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THE EFFECTS OF FATIGUE ON THE MECHANICS OF FORWARD MAXIMUM VELOCITY POWER SKATING IN SKILLED AND LESS-SKILLED SKATERS

by

Dan Drouin

A thesis submitted to the College of Graduate Studies and Research through the Department of Kinesiology in Partial Fulfilment of the requirements of the Degree of Master of Human Kinetics at the University of Windsor

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Abstract

The effects of fatigue on the mechanics of forward maximum velocity power skating in skilled and less-skilled skaters

To compare the effects of fatigue on the mechanics of maximum velocity power skating, 16 subjects (eight skilled, six less-skilled) were videotaped using two cameras while subjects performed a maximum exertion test covering 380 metres. Subjects were assigned to the skilled or less-skilled group based on their individual task times. Mean task times were 57.09 seconds for the skilled group and 63.12 seconds for the less-skilled group. The task required subjects to start, skate forward, and stop. Subjects were videotaped over three trials. The two views for each trial were digitized and transformed into one three-dimensional view via a human motion analysis program. Analyses of variance tests were conducted for each dependent variable to indicate differences in the skating mechanics between skaters of different skill levels and changes that occurred due to fatigue.

Few differences were found between the skilled and less-skilled group. At touchdown, the skilled skaters had their centres of gravity closer to the toe of the support leg. Skilled skaters had the knee of their support leg further ahead of the toe of their support leg at touchdown relative to the unskilled group members. Trunk lean at takeoff and mean trunk angle was greater for skilled skaters during the skating stride.
Several changes in the mechanics of the skating pattern occurred with fatigue. Single and double support time increased with fatigue which resulted in a decrease in the rate of striding. The decrease in horizontal skating velocity with fatigue was attributed to the decrease in stride rate as stride length did not decrease over the three trials. The majority of the skating stride was found to be spent in single support. Fatigue affected the skating stride in a beneficial manner as the centre of gravity of the body at touchdown was closer to the toe of the support leg during fatigue. Decreased displacement of the knee of the propulsive leg was noted during fatigue and resulted from a decrease in the degree of knee bend at touchdown. With fatigue, thigh abduction and extension decreased as the leg is more upright. This was attributed to fatigue of the leg musculature. Angular velocity of the thigh and shank decreased with the onset of fatigue.
Dedication

This paper is dedicated to my family and my new wife. To my mom and dad, I thank you for standing behind me throughout my academic career and believing in my abilities. Thank you for all your support and patience, especially over the past few years. To my sister and brother, Dana and Darren, I thank you for the encouragement you have given me. To my new wife Kim, this paper would not have been possible without your constant support and encouragement. I love you all.
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CHAPTER 1: Introduction

Biomechanists focus research efforts on aspects of a specific movement pattern that are critical to successful performance. Identifying factors that are common among elite athletes enables the researcher to make recommendations for coaches of the skill as to what should be taught to developing players. By analysing elite athlete’s performance of a skill and comparing it to lesser skilled athletes, these pertinent mechanical differences can be identified. It is to be expected that differences in the performance of a skill will occur when several athletes of the same skill level are analysed. However, by observing the common changes in a group of equally skilled athletes, useful information about the general mechanics of a particular movement may be found (Chapman, 1982).

Differences occur in performance techniques when comparing skaters of different abilities. This research involved two groups of skaters being analysed to identify pertinent mechanics of skilled skaters and show how they differ from lesser skilled players through analysis of a number of kinematic variables.

Individuals who teach and correct a sport skill should understand how the correct movement is executed. To accomplish this, coaches need to know what aspects of the movement to analyse. Kostka et al. (1979) suggested that it is essential for a coach to ensure precision in their analysis of a player’s skating technique and to provide the player with a correct analysis of their performance. This is accomplished by breaking down the movement into its components. Kostka et al. (1979) stated that skating is the basis of all hockey development for both skilled and less-skilled skaters and it is essential to develop and practice the correct
technique. Hull (1976) suggested that every hockey player has their own style of skating. When teaching skating, Hull (1976) suggested giving the skater the mechanical requirements of the skill while allowing the skater to adapt these to their own particular body build and movement pattern. Tarasov (1973) supported Hull’s view and added that posture and style of skating are individualistic. Tyler (1976) proposed that if the skill, and hence the performance of a player is to be changed, the coach must first be able to define the desired skill. He suggested that most coaches are not able to define the skill they want. With respect to teaching skating, Marcotte (1978) stated that the main concern of a coach is trying to identify the problems in a skater’s technique. To define the problem the coach must know what he or she wants. The coaches’ role is to understand the types of skills and the technical details of each skill so that players can develop styles of performance most suitable to their own body types (Holt, 1978).

It can be expected that as an athlete fatigues when performing a skill the mechanical patterns of the movement will deteriorate. Green (1987) described fatigue as an inability to maintain a desired physical capability, and suggested that fatigue is a persistent threat in ice hockey that has the potential to disrupt all dimensions of performance. Analysing the effects of fatigue on the performance of a skill and identifying what aspects of the movement pattern change as a result of the onset of fatigue, researchers can give insight to coaches on how to instruct players to combat the effects of fatigue and maintain an efficient movement pattern. A qualitative analyses by Green (1987) observed that skating behaviour deteriorates as a result of fatigue. Lagasse (1979) suggested that the mechanical patterns in ice skating will be affected by fatigue. In addition to analysing the differences in the movement patterns of skilled and less-skilled power skaters, the effects of fatigue on skating mechanics were examined to determine if
fatigue affects skaters of different abilities in a similar fashion. Like other areas of hockey skill mechanics, few studies have been done that show how fatigue affects power skating. The lack of kinematic data concerning the changes in the power skating technique brought on by fatigue justifies further research in this area.

Purpose of study:

Given the aforementioned concepts associated with power skating, and given the importance of effective power skating to overall hockey skill development, the purposes of this study are:

1) Identify the differences in the power skating mechanics between skilled and less-skilled skaters when skating at maximal velocity.

2) Identify the changes which occur in skating mechanics as a skater fatigues during a maximal effort power skating task.
**Definition of Terms**

The following operational definitions used in this study have been defined and used by several recognized authorities of skating mechanics which include Hay (1985), Holt (1978), Kirchner and Hoshizaki (1989), Lagasse (1979), Mahoney (1982), Marcotte (1978), Marino (1977), Marino (1979), McCaw and Hoshizaki (1987), and Page (1980).

**Angular acceleration**: The rate at which angular velocity changes with respect to time.

**Angular velocity**: Angular velocity is equal to the total angular displacement of some segment divided by the time it took for the angular displacement to occur.

**Fatigue**: A reversible state of the muscle characterized by a temporary decrease in performance capability associated with the intensity and duration of the activity being performed.

**Horizontal displacement of the centre of gravity of the body relative to the toe at touchdown**: The horizontal distance between the centre of gravity of the body and the toe of the support leg (see Appendix 9 for diagram).

**Horizontal displacement of the knee relative to the toe at touchdown**: The horizontal distance between the knee of the support leg and the toe of the support leg (see Appendix 10 for diagram).

**Knee angle**: Angle of the knee in degrees measured between the thigh and shank (see Appendix 11 for diagram).

**Lateral displacement of the centre of gravity**: The side to side movement of the centre of gravity of the body during the skating stride (see Appendix 13 for diagram).
Mean Horizontal Velocity: Stride length multiplied by stride rate. This assumes that the length of stride accurately reflects horizontal displacement during one stride.

Relative stride length: The ratio of stride length to leg length. Relative stride length = stride length/leg length.

Skating cycle: Toe-off of one leg to the subsequent toe-off of that same leg.

Skating stride: Toe-off of one leg to the toe-off of the opposite leg.

Stride length: Horizontal displacement between the takeoff point of one foot and the takeoff point of the other foot.

Stride rate: The inverse of stride time. Stride rate = 1/stride time.

Stride time: The time between takeoff of one foot to the takeoff of the opposite foot.

Successful trial: A trial was deemed successful and used for analysis if one complete skating cycle had been captured on video tape.

Thigh angle (frontal view): The angle of the thigh measured in degrees from the thigh to horizontal (see Appendix 14 for diagram). The angle of leg abduction seen from the skaters intended direction of motion.

Thigh angle (sagittal view): The angle of the thigh measure in degrees from the thigh to horizontal (see Appendix 15 for diagram). The angle of leg extension seen from the side, perpendicular to the skaters intended direction of motion.

Trunk angle: The angle of the trunk in degrees from the trunk to horizontal (see Appendix 16 for diagram). The angle of the trunk seen from the side, perpendicular to the skaters intended direction of motion.
**Vertical displacement of the centre of gravity:** The up and down movement of the centre of gravity of the body during the skating stride (see Appendix 12 for diagram).

**Power skating:**

The term “power skating” is often misunderstood, even by people associated with hockey. Power skating is the type of skating used in the game of ice hockey which has some defining characteristics which include, but are not limited to, the following:

- extension of the leg backward and laterally
- alternating periods of single and double support (biphasic movement pattern)
- single support period involving the skater being supported on one leg while the other leg is flexed and recovered
- double support period involving the skater being supported on one leg while the other leg is thrust backward and laterally
- alternating arm and leg movements (left leg extension with right arm flexion at the shoulder
- forward trunk lean
- at touchdown the leg is bent at the knee and the knee is over the ball of the foot
- the skate blade is angled away from the skaters intended direction of motion

For our purposes and based upon the mathematical equation, power in this instance will be defined as something equal to the product of force and distance divided by time (Hay, 1985). Having an efficient power skating stride will encompass increasing the force and distance of the stride while decreasing or maintaining the time in which the stride occurs. Increasing the force of the stride depends on the musculature of the body, in particular the muscles of the leg.
Increasing the distance of the stride (stride length) depends on the complete extension of the leg backward at the hip, knee and ankle while having the hips low to the ice. The latter is accomplished by maintaining the support leg in a flexed position at the hip and knee. The increase in force and distance must not compromise the stride time as this needs to be kept as short as possible. Based upon this information, instruction regarding power skating should emphasize four main areas which include: a forceful extension of the leg, flexion of hip and knee of the support leg, increasing stride length, and decreasing stride time.
CHAPTER 2: Review of Literature

Forward Ice Hockey Skating

Skating is a highly skilled activity which is fundamental to the game of hockey and forms the foundation for other aspects of the sport such as frequent changes in direction, checking, passing, and shooting. Forward ice hockey skating, in general, is a biphasic movement pattern consisting of alternating periods of single and double support. It was originally thought that maximum velocity skating (speed skating) was comprised of propulsion (positive acceleration) during double support, and gliding (negative acceleration) during single support (Mueller, 1972). The single support period involves the skater being supported on one leg while the other leg is flexed and recovered. The double support period involves the skater being supported on one leg while the other leg is thrust backward and laterally. Few studies have been performed in an attempt to identify the mechanical characteristics of the power skating movement pattern at maximum velocity, including research by Marino (1977), Page (1980), Marino and Weese (1978), Marino (1984), McCaw and Hoshizaki (1987), and Kirchner and Hoshizaki (1989).

A study by Marino (1977) was completed to determine if ice skating patterns change as the speed of skating varied. The purpose of the study was to compare the temporal aspects of the ice skating stride at three different horizontal velocities. Specifically, the study attempted to determine how stride rate and length change at different velocities as well as how single and double support times change. Ten subjects with ability levels ranging from high to moderately low skilled participated in the study. The three speeds that were analysed were maximum forward skating and two submaximal speeds. The submaximal speeds had no set criteria as
subjects were instructed to skate at medium and slow speeds (Marino, 1977). Mean horizontal velocities for the three speeds were 6.92 m/s, 6.13 m/s and 3.75 m/s for the fast, medium and slow skating speeds, respectively.

As skating speeds changed, there were several significant changes in the kinematic variables that occurred. These included changes in stride rate, single support time and double support time. Stride rates were recorded for the fast, medium and slow speeds at 2.68, 2.09 and 1.29 strides/sec., respectively. Single support times were 0.262, 0.317, and 0.436 seconds for the fast, medium and slow velocities, respectively. Double support times for the three speeds were 0.111 for fast, 0.161 for medium, and 0.339 seconds for slow. There were no significant changes in stride length accompanying the changes in skating velocity (Marino, 1977).

It was noted by Marino (1977) that the skating pattern was somewhat different as velocity changed. The position of the body was more upright during the slow and medium speeds and the glide phase was long and leisurely. During maximum velocity skating the recovery leg was brought forward very rapidly. As velocity increased, double support time decreased to a greater extent than did single support time.

Page (1980) analysed the skating velocity of several hockey players of varying abilities. Page suggests that speed is one of the most important variables in the skill of skating. The analysis by Page of players skating at top speed in a direct line over a distance of 40 feet provided some insight into characteristics affecting skating velocity. Appendix 7 shows the velocity obtained by 14 randomly selected people. Factors found to be correlated with skating speed were fast recovery of the drive leg, small angles at the knee as the skate contacts the ice prior to the initial thrusting action, application of forces to the side and backward, and a large
forward trunk lean (Page, 1980).

Page (1980) found that fast skaters recover their blade in 0.33 to 0.41 seconds while the slower skaters recover their blade in 0.46 to 0.50 seconds. The faster skaters recorded smaller angles of the knee at touchdown. Angles of the knee for the faster skaters ranged from 95 to 110°. No values were given by Page for thigh abduction angle or upper body lean. In addition, Page found that some professional hockey players had rather large vertical displacements and still recorded the fastest times. Page suggests that a large vertical displacement is not the most effective way to skate and that these skaters would not be able to maintain these high velocities for an extended period of time.

A study by Marino and Weese (1978) was conducted to determine the relationship between skating acceleration patterns and the execution of various phases of maximum velocity skating. Four highly skilled subjects performed a maximum forward velocity skating task. Measurement of kinematic patterns of the skating stride which included instantaneous velocity and acceleration were found. In addition, measures assessing stride rate and length, average horizontal velocity, and times of single and double support were determined.

The mean stride rate of 3.54 strides/sec. and a mean stride length of 2.48 m resulted in a mean horizontal velocity of 8.78 m/s. Mean single and double support times were 0.234 and 0.052 seconds respectively. This pattern of relatively short double support periods is similar to those found in acceleration tasks (Marino and Dillman, 1978; Marino, 1979; Marino, 1983).

Similar acceleration patterns existed for all four subjects. The distinctive pattern incorporated a period of deceleration during the initial stages of single support followed by acceleration which continued throughout the remainder of single support until the completion of
double support. At the beginning of single support, when the propulsive thrust was completed, all subjects were at or near a point of zero acceleration. Maximum acceleration occurred at, or just prior to, the touchdown of the recovery foot. This finding conflicts with the initial views that negative acceleration occurs during the single support phase as each subject began to accelerate around the midpoint of the single support phase.

Marino and Weese (1978) suggested that acceleration begins following the outward rotation of the thigh and with the initial extension of the hip and knee. These researchers suggested that propulsion of one leg begins while the other leg is still recovering off the ice. It is further postulated that the propulsion of the leg involves summation of muscle contractions in the leg with extension of the knee, hyperextension of the hip and plantar flexion of the ankle, and that this action begins midway through the single support phase. The completion of these muscle contractions occurs at the end of the double support phase (Marino and Weese, 1978). It was concluded that during single support, the support leg should be rotated quickly to a position where propulsion can occur. From the results of this study Marino and Weese (1978) identified three phases of skating rather than two. These include a period of deceleration during single support, a period of acceleration during single support, and a propulsive double support phase.

Marino (1984) attempted to identify selected mechanical factors of ice hockey skating and depict changes that occur in these patterns as a function of age. In his study, 104 subjects ages 8 to 15 were analysed performing full speed skating. Subjects were divided into groups depending on their age. The performance variables measured were similar to other studies analysing the skating stride and included: horizontal skating velocity, stride rate and length, single and double support times, angle of takeoff of the propulsive leg, and angle of trunk lean at
Mean horizontal velocities ranged from 4.7 to 7.13 m/s and velocity increased progressively with age. Mean stride rates ranged from 2.99 to 3.10 strides/sec and differences between age groups were found to be non-significant. Mean stride lengths ranged from 1.54 to 2.37 m for the age groups as stride length was found to increase with age. The difference between the groups for both horizontal velocity and stride length were found to be statistically significant (Marino, 1984). From these findings it can be assumed that the increases seen in horizontal skating velocity parallel the changes seen in stride length as opposed to changes in the rate of striding. Other studies measuring stride length and rate have found differences in ability and skating speed to be attributed to changes in stride rate (McCaw and Hoshizaki, 1987; Marino, 1977). No other studies have shown stride length to be a factor in changes in skating velocity.

Takeoff angle of the propulsive leg ranged from 58.6 to 69.9 degrees. The differences were not found to be statistically significant, however the younger subjects were noted as having somewhat higher values (Marino, 1984). This suggests that older skaters extend their leg further than younger skaters. Forward lean angle of the trunk ranged from 42.1 to 60.23 degrees. The differences between the groups for forward lean angle was found to be statistically significant.

Correlation coefficients were found by Marino (1984) and a significant positive relationship between skating velocity and stride length was noted. A statistically significant negative relationship was found between skating velocity and angle of takeoff. This implies that skaters who were able to complete the propulsive phase with a lower and more horizontal position of the leg achieved longer stride lengths and had higher skating velocities.
To get a better picture of how a proficient skating pattern develops, McCaw and Hoshizaki (1987) compared the parameters of the skating step and the angular kinematics of the propulsive leg during a skating step among novice, intermediate and elite ability levels. The researchers defined the basic unit of ice hockey skating as the step which encompasses the time between contra lateral foot takeoffs. The step begins with the onset of the single support phase and concludes with the completion of the double support phase of that same leg.

Subjects in the study by McCaw and Hoshizaki (1987) were 17 male university students who were placed into three groups. The novice group had 5 subjects with an average forward skating velocity of 6.94 m/s. The intermediate group had 6 subjects with an average forward skating velocity of 8.28 m/s. The elite group had 6 subjects with an average forward skating velocity of 9.18 m/s. All subjects performed a maximum velocity skating task. The three groups were compared on measures of step rate and length, single and double support times, and kinematics of the left hip (thigh to vertical) and knee (thigh to shank).

Mean step length for groups were 2.91, 2.77 and 2.95 m for the novice, intermediate and elite groups respectively. Step length did not differ significantly between the different skill levels. Mean step rate for the groups were 2.38 steps/s for novice, 3.04 steps/s for intermediate, and 3.13 steps/s for elite. These differences in step rate were found to be statistically significant as novice skaters had lower step rates than the skilled skaters. Single support times for the groups were 0.29, 0.25 and 0.24 seconds for the novice, intermediate and elite groups respectively. Double support times for the groups were 0.13, 0.08 and 0.08 seconds for the novice, intermediate and elite groups respectively. Differences in double support times were statistically significant as intermediate and elite groups had lower times than the novice group.
No significant differences were found between the skill levels for joint angle at the end of the step. A trend was noted by McCaw and Hoshizaki (1987) that there was a greater joint flexion prior to displacement and a greater joint displacement with increasing ability level. Hip and knee average and peak angular velocities were highest for the elite skaters. Only the hip values were statistically significant with both elite and intermediate skaters having higher values than the novice skaters.

It was noted by McCaw and Hoshizaki (1987) that instructing novice skaters to increase their stride rate may be misleading. The increase in stride rate must accompany an increased force production to ensure the stride length is not jeopardized. The faster skaters had the greatest range of motion at the hip and knee. This was primarily a result of greater joint flexion prior to extension as opposed to a greater extension at the end of the step. In addition, the hip values of the intermediates were closer to the elite skaters. Conversely, the knee values of the intermediates were closer to the novice skaters. This may indicate that the development of an effective hip movement during forward skating occurs prior to the development of effective movement at the knee.

By exerting a force against the ice through the skate blade a reaction force perpendicular to the blade occurs. To obtain forward motion in skating, the blade of the skate must be angled away from the skaters intended direction of motion. Kirchner and Hoshizaki (1989) stated that the skate through which the propulsive force is acting is moving in the opposite direction to the skater. This means the leg is driving backward resulting in forward motion of the skater. As the velocity of the skater increases, the time in which the leg is extended must decrease or the angle of propulsion must decrease in order for the leg to continue to produce force in the backward
direction (Kirchner and Hoshizaki, 1989). This would result in a greater stride rate or a larger angle of leg abduction as skating velocity increased.

Cady and Stenlund (1998) defined the basic principles of hockey skating and suggested that skaters must understand and execute these important aspects of skating before advancing into additional skills. By developing proper skating mechanics a skater will conserve energy as excess body movement will be avoided (Cady and Stenlund, 1998). In describing the skating stride, they stated that skating is an alternating, one-legged balancing act. Working from that premise, Cady and Stenlund provided several skating drills that emphasized balancing on one leg. The drills emphasized correct body posture which included bent knees and ankles; a slight forward lean at the waist; eyes looking forward; toe, knee and chin aligned from the front view; ankle, knee, hip, shoulder, and head aligned from the side view; and weight over the skates on the balls of the feet (Cady and Stenlund, 1998). To maintain correct posture, Cady and Stenlund (1998) stated that lower-body strength was essential.

**Power Skating and Fatigue**

It can be expected that as an individual fatigues in any sporting event the mechanical patterns of movement will deteriorate. Lagasse (1979) suggested that the mechanical patterns in ice skating would be affected by fatigue. He defined muscular fatigue as, “a reversible state of the muscle characterized by a temporary decrease in performance capability associated with the intensity and duration of the activity being performed” (p.100). No study was performed by Lagasse, but from the results of the effects of fatigue on running it was hypothesized that muscular fatigue would result in deterioration of the mechanical patterns of ice skating.
Few studies have been done that demonstrate how fatigue affects ice hockey skating. Marino and Potvin (1989) attempted to determine if muscular fatigue affected the basic stride characteristics and selected kinetic variables of the ice skating pattern. Stride characteristics found were stride length and rate. Skating velocity was determined and calculated as the product of the cycle rate and cycle length. Kinetic variables that were determined included lower limb energy outputs and swing leg muscle torques and power.

The researchers analysed 15 elite hockey players performing a starting and stopping activity. The activity required the subjects to skate 20 metres, stop, and skate back 20 metres to the original position. This was considered one trial, and six trials were performed in succession. Analyses were performed on one complete skating cycle. The skating cycle was defined as toe-off of one leg to the subsequent toe-off of that same leg. This resulted in analyses of two periods of single support, each followed by a period of double support. A portion of the first, fifth, and sixth trials were filmed with the first trial being considered a non-fatigued performance while the fifth and sixth trials were considered fatigued performances (Marino and Potvin, 1989).

The mean skating velocities of the three trials were 6.66, 5.55 and 5.64 m/s for the first, fifth and sixth trials respectively. Non-fatigued skating velocity was found to be statistically higher than both fatigued trials. Mean cycle length for the three trials were 4.76, 4.83, and 4.87 metres for the first, fifth and sixth trials respectively. No significant differences were found for cycle length. Mean cycle rates were 1.40 cycles/s for the first trial, 1.15 cycles/s for the fifth trial, and 1.16 cycles/s for the sixth trial. Cycle rate for the non-fatigued trial was found to be statistically higher than both fatigue trials. It was concluded by Marino and Potvin (1989) that the changes noted in skating velocity are due to changes in cycle rate. This finding is in
agreement with other maximum skating velocity studies (McCaw and Hoshizaki, 1987; Marino, 1977).

Peak muscle force moments and peak power at the knee for the non-fatigued trial were statistically higher than both fatigued trials. Marino and Potvin (1989) noted that the values found for both moments of force and power were relatively low as the recovery of the leg after the propulsive phase is a relatively passive event. If analysis of the propulsive leg was performed, it was hypothesized that higher values for peak muscle force and power would be obtained (Marino and Potvin, 1989). Peak energy of the thigh and lower leg were statistically higher in the non-fatigued trial compared to both fatigued trials. It was concluded that the changes in total energy over the duration of the activity was due to the changes in the velocity of segmental movements.

For all variables measured no significant differences were found between trials 5 and 6. This would suggest that the skaters had been fatigued after 5 trials and that no further fatigue occurred between trial 5 and 6. The values were actually higher in trial 6 compared to trial 5 for all variables except peak power at the knee. A possible explanation for the slight increases is that the subjects may have put forth a greater effort on the last trial compared to trial 5. It would be expected that if the subjects were to continue to perform the task until exhaustion all variables would decrease to support the possibility that subjects were maximally fatigued after the fifth trial (Marino and Potvin, 1989).

Marino and Goegan (1990) studied the effects of fatigue on the mechanics of the skating pattern. They attempted to identify how fatigue would effect total energy in specific body segments and identify passive energy exchanges both within and between segments. Nine highly
skilled subjects completed a similar skating task to the one employed by Marino and Potvin (1989). The task required the subjects to skate 20 metres, stop, and skate back 20 metres to the starting position. One 20 metre length was considered a trial and 12 trials were performed in succession. Analyses were performed on portions of the second, tenth and twelfth lengths of skating.

No statistically significant differences for either energy transference or work done by the body were found between the three skating trials. There were statistically significant findings reported for work rate and rate of energy exchange (except for work rate done by the body assuming energy exchange within and between segments) (Marino and Goegan, 1990). In all cases of statistically significant differences, values during the tenth and twelfth lengths were lower than the second length. There was also a statistically significant decrease in the rate of passive energy exchange within and between segments from the second length to the tenth length. No significant differences were found in absolute work done or energy transfer between the tenth and twelfth lengths of skating. This finding is consistent with the study by Marino and Potvin (1989) as they found no differences in skating mechanics between fatigue trials.

Biomechanical research of hockey skills have only touched the surface of a complex sport with many complex movement patterns. The majority of the research has been done on the kinematics of forward starting and full speed skating. Subjects studied were often of different ability levels which may have affected the results. The aforementioned studies provide a solid knowledge base for future researchers.

During the game of hockey it is likely that players are performing with some degree of
fatigue. The player or coach who understands the mechanical changes caused by fatigue on the movement pattern increases the likelihood of success (Elliott and Roberts, 1980). More research is required to determine the effects of varying levels of fatigue on performance.

This paper examines the mechanics of skating for skilled and less-skilled skaters during fatigued and non-fatigued conditions. Specific analysis is done to determine the differences between skilled and less skilled skaters during non-fatigued full speed skating and skilled and less-skilled skaters during fatigued full speed power skating. In addition, analysis is done to determine the differences in the mechanics of skilled skaters during fatigued and non-fatigued conditions and differences in the mechanics of less-skilled skaters during fatigued and non-fatigued conditions.
CHAPTER 3: Methods

The skating stride primarily involves the propulsion of the leg backward and laterally. Three dimensional analysis allows for the detection of the contribution of the lateral movement to the skating technique while two dimensional analysis can not. Previous studies conducted to date have used two dimensional film analysis to study the skating stride. In this study, using two pairs of x,y coordinates acquired from two single plane video cameras, three dimensional coordinates were calculated (see Appendix 1 for joints digitized). These 3-D coordinates were combined with several other sets of coordinates for the same body segments and displacement, velocity and acceleration values were found. The film was subjected to three dimensional analysis using the Ariel Performance Analysis System (APAS). Direct Linear Transformation (DLT) processing was used for data transformation and the cubic spline for data smoothing.

Calibration of data was performed using a cube with 12 control points located a known distance from a 0,0,0 point of an x,y,z coordinate system. Complying with the coordinate system used by the APAS system, x represents the horizontal axis, y represents the vertical axis, and z represents the lateral axis.

Subjects performed a task similar to that used in the studies by Marino and Potvin (1989) and Marino and Goegan (1990). In these studies, subjects skated 20m at maximum velocity, stopped and returned to the original starting position. Each subject skated the 20m distance 12 times without rest. Subjects were filmed on the second, tenth and twelfth length of skating. The task took an average of 45 to 50 seconds to complete. The task was found to be sufficient in fatiguing the subjects.
The task for this study required the subjects to start from a stationary position at one end of the ice and skate forward at maximum velocity to the opposite end of the ice. The starting technique that the subjects used was not regulated. It is assumed that the start technique chosen by each subject did not affect the maximum skating velocity attained at the analysis area. Due to the stop and start task in which changes in direction were necessary, it was assumed that the subjects used the technique that they were most comfortable with. Subjects were observed using the standard “v” method, the cross-over method, and the thrust and glide or “t-start” method. Upon reaching the end of the ice the subjects stopped and returned to the original starting position at maximum effort. The distance from one end of the ice to the other was 56m. Subjects stopped at the original starting position and skated 20m at maximum effort, stopped and returned to the original starting position. The 20m length was skated twice. At the conclusion of the second 20m length, the subjects stopped at the start line and skated at maximum effort to the opposite end of the ice and stopped. The subjects then skated 10m, stopped, skated 56m, stopped, skated 10m to the original starting position and stopped. The subjects then skated 56m. The total distance covered by the subjects was 380m.

Subjects were videotaped at the end furthest from the original starting position when they passed through the analysis area (Figure 1 on next page). The first full length of the ice was considered non-fatigued maximum forward velocity skating. The next two passes through the analysis area were considered the first fatigue and second fatigue trials. Marcotte (1976) suggested that it takes approximately 100 feet for a player to attain their maximum speed. The filming area was positioned 40m from the starting line (approx. 135 feet). Two video cameras were set up on one side of the skating path so that their optical axes were approximately 45
degrees to the skating motion (Figure 1). This provided the two views that are required by the APAS system for 3-D analysis.

![Diagram of experimental set-up](image)

**Figure 1**: Experimental set-up. Skating task and filming area are shown with camera positions.

Subjects performed the test wearing their own skates. They skated in shorts and joint centres were marked to aid in the digitizing process. Subjects carried a hockey stick in one hand. All subjects received a warm-up period of approximately 5 minutes in duration which consisted of submaximal skating, stopping, and stretching before the testing procedure began. Subjects were given details of the study and testing procedures and signed a waiver form (see Appendices 2 and 3).
**Statistical Methods**

Statistical analyses were performed in SuperANOVA version 1.11 (Abacus Concepts, Inc.). The two independent variables were fatigue (IV1) and skill level (IV2). Orthogonal means comparisons were used to determine the significance of differences between individual means when significant main effects for fatigue were observed. A significance less than p=0.05 was chosen for all tests. Dependent variables (listed below) were found for all subjects under all three fatigue conditions.

**Missing Data**

For some subjects, one of the three trials was missing. Missing data were filled in using mathematical equations so that all data could be used in the analysis. The method used to generate values for missing data is given in Appendix 4.

**Reliability and Validity**

Reliability of results was ensured through the redigitization protocol in the APAS system. This is a measure of the researchers ability to accurately digitize segmental endpoints. Five percent of the frames that were digitized were randomly selected by the APAS system to be redigitized. Successful digitization would occur only if a redigitized frame matched the initial digitized frame. Subject reliability could not be guaranteed as subjects were only tested once for all three trials. It is the opinion of the researcher that all subjects provided maximal effort during the entire duration of the task. It is expected that similar results would have been found if subjects were repeatedly examined.
It is standard practice in the area of biomechanics research to ensure validity of results by comparing results found, with other studies results which measured similar variables during a similar task. In this study of maximum velocity forward skating several variables were measured. These were compared with other studies which analysed maximum velocity forward skating including studies by Holt (1978), Marino (1977), Page (1980), Marino (1984), Marino and Weese (1978), McCaw and Hoshizaki (1987), and Marino and Potvin (1989). A few of the similarities are listed below. Other similarities will be reported in the Results and Discussion section that follows.

Maximum skating velocity values recorded in this study were compared to those found by Page (1980). For the skilled group values ranged from 8.92 to 9.94 m/s for a non-fatigued skater. Page reported values ranging from 9.38 to 10.96 m/s for university and professional hockey players. Horizontal velocities for this study and the study by Page (1980) are presented in Appendix 6 and 7.

Stride rates found in this study were similar to the findings of McCaw and Hoshizaki (1987). For the no fatigue trial, mean stride rate was 2.6 strides/second for all subjects analysed which is similar to McCaw and Hoshizaki’s values which ranged from 2.38 to 3.13 strides/second for skaters ranging in ability from novice to elite. Marino and Potvin (1989) also reported cycle rates of 1.4 cycles/second for non-fatigued skaters which would result a mean stride rate of 2.8 strides/second. For their study cycle rate was the time between the takeoff of the same foot. Stride rate is the time from takeoff of one foot to the takeoff of the opposite foot.

Single support times for this study were similar to those found by Marino (1977), Marino and Weese (1978), Marino (1984), McCaw and Hoshizaki (1987), and Page (1980). Mean single
support times ranged from 0.339 to 0.411 seconds in this study. Those found by other researches are wide ranging from 0.24 to 0.50 depending on the velocity and skill level of the skater.

Knee angle at touchdown values were compared with the findings of Page (1980), Holt (1978), and McCaw and Hoshizaki (1987). The mean knee angle found in this study for the non-fatigued trial was 102.9°. Knee angle at touchdown reported by the researchers listed above ranged between 90 and 110° for fast skaters.

Based on the comparison of results from this study with those of previous research it can be concluded that these results are valid and that they represent realistic values for the variables measured.
**Dependent Variables**

The following dependent variables were measured for all subjects under each fatigue condition:

- subject height, leg length, weight
- single and double support time
- single and double support time percentage
- stride rate
- stride length
- relative stride length
- horizontal skating velocity
- horizontal displacement of the centre of gravity relative to the toe at touchdown
- horizontal displacement of the knee relative to the toe at touchdown
- knee angle at touchdown
- knee angle at takeoff
- angular displacement of the knee
- vertical displacement of the body centre of gravity
- lateral displacement of the body centre of gravity
- thigh angle at takeoff (frontal and sagittal views)
- mean trunk lean
- trunk angle at touchdown and takeoff
- angular velocity of the leg segments (thigh, shank, foot)
- acceleration of the centre of gravity (horizontal)
Subjects

Subjects were placed into one of two groups, skilled or less-skilled, based on their individual task times. Table 1 (on next page) lists the task times for all subjects. Mean task times were 57.09 seconds for the skilled group and 63.12 seconds for the less-skilled group. These were found to be statistically different (p<0.05). Eighteen subjects were videotaped while performing maximum velocity skating. Four subjects were rejected due to a lack of a full skating stride in the viewing area. This resulted in a total of 14 subjects with 8 skilled subjects and 6 less-skilled subjects. All subjects in the skilled group had either University and/or Junior level hockey experience. All subjects in the less-skilled group had no University or Junior level hockey experience.
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<td>SD</td>
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</table>

*Table 1:* Time to complete task for skilled and less-skilled subjects in seconds. Task time for the less-skilled subjects was significantly greater than the skilled subjects (p<0.05).
CHAPTER 4: Results and Discussion

The analyses of the mechanics of skilled and less-skilled skaters performing a forward maximum velocity power skating activity revealed minor differences between the two groups. Across the fatigue trials, skating mechanics did change as the skaters in both skill groups fatigued.

Appendix 5 shows the individual subject’s anthropometric characteristics. Mean age of the groups were 22.0 and 21.8 years for the skilled and less-skilled groups respectively. Subjects’ mean height and leg length were 179.1 and 97.4 cm for the skilled group, and 180.4 and 100.9 cm for the less-skilled group. Mean weight of the groups was 84.5 and 74.6 kg for the skilled and less-skilled groups respectively.

**Single and Double Support Time**

Single support time represents the time it takes for the skate to recover off the ice after completing the propulsive phase. Single support times were .384 and .371 seconds for the skilled and less-skilled groups. These were not significant and support the findings of McCaw and Hoshizaki (1987) who found that skaters of different ability levels had similar single support times. These findings conflict with the findings of Page (1980) and Holt (1978) who stated that single support times were higher for less-skilled skaters. Single support times found in this paper for both skilled and less-skilled skaters fell into the time range Page (1980) found for fast skaters.

Double support times were .097 and .101 sec. for the skilled and less-skilled groups.
These were not significantly different. This conflicts with the findings of McCaw and Hoshizaki (1987) who found that intermediate and elite skaters had lower double support times than novice skaters. Findings for both double and single support are shown in Figure 2.

![Graph](image)

Figure 2: Single (SST) and double support times (DST) in seconds for skilled and less-skilled skaters.

Single support times for the different levels of fatigue were .339, .385, and .411 seconds for the no fatigue, first fatigue, and second fatigue trials respectively. Single support during the no fatigue trial was significantly lower than both fatigue trials. This conforms with the finding of Marino (1977) who demonstrated that single support time decreases as velocity increases. As a skater fatigues, the time required to recover the skate off the ice increases.

Double support time during the no fatigue trial was significantly lower than both fatigue
trials with means of .072, .110, and .113 for the three trials. This supports the findings of Marino (1977) who found that double support time decreased as skating velocity increased. As a skater fatigues, the time both skates are on the ice increases. This is similar to the effects that fatigue has on single support. Figure 3 shows the effects of fatigue on single and double support times. Collectively, an increase in both single and double support time results in an increased stride time with fatigue. It could be expected that an increase in stride time would result in a decreased horizontal velocity as the number of leg thrusts in a given period would be reduced.

Figure 3: Single and double support times in seconds for the fatigue trials. Significant findings for single support time: no fatigue significantly different than 1st fatigue; no fatigue significantly different than 2nd fatigue. Significant findings for double support time: no fatigue significantly different than 1st fatigue; no fatigue significantly different than 2nd fatigue.
Single and Double Support Time Percentages

Single and double support times were converted to a percentage of total stride time to determine if skill level or fatigue affected the percentage of time spent in each stage. Single support time percentage was 80.5% for the skilled group and 79.7% for the less-skilled group. Double support time percentages were 19.5% and 20.3% for the skilled and less-skilled groups. These differences were not found to be significant. The findings in this study verify that both skilled and less skilled skaters spend the same percentage of time during the stride in single and double support.

Single support time percentages during the fatigue trials were 83.5%, 78.5%, and 78.6% for the no fatigue, first fatigue, and second fatigue trials. Single support time percentage for the no fatigue trial was significantly higher than both fatigue trials. Double support time percentages for the fatigue trials were 16.5%, 21.5%, and 21.4% for the no fatigue, first fatigue, and second fatigue trials respectively. Double support time percentage for the no fatigue trial was significantly lower than both fatigue trials (see Figure 4).
**Figure 4:** Single and double support times as a percentage of stride time for the fatigue trials.

Significant findings for single support time percentage: no fatigue significantly different than 1st fatigue; no fatigue significantly different than 2nd fatigue. Significant findings for double support time percentage: no fatigue significantly different than 1st fatigue; no fatigue significantly different than 2nd fatigue.

Fatigue results in a decreased percentage of time spent in single support and an increased percentage of time in double support. Even though both single support time and double support time increases with fatigue, the relative percentage of time spent in single support decreases and the relative percentage of time spent in double support increases. This support the findings of Marino (1977) who also showed that as velocity decreased, double support time increased to a greater extent than single support time. It would therefore be beneficial to have a skating stride that has a greater amount of time in single support. It has been shown in this paper, and other
studies done on the skating stride (e.g. Marino, 1977), that single support time comprises the majority of stride time. From these results it is recommended that a high ratio of single support time to double support time is beneficial in attaining a high horizontal velocity and combatting the effects of fatigue.

**Stride Rate**

Stride rate is the number of strides performed in one second. This is determined by taking the inverse of stride time (one/stride time). Stride rates were 2.20 strides/second for the skilled group and 2.22 strides/second for the less-skilled group. The difference in stride rate was not significant for the two groups. This finding conforms with the finding of Marino (1984) who showed that stride rate did not differ between young skaters of different age levels. This differs from the finding of McCaw and Hoshizaki (1987) who found that intermediate and elite skaters stride rates were higher than novice skaters.

Stride rates were found to be significantly different for the fatigue trials (see Figure 5). Both fatigue trial stride rates were significantly lower than the no fatigue trial. Mean stride rates were 2.60, 2.10, and 1.94 strides/second for the no fatigue, first fatigue, and second fatigue levels respectively. The findings by Marino and Potvin (1989) are supported by these results and demonstrates that stride rate decreases with the onset of fatigue.
**Stride Length and Relative Stride Length**

Significant differences between the two skill levels were not found for stride length although a trend was noted. Skilled subjects had a mean stride length of 376.6 cm. Less-skilled subjects had a smaller mean stride length of 356.6 cm. Fatigue also did not affect stride length. Stride lengths were 361.2, 379.1, and 363.8 cm for the no fatigue, first fatigue, and second fatigue trials. These findings conform with the majority of studies examining stride length (Marino, 1977; McCaw and Hoshizaki, 1987; Marino and Potvin, 1989).

Relative stride length was found as the ratio of stride length to leg length. The skilled group had a mean relative stride length of 387.4 cm where as the less-skilled group had a mean
relative stride length of 353.6 cm. Although the skilled value was larger than the less-skilled, it was not statistically different. Relative stride lengths were 365.8 cm for the no fatigue trial, 383.8 cm for the 1st fatigue trial, and 369.1 cm for the 2nd fatigue trial. Fatigue level did not significantly affect relative stride length.

*Horizontal Skating Velocity*

Horizontal velocity was calculated by multiplying stride rate by stride length. This provided a mean horizontal velocity for the skating stride examined. The skilled group had a mean horizontal velocity of 8.08 m/s while the less-skilled group had a mean horizontal velocity of 7.85 m/s. Although the skilled group had a higher skating velocity than the less-skilled they did not differ significantly (see Figure 6). The velocities found in this study are similar to those found by Page (1980). Appendix 6 and 7 lists the individual horizontal velocities found in this study and the study by Page (1980).

The finding of no difference in horizontal velocity is of interest as groups were divided into skill and less-skilled based on the individual time to complete the task (see Methods Section). Other studies that examined the skating velocity of skaters with different abilities found significant differences between skilled and less-skilled skaters (McCaw and Hoshizaki, 1987). It would be expected that if additional hockey skills were required in the task such as agility and puck handling, the skilled group would have performed significantly better than the less-skilled. The task did not require the skaters to be proficient hockey players, rather, it only required that they be able to skate in the forward direction. Differences in task time for the two groups were probably due to differences in starting and stopping ability. The less-skilled group
probably took longer to get to maximum skating velocity and to stop than the skilled group. The
distance to the filming area was probably long enough to allow for any differences in
acceleration between the two groups to be overcome.

![Bar chart showing horizontal velocity for skilled and less-skilled groups in metres/second (m/s).]

**Figure 6:** Mean horizontal velocity for the skilled and less-skilled groups in metres/second (m/s).

Mean horizontal velocity did decrease significantly with fatigue. Horizontal velocities
for the three fatigue trials were 9.27 m/s, 7.71 m/s, and 6.97 m/s for the no-fatigue, first fatigue,
and second fatigue trials respectively. The no-fatigue trial was significantly higher than both
fatigue trials. The first fatigue trial was also significantly higher than the second fatigue trial
(see Figure 7). This suggests that the task was sufficient in fatiguing the subjects. This finding
is similar to the findings of Marino and Potvin (1989) who found that skating velocity decreased
as a skater fatigues. Speculations made by Lagasse (1979) are also confirmed, as he suggested

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that skating performance would decrease with the onset of fatigue.

![Graph showing horizontal velocity in m/s for fatigued trials.](image)

**Figure 7**: Mean horizontal velocity in m/s for the fatigue trials. Significant findings: no fatigue significantly different than 1st fatigue; no fatigue significantly different than 2nd fatigue; 1st fatigue significantly different than 2nd fatigue.

**Horizontal Displacement of the Centre of Gravity Relative to the Toe at Touchdown**

Horizontal displacement of the centre of gravity relative to the toe of the support leg was measured at touchdown (see Appendix 8 for diagram). It would be expected that the propulsive forces act relative to the centre of gravity of the body, therefore, acceleration of the body would only occur if the centre of gravity was ahead of the propulsive leg. Mahoney (1982) suggested that the weight of the body should be in line with the ball of the foot of the support leg. This allows for the thrust to occur slightly behind the body centre of gravity.
At touchdown, the centre of gravity was behind the toe of the support leg for both the skilled and less-skilled groups. The skilled group had a mean displacement of -4.7 cm while the less-skilled group had a mean displacement of -11.7 cm. This was found to be statistically significant as the less-skilled skater’s centre of gravity was further behind the toe of the support leg (see Figure 8). The ball of the foot was not measured in this study, however, it can be expected that the centre of gravity of the skilled skaters would be ahead of the ball of the foot as the toe of the support foot was 4.7 cm in front of the centre of gravity. This implies that the skilled skaters on average were able to generate the force of the leg behind the centre of gravity thus causing positive acceleration at touchdown.

![Figure 8](image.png)

**Figure 8:** Horizontal displacement of the centre of gravity of the body relative to the toe of the support leg at touchdown in cm for the skilled and less-skilled groups. Significant findings: skilled group significantly different than the less-skilled group.
Fatigue level affected the displacement of the centre of gravity with respect to the toe of the touchdown leg. Mean horizontal displacement of the centre of gravity to the toe was -11.3, -7.1, and -4.5 cm for the no fatigue, first fatigue, and second fatigue trials respectively. The centre of gravity was significantly behind the toe during the no fatigue trial compared with both the first and second fatigue trials. No significant difference was found between the two fatigue trials (see Figure 9). As a skater fatigues the placement of the recovery foot lands closer to the body centre of gravity. This is a beneficial act as the ball of the foot is placed closer to the centre of gravity and, as the foot is thrusted back, positive acceleration can occur immediately. In this instance, fatigue affects the skating stride in a beneficial way for all skaters as the weight of the body is closer to the toe of the support leg as a skater fatigues.

![Graph showing horizontal displacement of the centre of gravity](image)

**Figure 9:** Horizontal displacement of the centre of gravity of the body relative to the toe of the support leg at touchdown in cm for the fatigue trials. Significant findings: no fatigue significantly different than 1st fatigue; no fatigue significantly different than 2nd fatigue.
**Horizontal Displacement of the Knee Relative to the Toe at Touchdown**

Researchers have suggested that the knee of the touchdown leg needs to be ahead of the toe of the touchdown leg in order for propulsion to occur (Holt, 1978; Page, 1980). Horizontal displacement of the knee relative to the toe of the touchdown foot was measured (see Appendix 9 for diagram). Skilled skaters had a mean displacement of 7.6 cm while the less-skilled skaters had a mean displacement of 3.5 cm. This was significant as the skilled skaters had their knee farther in front of their toe compared to the less-skilled skaters (see Figure 10). The greater displacement is due to a greater shank angle as there is greater dorsi flexion of the ankle. In order for a skater to have a greater lean of the lower leg, strong thigh muscles are necessary to allow the lower leg to lean far enough forward so that the knee is ahead of the toe. This supports the finding of Page (1980) who stated that speed was related to a large angle of inclination of the lower leg. In both groups the knee of the touchdown leg was ahead of the toe. This finding supports the suggestions made by Holt (1978) that the knee should be ahead of the toes.

Fatigue level did not affect horizontal displacement of the knee with respect to the toe of the touchdown leg. Mean horizontal displacements were 6.2 cm for no fatigue, 5.8 cm for the first fatigue, and 5.5 cm for the second fatigue trials.

Comparing the findings of the centre of gravity relative to the toe, and the knee relative to the toe the skilled group had their centre of gravity closer to the toe of the support leg. They also had their knee ahead of the toe more so than the less skilled group. This would be expected as researchers have suggested that skilled skaters demonstrate both these qualities. When looking at the effects of fatigue on the variables, they do not change in the same way. Fatigue resulted in the centre of gravity moving closer to the toe of the support leg. The knee relative to
the toe of the support leg did not change with fatigue. It is suggested by this researcher that the change in the centre of gravity with respect to the toe is the result of a greater trunk lean at touchdown that occurs with fatigue rather than the placement of the knee ahead of the toe. Although trunk angle at touchdown did not differ with fatigue, there was a trend toward an increasing trunk lean with fatigue. This minor difference in trunk lean may have been large enough to have a significant effect on the centre of gravity position relative to the toe.

![Graph showing horizontal displacement of the knee of the support leg relative to the toe of the support leg at touchdown in cm for the skilled and less-skilled groups. Significant findings: skilled group significantly different than the less-skilled group.]

Figure 10: Horizontal displacement of the knee of the support leg relative to the toe of the support leg at touchdown in cm for the skilled and less-skilled groups. Significant findings: skilled group significantly different than the less-skilled group.
**Knee Angle at Touchdown**

Knee angle at touchdown was measured as the angle between the thigh and the shank (see Appendix 10 for diagram). The skilled group had a mean knee angle at touchdown of 107.2°. The less-skilled group had a mean knee angle at touchdown of 113.4°. The skilled group had a significantly greater knee bend at touchdown compared with the less-skilled group (see Figure 11). This supports the findings in the literature. Page (1979), Holt (1978), and McCaw and Hoshizaki (1987) found that fast skaters recorded smaller angles at the knee at touchdown. They recorded values between 90° and 110° for fast skaters. Holt (1978) found angles greater than 120° for poor skaters. Holt’s value is larger that the one found in this study for the less-skilled skaters and would suggest that the differences between the skilled and less-skilled skaters used in this study were not large.

![Knee Angle Chart]

**Figure 11:** Knee angle of the support leg at touchdown in degrees for the skilled and less-skilled groups. Significant finding: skilled group significantly different than the less-skilled group.
Fatigue also had a significant effect on the angle of the knee at touchdown. Mean angles of 102.3°, 110.9°, and 116.4° were measured for the no fatigue, first fatigue, and second fatigue trials respectively. Angle of the knee at touchdown during the no fatigue trial was significantly lower than both fatigue trials. The angle of the knee at touchdown was also significantly lower during the first fatigue trial compared with the second fatigue trial (see Figure 12). As a skater fatigues, less loading of the leg occurs and knee angles approach angles found by Holt (1978) of poor skaters. Holt (1978) suggested that in order for a skater to obtain an angle close to 90°, they need to have adequate muscle strength in the thigh. Fatigue results in the skater losing the ability to obtain an optimal flexion angle of the knee at touchdown (90-110°). The importance of obtaining a 90° angle of the knee was also emphasized by Cady and Stenlund (1998) in many of their forward skating drills.
Figure 12: Knee angle of the support leg at touchdown in degrees for the fatigue trials. Significant findings: no fatigue significantly different than 1st fatigue; no fatigue significantly different than 2nd fatigue; 1st fatigue significantly different than 2nd fatigue.

**Knee Angle at Takeoff**

The angle of the knee at takeoff was measured to determine if skill or fatigue affected the amount the leg was extended at the knee (see Appendix 10 for diagram). The mean angle of the knee at takeoff for the skilled group was 161.4°, for the less-skilled group, 163.1°. This difference was not found to be significant. These findings conflict with those observed by Holt (1978) who suggested that good skaters extend their drive leg to almost 180°. Meagher (1972) also suggested that failing to extend the leg fully at the end of the leg thrust is a common mistake made by skaters. Holt (1978) stated that weak skaters are only able to attain around
130° of extension. This seems hard to believe as he suggests a touchdown angle of 120° for weak skaters. This would result in only 10° of displacement of the knee during the skating stride. Fatigue also did not affect the angle of the knee at takeoff significantly. Mean knee angles recorded were 162.9° during no fatigue, 162.0° during the first fatigue trial, and 161.5° during the second fatigue trial. These values imply that during maximum velocity skating, skaters are unable to obtain maximum knee extension.

**Angular Displacement of the Knee**

Total angular displacement of the knee was determined by subtracting the angle of the knee at takeoff from the angle of the knee at touchdown. Total angular displacement of the knee was measured at 54.2° and 49.6° for the skilled and unskilled groups, respectively. These differences were not statistically significant although the skilled skaters tended to have a larger angular displacement compared with the less-skilled. Holt (1978) suggested that good skaters exert forces over a greater range of motion than less-skilled skaters. Findings by McCaw and Hoshizaki (1987) supported Holt’s (1978) findings and suggested that the greater joint flexion prior to extension as opposed to greater joint extension results in the greater angular displacement. Fatigue did significantly affect total angular displacement of the knee. The no fatigue trial with a mean angular displacement of 60.6° was significantly greater than both fatigue trials with mean values of 51.0° and 45.1° for the first and second fatigue trials. As the skater fatigues the total angular displacement of the knee decreases (see Figure 13). It would be expected from measurements made on the angle of the knee at both touchdown and takeoff that the changes which occur with fatigue are due to a decrease in knee flexion at touchdown rather
than knee extension at takeoff.

Figure 13: Total angular displacement of the knee during the skating stride in degrees for the fatigue trials. Significant findings: no fatigue significantly different than 1st fatigue; no fatigue significantly different than 2nd fatigue.

**Vertical Displacement of the Centre of Gravity**

Vertical displacement of the centre of gravity is a measure of how much up and down movement occurs to the body centre of gravity (see Appendix 11 for diagram). Vertical displacement of the centre of gravity of skilled skaters was 5.0 cm and 7.0 cm for less-skilled skaters. These were not found to be statistically significant. These results conflict with the findings of Page (1980) who showed that some professional players had rather large vertical displacements and still recorded the fastest skating times. However, Page (1980) suggested that
a large vertical displacement of the body is not the most effective way to skate and that those skaters would not be able to maintain these high velocities for an extended period of time. Holt (1978) also found that the speed of skating was not related to large vertical displacements.

Vertical displacement of the centre of gravity was not significantly affected by fatigue. Mean values of 6.6, 5.3, and 5.8 cm were recorded for the no fatigue, first fatigue, and second fatigue trials respectively. In both cases of skill and fatigue, the vertical displacement of the centre of gravity recorded were similar and values were small.

**Lateral Displacement of the Centre of Gravity**

Lateral displacement of the centre of gravity is a measure of the side to side movement that occurs to the body's centre of gravity (see Appendix 12 for diagram). The skilled group had a mean lateral displacement of the centre of gravity of 20.8 cm while the less-skilled had a mean lateral displacement of 14.5 cm. These differences were not statistically significant. Fatigue did not affect the lateral displacement of the centre of gravity. Mean lateral displacements were 18.0 cm for no fatigue, 16.8 cm for the first fatigue, and 19.5 cm for the second fatigue trials. It was previously noted that the skating stride involves the thrusting of the leg backward and to the side. It is expected that the sideways thrust of the leg will cause the centre of gravity to move laterally. Mahoney (1982) observed the movement of the head during skating and stated that movement to the side occurs as the body weight shifts from one leg to the other.
**Thigh Angle at Takeoff**

The angle of the thigh at takeoff was measured from the frontal view and sagittal view. From the frontal view, the angle of the thigh was measured as the angle from the thigh to horizontal (see Appendix 13 for diagram). A smaller angle represents the leg in greater abduction. The angle of the thigh at takeoff for the frontal view was 62.6° for the skilled group and 64.8° for the less-skilled group. This difference was not statistically significant. This conflicts with the findings of Page (1980) who found that fast skaters demonstrated a large angle of abduction of the thigh. Fatigue did have a significant effect on the angle of the thigh at takeoff. The no fatigue angle of 59.7° was significantly lower than the first fatigue angle of 63.9° and the second fatigue angle of 67.0°. The difference between first and second fatigue was not significant (see Figure 14). This implies that a decrease in leg abduction occurs with fatigue. This would be expected because as the velocity of the skater increases the leg must abduct to a greater extent to continue force production (Kirchner and Hoshizaki, 1989). Velocity decreases with fatigue and thus the leg does not have to abduct as far to allow for force production.
Figure 14: Thigh angle at takeoff (frontal view) in degrees for the fatigue trials. Angle decreases with greater leg extension. Significant findings: no fatigue significantly different than 1st fatigue, no fatigue significantly different than 2nd fatigue.

Angle of the thigh at takeoff from the sagittal view was measured as the angle from the vertical to the thigh (see Appendix 14 for diagram). A smaller angle corresponds to a greater extension of the leg. Angle of the thigh from the sagittal view for the skilled and less-skilled groups were 254.5° and 251.3°. This was not found to be a statistically significant difference.

The angles of the thigh during the fatigue trials were 247.6°, 252.3°, and 259.4° for the no fatigue, first fatigue, and second fatigue trials, respectively. Angle of the thigh during the no fatigue trial was significantly lower than both fatigue trials. There was also a greater extension of the leg recorded during the first fatigue trial compared with the second fatigue (see Figure 15).
Figure 15: Thigh angle at takeoff (sagittal view) in degrees for the fatigue trials. Significant findings: no fatigue significantly different than 1st fatigue, no fatigue significantly different than 2nd fatigue; 1st fatigue significantly different than 2nd fatigue.

During the no fatigue trial, the lower angle of the thigh represented a greater extension of the leg than the two fatigue trials. Values found in this study for leg extension are lower than those reported by other researchers. Fahey (1977) suggested that the pushing leg angle should be between 45 and 60°. This would correspond to an angle of 225 - 240° utilized in this study (180 + 45). Marino (1984) found the angle of the thigh at takeoff ranged from 58.6 to 69.9° (238.6 to 249.9°). Although values found in this study more closely correspond to those found by Marino (1984), the discrepancy is probably due to the velocity of skating. The skater is unable to push the leg to a large angle of extension due to the high velocity (Kirchner and Hoshizaki, 1989). The lower velocity of fatigue, however, did not increase the angle of leg abduction in this study.
Fatigue affected both thigh abduction and extension in the same manner, in that both decreased as the skater fatigued.

**Trunk Angle**

Mean trunk angle was measured during the skating stride with respect to vertical (see Appendix 15 for diagram). A larger angle represents the skater being more upright. Mean trunk angles were 221.4° for the skilled group and 229.4° for the less-skilled group. This was found to be significant as the skilled skaters had a greater mean trunk lean than the less-skilled skaters (see Figure 16). This finding supports the work of Page (1980) and Holt (1978) who found that fast skaters tended to have a greater upper body lean. Values found in this study also confirm the recommendations made by Marcotte (1976) and Mahoney (1982) who suggested that forward body lean be close to 45° (225° for this study). By bending forward, the skater can increase the length of the thrust (Marcotte, 1976). This would lead to a greater propulsion phase of the skating stride. This increase body lean leading to a longer stride is only made possible by an increased knee bend. Simply bending at the waist is not sufficient in lengthening the stride. Fatigue did not affect mean trunk angle. Values for mean trunk angle were 226.8°, 224.5°, and 223.1° for the no fatigue, first fatigue, and second fatigue trials respectively.

Trunk angle at touchdown was measured from vertical similar to the measurement of mean trunk angle. The skilled group had a mean touchdown angle of 219.6°. The less-skilled group had a mean touchdown angle of 226.2°. These were not found to be statistically different. Trunk angle at touchdown for the fatigue trials were 224.9° for the no fatigue trial, 222.6° for the first fatigue trial, and 219.8° for the second fatigue trial. Fatigue level did not affect trunk angle.
at touchdown.

Figure 16: Mean trunk angle in degrees for the skilled and less-skilled groups. Angle of the trunk is taken with respect to a horizontal line at the shoulders in the direction of movement (225° = 45°).

Significant findings: skilled group significantly different than the less-skilled group.

Trunk angle at takeoff was measured from the vertical similar to mean trunk angle and trunk angle at touchdown. Skill level was found to affect the angle of the trunk at takeoff. The skilled group had a mean trunk angle at takeoff of 221.6°, while the less-skilled group mean trunk angle at takeoff was 232.7°. The skilled group had a significantly greater trunk lean at takeoff (see Figure 17). Differences in mean trunk angles of the two skill groups can thus be attributed to the differences in the trunk angle at takeoff as opposed to touchdown. It can be recommended that coaches instruct learning skaters to stay in a more crouched position at the conclusion of each thrust. In order to accomplish this, the support leg needs to remain in a
flexed position.

![Bar chart showing trunk angle at takeoff in degrees for skilled and less-skilled groups.](chart)

**Figure 17**: Trunk angle at takeoff in degrees for the skilled and less-skilled groups. See Figure 16 for details of trunk angle. Significant findings: skilled group significantly different than the less-skilled group.

**Angular Velocity of the Leg Segments**

Mean angular velocity of the leg segments were analysed to determine which segment (thigh, shank, and foot) had the greatest contribution to skating velocity and whether skill or fatigue level affected the individual segment angular velocity.

Mean angular velocity of the thigh for the skilled and less-skilled subjects were 126.2 °/s and 129.3 °/s. The difference was not statistically significant. A fatigue effect was found for mean angular velocity of the thigh. No fatigue mean angular velocity of the thigh was 169.0 °/s. This was significantly higher than both fatigue levels. Mean angular velocity of the thigh during
the first fatigue trial was 112.5 %s and 101.3 %s for the second fatigue trial. The difference between the fatigue trials was not statistically significant (see Figure 18).

![Bar chart showing angular velocity for different fatigue levels.](image)

**Figure 18**: Mean angular velocity of the thigh in degrees/second for the fatigue trials. Significant findings: no fatigue significantly different than 1st fatigue; no fatigue significantly different than 2nd fatigue.

Mean angular velocity of the shank was 31.0 and 51.0 %s for the skilled and less-skilled groups. The less-skilled group had a significantly larger mean angular velocity of the shank compared with the skilled group (see Figure 19). This finding is of interest and may be related to the displacement of the knee with respect to the toe of the touchdown leg. The skilled skaters had their knee further ahead of the toe of the support leg at touchdown. The lower leg would thus have a greater lean than the less-skilled skaters. The shank at takeoff is also forward, and
therefore the shanks of the skilled skaters would not have as large an angular displacement to go through from touchdown to takeoff as would the less-skilled skaters. Since stride rates and lengths were similar for the two skill levels, it is expected that the angular velocity of the shank should be higher for the less-skilled group. Their shanks have a greater angular displacement to cover compared with the skilled group in the same amount of time.

![Bar chart showing angular velocity comparison between skilled and less-skilled groups.](image)

**Figure 19:** Mean angular velocity of the shank in degrees/second for the skilled and less-skilled groups. Significant finding: skilled group significantly different than the less-skilled group.

Fatigue significantly affected mean angular velocity of the shank. Mean angular velocity of the shank during the no fatigue trial was significantly higher than both fatigue trials. Values for the three fatigue trials were 51.5, 34.3, and 32.9 °/s for the no fatigue, first fatigue, and second fatigue trials respectively (see Figure 20).
Figure 20: Mean angular velocity of the shank in degrees/second for the fatigue trials. Significant findings: no fatigue significantly different than 1st fatigue; no fatigue significantly different than 2nd fatigue.

Mean angular velocity of the foot was 36.7 and 40.4 °/s for the skilled and less-skilled groups. These were not found to be significant. Fatigue also did not affect mean angular velocity of the foot. Values for mean angular velocity of the foot were 39.2 °/s for the no fatigue trial, 38.5 °/s for the first fatigue trial, and 37.2 °/s for the second fatigue trial.

Regarding the velocity of the leg segments during the skating stride, the thigh values were higher than both the shank and the foot. Fatigue affected thigh and shank angular velocities in a similar fashion in that both decreased as the skaters fatigued. The variability of the angular velocities of the leg segments were high. This can be attributed to the individuality of the skating stride. Since angular velocity is the change in angular displacement over time, any
change in either of these variables would affect velocity. In particular, small changes in
displacement or the time of displacement would greatly affect segmental velocity.

**Acceleration of the Centre of Gravity**

Acceleration patterns of the centre of gravity of the body were calculated by the APAS system using anthropometric data from each subject (height and weight) and joint centres of mass data (APAS). Acceleration patterns for the subjects varied for all three fatigue trials. Most subjects were accelerating through the filming area, however, the acceleration values of the centre of gravity recorded during the skating stride were not large. In some trials, subjects were found to be accelerating through the entire stride. It has been previously thought that the skating stride involves some period of deceleration (Marino and Weese, 1978). This indicates that subjects were able to begin propulsion of the support leg as soon as takeoff occurred. Marino and Weese (1984) also found that acceleration begins while the other skate is recovering off the ice.

Deceleration and acceleration patterns similar to those found by Marino and Weese (1984) were displayed in some trials with an initial deceleration occurring at takeoff followed by acceleration throughout the remainder of the stride. Occasionally, subjects did not display any acceleration and occasionally a skater was decelerating throughout almost the entire skating stride. Differences in acceleration patterns may be due to attainment of maximum skating velocity, different responses to fatigue, or effort level of the subjects.

Marcotte (1976) suggested that maximum skating velocity is attained after approximately 100 feet. The finding that some subjects were accelerating through the filming area disputes this
notion. After skating more than 40 metres (135 feet) some subjects in this study were still
accelerating. However, since acceleration values were minor, the maximum velocity that a
skater could attain would not be much higher than the values reported earlier. In addition, in the
game of hockey a skater is rarely able to skate in one direction at maximum effort the entire
length of the ice. Examining skaters’ maximum velocity at a distance greater than the length of
the ice is probably not warranted.
CHAPTER 5: Summary and Recommendations

Few differences were revealed in this study between the skating strides of skilled and less-skilled skaters. Both groups had similar maximum skating velocities in addition to similarities in several other variables. This is similar to the findings of McCaw and Hoshizaki (1989) who analysed the skating technique of novice, intermediate, and elite skaters. Few difference were found when they compared intermediate to elite skaters.

The onset of fatigue was observed as a decrease in the maximum skating velocity of the skaters. Several characteristics of the skating stride changes as a result of fatigue. These changes were noted during both the first and second fatigue trials.

1) Fatigue resulted in increases in both single and double support times. Combining these variables results in an increased stride time with fatigue. This is detrimental to a skaters performance (high skating velocity). The increased stride time corresponds to a decrease in the rate of striding with fatigue. The increase in stride time also decreases the power of the skating stride as power is inversely proportional to time. As stride time increases, the power of the stride decreases.

- **Recommendation:** Skaters should be instructed to stride quickly, however, in decreasing stride time the skater should not compromise the other aspects of a powerful skating stride which will be mentioned in following recommendations.
2) The majority of the skating stride is spent in single support. It is therefore essential that skaters have good balance while being supported by only one leg.

- Recommendation: Coaches and instructors should incorporate balancing drills that require the skater to use each leg separately. This is most important for weaker skaters as they often have better balance on their dominant leg. These balancing drills should emphasize the hip and knee in a flexed position. The importance of this will be made clear in a conclusion number 7.

3) Horizontal velocity is the product of stride rate and stride length. Horizontal velocity was found to significantly decrease with fatigue. Since stride length was not affected by the onset of fatigue, the change in velocity must have been the result of a decreased stride rate (increased stride time). Even though the length of the stride remained unchanged with fatigue, the increase in stride time would result in a less powerful stride assuming that the force of the stride remained constant.

- Recommendation: It is essential for instructors to focus not on increasing the length of a player's stride, but rather the time in which each stride occurs.

4) Horizontal displacement of the centre of gravity of the body at touchdown differed between the two skill groups. Although both groups placed their support leg down in front of their centre of gravity, the skilled groups foot was closer to the centre of gravity. Placement of the foot in a position where leg extension can occur immediately is crucial to prevent negative acceleration during the stride.
**Recommendation:** The foot must not only be placed behind the centre of gravity, it must also be rotated outward. This will allow the skater to apply immediate force against the ice in the backward and lateral direction causing the body to be propelled forward.

5) Fatigue affected the placement of the support foot relative to the centre of gravity of the body in a beneficial manner. As a skater fatigues the skating stride becomes more efficient as the placement of the foot gets closer to the centre of gravity of the body. This would result in less distance for the centre of gravity to travel over the foot before propulsion of the body could occur.

6) Horizontal displacement of the knee relative to the toe at touchdown was found to differ between the two skill groups. The skilled group had their knee further ahead of their toe at touchdown. The was accomplished by having a greater knee flexion at touchdown. It has been suggested by several other researchers that the knee should be flexed to 90 to 110° when it contacts the ice at touchdown. For this to be accomplished, the hip of the support leg must be flexed to maintain the skaters balance. This results in hips being lower and closer to the ice. This is also of benefit with respect to the extension of the leg which will be discussed in conclusion #10.

**Recommendation:** Coaches and instructors should incorporate skating drills which emphasize placement of the support leg with the knee and hip flexed.
7) Knee angle at touchdown was found to be in greater flexion for the skilled skaters. This is beneficial as it results in a greater loading of the leg before extension occurs. The greater the initial knee flexion, the greater the amount of angular displacement during extension of the leg. With respect to increasing the power of the stride, a larger angular displacement of the knee will result in a longer stride length as long as the time in which the displacement occurs remains constant.

8) As a skater fatigues, the angle of the knee at touchdown increases. This is detrimental to the skating stride. It reduces the amount of angular displacement of the knee during leg extension. With the decrease in knee flexion, hip flexion also decreases as the skater is standing in a more upright position when observing the leg. The hips are not low to the ground and the skater is probably not as balanced on his skates. In the game of hockey this would compromise the players ability to ward off a check from an opponent.

9) Abduction of the thigh at takeoff was found to differ as a skater fatigues. There is a decrease in the amount of abduction with fatigue. This is probably a result of the skaters support leg being more upright at touchdown. The more upright the leg is at touchdown the less abduction of the propulsive leg. Fatigue compromises the amount of flexion in the support leg. Fatigued leg muscles can probably account for the decrease in the hip and knee flexion especially fatigue of the hip and thigh musculature. To maintain effective abduction of the propulsive leg the hip must be kept low to the ice. There is another possible explanation for the decrease in leg abduction with fatigue. The decrease in skating velocity of the skater does not
require a large amount of lateral leg drive to continue force production. As referenced throughout this study, the skating stride involves the leg being thrust backward and laterally. The velocity of the leg drive backward must be greater than the velocity of the forward motion of the body in order for acceleration to occur. The faster a skater’s forward velocity the more lateral the leg drive. As the velocity of the skater decreases with fatigue, the leg drive can be more backward than lateral. The decrease in leg abduction with fatigue is due to decrease in hip and knee flexion of the support leg rather than the decreasing skating velocity as backward leg extension was not found to increase with fatigue.

10) Extension of the thigh at takeoff was found to differ as a result of the onset of fatigue. There was an decrease in the amount of leg extension with fatigue. This was probably due to the decreased hip and knee flexion of the support leg as mentioned earlier. To maintain a large leg extension and abduction during the skating stride, the support leg must be sufficiently flexed. This is only made possible by having strong leg musculature, especially the extensor muscles of the leg. It is suspected that fatigue in these muscles results in the skater’s legs being more upright.

11) Forward lean of the trunk was found to differ between the two skill groups. The skilled groups tended to have a greater mean trunk lean throughout the skating stride. The greater trunk lean is essential for a number of reasons. The position of the centre of gravity of the body is dependent upon the position of all the body segments. The greater the forward lean of the trunk, the further ahead the centre of gravity of the body. This is crucial as it has been stressed that the
placement of the recovery leg should be behind the centre of gravity to allow immediate forward acceleration. The increased forward lean must also accompany the flexion of the support leg. With the support leg flexed, the greater forward lean allows for the thrusting leg to be extended and abducted to a greater angle thus increasing the stride length.

12) Power was defined earlier as the product of force and distance divided by time. It is also the product of force and velocity. Therefore any decrease in velocity will decrease the power of the stride if the force of the stride remains constant. Fatigue was found to affect the velocity of the thigh. As a skater fatigues, the velocity of the thigh decreases. Fatigue affected the velocity of the shank in a similar manner. The greatest contribution to the skating stride was found to be the velocity of the thigh.

- **Recommendation:** Conditioning exercises should emphasize the strengthening of the musculature that causes hip extension and abduction. These exercises should also be performed at a high velocity to mimic the action of the leg in skating. Looking at the definition of power, exercises should attempt to increase the force (resistance) while maintaining a high velocity. That is, the movement should be explosive. This should also be emphasized when conditioning the other leg muscles (quadriceps, hamstring, and calf muscles).
The observation of the onset of fatigue occurring in a relatively short period of time has several implications for the sport of hockey. Not only does the maximum velocity of skating decrease with fatigue, but other skills would also be expected to deteriorate such as stopping, turning and checking. The first fatigue trial was recorded no longer than 42 seconds after the onset of the task for any subject. This further supports the recommendations made by other researchers and coaches that shift time should be kept below 45 seconds especially if play is continuous without stoppage.

*Recommendations for Future Research:* Attempts should now be made to ascertain why these changes in the skating patterns occur with fatigue and how they can be combatted through technique or conditioning modifications.
References


APPENDICES

Appendix 1: Digitized points entered into the APAS system.

- left and right toe
- left and right ankle
- left and right knee
- left and right hip
- left and right hand
- left and right elbow
- left and right shoulder
- point between left and right hip
- point between left and right shoulder
- top of head
Appendix 2: Details of study and testing procedure given to subjects before testing was performed.

Participant Information

Dan Drouin is a graduate student in the Department of Kinesiology, Faculty of Human Kinetics at the University of Windsor. Under the supervision of his advisor, Dr. G.W. Marino, professor at the University of Windsor, in the faculty of Human Kinetics, Dan Drouin will be video taping full speed skating that will later be analysed. Results will be used for Mr. Drouin's thesis paper and be presented to his thesis advisory committee.

Title of Study*:
The Effects of Skill Level on the Mechanics of Forward Maximum Velocity Power Skating During Non-Fatigued and Fatigued Conditions.

Testing Procedure:
Subjects will be required to skate from one end of the ice to the other at maximum effort until fatigued. Subjects will be filmed during both non-fatigued and fatigued conditions. Subjects will wear their own skates and carry a hockey stick in one hand. The subjects will wear only a pair of shorts and have their joint centres marked with markers or reflective tape. There is the slight possibility that injury can occur during the testing procedure. Every precaution has been taken to insure subject safety during the test.

Participation and Confidentiality:
Participation in the study is voluntary. As a subject you have the right to refuse to do any aspect of the test. You may also withdraw from the study at any time, including after collection of the data. Your name will be kept confidential and subjects will be assigned a random identification number for analysis purposes. The video will only be viewed by the researcher and his advisors. Any subject who feels that they are unable or unwilling to perform certain aspects of the testing procedure should inform the researcher before testing begins. The results of the study will be made available to the subjects after analysis at the subjects request.

A copy of this waiver will be given to each subject as a record of their participation and acceptance of the particulars listed herein.
Subjects can contact the University of Windsor Ethics Committee or the Faculty of Human Kinetics for any further questions you might have.

Dan Drouin, B.H.K.

*Addendum: The title of this study was changed after the data was collected. This was the original form signed by the participants prior to testing. New title: The effects of fatigue on the mechanics of forward maximum velocity power skating in skilled and less-skilled skaters.
Appendix 3: Consent form signed by subject and researcher before testing procedure.

Consent Form

Declaration of Participant

I have read and understand the contents of this waiver form. I understand that I have the right to withdraw from the study at any time at my request. I understand that my identity will be kept confidential.

Date Signed

Subject Name (print)  Subject Signature

Researcher Name (print)  Researcher Signature
Appendix 4: Missing data. A sample calculation for the method used to generate values is shown.

For the missing value $r_2c_2$:

$$\frac{r_2c_2}{r_2c_2 + \sum c_2} = \omega$$

where

$$\omega = \left[ \frac{\left( \frac{r_2c_1}{\sum c_1} \right) + \left( \frac{r_2c_3}{\sum c_3} \right) + \left( \frac{r_2c_4}{\sum c_4} \right)}{k} \right]$$

$k$ is the number of columns minus the number of columns with missing data, and $\sum c_2$ is the sum of column 2 with cell $r2c2$ empty.

Solving for $r2c2$:

$$r_2c_2 = \frac{\sum c_2 \times \omega}{1 - \omega}$$

This method fits the missing value to the ratio of the missing value's row (row 2 in the example) over the column total (column 2 in the example above).
### Skilled Subjects: Anthropometric Data

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<td>177.8</td>
<td>100.7</td>
<td>84.1</td>
</tr>
<tr>
<td>16</td>
<td>21</td>
<td>182.9</td>
<td>95.6</td>
<td>94.5</td>
</tr>
<tr>
<td>Mean</td>
<td>22.0</td>
<td>179.1</td>
<td>97.4</td>
<td>84.5</td>
</tr>
</tbody>
</table>

### Less-skilled Subjects: Anthropometric Data

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Leg Length (cm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>22</td>
<td>185.4</td>
<td>104.5</td>
<td>86.4</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>177.8</td>
<td>103.5</td>
<td>68.2</td>
</tr>
<tr>
<td>13</td>
<td>21</td>
<td>177.8</td>
<td>96.8</td>
<td>72.7</td>
</tr>
<tr>
<td>15</td>
<td>24</td>
<td>185.4</td>
<td>99.4</td>
<td>79.5</td>
</tr>
<tr>
<td>17</td>
<td>21</td>
<td>180.3</td>
<td>101.3</td>
<td>75.0</td>
</tr>
<tr>
<td>18</td>
<td>21</td>
<td>175.3</td>
<td>99.7</td>
<td>65.9</td>
</tr>
<tr>
<td>Mean</td>
<td>21.8</td>
<td>180.4</td>
<td>100.9</td>
<td>74.6</td>
</tr>
</tbody>
</table>

**Appendix 5:** Anthropometric data of all subjects in the skilled and less-skilled groups.
### Skilled Subject: Skating Velocity (cm/s)

<table>
<thead>
<tr>
<th>Subject #</th>
<th>No fatigue</th>
<th>1st fatigue</th>
<th>2nd fatigue</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>936.7</td>
<td>791.5</td>
<td>688.4</td>
</tr>
<tr>
<td>6</td>
<td>907.0</td>
<td>810.0</td>
<td>729.3</td>
</tr>
<tr>
<td>7</td>
<td>967.1</td>
<td>781.7</td>
<td>721.8</td>
</tr>
<tr>
<td>8</td>
<td>994.2</td>
<td>797.0</td>
<td>666.8</td>
</tr>
<tr>
<td>9</td>
<td>944.0</td>
<td>781.7</td>
<td>681.3</td>
</tr>
<tr>
<td>12</td>
<td>892.0</td>
<td>755.8</td>
<td>674.2</td>
</tr>
<tr>
<td>14</td>
<td>962.1</td>
<td>771.9</td>
<td>748.9</td>
</tr>
<tr>
<td>16</td>
<td>929.1</td>
<td>731.2</td>
<td>735.5</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td><strong>941.5</strong></td>
<td><strong>777.6</strong></td>
<td><strong>705.8</strong></td>
</tr>
</tbody>
</table>

### Less-skilled Subjects: Skating Velocity (cm/s)

<table>
<thead>
<tr>
<th>Subject #</th>
<th>No fatigue</th>
<th>1st fatigue</th>
<th>2nd fatigue</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1005.7</td>
<td>918.9</td>
<td>655.0</td>
</tr>
<tr>
<td>5</td>
<td>866.0</td>
<td>776.8</td>
<td>655.0</td>
</tr>
<tr>
<td>13</td>
<td>889.5</td>
<td>718.8</td>
<td>706.6</td>
</tr>
<tr>
<td>15</td>
<td>894.1</td>
<td>759.5</td>
<td>784.0</td>
</tr>
<tr>
<td>17</td>
<td>1006.9</td>
<td>707.3</td>
<td>680.6</td>
</tr>
<tr>
<td>18</td>
<td>780.8</td>
<td>699.0</td>
<td>629.8</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td><strong>907.1</strong></td>
<td><strong>763.4</strong></td>
<td><strong>685.4</strong></td>
</tr>
</tbody>
</table>

**Appendix 6**: Horizontal velocity for subjects in the skilled and less-skilled groups.
<table>
<thead>
<tr>
<th>Subject</th>
<th>Velocity ft/sec (cm/s)</th>
<th>Player Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35.1 (1096.3)</td>
<td>Fast pro</td>
</tr>
<tr>
<td>2</td>
<td>33.6 (1024.1)</td>
<td>Fast university</td>
</tr>
<tr>
<td>3</td>
<td>33.6 (1024.1)</td>
<td>Fast university</td>
</tr>
<tr>
<td>4</td>
<td>33.1 (1008.4)</td>
<td>Fast university</td>
</tr>
<tr>
<td>5</td>
<td>32.3 (984.5)</td>
<td>Pro</td>
</tr>
<tr>
<td>6</td>
<td>30.8 (938.8)</td>
<td>Pro</td>
</tr>
<tr>
<td>7</td>
<td>27.4 (835.2)</td>
<td>Slow adult</td>
</tr>
<tr>
<td>8</td>
<td>27.4 (835.2)</td>
<td>Slow adult</td>
</tr>
<tr>
<td>9</td>
<td>27.4 (835.2)</td>
<td>Fast 13 year old</td>
</tr>
<tr>
<td>10</td>
<td>27.2 (829.1)</td>
<td>Fast 13 year old</td>
</tr>
<tr>
<td>11</td>
<td>25.5 (777.2)</td>
<td>Fast 12 year old</td>
</tr>
<tr>
<td>12</td>
<td>21.6 (658.4)</td>
<td>Slow 12 year old</td>
</tr>
<tr>
<td>13</td>
<td>20.6 (627.9)</td>
<td>Slow 12 year old</td>
</tr>
<tr>
<td>14</td>
<td>18.1 (551.2)</td>
<td>Slow 12 year old</td>
</tr>
</tbody>
</table>

*Appendix 7:* Results from testing done by Page (1980). Skating velocity in ft/second and cm/second for players of different abilities (pp. 89).
Appendix 8: Horizontal displacement of the centre of gravity of the body relative to the toe of the support leg in cm.

Appendix 9: Horizontal displacement of the knee of the support leg relative to the toe of the support leg at touch down in cm.
**Appendix 10**: Angle of the knee at takeoff and touchdown measured in 3D in degrees.

**Appendix 11**: Vertical displacement of the centre of gravity of the body during the skating stride in cm.
Appendix 12: Lateral displacement of the centre of gravity of the body during the skating stride in cm.

Appendix 13: Angle of the thigh at takeoff measured from the frontal view in degrees.
Appendix 14: Angle of the thigh at takeoff measured from the sagittal view in degrees.

Appendix 15: Angle of the trunk measured from the sagittal view in degrees.
Vitae Auctoris

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