, and the elite skaters in the present study indicate that the size differential continues through college hockey. Since there were no significant differences in height or lower limb length between the levels, it was not necessary to express step length relative to the skaters' stature. This would be necessary to compensate for any influence of anatomical differences on step length.

5.4 Step Parameters Between Ability Levels

Comparison of the variables step length, step rate, single support time and double support time between this study and previous studies is confounded by the oversight of some researchers to identify the location of the skater to the starting line when the variables were measured. As was previously mentioned in this chapter, in relation to the comparison of velocity measures, without this information it is possible to erroneously compare studies of accelerating skaters to studies of skaters maintaining maximal velocity.

In a study which analysed four skaters of varying ability who were accelerating from a stationary position, Marino(1979) reported that step time and both single and double support time increased in duration as the subjects skated away from the starting line. Marino reported that mean step time increased from .30 seconds on the first step (single support time=.26 seconds, double support time=.04 seconds) to .34 seconds on the third step (single support time=.29 seconds, double support time=.05 seconds). These values indicate a shorter double support time for skaters who were accelerating than were reported for the skaters in this study, while the single support times are quite similar. The temporal components of the step have not been studied over a sufficently long skating trial to precisely quantify the changes as transition from the acceleration phase to the maintenance of maximal velocity occurs. Lacking this quantification, comparison between the present study and studies not identifying the location of the skater at the time of analysis was done cautiously.

Of four skating studies at "maximal velocity" (Marino,1977; Marino & Weese,1979; Hoshizaki et al,1982; Marino,1984), only Hoshizaki et al(1982) and Marino(1984) identified the location of the filming area. Their step parameter values were similar to this study. Hoshizaki et al(1982) reported a mean step rate of 3.2 steps/second and a mean step length of 2.71 metres for a group of seven advanced intramural and varsity level skaters through the center ice circle. The step rate was slightly higher than the value of 3.13 steps/second reported for the varsity skaters in this study, while the step length was shorter than the 2.77 metre step length reported for the intermediate skaters, the lowest measured step length in this study. Marino(1984) reported the mean step rate and mean step length of skaters 8 to 15 years old by age; the means of step rate ranged from 2.95 to 3.1 steps/second, and the means for step length ranged from 1.54 to 2.37 metres. Marino's reported means for step rate are within the range of this study. The shorter stature of Marino's young subjects could account for a large part of the difference in step length.

In the two studies in which the filming location was not specified, there was a greater discrepancy between their reported values and the values for this study. Marino(1977) reported a mean step rate of 2.68 steps/second and a mean step length of 2.58 metres for 10 subjects of varying ability skating at maximal velocity. While the step rate was within the range of the present study, the step length was shorter than that of any ability level. It is possible that the shorter step length reported by Marino reflects an analysis of the skater at a point much closer to the starting point, before the step is elongated by the incorporation of the glide phase. The values reported by Marino & Weese(1979) for four elite skaters were a step rate of 3.54 steps/second and a step length of 2.48 metres. The much higher step rate and the much shorter step length than that of the elite skaters in this study lead one to conjecture that the skaters in Marino's study were filmed much closer to the starting line than were the skaters in this study, and might still have been utilizing the rapid stepping pattern characteristic of skating starts. The low mean step rate reported by Marino(1977) may reflect his collapsing across the subjects' ability levels, and/or the possible skewing of the mean by a deviant score.

From the results of this study,, it appears that the increased horizontal velocity of elite skaters is a manifestation of both more rapid and more effective propulsive leg action. Marino(1977) and Hoshizaki et al(1982) have indicated that an individual changes velocity, either voluntarily or involuntarily, through significant changes in step rate with no accompagnying significant change in step length. Both Marino(1977) and Hoshizaki et al(1982) indicated a significant positive correlation between step rate and skating velocity, and no significant correlation between skating velocity and step length. Data presented by Marino(1984) demonstrated that the higher skating velocity accompagnying increased age resulted from an elongation of the step rather than an increase in step rate. Step length and not step rate was significantly correlated with skating velocity among the young skaters in Marino's 1984 study.

In the present study, there was a significant difference in step rate between the novice skaters and both the intermediate and the elite skaters. The elite skaters step rate was higher than the intermediate skaters, although this difference was not significant. Step rate was positively correlated with skating velocity. There were no significant differences in step length between ability levels, and step length was not significantly correlated with skating velocity. There was no trend for an increasing step length with higher ability levels; the intermediate skaters had the shortest step length and the elite skaters the longest.

The temporal components of step rate, single and double support time, were not significantly different between the intermediate and the elite skaters, while both levels' support times were significantly shorter than those of the novice skaters. Significant differences in single and double support time have previously been reported with voluntary (Marino,1977) and involuntary (Hoshizaki et al,1982) changes in velocity. In the present study, correlation coefficents indicated significant negative correlations for both support periods with skating velocity. A higher correlation was found for double support time ($r=-.74$) than for single support time ($r=-.49$). Similar negative correlations, including the higher correlation between double support time and skating velocity, were reported by Marino(1977)

(SST: r=-.74; DST: r=-.80) and Hoshizaki et al(1982) (SST: r=-.43; DST=-.60).

In this study, the intermediate skaters showed a large relative variation in their time of single support; the mean single support time was .25 seconds with a standard deviation of .05 seconds. The standard deviation of the intermediate skaters was larger than that of the novice and elite skaters, which was .02 seconds for both levels, on mean single support times of .29 and .24 seconds, respectively. The large standard deviation of the intermediates could reflect a possible transition stage from the long single support time of a novice skater to the shorter single support time of an elite skater. This wide standard deviation indicates that some intermediate skaters had a low rate of leg recovery during single support, prolonging the single support time to a duration similar to that of the novice skaters, while others recovered their leg rapidly, reducing single support time to a duration equal to or shorter than the elite skaters. A theory that intermediate level performers have more variability in their performance was proposed by Bernstein(1967), in relation to intra-trial variation within a subject. His theory proposes that novice performers have not developed more than one basic motor pattern that they use in any circumstance, and execute with minimal variation, while elite performers have a "library" of motor patterns for performing a skill, from which they can select the most appropriate pattern for any given situation and complete with minimal variation. Intermediate performers have learned more than the one basic motor pattern of the novices, but have not yet mastered their repertoire to the extent that the elites have. Therefore, an intermediate can execute the skill with an intra-trial variation ranging from the poor level of the novice to the high level of the elite. An adaptation of this theory to entire skill levels would propose that the novice skaters show minimal inter-group variabilty from the poor performance, the elite skaters demonstrate minimal inter-group variability from high performance, and the intermediate skaters show a high inter-group variabilty, with performance ranging from low to high. That the variability was apparent in the more demanding period of single support could mean that this variability is more evident within the most demanding component of the skill.

It would be a gross oversimplification to state that the faster velocity of elite and intermediate skaters results simply from an increase in the rate at which skaters at these levels move their legs. To use these results as the basis for instructing a skater to simply increase step rate could be misleading. Such instruction might induce the skater to "run" on the ice, successfully increasing step rate but to the detriment of horizontal force production, with a probable reduction in step length. Only if the skater can maintain or increase step length would the higher rate be beneficial. The step lengths reported for the three skill levels in this study suggest that the intermediate and elite skaters differed in their ability to exert propulsive forces while using step rates greater than those of the novice skaters. Elite skaters had a step length longer than the novice skaters, but the step length of the intermediate skaters was shorter than that of the novice skaters. Step length in skating is affected by both the duration of the step, since the skater continues to glide on the nearly frictionless skate blade/ice surface interface, and by the effectiveness of the forces exerted during the step. Maintaining a long step length while increasing step rate depends on the skater's ability to produce a resultant propulsive impulse with a sufficent horizontal component. This depends on the skaters capability to optimize the range, the rate and the coordination of the extension pattern of the propulsive leg joints during the step.

None of the above referenced studies analyzed the kinematics of the propulsive leg. A purpose of this study was to compare the angular kinematics of the propulsive leg between novice, intermediate and elite ice skaters. The results of this analysis are discussed in the next section.

5.5 Leg Kinematics Between Ability Levels

As the previous discussion has indicated, it is difficult to evaluate skating technique simply on the basis of the temporal and spatial parameters of the step. Without actual quantification of the actions of the propulsive leg, which are responsible for the skating performance, interpretation of the step parameter data is limited to conjecture concerning the propulsive limb kinematic pattern.

In this study, measures were made of the displacement and angular velocity of the propulsive leg hip and knee, and of the sequencing of joint extension initiation and peak angular velocity during a complete left step. There are few studies in the literature to which the values calculated in this study can be compared. Only position and displacement measures can be compared, since no measures of power skater's angular velocity or joint action coordination were located.

Previous investigators have measured angles such as trunk lean and propulsive leg inclination at the start and end of a step (Page,1975; Marino,1984). These are not comparable to the angles measured in this study. In the appendix of his thesis, Page(1975) reported the angle of the thigh to the trunk, and the angle of the thigh to the horizontal at the start of a step. He also calculated knee displacement as the difference between the propulsive leg knee angle at a time "prior to thrusting" (his definition) and at take-off, the end of thrusting. Page's angles and displacements are not directly comparable to angles in the present study for two reasons. The first is that possible differences exist in the time at which the angles were measured. The joint angle at the initiation of extension was reported in this study, and it is not known how this differs from Page's definition of "prior to thrusting". If "prior to thrusting" was defined as at take-off of the contralateral leg, the angle would be slightly different from that calculated in this study. Several skaters in this study flexed their knee within the step, and the minimum angle prior to extension was measured at the end of this period of flexion. Secondly, the mean values reported by Page collapsed across the youth to adult age groups and the low to high ability range of his subjects, while subjects from a homogenous age group were used in the present study, and variable means were reported according to ability level.

Page(1975) reported a mean angle of 42.43 degrees for the trunk to the horizontal at take-off, and a mean angle of 161.71 degrees for the trunk to the thigh. The difference between these two angles is a measure of the thigh to the horizontal, which was measured as the hip angle in the present study. The difference in Page's angles was calculated by the present investigator as 119.28 degrees, greater than the mean minimal hip angle reported for any level in this study. However, the value calculated for Page's study is the difference between means of two angles, and not the difference between the two angles for each of the 14 subjects in his study. This might account for the difference between his study and the present study. The mean values are not so deviant as to question the validity of either measure.

A comparison of knee values is also possible, with consideration given to possible variations in measurement techniques. The mean angle of knee flexion "prior to thrusting" was 112.36 degrees in Page's study, which is within the range of 118.4 to 103.6 degrees from the novice to the elite skaters in the present study. The mean for the propulsive leg knee angle at take-off was 168.07 degrees in Page's study, slightly higher than the means in the present study, which ranged from 156.5 for the novices to 153.9 for the intermediates. Similarly, Page reported a mean knee displacement of 57.43 degrees, higher than the ranges of 38.1 degrees for the novice and 52.4 degrees for the elite groups in the present study.

This study went beyond measurement of the skaters' position at the start and end of a step in an attempt to identify differences in the dynamics of leg action among three distinct ability levels. Norman(1975) stated that existing coaching and research literature which describes only static positions of the skater can lead an individual to believe that the position is the cause of the poor skating performance, and not a reflection of it. Skating performance is affected by the dynamics of the propulsive limb, not only the range of motion at the hip, knee and ankle, but also by the rate and sequencing of the extensions. Variables quantifying each of these three biomechanical principles were measured in this study, and compared between novice, intermediate and elite ability levels.

5.5.1 Angular Displacement

Measures of the propulsive leg ankle were not compared between groups because the measure was possibly distorted by lateral rotation at the hip during the step. The lower limb was displaced laterally from the sagittal plane to such an extent that minimal ankle plantarflexion displacement was calculated off the film. Norman(1975) stated that one of the major errors limiting the skating performance of poor skaters was minimal ankle action. In the present study, calculated ankle plantarflexion displacement was greatest for the novice skaters. This finding is not only contrary to Norman's statement, but also to the subjective description of ankle action available in the general coaching literature. To obtain a true measure of ankle kinematics during the step requires the use of

3-dimensional filming techniques, to quantify plantarflexion occuring in the oblique plane as a result of hip lateral rotation.

Concerning the low ankle measures obtained, and the descending magnitude of plantarflexion displacement from novice to elite skaters, it could be postulated that these results possibly represent the magnitude of hip lateral rotation within the skating levels. Lateral hip rotation is utilized by skaters to obtain a greater skate blade/ice surface contact angle, facilitating the application of a horizontal propulsive force. If elite skaters laterally rotate at the hip to a greater degree than intermediate skaters, and intermediate skaters laterally rotate at the hip to a greater degree than novice skaters, then the order of the measured ankle displacements could be explained by the increased perspective error present in the measure of the elite and intermediate skaters. The ankle of the novice skaters, hardly displaced from the sagittal plane by lateral rotation, might in fact be a relatively accurate measure of their ankle displacement. This conjecture can only be substantiated through further analysis of the ankle, utilising 3-dimensional techniques.

The influence of hip lateral rotation on hip and knee measures does not appear to be as drastic as its affect on the ankle measure. Hip lateral rotation would not displace the hip or knee as far into the oblique plane as it did the ankle, minimizing hip and knee measurement error relative to that imposed on the ankle. Analysis of hip and knee displacement measures indicate that faster skaters utilized a greater range of motion at both joints. The greater ranges resulted primarily from a greater flexion of the joint prior to extension as opposed to a greater end of step extension. This observation is based on the results of the statistical analysis of the study. One-way ANOVAs across the ability levels and Tukey post hoc tests identified significant differences in hip and knee minimum angles prior to extension between the elite and novice skaters, and significant differences in knee displacement between the elite and novice skaters. There were no significant differences between any of the ability levels for hip and knee angles at left foot take-off. Pearson Product Moment correlation analysis identified significant negative correlations between hip and knee minimum angles prior to extension and skating velocity, and significant positive correlations between hip and knee displacement and skating velocity. Hip and knee angles at left foot take-off were not significantly correlated with skating velocity. Although the intermediate skaters' values for minimum angle prior to extension and displacement of both joints were not significantly different from either the elite or the novice skaters', their values were consistently between those of the high and low skilled levels. These consistent results indicate that range of joint displacement is a possible limiting factor to performance at all less skilled levels, not only at the novice level. The implication of this would be that there may be a developmental continuum for joint range of motion as an individual improves skating performance. Such a continuum has been proposed and partially validated in studies by Roberton and her colleagues analyzing the development of the mature overhand throwing pattern. (Roberton,1980a; Roberton,1980b; Roberton et al,1980). Their "component model" of skill development proposes that the mature range of motion develops independently at each joint, but that the action at each joint develops in an intransitive order from the immature to the mature pattern. Their proposed developmental sequence for throwing provides coaches and teachers with a scientific basis for more effective pedagogical intervention, based on the performers position on the continuum. In the present study, the intermediate skaters had a mean hip minimum angle prior to extension and a mean hip displacement value closer to the elite skaters mean value than to the novice skaters mean value, and a mean knee minimum angle prior to extension and a mean knee displacement value closer to the novice skaters than to the elite skaters. These results could reflect a sequential development of the mature range of motion that occurs independently at the two joints as the skaters aquire the mature pattern. A conclusion as to the validity of this interpretation is well beyond the scope of this study, but the results do suggest that attempting to identify and quantify developmental sequences at the joints of the propulsive leg might be a viable focus of future research.

None of the levels exhibited full knee extension at left foot take-off. The highest knee extension angle was the novice skaters' mean of 156.5 degrees. While incomplete knee extension at the end of the running step has previously been reported for both elite and good runners (Cavanagh et al,1977), Norman(1975) stated that poor skaters do not extend the knee as completely as skilled skaters, and coaching literature proposes full knee extension as a indicator of good technique (Holt,1977; Watt,1975: Can-Am Group,1973). The similar knee angle for the three groups could be a manifestation of hip lateral rotation, with the rotation reducing the measured angle of the elite and intermediate skaters to an angle similar to that of the novice skaters. While all three groups displaced the knee through the maximal power range of 130-155 degrees (Holt,1977), the take-off angle of approximately 155 degrees for all groups, and the tendency for skaters from all ability levels to be flexing the knee at left foot take-off, would mean that the skaters were decelerating the extension near the end of the power range, with minimal follow through. Such a deceleration would restrict the skaters from optimizing the magnitude of the propulsive force created, and would not be compatible with effective performance. To obtain a more complete understanding of the displacement of the knee necessitates the use of 3-dimensional cinematographical techniques in future studies. Such an analysis would allow the quantification of knee extension as the knee displaces into the oblique plane, and perhaps would identify a greater angle of knee extension by the higher skilled skaters as proposed in the coaching literature.

5.5.2 Angular Velocity

The angular velocity of the propulsive leg hip and knee extension was quantified by two variables in this study: 1) average angular velocity during the step, and 2) peak instantaneous angular velocity within the step. Significantly higher hip average and hip peak instantaneous angular velocites were measured for the elite and intermediate skaters than for the novice skaters. There was no significant difference between the elite and intermediate skaters, although the elite skaters did have higher mean values on both variables. The intermediate skaters' mean value for both average and peak instantaneous angular velocity was closer to the value of the elite skaters than to the value of the novice skaters. Pearson Correlation analysis indicated significant positive correlations between skating velocity and both hip average and hip peak instantaneous angular velocity. A similar trend for higher values with higher skill levels was evident in the means for knee average and knee peak instantaneous angular velocity, although none of the group means were significantly different. The trend in the means was supported by positive correlations between the two variables and skating velocity.

The trend for higher angular velocity at the hip and knee joints with higher skating ability was also evident in the plotted curves of joint angular velocity over time. (Figures 2, 3 and 4). The curves indicate that skaters within each level were extending both their hip and knee in the early stage of single support, even before the corporeal center of gravity was ahead of the support foot. A striking difference in the angular velocity curves between the three ability levels was the rate of acceleration in hip and knee angular velocity once the center of gravity was ahead of the support foot. The angular velocity curve of the elite skaters exhibited a rapid angular acceleration once the center of gravity was ahead of the support foot; the slope in the angular velocity curve was less for the intermediate skaters, and less still for the novice skaters.

Extension of the joints prior to the center of gravity coming ahead of the support foot probably reflects movements by the skater to set the blades of the skate to create a propulsive angle with the ice. If the skate blade was set during hip and knee extension before the center of gravity was ahead of the support foot, the resultant action of these extensions would be to decelerate the skater's horizontal velocity and/or accelerate the skater's vertical velocity. Both of these results would be contraindicating to efficent skating performance, suggesting that the extension is used to set the blade. A more complete examination of the dynamics of leg action during the early period of single support, including measures of lateral hip rotation, is needed to fully explain the purpose of this early extension.

A higher rate of angular velocity with higher levels of skating ability reflects the trend to greater angular displacement of the joints by the better skaters and their shorter step time, and is indicative of more powerful torques applied at the joints by the more skilled skaters. This powerful torque is dependent on the skaters dynamic leg strength, since muscular force provides the motive force. Dynamic leg extensor strength is influenced by both the mass of the extensor muscles and the maturity of the motor pattern for leg extension. It is possible that differences in both strength and motor patterning are responsible for the observed differences in angular velocity between the ability levels in this study. This explanation is drawn from the biometric data describing the skaters and the difference in their hockey and years of skating experience.

The mean group values for height and mass presented in Table

4 show all three groups were approximately 1.75 metres tall, but the elite skaters had an average mass about 11 kilograms greater than both the intermediate and novice skaters. Shephard et al(1978) have presented data showing that elite adolescent ice hockey players were heavier than norms for their age group, and that elites were also stronger on measures of grip strength. Although no measure was made of body composition in the present study, it is reasonable to assume that the greater body mass of the elite skaters reflects greater muscle mass, considering the physical demands of intercollegiate hockey and the extensive training program the varsity players follow. As a result of the greater muscle mass the elite skaters would be stronger than the intermediate and novice skaters.

The motor pattern of the skill refers to the recruitment and coordination of muscular activity to perform a skill (Wickstrom,1982). Since the efficacy of a motor pattern can be improved through repeated practice, it is conceivable that the ability levels with more years of skating experience would have more effective motor patterns. The elite skaters in this study had extensive experience at a high level of hockey, and had an average of 17.5 years of skating experience. Intermediate skaters had not had the same exposure to high levels of ice hockey, and had an average of 12.5 years of skating experience. The novice skaters were all participants in an introduction to ice hockey program with no previous experience at the sport, and had an average of 1.6 years skating experience. These means representing years skating experience are of interest when compared to a study investigating when skating becomes automated to the point that it no longer requires conscious control. Based on a cross-sectional study of skaters aged 6 to 20 years old, Leavitt(1979) reported that after 8 years of hockey experience, subjects had developed their skating pattern to a level such that successful performance no longer required conscious attention to the task. Leavitt's results, and the mean years of skating experience of the groups in this study, suggest that the mature pattern would be present at both the intermediate and elite levels, but not at the novice level.

The evidence suggesting both greater muscle mass and advanced motor pattern development provides a reasonable explanation for the reported differences in angular velocity. The elite skaters significantly higher angular velocity than the novice skaters would result from both their greater muscle mass and their more mature motor pattern, while the non-significant higher mean values of the elites to the intermediates could be attributed to the elite skaters' greater strength. The higher angular velocities of the intermediates to the novices would be explained by the more mature motor pattern of the intermediate skaters.

The validity of this explanation requires further research, since there is a paucity of research defining the mature motor pattern of skating, as has been previously outlined, and also investigating the relationship of leg strength to skating. The few strength and skating studies in the published literature include: the correlation of isometric leg strength of varsity hockey players to their skating acceleration (Song & Reid,1979), which did not identify any significant correlations between extensor strength and speed; a comparison of the effects of leg presses, resistance skating and skating instruction on skating speed of varsity hockey players (Hollering et al,1977), which did not find any significant improvements in performance as a result of the training programs; and the correlation of isokinetic hip and knee extensor peak torques to the coach's subjective evaluation of the speed of players on a professional hockey team (Minkoff,1982), which reported significant correlations between peak knee extensor torque and skating speed. Additional research utilizing subjects of different ability levels and isokinetic testing of lower limb extensor groups at angular velocities within the range reported in this study has the potential to provide a greater understanding of the influence of strength on skating speed.

5.5.3 Coordination of Extension

Coordination of the skaters' leg action in this study was quantified as the percent of total step time to initiation of hip and knee extension (2 variables), and the percent of total step time to peak hip and knee instantaneous angular velocity (2 variables). No significant differences were found on these variables.

The validity of measuring the initial extension movements at the joints as an indicator of motor pattern coordination is doubtful as a result of information provided by this study. When these variables were formulated, it was assumed by the investigator that action of the propulsive leg hip and knee during early single support would be characterised by flexion as the leg absorbed the transfer of corporeal body weight, and that extension would not commence until later in the single support period, after the center of gravity was anterior to the support foot. This assumption was based on a subjective evaluation by Marino & Weese(1979) that the horizontal acceleration of the corporeal center of gravity, which commenced approximately half-way through the single support period, coincided with the initial extension movements of the hip and knee. The purpose of these variables in the present study was to compare the percent of total step time between the start of single support and the initiation of propulsive force production, to determine if there was a difference among the three ability levels. However, analysis of the angular velocity values and graphical presentation of the values showed that the majority of the skaters started hip and knee extension much earlier in the step than was anticipated. Previously in this chapter, the purpose of the initial hip and knee extension was explained as movements to set the skate blade and create a suitable ice surface/skate blade interface against which force could be applied. Thus, as a measure of the initiation of propulsive force producing extension movements, these variables are not appropriate.

Graphical presentation of the angular velocity values showed an interesting feature of leg action that was not quantified in this study. The onset of the rapid increase in angular velocity for the elite skaters occurred close to the mid-point of the single support period, just after the center of gravity was first located ahead of the support foot. This timing of rapid acceleration is in agreement with curves of the corporeal center of gravity acceleration within the step presented by Marino &

Weese(1979), which showed positive acceleration of the skater commencing near the mid-point of single support. Hip and knee angular velocity curves of the intermediate and novice skaters showed a similar acceleration once the center of gravity was ahead of the support foot, although the magnitude of the acceleration was not as high.

There is some evidence to indicate that the relative duration of the swing and stance phases in walking, running and stepping in place do not change as the velocity or tempo of execution is increased (Shapiro et al,1981; Dickinson et al,1984) The authors have suggested that these skills maintain a consistent phasing with changes in speed, and that only the absolute time of the phases changes, not the relative timing. The results of the present study may reflect an invariant phasing in the recovery and propulsion phases within skating, that is evident in the motor pattern of skaters of all ability levels. Improvements in balance, strength and the motor pattern may increase the rate at which the skill is executed, decreasing the absolute time for each phase, while the relative phasing of the skill remains constant.

The variable percent step time to peak joint angular velocity was intended to quantify the coordination of the most rapid periods of joint extension by the skaters. The lack of significant differences between the groups on either the hip or the knee measures, and the lack of a significant trend in the means, is reflective of the variability in the timing both within and between the levels. The mean time for all three levels on percent time to hip peak angular velocity was within the range of

86-89%, and had a standard deviation of approximately 5%. The novice skaters had a time to knee peak angular velocity equal to 78% of their step, while the elite and intermediate skaters had respective means of 85 and 86%, closer to their hip values. All levels tended to reach peak knee velocity before peak hip velocity, and the peak hip velocity was higher. While these results could be interpreted as indicative of no difference in the coordination of joint movements between the levels, more research is needed before this conclusion can be drawn. This variable measures only one simple aspect of the complex coordination of the leg actions within a step, and a much closer examination of the timing is warranted. There is very little research available, in any locomotory skill, describing the coordination of propulsive leg joint extensions. In throwing or striking activities, the extension of joints in a proximal to distal sequence produces optimal velocity at the distal segment at time of release or contact. How the propulsive limb joints are sequenced as the body rotates over the support foot prior to extension, and how the segments are extended to accelerate the body, is a complex question that has important ramifications in teaching skills to novice performers and in optimizing the performance of elite performers. This aspect of skill performance deserves much more detailed study.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Most of the previous research on power skating has investigated the relationship among the basic parameters of the skating step, step length and step rate, and the temporal components of step rate, single support time and double support time, as skating velocity is changed. Some of these studies have measured body position at certain points in the step, but such studies have not provided an understanding of the kinematics of the propulsive leg during the step. Minimal angular displacement, reduced angular velocity and poor coordination of the joints of the propulsive leg have been identified as the probable sources of poor skating performance. The purpose of the present study was to compare the basic parameters of the step, and the kinematics of the propulsive leg, between skaters of novice, intermediate and elite ability levels. It was hypothesized that there would be an increase in step length and step rate, and a decrease in single and double support time with higher ability. It was also hypothesized that the higher ability levels would show a greater displacement and a higher angular velocity at the hip, knee and ankle joints, and that they would initiate joint extension and reach peak angular velocity at each of the joints earlier in the step relative to total step time.

6.1 Summary of Procedures

A subject's classification to one of the ability levels was made first on the basis of highest level of ice hockey experience, and then on skating velocity. The five subjects in the novice level were participants in an Introduction to Ice Hockey course, the fifteen intermediate subjects were members of an intramural ice hockey team, and the eight elite skaters were members of a varsity hockey club. Preliminary screening of the skaters was accomplished by timing them as they skated between the blue lines on the ice. Six intermediate skaters were excluded from the filming session, and further analysis, based on their skating time.

Each remaining subject performed three trials of skating from a goal line to the blue line at the opposite end of the ice surface, and were filmed at 100 fps as they skated through the center ice circle at maximum velocity. From the filmed recording of the trial, one trial was selected for analysis based on the criterion that a complete right step, from take-off of the right foot to take-off of the left foot, occurred in the middle of the film frame. Step length and step rate were measured from the film, and skating velocity was calculated as the product of these two variables. Further subject selection was made on the basis of calculated velocity, such that no skater had a velocity overlapping into an adjacent ability level. After this selection process, there were 5 intermediate subjects, and six in each of the intermediate and elite ability levels. Further analysis of the film recordings of these skaters provided the following dependent variables to test the hypotheses of the study:

Parameters of the Step:

step length
step rate
:single support time
:double support time

Propulsive Leg Kinematics:

angular displacement
:minimum angle prior to extension
:angle at left foot take-off
average angular velocity
peak instantaneous angular velocity
percent step time to minimum angle
percent step time to peak angular velocity

These measures were made at the hip, knee and ankle.

The data for each dependent variable were then subjected to one-way analysis of variance for unequal cell size to determine significant differences among the levels. Tukey post hoc tests, modified for unequal cell size, were used to identify which levels were significantly different. Pearson Product Moment correlation analysis was used to determine the association between each of the dependent variables and skating velocity.

6.2 Summary of Results

The statistical analysis revealed the following results related to the hypotheses of the study:

1) There was a trend for increasing step rate with higher ability, and a significant difference was found between the step rates of the elite and novice skaters. A significant positive correlation was reported for step rate and skating velocity. There was no significant difference in step length, nor was it significantly correlated with skating velocity.
2) The double support time of both the elite and intermediate skaters was significantly shorter than that of the novice skaters. No groups were significantly different for single support time. Both single and double support time were negatively correlated with skating velocity.
3) Perspective error, possibly resulting from lateral hip rotation of the propulsive leg, prevented comparison of ankle measures between the levels of skating ability.
4) A mean trend was evident for increased hip displacement by skaters of the higher ability levels. Although there were no significant differences among ability levels for hip displacement, hip displacement was positively correlated with skating velocity. Knee displacement means indicated a trend for increased knee displacement with higher ability, and the elite skaters' displacement was significantly greater than the novices'. Knee displacement was positively correlated with skating velocity.

5) The elite and intermediate levels had significantly higher hip average angular velocities and significantly higher peak instantaneous hip angular velocities than the novice skaters. Both hip variables were positively correlated with skating velocity. There was a mean trend for increased knee average, and knee peak, instantaneous angular velocities with higher ability levels, but no means were significantly different. Both knee variables were positively correlated with skating velocity.
6) There were no significant differences among ability levels, and no mean trend was evident, for decreased percent step time to initiation of hip and knee extension. Neither variable was significantly correlated to skating velocity.
7) There were no significant differences among ability levels, and no mean trend was evident, for decreased percent step time to peak instantaneous angular velocity for either the hip or knee. Neither variable was significantly correlated to skating velocity.

6.3 Conclusions

Based upon the results of the study, certain conclusions can be drawn. The limitations, delimitations and methodology of the study should be considered when interpreting the following conclusions.

1) Skilled skating performance is characterised by higher step rates and shorter double support periods.
2) Skilled skating performance is not characterised by a longer step length.
3) Skilled skaters extend their hip and knee through a greater range of motion during a step than less-skilled skaters. The increased range results from greater joint flexion prior to extension.
4) Skilled skaters extend their hip and knee at a higher average angular velocity, and they attain higher peak instantaneous angular velocity during a step, than less-skilled skaters.
5) It is inconclusive whether differences exist in the coordination of hip and knee extension between skilled and unskilled skaters.

6.4 Implications of the Study

Hockey coaches and skating instructors must evaluate skating technique based on more than the body position of the skater at the start and end of the step. They must learn to qualify not just the displacement which occurs at the joints, but more importantly the rate at which the skater extends the joints, since this reflects both motor patterning and dynamic strength. Coaches must also evaluate skating technique from the front or rear as well as from the side, to qualify hip lateral rotation. The hip and knee action of the skater should be evaluated independently, since it is possible that the mature pattern of skating does not develop simultaneously at both joints.

6.5 Recommendations for Further Research

Based on the results of this study, it is the investigator's recommendation that future studies of skating incorporate 3-dimensional cinematographical procedures to quantify the magnitude of hip lateral rotation and abduction, and their effects on hip, knee and ankle flexion and extension.

Future research should also evaluate differences in the magnitude of intra-individual variability across trials by skaters of different ability levels, and the magnitude of the inter-individual variability present among skaters of the same ability level.

A more complete study of the differences in skating requires that analysis go beyond the comparative statistical approach of the present study. More subjects from each level should be analyzed, and the techniques of multiple regression or discriminant analysis should be utilized to accurately identify how the variables influence performance.

Valid tests of dynamic strength specific to skating are needed to determine the influence of strength on skating performance.

Variables appropriate for quantifying the coordination of lower limb joint action during locomotion must be developed. Without such variables, comparative studies of different skill levels is severely restricted in terms of providing useful insight to proper performance.

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APPENDICES

APPENDIX A

McGill University

Faculty of Graduate Studies and Research
Dawson Hall

CERTIFICATION OF ETHICAL ACCEPTABILITY FOR RESEARCH INVOLVING HUMAN SUBJECTS

A review committee consisting of:

Name	Field of Research
[illegible]	
[illegible]	[illegible]
[illegible]	Secondary Education
[illegible]	Elementary Education

has examined the application for funds in support of a project titled:

A biomechanical comparison of beginner intermediate and elite ice skaters

As proposed by Steven T. McCaw (Applicant) to ______ (Granting agency, if any)

and consider the experimental procedures, as outlined by the applicant, to be acceptable on ethical grounds for research involving human subjects.

[illegible]

March 2, 1983 — John R. Wolforth

Date — Director of Graduate Studies in Education

Ethical review committees are to be convened by the Head of the Department, or Administrative Unit, in which the proposed research is to be done and are to consist of a representative appointed by the Dean, two individuals knowledgeable in the field of the proposed research but not associated with the proposed project and preferably not from the department in which the project is to be carried out, and one or more individuals who would represent a general point of view. The applicant should not serve on the Committee nor should he sign on behalf of the department or the faculty.

APPENDIX B

Informed Consent Form

Name:(print)______________________________

The study you will participate in is designed to compare the movement pattern of skaters of different ability levels. You will be asked to perform 3 skating trials, at full speed, from one goal line to the other goal line of the McGill Winter Stadium, wearing only your skates and shorts, and with contrasting markers placed over specific bony landmarks on your body. During these trials, you will be filmed with a high speed camera, which will allow me to analyze your skating performance and compare it to skaters of different ability levels.

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, can ask to have your filmed trials destroyed before analysis, or may have your results withdrawn from the comparisons.

It will be possible for you to see the filmed recording of your trials, and to receive an analysis of your skating technique once the study 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 C

Modification of Dempster's Model to Incorporate Skate Mass

Segment	% TBM[1]	Segment mass[2]	Segment Mass, skate added[3]	Modified % TBM[4]
Rt Upper Arm	2.77	1.75	nc	2.71
Lt Upper Arm	2.63	1.66	nc	2.57
Rt FArm/Hand	2.30	1.45	nc	2.25
Lt FArm/Hand	2.22	1.40	nc	2.17
Rt Thigh	9.86	6.22	nc	9.63
Lt Thigh	9.95	6.27	nc	9.71
Rt Shank	4.69	2.96	nc	4.58
Lt Shank	4.68	2.95	nc	4.57
Rt Foot	1.42	.89	1.80	2.78
Lt Foot	1.49	.94	1.85	2.86
Tnk/Hd/Nk	57.99	36.56	nc	56.61
Total	100.00	62.76	64.58	100.40

Legend

nc = no change

[1] % Total Body Mass, from Dempster (1955)

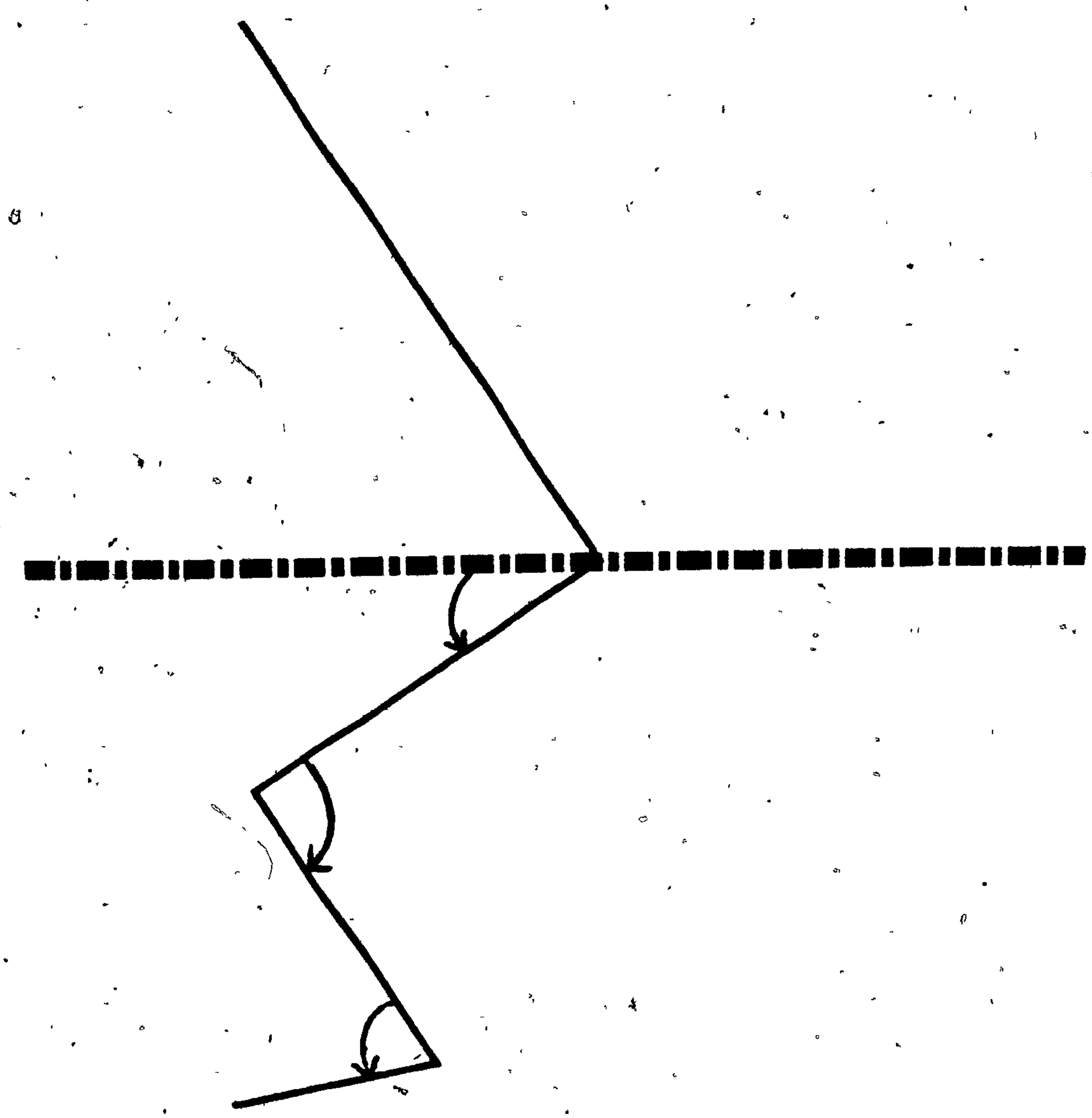
[2] based on a 63 kg skater; rounding errors account for the discrepancy in total mass of segments

[3] Effect on segment mass of a 63 kg skater when a pair of size 6.5 CCM Tack skates are worn (leather boot, steel blade)

[4] Modified % TBM = $\frac{\text{mass, skate added}}{64.58}$

APPENDIX D

Diagram of the Calculated Body Angles



Note: Direction of Arrow Indicates Extension

APPENDIX E

Comparison of Two Methods of Calculating Step Length

Ability Level	ID#	---Step Length--- c of g	toe diff	Step Rate	----Velocity----- c of g	toe diff
N	15	2.89	2.96	2.17	6.27	6.42
N	14	2.95	3.14	2.17	6.41	6.81
N	7	2.59	2.49	2.50	6.47	6.23
N	5	3.02	3.05	2.56	7.75	7.81
N	12	3.12	3.27	2.50	7.81	8.18
I	6	2.62	2.87	3.03	7.93	8.70
I	10	3.06	3.16	2.70	8.28	8.53
I	11	2.24	2.09	3.70	8.29	7.73
I	19	2.84	2.95	2.94	8.36	8.67
I	1	2.51	2.37	3.33	8.38	7.89
I	20	3.36	3.20	2.50	8.42	8.00
I	2*	2.33	2.40	3.88	9.02	9.31
I	4*	2.44	2.22	3.85	9.39	8.55
E	18*	2.99	3.23	2.78	8.31	8.97
E	16*	2.68	2.70	3.13	8.39	8.45
E	9	3.13	3.14	2.78	8.68	8.72
E	21	2.61	2.49	3.33	8.69	8.29
E	17	2.78	2.81	3.23	8.98	9.08
E	22	2.98	3.12	3.13	9.32	9.76
E	13	3.29	3.29	2.86	9.40	9.40
E	8	2.90	3.08	3.45	10.01	10.63

Note: underlined step length is skater's longest

N= novice I= intermediate E= elite

* Indicates subjects dropped from the study on the basis of skating velocity calculated with the c of g step length

c of g = center of gravity   toe diff = difference in toe markers

APPENDIX F

Biometric Characteristics of the Subjects (n=17)

Ability Level	ID#	Age (years)	Height (cms)	Lower Limb Length (cms)	Mass (kg)
N	15	21	174.5	88.0	64.4
N	14	26	177.0	89.5	72.6
N	7	26	170.5	90.0	56.7
N	5	23	173.0	89.0	65.8
N	12	26	191.0	102.0	81.7
I	6	26	174.5	91.5	69.0
I	10	32	177.0	92.0	73.0
I	11	2[illegible]	167.5	85.0	62.2
I	19	22	167.5	85.0	62.2
I	1	22	185.0	97.0	81.7
I	20	24	177.0	93.0	67.1
E	9	22	174.0	90.0	81.2
E	21	21	177.0	92.0	82.6
E	17	21	169.0	86.0	80.3
E	22	22	176.0	91.0	84.4
E	13	23	176.0	94.0	76.7
E	8	21	179.0	96.0	76.7

N= novice I= intermediate E= elite

APPENDIX G

Complete ANOVA Tables for Skating Velocity and Parameters of the Skating Step

Variable: SKATING VELOCITY

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	13.69	6.84	25.27	.0001
Within	14	3.79	0.27		
Total	16	17.48			

Tukey Critical Range: .666

Variable: STEP LENGTH

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	0.10	0.05	0.56	.5854
Within	14	1.28	0.09		
Total	16				

Variable: STEP RATE

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	1.75	0.88	8.51	.0038
Within	14	1.44	0.10		
Total	16	3.19			

Tukey Critical Range: .411

Appendix G, cont'd.

Variable: SINGLE SUPPORT TIME

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	0.007	0.003	3.36	.0642
Within	14	0.016	0.001		
Total	16	0.024			

Variable: DOUBLE SUPPORT TIME

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	0.008	0.004	6.74	.0089
Within	14	0.008	0.001		
Total	16	0.016			

Tukey Critical Range: .032

APPENDIX H

Angular Kinematics of the Propulsive Leg Ankle
(Mean ± standard deviation)

Level	Min θ	TOL θ	Δθ	Time Min θ	% ToS Min	$\bar{\omega}$	Time Peak ω	% ToS Peak	Peak ω
N	64.0	83.67	19.7	.28	67	2.81	.38	91	4.57
(n=5)	5.1	4.8	7.3	.04	11	1.48	.04	9	2.07
I	60.8	79.1	18.3	.24	71	3.40	.33	98	6.16
(n=6)	3.8	7.6	8.8	.05	8	1.78	.05	4	2.98
E	57.0	72.1	15.0	.22	70	2.70	.31	96	4.19
(n=6)	3.6	3.4	4.3	.03	5	.61	.03	5	1.24

Legend

- Min θ : Minimum ankle angle prior to extension, in degrees
- TOL θ : Ankle angle at left foot take-off, in degrees
- Δθ : Ankle displacement during the step, in degrees
- Time Min θ : Time to minimum ankle angle from take-off right, in seconds
- % ToS Min θ : Time Min θ, expressed as % of total step time
- $\bar{\omega}$: Average ankle angular velocity during the step, in radians per second
- Time Peak ω : Time to ankle peak instantaneous angular velocity from take-off right, in seconds
- % ToS Peak : Time to peak ω, expressed as % of total step time
- Peak ω : Ankle peak instantaneous angular velocity, in radians per second

Note: no statistical means comparison was conducted on ankle measures

APPENDIX I

Complete ANOVA Tables for Propulsive Leg Kinematics

Tables are included for the following measures of the left leg hip and knee:

- Minimum angle prior to extension
- Angle at take-off left
- Angular displacement
- Time to minimum angle prior to extension
- Percent step time to minimum angle
- Average angular velocity
- Time to peak instantaneous angular velocity
- Percent step time to peak instantaneous angular velocity
- Peak Instantanous angular velocity

Appendix I, cont'd

HIP MEASURES

Variable: MINIMUM HIP ANGLE PRIOR TO EXTENSION

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	290.24	145.12	6.15	.0121
Within	14	330.22	23.59		
Total	16	620.46			

Tukey Critical Range: 6.22

Variable: HIP ANGLE AT LEFT FOOT TAKE-OFF

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	46.50	23.25	0.48	.6267
Within	14	673.66	48.12		
Total	16	720.16			

Variable: HIP DISPLACEMENT

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	446.60	223.30	3.45	.0605
Within	14	906.14	64.72		
Total	16	1352.74			

Appendix I, cont'd

Variable: TIME TO MINIMUM HIP ANGLE PRIOR TO EXTENSION

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	0.0012	0.0006	1.08	.3675
Within	14	0.0076	0.0005		
Total	16	0.0088			

Variable: PERCENT STEP TIME TO HIP MINIMUM ANGLE

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	0.0056	0.0028	0.90	.4284
Within	14	0.0438	0.0031		
Total	16	0.0494			

Variable: HIP AVERAGE ANGULAR VELOCITY

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	5.794	2.897	8.72	.0035
Within	14	4.653	0.332		
Total	16	10.446			

Tukey Critical Range: .738

Appendix I, cont'd

Variable: TIME TO PEAK HIP INSTANTANEOUS ANGULAR VELOCITY

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	0.026	0.013	6.62	.0095
Within	14	0.027	0.002		
Total	16	0.053			

Tukey Critical Range: .057

Variable: PERCENT STEP TIME TO PEAK HIP INSTANTANEOUS ANGULAR VELOCITY

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	0.000	0.000	0.35	.7122
Within	14	0.000	0.000		
Total	16	0.000			

Variable: PEAK INSTANTANEOUS HIP ANGULAR VELOCITY

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	24.779	12.390	10.19	.0019
Within	14	17.028	1.216		
Total	16	41.807			

Tukey Critical Range: 1.412

Appendix I, cont'd

KNEE MEASURES

Variable: MINIMUM KNEE ANGLE PRIOR TO EXTENSION

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	667.48	333.74	4.49	.0312
Within	14	1041.12	74.36		
Total	16	1708.60			

Tukey Critical Range: 11.04

Variable: KNEE ANGLE AT LEFT FOOT TAKE-OFF

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	22.275	11.137	0.24	.7876
Within	14	642.148	45.868		
Total	16	664.423			

Variable: KNEE DISPLACEMENT

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	731.06	365.53	2.34	.1325
Within	14	2183.98	156.00		
Total	16	2915.04			

Appendix I, cont'd

Variable: TIME TO MINIMUM KNEE ANGLE

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	0.017	0.008	1.05	.3767
Within	14	0.113	0.008		
Total	16	0.130			

Variable: PERCENT STEP TIME TO KNEE MINIMUM ANGLE

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	0.054	0.027	0.43	.6572
Within	14	0.867	0.062		
Total	16	0.920			

Variable: AVERAGE KNEE ANGULAR VELOCITY

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	3.722	1.861	1.27	.3121
Within	14	20.560	1.469		
Total	16	24.282			

Appendix I, cont'd

Variable: TIME TO KNEE PEAK INSTANTANEOUS ANGULAR VELOCITY

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	0.0097	0.0049	2.00	.1717
Within	14	0.0339	0.0024		
Total	16	0.0436			

Variable: PERCENT STEP TIME TO KNEE PEAK INSTANTANEOUS ANGULAR VELOCITY

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	0.018	0.009	2.36	.1313
Within	14	0.052	0.004		
Total	16	0.070			

Variable: PEAK KNEE INSTANTANEOUS ANGULAR VELOCITY

Source of Variance	df	Sum of Squares	Mean Square	F Ratio	p
Between	2	20.09	10.05	3.4	.0628
Within	14	41.41	2.96		
Total	16	61.50			