A biomechanical analysis of the single toe loop and the single loop jump of novice figure skaters by Carolyn Marie Petrie Sharp

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Health and Human Development
Montana State University
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Abstract:
The primary purposes of this study were to 1) document the kinematics of a single toe loop and a single loop as performed by novice figure skaters and to 2) determine significant differences in maximum jump height, angular momentum during the flight phase and radial velocity of the right leg during take-off. Each jump consisted of three phases, the approach, take-off and flight phase. For all phases, time duration, average joint range of motion, average maximum and average minimum position were calculated for the following joint angles: shoulder adduction/abduction, shoulder flexion/extension, elbow flexion/extension, hip abduction/adduction, hip flexion/extension, trunk flexion with the ice surface, knee flexion/extension, ankle dorsiflexion/plantar flexion. Additionally, resultant take-off, horizontal, vertical velocities, take-off angle and radial velocity of the right leg were calculated for the takeoff phase. For the flight phase, maximum jump height, jump length, total moment of inertia, segmental contribution to total moment of inertia, angular momentum and angular velocity were also calculated.

The six novice female subjects of this study completed at least one single toe loop and one single loop jump in the field of view of two cameras. The video data were synchronized using an algorithm developed by Yeadon and King (1999) using Matlab (MathWorks, Inc., 1999). The kinematic data was analyzed using the Peak Motus Motion Analysis system (Peak Performances Technologies, Inc., Englewood, CO) to obtain the angular position of the elbow, trunk, knee, ankle as well as the linear positions of all segment endpoints. Angular momenta was calculated, as outlined in Hay, Wilson and Dapena (1977), using Jensen’s (1989) inertial data sets. Radial velocity was calculated as the time rate of change of the distance between the right ankle and the right hip.

In this study, it was found that there were differences, between the two jumps, in the lower extremity during take-off and flight. The left knee and ankle in the toe loop showed more range of motion than in the loop. However, in the loop, the left leg tended to “wrap” around the right leg during flight. No significant differences were found, in maximum jump length, angular momentum and radial velocity. It was concluded that there are other more significant elements of the toe loop that show a distinct advantage over the loop.
A BIOMECHANICAL ANALYSIS OF THE SINGLE TOE LOOP AND THE SINGLE LOOP JUMP OF NOVICE FIGURE SKATERS

By

Carolyn Marie Petrie Sharp

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

The primary purposes of this study were to 1) document the kinematics of a single toe loop and a single loop as performed by novice figure skaters and to 2) determine significant differences in maximum jump height, angular momentum during the flight phase and radial velocity of the right leg during take-off. Each jump consisted of three phases, the approach, take-off and flight phase. For all phases, time duration, average joint range of motion, average maximum and average minimum position were calculated for the following joint angles: shoulder adduction/abduction, shoulder flexion/extension, elbow flexion/extension, hip abduction/adduction, hip flexion/extension, trunk flexion with the ice surface, knee flexion/extension, ankle dorsiflexion/plantar flexion. Additionally, resultant take-off, horizontal, vertical velocities, take-off angle and radial velocity of the right leg were calculated for the take-off phase. For the flight phase, maximum jump height, jump length, total moment of inertia, segmental contribution to total moment of inertia, angular momentum and angular velocity were also calculated.

The six novice female subjects of this study completed at least one single toe loop and one single loop jump in the field of view of two cameras. The video data were synchronized using an algorithm developed by Yeadon and King (1999) using Matlab (MathWorks, Inc., 1999). The kinematic data was analyzed using the Peak Motus Motion Analysis system (Peak Performances Technologies, Inc., Englewood, CO) to obtain the angular position of the elbow, trunk, knee, ankle as well as the linear positions of all segment endpoints. Angular momenta was calculated, as outlined in Hay, Wilson and Dapena (1977), using Jensen’s (1989) inertial data sets. Radial velocity was calculated as the time rate of change of the distance between the right ankle and the right hip.

In this study, it was found that there were differences, between the two jumps, in the lower extremity during take-off and flight. The left knee and ankle in the toe loop showed more range of motion than in the loop. However, in the loop, the left leg tended to “wrap” around the right leg during flight. No significant differences were found, in maximum jump length, angular momentum and radial velocity. It was concluded that there are other more significant elements of the toe loop that show a distinct advantage over the loop.
CHAPTER ONE

INTRODUCTION

The technical details of figure skating have rapidly increased in difficulty over the past twenty years. Over that time, figure skaters have developed from graceful performers to stellar athletes (Aleshinsky 1987). Most of the current elite male and female figure skaters incorporate a variety of triple revolution jumps into their programs. Even more amazingly, a few male figure skaters have been able to complete “quad” jumps, quadruple revolutions, in competition. As more skaters perform outstanding feats, each skater must strive for innovative and more impressive elements to outdo their competition.

This pressure is also realized by coaches. A typical jump lasts less than one second, making it extremely hard for a coach to “see” the small details of any jump. Correcting or emphasizing even the smallest of details may help the skater to achieve greater accomplishments on the ice. Therefore, elite coaches have expressed a need to have a complete understanding of what is happening during a jump. In an effort to assist coaches and athletes, biomechanists have been recruited to carefully analyze the finer details of figure skating jumps.

Aleshinsky (1987) launched one of the first biomechanical studies of figure skating jumps. He emphasized the waltz, Axel, Salchow, toe loop, and flip of two
figure skaters. Takeoff velocity, mechanical energy, actual number of revolutions, time of flight, and moment of inertia were reported for each jump. From this study, Aleshinsky revealed several interesting characteristics related to better jump techniques.

The first and foremost discovery was the importance of generating a high vertical take-off velocity. A high take-off velocity yields greater jump heights and therefore more time for additional revolutions in the air. One of the training recommendations suggested by Aleshinsky was that the skaters improve their adductor muscle strength. Strong adductor muscles are important for the skater to initiate large angular velocities in flight. Since a skater has constant angular momentum after take-off, if the skater wants to increase angular velocity, s/he must decrease her/his moment of inertia during flight. Decreasing one's moment of inertia can be done by quickly pulling in his/her limbs toward the body. A motion that requires strong adductor muscles. Aleshinsky concluded with a call for a more detailed analyses of figure skating jumps, as well as understanding the differences among novice, advanced and elite figure skaters.

King, Arnold & Smith (1994) developed a detailed kinematic study of the Axel jump in figure skating, the most difficult of jumps. Five elite skaters performed single, double and triple Axels. The authors selected the following variables to analyze the jumps; take-off lengths, skid lengths, skid widths, jump lengths, hip flexion at take-off, take-off angle, vertical velocity at take-off, horizontal velocity at take-off, jump height, rotational velocity, time to the rotating position and tilt. It was determined that as the skaters increase their revolutions, they tended to
have shorter horizontal jump distances and similar jump heights. The authors found that as skaters increased their number of revolutions, the skaters increased their rotational velocities at take-off and decreased their moments of inertia.

Albert and Miller (1996) focused their research on take-off characteristics of single and double Axels. These researchers emphasized the defining features of the three phases of the take-off; the glide, the transition and the pivot. During the glide phase, more than half of the angular momentum was generated. As the skater moved into the transition phase, they changed from a horizontal direction to a vertical direction of motion. This resulted from the blocking motion of the skate where they rotated over a fixed point, or the contact skate with the ice surface. This was defined as the tangential component of a skaters motion. A radial component was also calculated for these skaters. The radial component was defined as the vertical length rate of change between the contact toe and the center of gravity of the skater. The sum of the vertical component of the tangential and the radial component equaled that of the vertical velocity of the center of gravity. Towards the end of the transition phase, the radial component became positive and essentially the total upward velocity. Angular momentum remained constant or decreased throughout the transition phase. During the pivot phase, the skater tended to lose horizontal and vertical speeds as well as angular momentum.

Little research has been conducted on the kinematics of toe pick jumps, namely, flip, lutz and toe loop jumps. The toe loop is perhaps the easiest of all the toe-pick jumps. It is the first pick jump taught before the loop. Both jumps only require a half of revolution for a single jump. The approach for the toe loop and the
loop are very similar. The only difference is that the toe loop is performed with a toe assist, hence a pick jump, whereas the loop uses the edge of the blade for take-off.

To perform a typical toe loop, the skater uses the left toe to pick into the ice and extend the right leg. The skater then spins counterclockwise. The loop jump is executed by crossing the left leg, or the free leg, over the right leg. The right leg is extended and using the long edge of the skate to push against the ice. Then, the skater is able to propel themselves into the air. These two jumps are taught early in a skater’s career, first learning the single toe loop jump and followed by the single loop jump. So, in the spirit of Aleshinsky’s recommendations, this study included a novice figure skating sample performing both single loop jumps and single toe loop jumps.

The main goal of this study was to compare the take-off of the toe loop with that of the loop. The defining difference, as above mentioned, is the use of an edge versus the use of a toe pick. The potential differences between these two jumps are the resulting airborne angular momentum and the radial velocity on ice as well as maximum vertical distance achieved in air. Therefore, it is possible that the two most critical parameters for successful jumps are angular momentum and vertical velocity.

The first hypothesis was that angular momentum would be different between the two jumps since the toe loop appears to possess an advantage to allow the current elite athletes in completing “The Quad”, actually a 3.5 revolution jump. The second hypothesis stated that maximum jump heights of the toe loop would be greater than the loop. Although, King et al (1994) found that jumps heights did not change as the
number of revolutions increased for the Axel jumps, it was thought that this may not be the case between two different jumps. Again, this was an attempt to discern between two jumps. The final hypothesis of this study concerned the radial velocities of the skaters. The loop jump is essentially a one leg jump whereas the toe loop uses both legs to send the skater into the air. Therefore, it seemed that the right leg of the loop would show a greater rate of hip and knee extension. The radial velocity in this study, ankle to hip, was not defined in the same way as Albert and Miller (1996), toe to center of mass.

The results of this study will help to understand some of the differences between the take-off of the single toe loop jump with the combined extension of both the right and left legs with the left toe assist and take-off on the right edge of the skate in the single loop jump. This information may aid coaches in finding techniques to help a skater progress to the next ability level and/or isolate techniques that have a distinct advantage to completing greater physical accomplishments. The data from this study may also serve to understand the continuum of abilities and techniques of a developing novice figure skater to the most accomplished elite figure skaters.

Statement of Purpose

The primary purpose of this study was to describe selected kinematic and kinetic differences between single toe loop jumps and single loop jumps of novice figure skaters, particularly limb joint angles, ranges of motion, whole body moments
of inertia, angular momenta, and limb contribution to whole body angular momentum.

**Descriptive Goals**

The descriptive goals of this study were:

1. To describe selected kinematic and kinetic variables of a single toe loop jump.
2. To describe selected kinematic and kinetic variables of a single loop jump.

**Hypotheses.**

The three hypotheses of this study were:

1. The take-off phase of the single loop jumps require significantly faster radial extension velocities \( (RV_L) \) of the right leg (support leg) than the single toe loop \( (RV_{TL}) \) jumps during the take-off phase.

   \[ H_0: RV_L = RV_{TL} \]
   \[ H_a: RV_L > RV_{TL} \]

2. Single toe loop jumps have significantly greater angular momenta \( (AM_{TL}) \) about the vertical axis in the flight phase than single loop jumps \( (AM_L) \).

   \[ H_0: AM_{TL} = AM_L \]
   \[ H_a: AM_{TL} > AM_L \]
3. Single toe loop jumps have significantly higher maximum jump heights ($JH_{TL}$) during the flight phase than single loop jumps ($JH_L$).

$H_0$: $JH_{TL} = JH_L$
$H_a$: $JH_{TL} > JH_L$

Limitations

The limitations of the study resulted from sample size, instrumentation, and skater consistency. The sample size limitation in this study was due to the availability and ability of the novice skaters. Limitations inherent to data collection included the inability to gen-lock the cameras and lighting. The sample frequency of the data collection was 60 Hz. To place three cameras around the Great Falls' rink, some compromises were made in lieu of ideal camera angles for data collection. Two sides of the rink were adjacent to walls. A third side was adjacent to a set of bleachers. The remaining fourth wall was sufficient to place two cameras. The third camera was placed through a doorway to the rink. Manual digitizing each video frame created additional error in data gathering as well as using surface markers to locate joint centers. An additional limitation may have been introduced by the skaters inability to perform both jumps with equal ability.
The scope of this study was delimited to novice skaters in the Great Falls, Montana area. These skaters had learned both the single toe loop and the single loop jump within the last two years and were able to complete these jumps prior to filming.

**Definitions**

- **RBO:** Right back outside edge
- **LBO:** Left back outside edge
- **RBI:** Right back inside edge
- **LBI:** Left back inside edge
- **COM:** Center of Mass
- **ROM:** Range of Motion

**Angular Momentum:** the product of an object’s moment of inertia and its angular velocity, the rate change of angular position.

**Center of mass:** (COM) The point at which a body would balance if it were supported at that point; the point at which the body’s mass is assumed to be concentrated. (Kriegbaum & Smith, 1996).

**Moment of Inertia:** (MOI) the measure of an object’s resistance to change its motion about an axis. Within the human body, the rotation is specified to one of the three cardinal axes of the body. In this study, mediolateral and longitudinal rotations of a limb were referenced to the global vertical axis. The moment of inertia is precisely defined as the product of an object’s mass and its radius of gyration squared.
Radius of Gyration: A measure of the distribution of a body's mass relative to an axis of rotation around which it is being rotated. (Kriegbaum & Smith, 1996).

Radial Velocity: the time rate of change in distance between the ankle and hip.

Tangential Velocity: forward motion of a skater as they rotate over a fixed point.

Jumps

Flip: skating backward on the inside edge of the left leg, the right toe pick is used to assist the take-off. After flight, landing is backward on the right leg outside edge (USOC & IBM, 1998).

Lutz: skating backward on the outside edge of the left leg, the right toe pick is used to assist the take-off. After flight, landing is backward on the right leg outside edge (USOC & IBM, 1998).

Salchow: taking off from the left leg, skating backwards on the inside edge of the skate. After flight, landing is backward on the right leg, outside edge (USOC & IBM, 1998).

Loop: taking off from the right leg on the outside edge, backwards. After flight, the landing is backward on the right leg, outside edge (USOC & IBM, 1998).

Toe Loop: taking off from the right leg on the outside edge, backwards, the left leg is planted into the ice for the left toe assist. After flight, the landing is backward on the right leg, outside edge (USOC & IBM, 1998).

Axel: taking off from the left leg, outside edge, skating forward. After flight, the landing is on the right leg, outside edge (USOC & IBM, 1998).
CHAPTER TWO

REVIEW OF LITERATURE

Introduction

There are seven major jumps in figure skating: flip, lutz, toe-loop, loop, Salchow, waltz and Axel. The general differences between all the jumps are differences in the support leg during take-off, edge used for the approach, and how landing is accomplished. The beginning skater starts by learning each jump with a single revolution. They can progress to triple revolutions but rarely to a quadruple revolution. For those skaters willing to stay with the sport and compete, they must not only develop their skills through practice, but they must also understand the technical details of the jumps. Fitz & Postner recognized that this enables a skater to develop cognitive skills which help develop better motor coordination necessary in completing the sequential elements of a jump (FitSumway-Cook & Woollacott, 1995). This knowledge usually comes from highly skilled coaches. However, the jumps and the skills have become more advanced as the competitors themselves have become more athletic. These coaches must grapple with several technical details in less that one second and make good judgements as to what transpired throughout the jump. Therefore, a more sophisticated understanding of figure
skating jumps is needed to help coaches and skaters make better adjustments to the skater's techniques. This requires biomechanists to perform detailed analyses of the jumps and find the essential elements. Over the last twenty years, a number of studies have been conducted to reveal the hidden conditions that comprise a successful jump (Albert & Miller (1996), Aleshinsky (1986), Aleshinsky (1987), King (1997), King, Arnold & Smith (1994).

Despite the analyses performed over the last years, the comprehensive understanding of the biomechanical aspects of figure skating is seemingly in its infancy. Only a few jumps of elite athletes have been studied. However, numerous biomechanical studies have been conducted on similar sports such as: gymnastics, diving and pole vaulting. Notably, many elements in gymnastics require similar techniques to generate the necessary angular momentum to complete the desired revolutions. In particular, the vault is an event in female gymnastics whereby the gymnast must run forward along a track, spring off a board, block with their hands to hurl themselves into the air, complete the desired element in rotation and firmly land onto the mat.

The principle of the conservation of angular momentum is a mechanical concept which is critical to the execution of required elements in both sports. Since angular momentum is the product of an object's moment of inertia and the angular velocity, to maximize their angular rotation, athletes must regulate their body distribution such that it is in the “tightest” position about the rotating axis. Angular momentum is generated from an external torque or eccentric force, a force that does
not act through an object's center of mass. An applied torque induces an acceleration or rotation about an axis.

Algorithms have been developed to quantify a person's angular momentum in flight. For this study, the most appropriate was one developed by Hay, Wilson and Dapena (1977) for a rigid, linked body system. These algorithms have been supplemented with anthropometric data that are appropriate for certain population types. In this study, it was necessary to use the data set from Jensen (1989) which documented the inertial characteristics of a group of subjects between the ages of four and twenty.

In this chapter, some coaching techniques and published biomechanical analyses of figure skating are presented. Certain gymnastic elements reveal some technical aspects of arial performances in athletics. Also, a discussion of calculating angular momentum will be included and the current ideas and methods in synchronizing video data.

**Coaching Techniques of Figure Skating Jumps**

There are several coaching techniques available to skaters in perfecting their style and their jumps. This chapter does not serve as a comprehensive collection of the various coaching styles for all jumps, but rather as to understand the general progression of completing a single toe loop and a single loop jump. The skating techniques are described in terms of counterclockwise rotations, although there are skaters who rotate in a clockwise manner. The information was obtained from
Kathy Weiner, figure skating coach from the Bozeman Valley Ice Garden in Bozeman, Montana.

Much emphasis of coaching is devoted to perfecting a jump. Contemporary skating programs involve several jumps since they constitute a high percentage of the scoring. Before a skater learns any jump in figure skating, they must first master simple skating techniques and balance. The skater learns how to skate forwards, backwards then learns to balance on one foot. After a series of lessons, the skater learns how to skate in a circle, forwards and backwards, then to balance on one inside edge and one outside edge. Next, the skater is ready to rotate 180 degrees on the ice from a forward motion to a backward motion. There are generally two techniques used to do this. The first is a three turn. On one foot, the skater glides forward then arcs to a pivot and rotates the skate such that the skater is then moving backwards. This pattern is shown in Figure 2.1A. The other technique is known as a Mohawk. In this turn, the skater skates forward on one skate and replaces it with the other skate that is in the opposite position as shown in Figure 2.1B (Weiner, 1999).

Figure 2.1 Trace of a Three Turn (A) and a Mohawk (B)
There are several jumps that the skater is capable of learning after mastering the three turn and the Mohawk. Figure skating jumps are grouped by the take-off edge (inside or outside), direction of the take-off edge (forwards or backwards), take-off foot (edge or toe-assisted), and number of revolutions. There are four main parts to any jump; preparation (or approach), take-off, flight and landing. Preparation is the phase just prior to take-off where the body is balanced over the skates and an optimum speed is developed. Take-off is the point at which the skater must begin rotation and generate take-off velocity for optimal height and length of the jump. Jump height is determined by the vertical component of the total velocity, jump length from the horizontal component and take-off angle as the relationship between the vertical and horizontal components. The support leg must rapidly extend to lift the skater into the air. During flight, the skater must adjust their body position such that they may accomplish the number of required revolutions. The skater can increase his/her angular velocity by drawing in his/her arms. For a successful landing, the skater must extend his/her arms to slow the rotation speed. Once the skater makes contact with the ice, s/he must “check” the ice by stopping the rotation, balance on the landing foot, hold the upper body in an upright position and absorb the landing force with a well-bent knee (Keohane, 1978).

All figure skating jumps can be classified into two general types; toe assist jumps and edge jumps. The edge jumps uses the blunt side of the skate to push off from the ice and into the air. A toe assist jump places the toe pick of one skate into the ice and uses the other leg to push up and over the planted skate. After the take-
off, the skater's rotating position is the same for all jumps. Some of the key features to a proper rotating position are: left leg crosses over the right, legs straight, hands are together in front of chest, elbows down and head looking over the left shoulder (Petkevich, 1989).

When the skater is practicing any jump, s/he must constantly consider posture. An erect posture is one of the more aesthetic appeals to figure skating. Solid positioning of the limbs throughout a skating program is essential to winning, however an erect posture can use up to 20% more energy than easy standing (Woch, 1977). While the skaters are mastering these jumps, they must find a way to be poised but not exhaust all their energy. They have to be well-positioned prior to a jump and after completion. Beginner skaters have a tendency to relax after their jump has been completed. Their body position becomes slumped which does not look aesthetically pleasing (Weiner, 1999).

The toe-loop jump is a toe assisted jump and one of the easiest jumps to learn since the upper body and hips rotate half a revolution the ice prior to take-off. One of the first quadruple jumps completed by elite skaters was the quadruple toe loop. In preparing for this jump, the skater is on the left forward inside edge with the left arm and shoulder in front of the right arm and shoulder (Figure 2.2). As the skater steps onto the right forward inside edge, the upper body is square to the direction of motion. By first positioning the left leg behind the skater, s/he swings the leg around during the three turn of the right foot on the ice. This action generates the initial rotation of the jump. The left leg is then placed on the ice behind and just to the side of the skater as the upper body winds up in the clockwise direction. The take-off is a
series of precisely coordinated events. The skater must bring the arms down as the upper body starts to rotate in the counterclockwise direction as the left foot is planted into the ice. After the right leg has been in a deep knee bend, the right leg must quickly extend to direct the skater upward. This motion, along with moving the arms upward, will help the skater generate height in the jump. The toe pick is then used to redirect the horizontal motion of the skater in the vertical direction.

Therefore, the skater should roll over the toe pick and extend their support leg to redirect their motion upward. This single toe loop consists of one half revolution in the air. Finally, the landing edge should line up with the tip of the three turn at the end of the take-off mark. The skater should be balanced over the right back outside edge (Petkevich, 1989). The single toe loop jump tracing is depicted in Figure 2.2.

![Figure 2.2 Pattern of the Single Toe Loop (adapted from Petkevich (1989)).](image)
The loop jump is an edge jump for which the take-off is from the back outside edge of the right foot and landing on the same edge. The preparation into the jump consists of shifting from a left back inside edge and transferring the motion to the right back outside edge. Throughout the entire preparation, the skater is facing in the backward direction. As the skater places the right foot down, his/her legs should begin to bend as the left foot is placed about two feet and at about 40 degrees from the right foot. The left foot then begins to cross over the right and the skater dips down with the arms to the side. During the actual take-off from the ice, the right leg will begin to explosively extend upward with the left leg remaining crossed over the right. The upper body should rotate whilst the support foot is in contact with the ice and at take-off, the upper body is forward, into the jump. Therefore, this jump also consists of one half revolution in the air. The radius of curvature for the take-off edge should be very small, creating a tight circle. Take-off and landing should be in a straight line (Petkevich, 1989). The pattern of the single loop jump is illustrated in Figure 2.3.

Figure 2.3 Pattern of a Single Loop Jump (adapted from Petkevich (1989)).
It has only been in the past twenty years that the undertaking of biomechanical studies of figure skating began. Aleshinsky’s 1986 article in Skating Magazine was one of the first studies conducted on the mechanics of a figures skating jump. The author reported jump lengths, mechanical energy, actual number of revolutions, flight time, and moment of inertia throughout a number of jumps performed by two skaters. Some of the major jumps used in the analysis were namely, the waltz, Axel, 2-Axel, Salchow, 2-Salchow, 3-Salchow, toe loop, 2-toe loop, 3-toe loop and 3-flip. Two other skaters participated in the study, however, they did not perform as many jumps and were often excluded from the analysis. One of the more surprising results was the technique with which elite skaters increase their angular momentum to complete more than one revolution. It was hypothesized that to achieve multiple revolutions, a skater must be very open, increasing his/her moment of inertia at the instant of take-off, and then quickly pulls his/her limbs into a tight position to reach maximal angular velocity. However, as a result of Aleshinsky’s study, it was found that an elite skater would start the rotation in a more closed position on the ice. The author determined that the adductor muscles of the skaters were relatively weak since the skaters were unable to quickly bring their limbs to the longitudinal axis. In the concluding remarks, Aleshinsky emphasized the importance of understanding the mechanics of not only the elite skater but also the advanced and novice skaters. He also made a petition for further research to
"...reveal...biomechanical essence of all key elements of figure skating:...jumps..." (Aleshinsky, 1986).

In a subsequent article by Aleshinsky (1987), a more detailed report was made on junior elite skaters performing the single Axel, the double Axel and if they could, the triple Axel jump. The United States Figure Skating Association Sports Medicine Committee recommended that scientific investigations should begin with the analysis of jumps since "...they are the most crucial, complicated and appreciated part of skating" (Aleshinsky, 1987). In particular, the Axels were chosen to be the first figure skating jumps studied since they are the most difficult to complete.

A three-dimensional analysis was conducted on twenty-two junior elite athletes. Twenty-one anatomical coordinates were used for computations in moment of inertia. Jump height, jump length, horizontal velocity, trajectory angle, support leg knee angle, flight time, number of revolutions, and rotational velocity were obtained from the video footage of the skaters. The information gathered from this study helped researchers and coaches determine the biomechanical characteristics which have the greatest influence on the quality of figure skating jumps. The author concluded that adductor muscles of the arms were the most influential component in the radical change in degree of openness while in mid-flight. Therefore, upper arm exercises are imperative for successful rotations in flight. He also urged the reader to consider the degree of difficulty of gymnastics and track and field in comparison to figure skating. Aleshinsky believed that athletes in figure skating are capable of performing more astonishing jumps. He believed that the athletes were not yet
reaching the maximum jump height, jump length or number of revolutions possible (Aleshinsky, 1987).

Since the publication of the Aleshinsky articles, King, Arnold & Smith (1994) completed a more detailed investigation of single, double, and triple Axels of five elite male skaters. Their goal was to determine which parameters of a jump were the most critical to the completion of a triple Axel and to compare characteristics of a single, double and triple Axel jump. From this study, they were able to conclude that these elite athletes increased the number of revolutions by increasing their rotational velocity, not by increasing their time in the air. This was accomplished by minimizing mass moment of inertia, meaning that skaters quickly drew their arms in towards their body. The authors also found differences among the single, double and triple Axel. The horizontal distance of the triple Axel was 70% the single Axel jump distance. The difference in jump distances was due to the fact that there is a greater skid prior to takeoff in a triple Axel, thereby decreasing their horizontal velocity. It was also found that the triple Axel jump heights did not differ from not only double Axels but also single Axels. They discovered that the skaters would increase their rotations by generating greater levels of angular velocity and not by increasing their time in the air. Therefore, the skater would increase angular velocity about their longitudinal axis by greatly minimizing their moment of inertia (King et al., 1994).

The next step in this investigation of figure skating jumps was to investigate how angular momentum and vertical velocities were generated. Albert and Miller (1996) chose to further analyze takeoff characteristics of single and double Axel
jumps. The authors determined the defining characteristics for each of the three phases in takeoff, namely, glide, transition, and pivot. The glide was defined as free running of the support leg on the forward outside edge. The pivot phase was defined as the very end of the takeoff and characterized as a forward rocking onto the toe picks. The transition phase was between the glide and the pivot phase and usually included a skidding of the blade on the ice surface. They marked the beginning of the transition phase as the point where the skater's center of gravity started an upward motion. They discovered that over half of the angular momentum for flight was generated during the glide phase. During the transition phase, the total vertical velocity was composed of radial and tangential components. The tangential component was the forward motion of the skater as s/he rotated over the “fixed” skate. The radial component was the vertical length rate of change from the toe to the center of gravity (cog) of the skater. At the beginning of the transition phase, the cog total vertical velocity was composed primarily of the vertical tangential velocity. Near the end of this phase, the total vertical velocity was composed mainly of the radial velocity, or the extension rate between the cg and the toe. During the pivot phase, angular momentum, horizontal and vertical velocities were decreased.

In Tables 2.1 and 2.2, characteristics of single revolution figure skating jumps from the previously discussed studies are presented. Dashed lines indicate that those values were not reported in the specified article. The elite skaters in these studies had jumps lengths greater than 2 meters, up to about 4 meters, and jumps heights around 0.5 m, shown in Table 2.1. The skaters' masses ranged from about
47-67 kg and moments of inertia of about 3 kg m² (Albert & Miller (1996), Aleshinsky (1986), King (1997)).

Table 2.1. Compiled averaged (±SD) flight characteristics from literature of single revolution jump.

<table>
<thead>
<tr>
<th></th>
<th>Jump Length (m)</th>
<th>Jump Height (m)</th>
<th>Time of flight (s)</th>
<th>Take-Off Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>King, Arnold &amp; Smith (1994)¹</td>
<td>4.1 (0.31)</td>
<td>0.68 (0.12)</td>
<td>----</td>
<td>32 (4.8)</td>
</tr>
<tr>
<td>Aleshinsky (1986)²</td>
<td>2.30 (0.72)</td>
<td>----</td>
<td>0.55 (0.06)</td>
<td>----</td>
</tr>
<tr>
<td>King (1997)³</td>
<td>2.77 (0.8)</td>
<td>0.43 (0.1)</td>
<td>0.62 (0.1)</td>
<td>----</td>
</tr>
<tr>
<td>Aleshinsky (1987)⁴</td>
<td>2.71</td>
<td>----</td>
<td>0.54</td>
<td>----</td>
</tr>
</tbody>
</table>

1. Reported values for elite male skaters and their single Axel
2. Averaged values for single toe loop, single Axel and single Salchow
3. Reported values for females skaters and their single Axel
4. Reported values for junior elite ladies and their single Axel

Fewer studies have evaluated inertial characteristics of figure skating jumps. Results from these studies are presented in Table 2.3. Vertical velocities ranged from 2.3-3.3 m/s and horizontal velocities from 3.5 to 5.3 m/s. Only Aleshinsky (1986) cited overall take-off velocity with a value of 5.4 (±0.5)m/s. Time of flight was generally around 0.5 s and one averaged take-off angle was reported as 32° (±4.4). Average angular velocities were found to be 4.8 (±0.7) rev/s. All velocities are shown in Table 2.2.

Table 2.2. Compiled averaged (±SD) inertial flight characteristics from literature of single revolution jumps

<table>
<thead>
<tr>
<th></th>
<th>Mass (kg)</th>
<th>Moment of Inertia (kg m²)</th>
<th>Angular Momentum (kg m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albert &amp; Miller (1996)¹</td>
<td>50.2 (4.8)</td>
<td>2.9 (0.8)</td>
<td>16.5 (3.1)</td>
</tr>
<tr>
<td>King (1997)³</td>
<td>67.3 (5.0)</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Aleshinsky (1987)⁴</td>
<td>47.6</td>
<td>3.3</td>
<td>----</td>
</tr>
</tbody>
</table>

1. Reported values for female skaters and their Axel jump
2. Reported values for females skaters and their single Axel
3. Reported values for Ladies single Axel
Table 2.3. Velocity profile of elite skaters in single revolution jumps.

<table>
<thead>
<tr>
<th></th>
<th>Total Velocity (m/s)</th>
<th>Vertical Velocity (m/s)</th>
<th>Horizontal Velocity (m/s)</th>
<th>Flight Angular Velocity (rev/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>King, Arnold &amp; Smith (1994)</td>
<td>---</td>
<td>3.3 (0.31)</td>
<td>5.3 (1.2)</td>
<td>---</td>
</tr>
<tr>
<td>Albert &amp; Miller (1996)</td>
<td>---</td>
<td>2.3 (0.1)</td>
<td>3.5 (0.3)</td>
<td>---</td>
</tr>
<tr>
<td>Aleshinsky (1986)</td>
<td>5.4 (0.50)</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>King (1997)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>4.8 (0.7)</td>
</tr>
<tr>
<td>Aleshinsky (1987)</td>
<td>---</td>
<td>---</td>
<td>5.1 (0.65)</td>
<td>---</td>
</tr>
</tbody>
</table>

1. Reported values for elite male skaters and their single Axel
2. Reported values for female skaters and their Axel jump
3. Averaged values for single toe loop, single Axel and single Salchow
4. Reported values for females skaters and their single Axel
5. Reported values for junior elite ladies and their single Axel

These initial studies have revealed essential details in figure skating jumps. The Axel jump was considered the most difficult jump in a skater’s repertoire and was a logical beginning. However, the most sought after accomplishment of the 1990’s was a quadruple jump. The impressiveness of this jumps has amazed viewers and athletes alike. This new goal for would be champions have aroused researchers to take a closer look into this jump. Since the Quad Toe was the first quad jump completed on the elite level, it was decided to study the single toe-loop versus the single loop, in an effort to understand the essential elements of this jump, which must be one of the easiest jumps with which to complete a jump.
Although some extensive research has been conducted on figure skating jumps, vaulting events in gymnastics provide additional information on the characteristics which may be relevant to the toe loop. Therefore, methods in similar vaulting sporting events, such as gymnastics, were compiled to support this seemingly vaulting technique of the toe loop jump in figure skating. Aleshinsky (1986) believed by looking at the accomplishments of gymnasts, figure skaters were at the beginning of their physical potential in jump height and rotations in the air. In the toe loop jump of figure skating, for example, the left leg is planted into the ice and the skater is vaulted into the air. This action is potentially similar to blocking techniques used in gymnastics.

Kwon, Fortney, & Shin (1990) conducted analyses of the Yurchenko vaults. The researchers found that the Yurchenko vaults with the full twist, as opposed to the layout, resulted in higher performance scores. The full twist was accomplished by shorter contact time with the board, therefore resulting in longer postflight times. The athletes who achieved the full twist also minimized the vertical velocity loss during horse contact. The figure skater may minimize his/her vertical velocity loss as well so they may be able to achieve greater maximum jump heights.

Bruggemann (1994) moved beyond descriptive studies of gymnastics, looking for specific principles, or general mechanisms of gymnastic techniques. Bruggemann found that the authors Prassas (1985) and Prassas, Kelley, and Pike (1986) reported that the limiting factor in the skill of the Schweizer handstand was
due to poor motor coordination and not lack of strength. Motor coordination as well as strength was quintessential in high achievements in sport performance. So, it seemed that an athlete may have the strength to successfully perform aerial events but may have lacked the motor coordination to sequence the events. Therefore, it was imperative that the athletes practice the sequence of their performance to have become more proficient in their skill. Determining the principles of figure skating is the step beyond the kinematic study of figure skating jumps. However, compilation of the descriptive analysis of gymnastics reveals some outlying considerations relevant to this study.

The inexperienced athlete may be hindered by poor motor coordination. The old adage “Practice makes perfect” enforces the idea that perfecting a sequence of steps in any maneuver requires diligent practice. Novice skaters may certainly find that they have not had enough hours on ice to train their central nervous system in physically mastering a jump. Figure skating seems especially difficult for motor coordination. Not only must a skater balance on thin metal blades about 3-4 mm wide, but the skater must also perform aerial feats and do this all on ice! The amazing coordination and skill of the skater is heavily dependent upon motor coordination.

Angular Momentum and Moment of Inertia Calculations

Whilst in the air, the skater must carefully orchestrate their movements as to take advantage of the conservation of angular momentum and complete their specified number of revolutions. While, researchers have been able to quantify a
skater's angular momentum using a compilation of data sets involving moment of inertia and protocols for segmented non-rigid bodies, the methods are not entirely accurate, especially pertaining to children. Therefore, it is necessary to use the most relevant data set to a subject population. Therefore, in this study, the data set from Jensen (1989) was most appropriate for females between the ages of 9 and 16.

The most important parameter used to describe rotational motion is angular momentum. Angular momentum is defined as the product of the angular velocity and the moment of inertia of a rotating object. Angular momentum is generated through a torque which is a force applied to an object that does not pass through its axis of rotation. Angular momentum can be generated from a ground reaction force of a skater extending their leg on the ice. The moment of inertia is an object's tendency to resist change in motion about an axis for a non-rigid body. If the mass is constant, moment of inertia can also be considered an indication of how the mass is distributed about that axis. The degree of mass distribution about an axis is known as the radius of gyration. It is the radial distance from an axis where the mass of a body could be concentrated without altering the rotational inertia of that body about the axis. Moment of inertia is defined as the product of the object's mass and the radius of gyrations squared. The greater the object's mass, the greater the moment of inertia. Also, the greater an object's distribution, such as outstretched arms of a skater, the greater the moment of inertia (Halliday and Resnick, 1988).

Angular momentum is conserved so long as no other external torques or eccentric forces act on the object. This is best demonstrated with the figure skater in a spin. As s/he begins the rotation (angular velocity), the arms are greatly extended
(large moment of inertia). The angular momentum is then a constant value. The skater then brings the arms towards their body, decreasing the moment of inertia, and the angular velocity rapidly increases, therefore conserving the quantity of angular momentum, assuming no influence of friction.

The angular moment of the skater in the air is conserved and generated on the ice immediately before the flight phase. Aleshinsky realized that stronger adductor muscles would allow a skater to quickly minimize moment of inertia and give more room for more revolutions in the air (Aleshinsky 1987).

In human motion, there are generally three axes of rotation about which angular momentum and moment of inertia is calculated: anterior-posterior axis, mediolateral axis and the longitudinal axis. Each axis has its own radius of gyration and thus moment of inertia, and will also have its own angular momentum. For figure skaters, the principle axis of rotation that is of concern is rotation about the longitudinal axis, since jumps and spins involve rotation about the longitudinal axis.

For a non-rigid body, the moment of inertia of the total body is the sum of the individual segment moments of inertia. Therefore, to calculate the total body moment of inertia, the inertial properties of each segment must be calculated. These inertial properties have been measured and estimated by a number of researchers. Segment inertial characteristics vary with gender, age, height and weight. Therefore, the proportions are not the same for everyone and are further complicated if applied to populations before they mature, such as the case in this study. Consider the growth an infant to adolescence, the proportional mass changes at different times
during growth. In Figure 2.4, notice how the infant’s head is a greater proportion of the whole body mass than that of an adult.

Most of the research conducted in this area has restricted the analyses to adult subjects. Moreover, the data sets available have used different approaches to determining the adult inertial characteristics. Dempster (1955) and Chandler et al. (1975) used cadavers as their subject pool. The cadavers were similar to males of small stature. Zastiorsky et al. (1990) used a gamma ray scanning technique to determined live subject inertial characteristics and separate females from the males. The males were more muscular than the Dempster (1955) and Chandler et al. (1975) data sets and the females used were younger as well. Jensen (1986a, 1986b, 1988, 1989) has begun to characterize inertial characteristics of children. His work has lead to regression equations, dependent upon a subject’s age, to determine a segment’s mass, center of mass and radius of gyration (Jensen, 1986).

![Figure 2.4 Changes of the human body during growth. (Adapted from Brooks et al., 1996, p.669.)](image-url)
Synchronizing Video Data

This final section reviews the problems and successes of synchronizing non Gen-locked cameras. Synchronizing is one important method to ensure accurate data. If cameras are not synchronized, it is highly likely that each camera records at different times in an activity. For instance, if two cameras sample at the same rate, but are half a frame out synch, when a direct linear transformation is applied to the data to get 3-dimensional data, the two cameras would be matched at different points in time. This results in an erroneous three dimensional reconstruction of the data. There are three ways to synchronize data.

The first method uses a Gen-locked system, in which all cameras are physically linked to one another. A Gen-locked system of cameras is when one camera is designated as the “master” camera and the other cameras are hard wired from the masters camera as “slaves”. The slave cameras receive the video signal of the master camera, which is used to ensure the video images from each camera are perfectly synchronized in time. This method is an excellent way to synchronize cameras, however, there are some problems with this method. If the camera set-up encompasses a large area, it maybe difficult and expensive to obtain the large footage of wire to link all cameras. If the filming is to happen at a public event, a spectator may unknowingly break the connection.

A second way to synchronize data is to use a timer and revolve it in the calibrated space of the cameras. It would then be possible to know how far off the cameras are from one another. The problem with this method is to find a high
precision timer, capable of marking time faster than the recording rate of the cameras, since a typical recording frequency may be 60-1000 Hz. And similar to method one, if the filming is to take place at a public event, it may not be possible to place a timer in a highly active area.

The third way to synchronize cameras is to determine the disparity between the different cameras using the DLT parameters. In a 1971 article by Abdel-Aziz and Karara, the derivation of eleven DLT parameters is outlined. Typically in photogrammetry, a calibration object is filmed. The filmed object is placed onto a comparator plane such that the calibration points are digitized. For example, a projection of the video onto a screen or monitor, marking the known calibration points is done using a comparator plane. The algorithm outlined in this article relates the calibration points back to object (or three dimensional) space. From this method, eleven DLT parameters are obtained and are unique for each camera. By manipulating these parameters, any point in the camera’s field of view can be related back to the object space (Abdel-Aziz and Karara, 1971).

Yeadon and King (1999) provide a method using the DLT parameters to determine time offset of the cameras. The eleven DLT parameters of two cameras and the pixel two-dimensional coordinates of a joint center of each comparator image are used to find a common x, y, z coordinate.
Four independent equations involving \(x, y,\) and \(z\) are created by expanding equation 1 into the form \(a_i x + b_i y + c_i z = d_i\). Each of the four equations are normalized using \(\sqrt{a_i^2 + b_i^2 + c_i^2}\) and a least squares solution is used to determine \(x, y\) and \(z\). Then a residual term is found for each digitized point on the subject in the form of equation 2.

\[
|r_i| = \frac{|ax_0 + by_0 + cz_0 - d_i|}{\sqrt{a_i^2 + b_i^2 + c_i^2}} \quad (i = 1, 2, 3, 4) \quad \text{(Equation 2)}
\]

For each body landmark that is digitized, a residual is computed for each of the four equations and used to determine a RMS distance expressed as equation 3.

\[
r = \sqrt{\frac{r_1^2 + r_2^2 + r_3^2 + r_4^2}{4}} \quad \text{(Equation 3)}
\]

The RMS is determined from each body landmark in every frame and a global RMS value is calculated using equation 4.
All position data points are interpolated, then the slave camera is shifted by a fraction of the sampling frequency and another global RMS error was calculated. The frames are shifted in both directions, forward and backward until the slave camera is offset by two frames in both directions. The end result is a group of global RMS distances. When plotted, the shape of the graph should look similar to a parabola where there is a distinct minimum. This minimum value is the time offset of the slave camera with the master camera.

In Figure 2.5, this sample data set indicates that the smallest RMS value of 0.0 is at a time offset of 0.5 seconds. This is a mock data set and not actual data time offsets. The slave camera would then be adjusted 0.5 seconds back to line up with the master camera. All position data of the slave camera would be interpolated such that new position data could be selected and lined up with the master camera.
Sample Global RMS Distances and Time Offset Between Two Cameras

![Graph showing sample global RMS distances and time offset between two cameras.](image)

Figure 2.5. Global RMS distances and time offset between two cameras.

**Summary**

To understand the pertinent biomechanical principles of figure skating jumps, one must first realize what is expected of the skater and the fundamental physics that apply to the elements. There are various techniques used by coaches to get a skater to that next level. This discussion does not serve to examine every coaching technique used to help a skater complete the single toe loop or the single loop, rather, outlined here are the basic elements which comprises both of those jumps. There have been numerous studies examining figure skating jump characteristics. This culmination of research in not all encompassing, rather it has been limited to elite athletes and the Axel jump. The jumps, examined in this study, possess similarities to other sporting events, especially gymnastics. Some of the research devoted to gymnastics can be used to extrapolate information to figure skating. Angular
momentum is one of many characteristics, possibly the most difficult to measure, used to catalog the defining features of a figure skating jump. New, innovative ways have been developed to calculate angular momentum, and its component of moment of inertia, of a non-rigid, multi-segmented body, such as a human being. Additional challenges arise with videotaping non-synchronized data. Algorithms have also been developed to rectify this problem; although, there is much room for improvement.
CHAPTER THREE

METHODOLOGY

The methodology used for this study was derived from several sources. Before any data was collected, a pilot study was conducted in an attempt to reduce errors and to find an optimal methodology to collect valid and reliable data. In this chapter, the subject characteristics, data collection and data analyses are presented. Included in this chapter are outlines of algorithms used to write computer programs in which some parameters were calculated. Finally, the statistical procedures for the stated hypotheses of this study are documented.

Pilot Study

A pilot study was conducted on one skater from the Bozeman Valley Ice Garden’s Figure Skating Club in Bozeman, Montana. The pilot study was used to develop the methodology for the actual study conducted in Great Falls, Montana. One female skater, age 8, was selected for analysis. This skater was not included in the overall study because she had not yet mastered the single loop and single toe loop jump.
Three cameras were placed around the rink, at the entrance doors onto the ice (Figure 3.1). A calibration frame of seventeen known points was placed in the jump zone. The calibration frame was comprised of eight poles, each pole extending from a corner of a center cube (Figure 3.2). The cameras were zoomed so that the field of view just encompassed the calibration frame.

C1, C2, C3 = Cameras

Figure 3.1. Schematic of camera set up at Bozeman ice rink.

Figure 3.2. Seventeen point calibration frame.
Joint markers were placed on the lateral side of each shoulder, elbow, knee, and ankle joints as well as, the lateral heel and toe. The subject was wearing dark clothing so that the reflective markers would be visible in camera view. Black electrical tape was used to mark the ankle joint on the white boots. The skater was instructed to perform any jump in the jump zone. The subject did her jumps continuously for ten minutes.

Upon reviewing the video tapes, it was found that bands of white tape would help digitize the joint from more medial views of the joints. Additionally, there was a problem with the white ice skates blending into the floor of the ice rink. This is inherent to collecting figure skating data and no immediate solution was available. During the video review, it was also found that numbering the trial and subject would help determine the correct jump for all three camera views. Lastly, it was not possible to gen-lock the cameras in the ice rink thus, the cameras were not synchronized for the pilot study.

Experimental Sessions

Subjects

Nine novice skaters volunteered to participate in the study. All skaters were members of the Great Falls Skating Club in Great Falls, Montana. Those skaters who could complete a single toe loop and single loop jumps were selected to perform three trials of each jump. Prior to data collection, an informed consent form
and explanation of the study were sent to the participants. Written permission from
the skaters and their parents or guardians was obtained prior to their participation.
The consent forms were written in accordance with the Office of Regulatory
Compliance, Montana State University. Copies of the consent forms are located in
the appendix.

One skater was removed from further analysis because she was well beyond
the age range of the other eight. Two of the remaining skaters were unable to
perform a single loop jump in the field of view of all cameras. The remaining six
skaters averaged (±SD) 12.3 (±2.4) years with a height of 1.5 (±0.1) m and a mass of
42.5 (±14.0) kg. These skaters were able to perform at least one single toe loop and
one single loop in all three camera views.

**Experimental Protocol**

Prior to data collection, skaters were prepared for the study. This consisted
of checking the skater’s clothing for color and fit as well as placing the markers on
anatomical landmarks. The skaters had been instructed to wear dark, form fitted
clothing. They were not allowed to participate unless they complied with this
request.

Eighteen markers were placed on each skater. The locations of the markers
are represented in Figure 3.3. Bands of reflective tape were placed at the shoulder,
elbow, wrist, hip and knee joints. Black electrical tape was used to mark around
each ankle. For the heel and toe, black electrical tape was placed on the lateral and medial sides.

Figure 3.3. Schematic of joint marker locations.

All skaters were asked to warm-up for 15 minutes, prior to performing the jumps. Each skater completed three single toe loops and three single loop jumps during the testing session. The skaters were instructed to perform their jumps in the 2 meter radius jump zone. If any skater missed the jump zone during a trial, that jump was not digitized, and thus, not included in the analyses.

Data Collection

Three Panasonic AG450 cameras (Matsushita Electric Industrial Co., Okayama, Japan) were placed around the rink. Camera 1 was placed 80 meters from the center of the jump zone, area designated for all jumps, and 4 meters from the
Camera 2 was placed on the balcony, 51 meters from the center of the jump zone and 6 meters from the ground. Camera 3 was placed on the balcony, 14.7 meters from the center of the jump zone and 2.9 meters from the ground. The location of all cameras was determined from Kwon (1998), expressed in equation 5.

\[
\begin{bmatrix}
    x_0 \\ y_0 \\ z_0
\end{bmatrix} =
\begin{bmatrix}
    L1 & L2 & L3 \\ L5 & L6 & L7 \\ L9 & L10 & L11
\end{bmatrix}^{-1}
\begin{bmatrix}
    -L4 \\ -L8 \\ -1
\end{bmatrix}
\]

(Equation 5)

\(L_i\) DLT parameters
\(x_0, y_0, z_0\) camera’s global coordinates

The angles between the cameras were calculated to be 27 and 141-degree angles between cameras C1 & C2 and C2 & C3, respectively (Figure 3.4). The shutter speed was set at 1/500 for all cameras. Each jump was recorded on TDK SVHS tapes at 60 Hz.

Figure 3.4 Camera angles and setup at Great Falls ice rink.
A calibration frame of eight rods, containing three, two inch diameter white balls was placed into the jump zone prior to data collection of the jumps. The calibration frame was set on a tripod whereby each rod extended from the corner of a center cube (Figure 3.2). All three cameras were set to record the individual view of the calibration frame for one minute prior to the jumps of the skaters. After the calibration frame was removed from the ice, the cameras were not moved during the entire data collection period. The resulting error after the calibrations was an average volume percent error of 0.37% and an average mean square error of 0.012 meters. These were acceptable results of the calibration.

Data Analysis

Data Reduction

All video footage was digitized and analyzed with the Peak Motus Motion Analysis System (Peak Performance Technologies, Inc., Englewood, CO), referred to as PEAK throughout this study. Prior to digitizing the data, the calibration frame was digitized so that the jump zone was correctly scaled in three-dimensional space. Afterward, each jump was manually digitized in all three cameras views. During the manual digitizing of the anatomical landmarks of each skater, if a particular landmark was not visible in one camera view, the point was not digitized. Two techniques were used to obtain the missing data which resulted from the non-digitized landmarks. The first step was to plot the trajectory of each point and fill in
the missing data points by manually digitizing. However, this method was not able to fill in all gaps. Thus, the remaining gaps were interpolated in PEAK. The position data obtained from the PEAK system were filtered with an 8 Hz Butterworth Low Pass Filter.

Next, the cameras were synchronized using methods describes in Yeadon and King (1999). The algorithm was written in Matlab v.5 Student Edition (MathWorks, Inc., Natik, MA). Camera one (C1) was determined to be the master camera whereas camera two (C2) and three (C3) were chosen to be the slave cameras. It was found that C2 could be synchronized with C1. However, C3 could not be synchronized with C1 or C2. It was then decided that two cameras would be used for the transformation of the two-dimensional coordinates to three-dimensional object space. Using direct linear transformation equations, the filtered data was transformed from each of the two dimensional camera coordinates to the actual three dimensional coordinates.

Calculation of Joint Angles

From the transformed, filtered data, trunk flexion/extension with the ice surface, knee flexion/extension, ankle plantar flexion/dorsiflexion and elbow flexion/extension were calculated using PEAK. The knee and elbow were referenced to 180 degree full extension. A trunk angle of 90 degrees was set for a fully erect position and zero degrees would indicate the trunk as parallel with the ice surface. Ankle angle was computed as the included angle, between the foot and the
leg, and adjusted in an Excel (Microsoft Excel 97) worksheet such that a negative value indicated dorsiflexion and a positive value was plantar flexion. The greater the magnitude of the ankle angle, the greater the state of a particular flexion. All angles were calculated in their local reference frame except the trunk angle which was defined for a global reference frame. Figure 3.5 illustrates how each angle was defined.

![Diagram of angles](image)

Figure 3.5. Angles calculated using PEAK

Calculations of hip adduction/abduction, hip flexion/extension, shoulder adduction/abduction, shoulder flexion/extension, whole body center of mass and take-off velocities were computed in a separate Matlab program. Adduction and abduction angles were calculated in a local reference frame, one for the shoulder complex and another for the hip complex. Figure 3.6 illustrates the adduction and
abduction angles. Adduction was allocated a negative value and abduction positive.

An absolute increase in any angle indicated a greater degree of the adducted or abducted position. Hence, the shoulder and hip adduction/abduction angles in degrees were determined by equations 6 & 7.

\[
\Theta_{SAA1} - \Theta_{SAA2} = \Theta_{\text{Shoulder Adduction/Abduction}} \quad \text{(Equation 6)}
\]

\[
\Theta_{HAA1} + \Theta_{HAA2} - 180 \text{ degrees} = \Theta_{\text{Hip Adduction/Abduction}} \quad \text{(Equation 7)}
\]

Where

- \( SAA1 \): the angle with the shoulder line with the forearm
- \( SAA2 \): the angle between the shoulder line and the trunk
- \( HAA1 \): the angle between the hip line and the trunk
- \( HAA2 \): the angle between the hip line and the thigh

Figure 3.6. Illustration of hip and shoulder adduction and abduction angle calculations.
Similarly, hip and shoulder flexion/extension angles in equations 8 & 9 were determined in the respective reference frames. The schematic shown in Figure 3.7 demonstrates how these angles were calculated. The abbreviation, A/P refers to the anteroposterior line of each coordinate system (a separate hip and shoulder coordinate system)

\[
\Theta_{SFE2} - \Theta_{SFE1} = \Theta_{\text{Shoulder Flexion/Extension}} \tag{Equation 8}
\]

\[
180 \text{ degrees} - \Theta_{HFE1} + \Theta_{HFE2} = \Theta_{\text{Hip Flexion/Extension}} \tag{Equation 9}
\]

Where
- SFE1: the angle between the shoulder A/P line and the forearm
- SFE2: the angle between the shoulder A/P line and the trunk
- HFE1: the angle between the hip A/P line and the trunk
- HFE2: the angle between the hip A/P line and the thigh.

Figure 3.7. Illustration of hip and shoulder flexion and extension calculations.
Flexion was marked as a positive value and extension, negative. Absolute increases in both values indicated a greater degree of either position. The whole body center of mass (COM) was determined in a Matlab algorithm. Percent mass and center of mass location of each segment was obtained from regressions equations listed in Jensen (1989). Jensen’s data is pertinent to subjects between the ages of four and twenty and thus appropriate for the subjects selected for this study.

Linear Velocity Calculations

The displacement of the whole body COM was then used to determine vertical and horizontal velocities at take-off. The whole body COM location was determined by Equation 10.

\[
\text{Coordinate Total COM} = \frac{\sum_{i=1}^{12} \sum_{j=1}^{3} \text{Mass}_i \times \text{COM}_{ij}}{\text{Total Mass}} \quad \text{(Equation 10)}
\]

Equation 11 & 12 demonstrate how these velocities were calculated whereas Figure 3.8 pictorially represents the results of the calculations.

\[
\text{Vertical Velocity} = V_v = \frac{\Delta Y}{\Delta \text{time}} \quad \text{(Equation 11)}
\]

\[
\text{Horizontal Velocity} = V_h = \sqrt{\Delta X^2 + \Delta Y^2} / \Delta \text{time} \quad \text{(Equation 12)}
\]
From the vertical velocity at take-off, maximum jump height during flight was calculated using the projectile motion Equation 13. Jump length of the flight phase was calculated from another projectile motion equation (Equation 14).

\[ D_{\text{vertical}} = \frac{V_v^2}{2a} \]  

(Equation 13)

\[ D_{\text{vertical}} = V_{hf} \times \text{time} \]  

(Equation 14)

Where: \( a \) acceleration due to gravity
Airborne Rotational Calculations

The transformed three-dimensional position data was also used in a computer program, created in Matlab, to calculate the skaters moment of inertia, angular velocities, angular momentum and segmental contribution of inertia to whole body moment of inertia. The data was truncated to only account for the flight phase of each jump. Anthropometric and inertial characteristics were obtained from Jensen (1988, 1989) to determine segment center of mass, moments of inertia of all segments in all three anatomical axis systems and segment mass. All parameters were a function of an individual’s age.

Angular momentum and moment of inertia was calculated using the following algorithms. Angular momentum (H) was defined as the product of moment of inertia and angular velocity. The moment of inertia was defined as the product of the mass (m) of an object with its radius of gyration (k) squared. The radius of gyration is a measure of how spread out the object it. For a rigid, non-linked body, angular momentum is calculated using Equation 15.

\[ H = m \times k^2 \times \omega \]  
(Equation 15)

The human segment model is a linked, non-rigid system. A procedure derived from Hay, Wilson and Dapena (1977) was used to obtain angular momentum and moments of inertia for a human, or a linked, subject. Modifications of the program were made to calculate along the longitudinal axis of an athlete as opposed to the transverse axis in the article. Adjustments were also made with respect to the authors’ assumption that there was no motion out of the plane of rotation.
Within the method developed by Hay et al. (1977), the total angular momentum is derived from the sum of a local and transfer term of all segments. The local term (Equation 16) is the calculation of the moment of inertia of a segment through its center of gravity that is parallel to the vertical axis. Jensen's (1989) calculated inertial characteristics in each of the cardinal axes (anteroposterior, mediolateral, longitudinal) for each segment of the human body were used in these analyses.

\[ H_{\text{local}} = \sum_{i=1}^{12} (I_{sy})_{ni} * (I_{sy})_{i2} \sin \theta / \delta t \]  

(Equation 16)

- \( H \)  local angular momentum
- \( i \)  segment number
- \( I \)  moment of inertia of individual segment's com
- \( s \)  segment's com
- \( y \)  vertical axis
- \( \theta \)  angular position of segment onto x-z plane
- \( \delta t \)  time step between frames

In this study, the segments did not necessarily remain in one cardinal plane throughout the jump. Therefore, an adjustment was made to each segment, whereby the ratio of the segment's projected length onto the x-z, or horizontal, plane to the actual length was calculated. This resulted in an angle from which a segment was separated from the vertical line through the total center of mass. The mediolateral (MMOI) and longitudinal (LMOI) moments of inertia were calculated to help acquire a more precise moment of inertia about each segment. For example, when the projected length was equal to the actual length, the quotient would equal one, and the longitudinal axis of a segment was parallel to the horizontal plane. Therefore,
the local moment of inertia would be about the mediolateral axis. In another example, when the segment’s longitudinal axis was completely in line with the vertical axis, the quotient would equal zero. Here, the local moment of inertia would be about the longitudinal axis of rotation. So, when a segment was at an angle with both the horizontal and vertical axis, the appropriate proportion of both the mediolateral and longitudinal axis of rotation of the segment, as it related to the vertical axis, was calculated. The angular displacement, theta, was that of the rotation of a segment projected onto the x-z or horizontal plane.

\[
SEGMOI_{\text{vertical}} = LMOL_{\text{seg}} + \left( MMOL_{\text{seg}} - LMOL_{\text{seg}} \right) \times \left( \frac{\text{Length}_{\text{projected}}}{\text{Length}_{\text{actual}}} \right)^2 \tag{Equation 17}
\]

The transfer term of the angular momentum was calculated using Equation 18. Here, the distance of a segment’s center of gravity with the total center of gravity were used to account for the positioning of all segments about the vertical axis through the total center of gravity. Phi was the rate change of the line between a segment’s center of gravity and the total center of gravity.

\[
H_{\text{transfer}}(\tau) = \sum_{i=1}^{12} \left[ m_i \times (r_{SR})_i \times (r_{SR})_2 \times \sin \phi \right] / \Delta t \tag{Equation 18}
\]

- \( H \): transfer angular momentum
- \( i \): segment number
- \( m \): mass of individual segments
- \( r \): distance between segment’s com and the whole body com
- \( s \): segment’s com
- \( y \): vertical axis
- \( \phi \): change in angular position of the vector \( r \)
- \( \Delta t \): time step between frames
The basic design of the angular momentum algorithm was to calculate individual segmental rotation about the longitudinal axis, or the local term of the segment, and the rotation about the center of the body, or the transfer term. Then, the two terms were combined to produce the total moment of inertia or angular.

Jump Phases

Each jump was partitioned into four stages; the approach, takeoff, flight, and landing. The approach is defined as the skater traveling backwards with their entire body fully in view of the camera until the point at which the skater turns perpendicular to the general approach and flight path. This phase was fixed to contain only 0.10 seconds prior to the approach endpoint. The takeoff was defined as the point at which the skater was perpendicular to their approach and flight path to the instant in time where the last skate leave the ice surface. The flight phase was defined as the instant the last skate leaves the ice to the instant the first skate touches the ice surface. Landing was the instant in time where the first skate touches the ice surface to the point where the free leg leads the body in motion. The phases are illustrated in Figure 3.9 with a representative single loop jump. It should be noted that both jump phases were partitioned, by using the same phase definitions.
Figure 3.9. Positioning of skater to denote phase endpoints.

For all phases, excluding the landing phase, average range of motion, average maximum and minimum joint position for shoulder flexion/extension, shoulder adduction/abduction, elbow flexion, hip flexion/extension, hip adduction/abduction, knee flexion, trunk angle with the ice surface and ankle dorsiflexion/plantar flexion were tabulated. Additionally, the take-off included radial velocity of the right (support) leg, takeoff angle, vertical speed, horizontal speed and total speed. Radial velocity was calculated as the length rate of change of the distance between the right ankle and the right hip. The flight phase included jump height, jump length, time in air, angular momentum, moment of inertia, angular velocity, and segmental contribution to whole body moment of inertia. Segmental contribution was organized as right and left arm (including upper arm, lower arm and hand), right and left leg (including thigh, shank and foot) and the trunk (including trunk, head and neck).
Summary or descriptive statistics were computed for trunk angles, shoulder angles, elbow angles, hip angles, knee angles, and ankle angles for each phase of each jump. Means and standard deviations of all joint angle's range of motion, maximum and minimum position were tabulated in the results and discussion chapter. Mean age, weight and height of the six skaters were reported along with standard deviations.

The hypotheses were tested with a paired T-test. The radial velocity of the right leg during take-off was thought to be greater in the single loop than the single toe loop. Angular momentum throughout the flight phase anticipated to be greater for the single toe loop than for the single loop. Maximum jump height during flight was hypothesized to be greater for the single toe loop than the single loop. The significance level of these tests were chosen to be at an alpha of 0.05, with the corresponding Bonferroni adjustment, $0.05/3 = 0.0167$.

Another adjustment made to the data set was to average the trials of each jump of one skater. Every skater selected for analysis completed at least one of each jump in the field of view of all cameras. Therefore, some skaters were able to complete only one jump whereas others could complete two or three. In all there were 14 completed loop jumps and 10 completed toe loop jumps. Table 1 shows the number of jumps available for analysis for each skater. All parameters were calculated across all trials. Then, averages of the parameters were obtained by each skater therefore, resulting in six values for each variable in each jump.
Table 3.1. Number of completed jumps by subject

<table>
<thead>
<tr>
<th></th>
<th>Subject 1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Toe Loop</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
CHAPTER FOUR

RESULTS AND DISCUSSION

Subject Characteristics

Initially nine female individuals, seven senior level and two junior level as defined by the Great Falls Skating Club, participated in this study. They were all able to complete both the single toe loop and single loop jump. One senior level subject was several years older than the other eight and therefore completely eliminated from further analysis. Two other subjects were not included in the results because they were unable to perform their single loop jumps in the jump zone. The remaining six subjects were able to perform at least one single loop and one single toe loop jump in the jump zone. All skaters were counterclockwise rotators and used similar approaches into all jumps. Their right leg was the support leg, they rotated counterclockwise, the left leg was used for the toe assist in the toe loop and all landings were on the right leg. Descriptive statistics of the six subjects are presented in Table 4.1.
Table 4.1. Subject Summary (n=6)

<table>
<thead>
<tr>
<th></th>
<th>Age (yrs)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>12.3</td>
<td>1.49</td>
<td>42.48</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.4</td>
<td>0.10</td>
<td>13.97</td>
</tr>
</tbody>
</table>

In the following discussions, most joint positions and ranges of motion were not different from one another. This study was not designed to test for significant differences in these particular qualities of the jumps. Large standard deviations illustrated the wide range of techniques used by the novice skaters. Thus, while many of the unique individual characteristics were lost by averaging the data, general trends were observable in the data and are discussed in this section.

Both jumps were broken into three phases. The approach phase was 0.1 s prior to the skater rotating their hips perpendicular to the line of motion. The second phase, take-off, was from the end of the approach phase until the skater left the ice. The third phase, flight, was the time the skater was in the air until the very instant of landing when the skater touched the ice surface. In Table 4.2 the average time elapsed for all phases is reported as well as the percent time of the entire jump sequence. The flight phase of the single loop was a slightly greater percentage than the loop, whereas the take-off phase of the toe loop was slightly greater percentage. During the toe loop, the skaters must take more time for the left toe pick during the take-off phase which may account for the greater time period during the jump.
Table 4.2. Average (SD) elapsed time and percent duration for each phase

<table>
<thead>
<tr>
<th></th>
<th>Approach Phase</th>
<th>Take-Off Phase</th>
<th>Flight Phase</th>
<th>Total Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop</td>
<td>0.1 (+0) s</td>
<td>0.12 (+0.03) s</td>
<td>0.31 (+0.03) s</td>
<td>0.53</td>
</tr>
<tr>
<td>%</td>
<td>19%</td>
<td>23%</td>
<td>58%</td>
<td>100%</td>
</tr>
<tr>
<td>Toe Loop</td>
<td>0.1 (+0) s</td>
<td>0.17 (+0.06) s</td>
<td>0.27 (+0.07) s</td>
<td>0.54</td>
</tr>
<tr>
<td>%</td>
<td>19%</td>
<td>31%</td>
<td>50%</td>
<td>100%</td>
</tr>
</tbody>
</table>

The first part of this section is devoted to a kinematic description of the single loop followed by a kinematic description of the single toe loop. Each jump is partitioned by phase; approach, take-off and flight. Within each phase, kinematics of the upper extremity, trunk and lower extremity are presented and discussed along with unique characteristics of each phase.

**Single Loop Jump**

The single loop jump is an edge jump where take-off is from the right leg on the outside edge, backwards. After flight, landing is on the right outside edge. This jump is usually taught as the next jump after the student has learned the toe loop.

**Approach Phase**

The approach phase of each jump was defined as 0.10 seconds prior to the point where their hips and contact foot were perpendicular to the line of motion. This time period was the same for both the single loop and the single toe loop.
Upper Extremity. The variables for the upper extremity in this study consisted of the shoulder and elbow joints. The averaged ranges of motion, averaged maximum joint position and averaged minimum joint position are presented in Table 4.3.

Table 4.3. ROM, max and min joint angles for the upper extremity of the loop jump in the approach phase.

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Flexion/Extension</td>
<td>Mean ° (±SD)</td>
<td>Mean ° (±SD)</td>
</tr>
<tr>
<td>ROM</td>
<td>27.65(±26.31)</td>
<td>38.50 (±37.06)</td>
</tr>
<tr>
<td>Maximum</td>
<td>45.50(±25.34)</td>
<td>23.65(±42.31)</td>
</tr>
<tr>
<td>Minimum</td>
<td>17.85(±39.08)</td>
<td>-14.85(±28.40)</td>
</tr>
<tr>
<td>Shoulder Adduction/Abduction</td>
<td>Mean ° (±SD)</td>
<td>Mean ° (±SD)</td>
</tr>
<tr>
<td>ROM</td>
<td>31.95(±13.16)</td>
<td>35.78(±18.63)</td>
</tr>
<tr>
<td>Maximum</td>
<td>65.84(±15.52)</td>
<td>69.55(±18.39)</td>
</tr>
<tr>
<td>Minimum</td>
<td>33.87(±14.24)</td>
<td>33.78(±25.77)</td>
</tr>
<tr>
<td>Elbow Flexion</td>
<td>Mean ° (±SD)</td>
<td>Mean ° (±SD)</td>
</tr>
<tr>
<td>ROM</td>
<td>35.66(±5.57)</td>
<td>26.97(±12.69)</td>
</tr>
<tr>
<td>Maximum</td>
<td>147.42(±14.93)</td>
<td>136.53(±22.10)</td>
</tr>
<tr>
<td>Minimum</td>
<td>111.76(±16.63)</td>
<td>109.56(±23.96)</td>
</tr>
</tbody>
</table>

The left shoulder tended to flex in this phase, starting at an average position of 18° (±39) with an average range of motion of about 38° (±37). However the right shoulder extended during this phase from 24° (±42) with an average range of motion around 28° (±26). The upward motion of both shoulders, similar to shrugging, may contribute to the vertical motion of the upper body the approach phase. In addition to this motion, both shoulders had a tendency to adduct. Both the right and left shoulder exhibited about the same range of motion and maximum and minimum position.
Trunk Flexion. The trunk segment was always in a flexed position with the ice (Table 4.4). At no point in the loop jump did the trunk extend for any skater. Additionally, just prior to take-off, each skater exhibited a sharp increase in trunk flexion. Although both the right and left side of the trunk had similar ranges of motion, they were not always in the same position, thus the trunk did not act like a rigid body. The max and min position of the left trunk, \((77° (±10)\) and \(67° (±7)\)), seem to indicate a more erect position as compared to the right trunk, \((64° (±5)\) and \(55° (±7)\)). However, this variable was very individualistic and the left was not always more erect than the right trunk.

Table 4.4. ROM, max and min joint angles for the trunk of the loop jump in the approach phase.

<table>
<thead>
<tr>
<th>Trunk Flexion</th>
<th>Right Mean ° (±SD)</th>
<th>Left Mean ° (±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM</td>
<td>8.70(±5.15)</td>
<td>9.67 (±3.19)</td>
</tr>
<tr>
<td>Maximum</td>
<td>63.97(±5.06)</td>
<td>76.57(±9.54)</td>
</tr>
<tr>
<td>Minimum</td>
<td>55.28(±7.08)</td>
<td>66.90(±7.42)</td>
</tr>
</tbody>
</table>

All the skaters moved their left shoulder closer to the ice for a brief moment, therefore causing a “dip”. This flexion occurred in the approach phase for three of skaters and the take-off phase for the other three skaters. This left trunk forward flexion may serve the skater in two ways 1) to add additional acceleration for a greater ground reaction force with the ice surface and 2) to balance over the right leg. A forward flexion, along with knee and hip flexion, brings a person’s center of
mass closer to the ground, allowing greater horizontal motion without the COM falling outside their support base (Figure 4.1). It is more stable for them to lean forward with the left side than the right if the skater needs to get the additional flexion from the trunk. The skater balances over the side of the foot as opposed to the ball of the their foot. By doing this, the skater is able to abduct their right hip and keep their COM over the base of the right foot and not topple over.

Figure 4.1. Center of mass over support base standing and squatting

**Lower Extremity.** The lower extremity average ranges of motion, average max and min positions are summarized in Table 4.5. Both hips were flexed throughout the approach phase with similar average maximum and minimum positions, as well as range of motion. The hip was adducting for both sides throughout the approach phase. However, the right hip moved from an adducted position of -26° (±20) to an abducted position of 3° (±11) through a range of motion
of $29^\circ$ ($\pm19$). The left hip was in a more abducted position starting at about $4^\circ$ ($\pm16$), moving to a greater abducted position of $38^\circ$ ($\pm21$). The left hip had a slightly greater average range of motion, around $34^\circ$ ($\pm20$), as compared to the right hip, $29^\circ$ ($\pm19$).

Table 4.5. ROM, max and min joint angles for the lower extremity of the loop jump in the approach phase.

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hip Flexion/Extension</strong></td>
<td>Mean ° (+SD)</td>
<td>Mean ° (+SD)</td>
</tr>
<tr>
<td>ROM</td>
<td>7.51 (±10.12)</td>
<td>12.93 (±5.02)</td>
</tr>
<tr>
<td>Maximum</td>
<td>44.36 (±16.24)</td>
<td>49.34 (±7.74)</td>
</tr>
<tr>
<td>Minimum</td>
<td>26.85 (±11.67)</td>
<td>36.42 (±10.31)</td>
</tr>
<tr>
<td><strong>Hip Adduction/Abduction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>29.16 (±18.85)</td>
<td>33.79 (±19.83)</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.75 (±10.90)</td>
<td>38.27 (±20.80)</td>
</tr>
<tr>
<td>Minimum</td>
<td>-26.42 (±19.99)</td>
<td>4.48 (±16.49)</td>
</tr>
<tr>
<td><strong>Knee Flexion</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>16.86 (±8.25)</td>
<td>14.11 (±5.73)</td>
</tr>
<tr>
<td>Maximum</td>
<td>129.25 (±10.51)</td>
<td>145.34 (±17.03)</td>
</tr>
<tr>
<td>Minimum</td>
<td>112.39 (±5.89)</td>
<td>131.23 (±18.76)</td>
</tr>
<tr>
<td><strong>Ankle Plantar Flexion/Dorsiflexion</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>11.20 (±4.02)</td>
<td>13.92 (±6.48)</td>
</tr>
<tr>
<td>Maximum</td>
<td>21.92 (±8.13)</td>
<td>-2.25 (±8.07)</td>
</tr>
<tr>
<td>Minimum</td>
<td>10.72 (±9.42)</td>
<td>-16.17 (±7.93)</td>
</tr>
</tbody>
</table>

Left hip abduction and right hip adduction are required so that the skater can correctly execute the take-off of the loop, crossing free left leg over the right leg, or support leg. The skater positions herself to balance over the right blade of the skater with the left foot outside of her right. This is illustrated in Figure 4.2.
The right knee had an average maximum position of $129^\circ$ ($\pm 11$) and an average minimum position of $112^\circ$ ($\pm 6$). Left knee maximum position was $145^\circ$ ($\pm 17$) and a minimum of $131^\circ$ ($\pm 19$). Three of the six skaters extended their left knee and the other three skaters flexed their left knee during the approach phase. Whereas, five of the six skaters extended their right knee. The other skater flexed the right knee during the approach phase. There were no major differences in the range of motion nor its endpoints. Additionally, four of the six skaters illustrated a rapid right knee flexion before take-off. The other two showed this event in their take-off phase.

The left ankle was in greater dorsiflexion than the right ankle; left max and min positions were $-2^\circ$ ($\pm 8$) and $16^\circ$ ($\pm 8$) with a range of motion of $14^\circ$ ($\pm 6$). The right ankle on the other hand had a max and min position of $22^\circ$ ($\pm 8$) and $10^\circ$ ($\pm 9$) and a range of motion of $11^\circ$ ($\pm 4$). A higher degree of dorsiflexion in the left ankle shows that the skater minimizes the length of the left leg to clear the top of the right
foot when crossing the left foot over the right foot. The right foot is in dorsiflexion to prepare for the jump when the skater rapidly plantar flexes for the push upward.

**Take-Off Phase**

The take-off phase, which began at the end of the approach phase, generally lasted 0.12 (±0.03) s. Resultant take-off velocities as well as take-off angle, horizontal velocity and vertical velocity were computed at the instant at take-off. These velocities were calculated for the whole body COM. These results are presented in Table 4.6.

<table>
<thead>
<tr>
<th></th>
<th>Mean (±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resultant Velocity (m/s)</td>
<td>3.14 (±0.52)</td>
</tr>
<tr>
<td>Horizontal Velocity (m/s)</td>
<td>2.74 (±0.63)</td>
</tr>
<tr>
<td>Vertical Velocity (m/s)</td>
<td>1.43 (±0.35)</td>
</tr>
<tr>
<td>Take-Off Angle (deg)</td>
<td>28.21 (±8.40)</td>
</tr>
</tbody>
</table>

The take-off phase of the loop jump is the time period when the skater rapidly extends the right leg. This rate of extension was expressed as the average radial velocity. A radial velocity is not necessarily directed upward but along the line from the skater’s right ankle to their right hip. It is the rate of change of the length between the ankle and the hip (Figure 4.3). The average radial velocity for the single loop was 0.68 (±0.18) m/s.
Upper Extremity. Both shoulders were flexing during the take-off phase. However, the right shoulder started with minimum flexed position of 27° (±36) and ended in a maximum flexed position of 59° (±26) (Table 4.7); whereas, the left shoulder started in a minimum extended position of -3° (±47) and a maximum flexed of 39° (±34). The left shoulder had about the same range of motion as the right.

Table 4.7 ROM, max, and min joint angles for the upper extremity of the loop jump in the take-off phase.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Flexion/Extension</td>
<td>Mean ° (+SD)</td>
<td>Mean ° (+SD)</td>
</tr>
<tr>
<td>ROM</td>
<td>32.32 (31.85)</td>
<td>42.12 (30.09)</td>
</tr>
<tr>
<td>Maximum</td>
<td>59.46(26.09)</td>
<td>38.94(34.44)</td>
</tr>
<tr>
<td>Minimum</td>
<td>27.14(35.80)</td>
<td>-3.18(47.04)</td>
</tr>
<tr>
<td>Shoulder Adduction/Abduction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>21.59 (14.89)</td>
<td>23.96 (8.93)</td>
</tr>
<tr>
<td>Maximum</td>
<td>61.47(19.76)</td>
<td>76.87(17.68)</td>
</tr>
<tr>
<td>Minimum</td>
<td>39.87(16.41)</td>
<td>52.91(22.17)</td>
</tr>
<tr>
<td>Elbow Flexion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>40.11 (4.21)</td>
<td>45.86 (28.27)</td>
</tr>
<tr>
<td>Maximum</td>
<td>116.39(15.88)</td>
<td>118.40(26.27)</td>
</tr>
<tr>
<td>Minimum</td>
<td>76.28(14.26)</td>
<td>72.54(30.14)</td>
</tr>
</tbody>
</table>
During the single loop, both shoulders were moving away from the body, hence abducting of both arms. Additionally, both elbows were flexing in the take-off phase. The average range of motion was 22° (±15) of flexion for the right and 24° (±9) of flexion for the left, with little difference between the maximum and minimum positions.

**Trunk Flexion.** Trunk flexion during the take-off for the loop (Table 4.8) indicated a forward position over the ice surface. Also, the right side of the trunk experienced about two times the range of motion, 14° (±6), as the left, 8° (±3). Generally, the right trunk started in a position of 63° (±5) and ended at 78° (±6). The left trunk moved in the opposite direction for five of the six skaters, starting in a position of 76° (±3) to a final position of 67° (±5). This means the right side of the trunk was more erect than the left, suggesting a twisting of the trunk at this stage.

<table>
<thead>
<tr>
<th>Trunk Flexion</th>
<th>Right Mean ° (±SD)</th>
<th>Left Mean ° (±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM</td>
<td>14.78 (±5.96)</td>
<td>8.47 (±3.17)</td>
</tr>
<tr>
<td>Maximum</td>
<td>78.23 (±6.07)</td>
<td>75.51 (±2.68)</td>
</tr>
<tr>
<td>Minimum</td>
<td>63.44 (±4.73)</td>
<td>67.04 (±4.94)</td>
</tr>
</tbody>
</table>

**Lower Extremity.** During the take-off phase of the single loop, the left hip was in a greater state of flexion than the right hip (Table 4.9). The maximum left hip flexion was 51° (±17) and minimum of 26° (±21) versus the right hip of 36° (±10)
and $7^\circ$ ($\pm 8$). Ranges of motion for both sides were the same and both were extending for the take-off. The right leg, which is the support leg for the loop, was almost in full extension showing that the hip was nearing its endpoint for the joint’s range of motion. During this phase, the two eldest skaters showed a slight hyperextension just prior to take-off.

The right hip showed more abduction, with a max and min of $12^\circ$ ($\pm 7$) and $-6^\circ$ ($\pm 7$), than the left, $26^\circ$ ($\pm 18$) and $-13^\circ$ ($\pm 19$), and with less range of motion, $18^\circ$ ($\pm 5$) versus $38^\circ$ ($\pm 18$). Again, the two eldest had more hip abduction in their left hip, as compared with their right, than the younger skaters.

| Table 4.9. ROM, max and min joint angles for the lower extremity of the loop jump in the take-off phase. |
|---------------------------------|---------------------------------|
| **Right**                      | **Left**                        |
| **Hip Flexion/Extension**      | **Mean ° ($\pm SD$)**          |
| ROM                            | 28.50 ($\pm 10.36$)            |
| Maximum                        | 35.80 ($\pm 9.98$)             |
| Minimum                        | 7.29 ($\pm 8.46$)              |
| **Hip Adduction/Abduction**    | **Mean ° ($\pm SD$)**          |
| ROM                            | 17.97 ($\pm 5.17$)             |
| Maximum                        | 12.06 ($\pm 7.22$)             |
| Minimum                        | -5.92 ($\pm 6.97$)             |
| **Knee Flexion**               | **Mean ° ($\pm SD$)**          |
| ROM                            | 29.07 ($\pm 6.30$)             |
| Maximum                        | 147.32 ($\pm 8.03$)            |
| Minimum                        | 118.25 ($\pm 6.22$)            |
| **Ankle Plantar Flexion/Dorsiflexion** | **Mean ° ($\pm SD$)** |
| ROM                            | 36.14 ($\pm 7.69$)             |
| Maximum                        | 19.02 ($\pm 7.68$)             |
| Minimum                        | -17.12 ($\pm 10.69$)           |
No apparent trends were found with respect to left knee flexion, it seemed to vary by skater. However, the right knee was consistently extending across the skaters. Both the right and left side showed similar maximum and minimum positioning with an average range of motion.

Four of the six skaters demonstrated a greater right ankle dorsiflexed position during the take-off phase than the left (Table 4.9). The right maximum and minimum ankle positions were -8° (+7) and -22° (+8) and the left was 19° (+8) and -17° (+11), respectively. The right ankle range of motion was 36° (+8) as compared to the left ankle ROM which was about half that (14° (+5)). This indicates that the right ankle has a greater average angular velocity than the left ankle and implies that the right ankle contributes with a greater significance to the vertical velocity of the skater at take-off.

Flight Phase

The flight phase of a skater’s jump was defined as the instant the skater left the ice to the instant the skater touched the ice. The time period for this phase was 0.31 (±0.03) s. The maximum jump height for the loop was calculated as 0.11 (±0.05) m and an overall jump length of 0.84 (±0.16) m. The skaters had an average angular, or rotational, velocity of -4.2 (±1.6) rad/s and an angular momentum of -7.4 (±2.8) kg m²/s. The negative value indicates a counterclockwise rotation of all the skaters.
Angular momentum is composed of both angular velocity and moment of inertia. The whole body moment of inertia (MOI) and the segmental contributions are shown in Figure 4.4.

**Moment of Inertia and Segmental Contributions In the Single Loop**

![Graph showing MOI and segmental contributions](image)

**Legend:**
- MOI: whole body moment of inertia
- Rt: right
- Lf: left
- HAT: Head And Trunk

Figure 4.4. Moment of inertia and segmental contributions in the single loop.
Note: the right arm contributed to 8% of the total moment of inertia, the left arm and right leg each 16%, the left leg, 25%, and the head and trunk, 35%.

Since angular momentum is the product of moment of inertia and angular velocity, if one characteristic is changed, the other must adapt so to keep angular momentum constant. So, if the moment of inertia is decreased, by drawing arms towards a skater’s body, the angular velocity must increased. As would be expected, this is exactly what occurs during the flight phase of the single loop. The moment of
inertia gradually decreases after take-off and then increases prior to landing (Figure 4.5). The change in moment of inertia is accomplished by drawing the arms and legs in towards or moving them away from the body.

Figure 4.5. Total moment of inertia and angular velocity during the flight phase.

Upper Extremity. In Table 4.10, the characteristics of the upper extremity are compiled. Both shoulders were in flexion. The mean maximum and minimum flexion positions were 53° (±28) and -10° (±32) for the right and 64° (±12) and 7° (±26) for the left, respectively. The left shoulder was in a more flexed position than the right during the flight phase. With the counterclockwise rotation, the left arm swings across the body, therefore increasing the degree of flexion in the left shoulder.
The adduction and abduction of the shoulder were quite similar for both the right and left shoulder. There was a u-shaped curve, reminiscent of the moment of inertia curve. The arms started out in an abducted position by mid-flight, the skater adducted their arms closer to their body, with an average range of motion of 49° (±36), for the right, and 63° (±22), for the left. As they prepared for landing, the skaters abducted their arms thereby increasing the upper body moment of inertia and decreasing their overall rotational velocity. It should be noted that some skaters were more inclined to bring their arms not only out but also forward into shoulder flexion, while other skaters placed their arms directly outward.

Elbow range of motion, maximum and minimum positioning were about the same for both sides. The average range of motion for the right elbow was 59° (±24) and for the left, 60° (±14). There was also a lot of variability in the techniques of the skaters. Some skaters demonstrated increased elbow flexion, others increased elbow extension while others held their elbow position constant.

It seems that the single loop does not depend upon a distinct motion of the elbows to successfully complete the jump. However, it may prove to be important in a multi-revolution loop jump, where the skater tries to generate most of their angular momentum. One way the skater does this is to initiate their rotation with their arms out to their side so that they increase their moment of inertia. Then, in the air, they have more angular momentum in which to create larger angular velocities simply by pulling in their arms.
Table 4.10. ROM, max and min joint angles for the upper extremity of the loop jump in the flight phase.

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shoulder Flexion/Extension</strong></td>
<td><strong>Mean ° (±SD)</strong></td>
<td><strong>Mean ° (±SD)</strong></td>
</tr>
<tr>
<td>ROM</td>
<td>62.92 (±20.93)</td>
<td>56.76 (±19.49)</td>
</tr>
<tr>
<td>Maximum</td>
<td>52.55 (±27.84)</td>
<td>63.76 (±11.82)</td>
</tr>
<tr>
<td>Minimum</td>
<td>-10.32 (±32.07)</td>
<td>7.01 (±25.80)</td>
</tr>
<tr>
<td><strong>Shoulder Adduction/Abduction</strong></td>
<td><strong>Mean ° (±SD)</strong></td>
<td><strong>Mean ° (±SD)</strong></td>
</tr>
<tr>
<td>ROM</td>
<td>48.73 (±35.78)</td>
<td>62.98 (±22.40)</td>
</tr>
<tr>
<td>Maximum</td>
<td>80.12 (±13.47)</td>
<td>86.19 (±13.58)</td>
</tr>
<tr>
<td>Minimum</td>
<td>31.39 (±37.07)</td>
<td>23.22 (±25.83)</td>
</tr>
<tr>
<td><strong>Elbow Flexion</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>58.52 (±23.90)</td>
<td>60.02 (±14.29)</td>
</tr>
<tr>
<td>Maximum</td>
<td>114.65 (±21.63)</td>
<td>130.62 (±21.61)</td>
</tr>
<tr>
<td>Minimum</td>
<td>56.13 (±9.28)</td>
<td>70.60 (±14.28)</td>
</tr>
</tbody>
</table>

**Trunk Flexion.** Trunk flexion for the flight phase is shown in Table 4.11.

One of the more defining features in the loop jump was the positioning of the trunk during flight. The skaters were more inclined to lean forward as compared to the single toe loop. This is directly related to the fact that the upper trunk was further away from the imaginary vertical line that passed through the body’s center of mass. The greater trunk flexion influences the total moment of inertia, as shown in Figure 4.5.

Table 4.11. ROM, max and min joint angles for the trunk of the loop jump in the flight phase.

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trunk Flexion</strong></td>
<td><strong>Mean ° (±SD)</strong></td>
<td><strong>Mean ° (±SD)</strong></td>
</tr>
<tr>
<td>ROM</td>
<td>21.39 (±3.99)</td>
<td>15.79 (±5.93)</td>
</tr>
<tr>
<td>Maximum</td>
<td>86.20 (±2.47)</td>
<td>77.53 (±4.43)</td>
</tr>
<tr>
<td>Minimum</td>
<td>64.81 (±4.02)</td>
<td>61.74 (±5.55)</td>
</tr>
</tbody>
</table>
Lower Extremity. Generally, there were no differences in range of motion between both the right and left hip in flexion and extension (Table 4.12). However, the right hip tended to be in less flexion as compared to the left. The right hip had an average maximum position of $34^\circ (\pm 13)$ and an average minimum of $2^\circ (\pm 8)$, whereas, the left had an average maximum of $74^\circ (\pm 14)$ and an average minimum of $22^\circ (\pm 30)$. Upon observation of both the video and 3D model, the skaters had greater left thigh flexion with the hip, which likely prepares the skater for landing.

Hip adduction/abduction was fairly constant position during the middle of the flight, not the beginning or the end of the flight. The left hip tended to be in a more abducted position, as compared with the right hip, although not with any regularity throughout the flight. This was the case for all but one skater.

Table 4.12. ROM, max and min joint angles for the lower extremity of the loop jump in the flight phase.

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th>Mean $^\circ$ (±SD)</th>
<th>Left</th>
<th>Mean $^\circ$ (±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Flexion/Extension</td>
<td><strong>ROM</strong></td>
<td>32.16 (±5.74)</td>
<td>51.61 (±27.28)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Maximum</strong></td>
<td>33.91 (±13.37)</td>
<td>73.95 (±14.27)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Minimum</strong></td>
<td>1.75 (±8.35)</td>
<td>22.35 (±30.17)</td>
<td></td>
</tr>
<tr>
<td>Hip Adduction/Abduction</td>
<td><strong>ROM</strong></td>
<td>27.20 (±6.21)</td>
<td>77.28 (±25.56)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Maximum</strong></td>
<td>13.68 (±4.35)</td>
<td>60.67 (±24.11)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Minimum</strong></td>
<td>-13.52 (±9.52)</td>
<td>-16.61 (±18.51)</td>
<td></td>
</tr>
<tr>
<td>Knee Flexion</td>
<td><strong>ROM</strong></td>
<td>25.29 (±7.87)</td>
<td>35.67 (±12.57)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Maximum</strong></td>
<td>152.16 (±5.49)</td>
<td>150.15 (±24.81)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Minimum</strong></td>
<td>127.87 (±12.12)</td>
<td>114.48 (±15.39)</td>
<td></td>
</tr>
<tr>
<td>Ankle Plantar</td>
<td><strong>ROM</strong></td>
<td>41.45 (±9.83)</td>
<td>31.95 (±6.27)</td>
<td></td>
</tr>
<tr>
<td>Flexion/Dorsiflexion</td>
<td><strong>Maximum</strong></td>
<td>7.64 (±14.11)</td>
<td>10.07 (±9.43)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Minimum</strong></td>
<td>-33.81 (±18.80)</td>
<td>-21.88 (±9.43)</td>
<td></td>
</tr>
</tbody>
</table>
The left knee during flight had greater flexion and was in a more flexed position than the right knee for four out of the six skaters. The average maximum and minimum position for the left knee was $150^\circ \pm 25$ and $114^\circ \pm 15$, respectively, as compared to $152^\circ \pm 5$ and $128^\circ \pm 12$ for the right knee. Also, the left knee has a greater range of motion. From the data, it is very apparent that the skater’s left leg in the single loop “wraps” around the right leg during the flight phase. This will be discussed in a later section of this chapter.

The right ankle was shown to go through a greater range of motion than the left ankle. Since the right leg was the take-off leg, the right ankle showed a dorsiflexed position in the graphical data immediately after take-off (Figure 4.6). The right ankle would recover to a more neutral position then continue to a plantar flexed position nearer landing. This in essence would help the skater 1) feel for the ice with

![Figure 4.6. Right ankle dorsiflexion and plantar flexion during flight.](image)
their toe and 2) absorbing force with the landing by giving in first with their right ankle.

**Single Toe Loop**

The single toe loop is initiated with a backward approach on the right outside edge. The left foot is planted onto the ice for a left toe assist into the air. After the revolution is completed, the skater lands on the outside edge of the right foot.

**Approach Phase**

The approach phase was defined the same was as for the single loop. Each approach lasted 0.1 seconds. The end of the approach phase was when the skater would turn their hips and left foot perpendicular to the line of motion. The toe assist occurred in this phase for all but one skaters. For the one skater, the toe assist occurred during the take-off phase.

**Upper Extremity.** Both shoulders were flexing throughout the approach. Four of the six skaters had a greater flexed position of the left shoulder and three of the four skaters held the right shoulder in an extended position (Table 4.13). The action of both shoulders varied greatly throughout this phase. The right shoulder tended to move in adduction, with a greater range of motion, 46° (±24) than the left shoulder, 26° (±12). The left shoulder had a tendency to abduct. The right shoulder
was mostly in a greater abducted position, max of $34^\circ \pm 22$ as compared to the left shoulder $28^\circ \pm 39$. The elbows were flexing in this phase, however, the range of motion was moderate, $22^\circ \pm 10$ for the right and $24^\circ \pm 15$ for the left.

Table 4.13. ROM, max and min joint angles for the upper extremity of the loop toe jump in the approach phase.

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shoulder Flexion/Extension</strong></td>
<td>Mean $^\circ (\pm SD)$</td>
<td>Mean $^\circ (\pm SD)$</td>
</tr>
<tr>
<td>ROM</td>
<td>45.87 (±24.12)</td>
<td>26.30 (±11.65)</td>
</tr>
<tr>
<td>Maximum</td>
<td>33.71 (±21.87)</td>
<td>27.87 (±38.77)</td>
</tr>
<tr>
<td>Minimum</td>
<td>-12.16 (±17.04)</td>
<td>1.57 (±30.15)</td>
</tr>
<tr>
<td><strong>Shoulder Adduction/Abduction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>19.37 (±19.05)</td>
<td>30.24 (±23.20)</td>
</tr>
<tr>
<td>Maximum</td>
<td>82.16 (±9.48)</td>
<td>60.38 (±19.57)</td>
</tr>
<tr>
<td>Minimum</td>
<td>62.79 (±24.63)</td>
<td>30.14 (±25.47)</td>
</tr>
<tr>
<td><strong>Elbow Flexion</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>21.57 (±10.40)</td>
<td>23.58 (±15.02)</td>
</tr>
<tr>
<td>Maximum</td>
<td>157.86 (±10.89)</td>
<td>151.86 (±16.39)</td>
</tr>
<tr>
<td>Minimum</td>
<td>136.07 (±17.67)</td>
<td>128.28 (±24.38)</td>
</tr>
</tbody>
</table>

**Trunk Flexion.** The trunk always showed some degree of flexion with the ice surface (Table 4.14). The trunk tended to have an asymmetrical position with the ice before the take-off phase. The left side of the trunk was more flexed, with an average maximum of $76^\circ \pm 3$ and minimum of $59^\circ \pm 7$, or at a shallower angle with the ice surface, than the right, average maximum of $67^\circ \pm 8$ and minimum of $59^\circ \pm 5$. This may be an after effect of the toe plant onto the ice.
Table 4.14. ROM, max and min joint angles for the trunk of the toe loop jump in the approach phase.

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th></th>
<th>Left</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk Flexion</td>
<td><strong>ROM</strong> 8.71 (±6.39)</td>
<td>Mean °</td>
<td><strong>Mean ° 16.75 (±5.22)</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Maximum</strong> 67.24 (±7.91)</td>
<td>Mean °</td>
<td><strong>Maximum 75.87 (±2.59)</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Minimum</strong> 58.53 (±4.77)</td>
<td>Mean °</td>
<td><strong>Minimum 59.12 (±6.74)</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Lower Extremity.** In Table 4.15, the lower extremity range of motion, max and min positions are presented. The left hip moved towards more extension just before the toe pick and in four of the six skaters, the hip actually was in a hyperextended position (~10°). So, the skater would raise their leg prior to the toe pick and have to place it behind and across the skaters path of motion. The motion of the left hip, after the hyperextension, was that of flexing and in all but one skater. The right leg was extending as illustrated in Figure 4.7.
The right hip had a tendency to abduct and was in a greater state of abduction than the left hip. The right max and min positions were $40^\circ \pm 19$ and $20^\circ \pm 21$, whereas the left showed more adducted positions of $8^\circ \pm 9$ and $-4^\circ \pm 9$ (Table 14). The range of motion in the right hip ($20^\circ \pm 8$) tended to be greater than the left hip ($12^\circ \pm 4$). The right and left knees moved in opposite angular directions during this phase.

During the approach phase of the toe loop, the right knee flexed from a more extended position whereas the left extended from a more flexed position. At the instant of toe-pick, both knees were in almost identical positions with an estimated angle of $130^\circ$.

Table 4.15. ROM, max and min joint angles for the lower extremity of the toe loop jump in the approach phase.

<table>
<thead>
<tr>
<th>Hip Flexion/Extension</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM</td>
<td>$22.52 \pm 11.01$</td>
<td>$15.47 \pm 8.31$</td>
</tr>
<tr>
<td>Maximum</td>
<td>$50.97 \pm 16.13$</td>
<td>$25.79 \pm 10.84$</td>
</tr>
<tr>
<td>Minimum</td>
<td>$28.45 \pm 131.78$</td>
<td>$10.32 \pm 13.65$</td>
</tr>
<tr>
<td>Hip Adduction/Abduction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>$19.57 \pm 8.26$</td>
<td>$11.92 \pm 4.46$</td>
</tr>
<tr>
<td>Maximum</td>
<td>$39.51 \pm 18.51$</td>
<td>$7.53 \pm 9.35$</td>
</tr>
<tr>
<td>Minimum</td>
<td>$19.94 \pm 21.03$</td>
<td>$-4.39 \pm 8.96$</td>
</tr>
<tr>
<td>Knee Flexion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>$12.79 \pm 6.07$</td>
<td>$14.22 \pm 8.31$</td>
</tr>
<tr>
<td>Maximum</td>
<td>$133.43 \pm 10.61$</td>
<td>$141.28 \pm 15.45$</td>
</tr>
<tr>
<td>Minimum</td>
<td>$120.64 \pm 6.44$</td>
<td>$127.06 \pm 9.15$</td>
</tr>
<tr>
<td>Ankle Plantar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion/Dorsiflexion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>$14.69 \pm 4.78$</td>
<td>$15.27 \pm 3.76$</td>
</tr>
<tr>
<td>Maximum</td>
<td>$16.90 \pm 5.58$</td>
<td>$0.21 \pm 10.34$</td>
</tr>
<tr>
<td>Minimum</td>
<td>$2.20 \pm 5.09$</td>
<td>$-15.06 \pm 10.36$</td>
</tr>
</tbody>
</table>
The left ankle tended to be in greater dorsiflexion, positions from 0.2° (±10) to -15° (±10) and the right ankle in plantar flexion, positions from 17° (±6) to 2° (±5). The skaters may have been on the right back edge of the skate as they approached the take-off phase at instant of take-off, supporting their weight with the left foot. Also, as the skater prepared for the toe pick, the left ankle was in a dorsiflexed position and not a plantar flexed position. This may have provided better stability for the right leg by resting the pick of the skate under the ball of their feet, as opposed to their toes.

Take-Off Phase

The take-off phase elapsed from the end of the approach phase to the instant the skater left the ice. The average time period was 0.12 (±0.03) seconds. A radial velocity of 0.12 m/s (±0.64) was found for the single toe loop. Take-off angle, resultant, horizontal and vertical velocities are presented in Table 4.16. These values did not differ significantly from the single loop.

Table 4.16. Take-off velocities and take-off angle of the single toe loop.

<table>
<thead>
<tr>
<th></th>
<th>Mean (±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resultant Velocity (m/s)</td>
<td>3.14 (±0.44)</td>
</tr>
<tr>
<td>Horizontal Velocity (m/s)</td>
<td>2.88 (±0.39)</td>
</tr>
<tr>
<td>Vertical Velocity (m/s)</td>
<td>1.21 (±0.29)</td>
</tr>
<tr>
<td>Take-Off Angle (deg)</td>
<td>22.72 (±4.79)</td>
</tr>
</tbody>
</table>
Upper Extremity. Both shoulders were flexing in the take-off phase, bringing the arms into greater flexion from the approach phase. The left shoulder started in a more adducted position, $27^\circ (\pm 48)$, than the right shoulder, $67^\circ (\pm 21)$ and moved to greater abducted position, $80^\circ (\pm 17)$ surpassing the right shoulder, $44^\circ (\pm 25)$ (Table 4.17).

Table 4.17. ROM, max and min joint angles for the upper extremity of the loop toe jump in the take-off phase.

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Flexion/Extension</td>
<td><strong>ROM</strong> Mean (±SD)</td>
<td>**Mean (±SD)</td>
</tr>
<tr>
<td>ROM</td>
<td>56.21 (±36.23)</td>
<td>61.88 (±24.12)</td>
</tr>
<tr>
<td>Maximum</td>
<td>42.00 (±28.05)</td>
<td>57.91 (±30.72)</td>
</tr>
<tr>
<td>Minimum</td>
<td>-14.21 (±27.91)</td>
<td>-3.97 (±23.98)</td>
</tr>
<tr>
<td>Shoulder Adduction/Abduction</td>
<td><strong>ROM</strong></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>24.72 (±14.38)</td>
<td>52.48 (±41.40)</td>
</tr>
<tr>
<td>Maximum</td>
<td>68.73 (±21.33)</td>
<td>79.54 (±16.50)</td>
</tr>
<tr>
<td>Minimum</td>
<td>44.01 (±24.94)</td>
<td>27.05 (±48.25)</td>
</tr>
<tr>
<td>Elbow Flexion</td>
<td><strong>ROM</strong> Mean (±SD)</td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>66.13 (±23.78)</td>
<td>58.60 (±34.42)</td>
</tr>
<tr>
<td>Maximum</td>
<td>142.40 (±16.47)</td>
<td>132.52 (±23.84)</td>
</tr>
<tr>
<td>Minimum</td>
<td>76.27 (±19.90)</td>
<td>73.92 (±24.18)</td>
</tr>
</tbody>
</table>

Adduction/abduction range of motion for the left shoulder, $53^\circ (\pm 41)$ was twice as much than the right, $25^\circ (\pm 14)$. The right arm was brought across the skaters body and the left would move outward, away from their body. This may serve to help the skater prepare for the take-off by pivoting on the left toe pick of the ice skate and to counter act the positioning go the left leg as it assists in the toe loop (Figure 4.8). Both elbows exhibited similar ranges of motion, max and min positions.
Direction of
Motion

Figure 4.8. Crossing the left leg behind and across the skaters direction of motion

Trunk Flexion. The skaters were more erect in the single toe loop than the single loop. Furthermore, in the single toe loop, the left side was more erect than the right. Notice the max positions of the right, 79° (±4), are less than the left 85° (±2) and the min position of the right, 62° (±4) compared with the left 74° (±2) (Table 4.18).

Table 4.18. ROM, max and min joint angles for the trunk of the toe loop jump in the take-off phase.

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk Flexion</td>
<td>Mean ° (±SD)</td>
<td>Mean ° (±SD)</td>
</tr>
<tr>
<td>ROM</td>
<td>16.79 (±7.51)</td>
<td>10.71 (±2.54)</td>
</tr>
<tr>
<td>Maximum</td>
<td>79.20(±4.20)</td>
<td>85.19(±2.24)</td>
</tr>
<tr>
<td>Minimum</td>
<td>62.41(±3.53)</td>
<td>74.48(±2.38)</td>
</tr>
</tbody>
</table>

Lower Extremity. The skaters left hip extended, then flexed and then extended. Both the right and left hip had the same range of motion, however, the left hip was in a more extended position, 27° (±9) to -4° (±6), versus the right hip, 46°
The right hip was in a more adducted position, 38° (+15) to 2° (+6), than the left hip, 15° (+10) to -3° (+4). This right thigh position was a counter movement to the left toe assist. This may provide a more stable base for the skater as she rotates on the toe pick of the skate.

Table 4.19. ROM, max and min joint angles for the lower extremity of the toe loop jump in the take-off phase.

<table>
<thead>
<tr>
<th></th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hip Flexion/Extension</strong></td>
<td>Mean ° (±SD)</td>
<td>Mean ° (±SD)</td>
</tr>
<tr>
<td>ROM</td>
<td>31.68 (±11.56)</td>
<td>31.09 (±12.56)</td>
</tr>
<tr>
<td>Maximum</td>
<td>45.53 (±9.42)</td>
<td>27.13 (±9.46)</td>
</tr>
<tr>
<td>Minimum</td>
<td>13.85 (±12.75)</td>
<td>-3.96 (±6.18)</td>
</tr>
<tr>
<td><strong>Hip Adduction/Abduction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>36.16 (±15.14)</td>
<td>18.60 (±6.92)</td>
</tr>
<tr>
<td>Maximum</td>
<td>38.20 (±15.26)</td>
<td>15.47 (±10.04)</td>
</tr>
<tr>
<td>Minimum</td>
<td>2.04 (±6.05)</td>
<td>-3.13 (±4.35)</td>
</tr>
<tr>
<td><strong>Knee Flexion</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>40.21 (±15.35)</td>
<td>40.74 (±10.50)</td>
</tr>
<tr>
<td>Maximum</td>
<td>147.48 (±14.91)</td>
<td>160.89 (±8.50)</td>
</tr>
<tr>
<td>Minimum</td>
<td>107.27 (±25.55)</td>
<td>120.16 (±4.01)</td>
</tr>
<tr>
<td><strong>Ankle Plantar</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion/Dorsiflexion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>25.19 (±10.18)</td>
<td>35.37 (±4.17)</td>
</tr>
<tr>
<td>Maximum</td>
<td>8.84 (±10.08)</td>
<td>7.34 (±4.70)</td>
</tr>
<tr>
<td>Minimum</td>
<td>-16.35 (±8.13)</td>
<td>-28.03 (±2.78)</td>
</tr>
</tbody>
</table>

The knee range of motion, maximum and minimum positions were very similar for both knees. All six skaters extended their left knee. However, three of the six skaters extended their right knee while the remaining three flexed their right knee. Also, there were observed differences between the two ankles. For five of the six skaters, both the right and left ankle were in a greater dorsiflexed position for the
average minimum and maximum. The sixth skater demonstrated plantar flexion of
the left ankle.

Several differences were observed between the single loop and the single toe
loop in the lower body kinematics. It was found that that the left knee went through
much less range of motion in the single loop than it did for the toe loop. During the
toe-assist of the toe loop, the skater uses greater left knee extension to help the skater
rise into the air. Also in the toe loop, the left ankle showed a greater range of motion
than the left ankle of the loop. The greater knee and ankle range of motion of the toe
loop occurred over a similar time period as for the loop, which indicates that there
were greater extension velocities of the left leg in the toe loop than in the loop. The
left ankle in the toe loop showed the same range of motion of the right ankle in the
loop. However, the left knee of the toe loop showed a greater range of motion than
the right knee of the loop.

Flight Phase

The flight phase was defined in the same manner as the loop, the period of
time in the air and the same flight characteristics were calculated. A maximum jump
height was calculated to be 0.08(±0.04) m and a jump length of 0.81 (±0.34) m
where their average time in air was 0.27(±0.07) s. These values were similar to the
ones calculated for the single loop. The skaters had an average angular momentum
of −6.3 (±2.7) kg m²/s and an average angular velocity of −3.2 (±1.0) rad/s. These
numbers also did not differ noticeably between the two jumps. Moment of inertia and segmental contribution to moment of inertia are shown in Figure 4.9.

![Image: Moment of Inertia and Segmental Contributions in the Single Toe Loop]

MOI the whole body moment of inertia  
rt right  
lf left  
HAT Head And Trunk

Figure 4.9. Moment of inertia and segmental contribution in the single toe loop. Note: the right arm contributed to 10% of the total moment of inertia, the left arm and right leg each 15%, the left leg, 36%, and the head and trunk, 24%.

The greater contribution of the left leg for the total moment of inertia reflects what was observed in the video data. The skaters lifted their left leg up and away from their trunk during flight of the toe loop. This created a greater moment of inertia for the left leg as it rotated about the skater’s center of mass. The decreased contribution and absolute value of the head and trunk were attributed to a more erect position of the skater during the flight of the toe loop. Recall that in the loop, the skaters tended to lean more forward. The toe loop showed the same u-shaped curve
of the moment of inertia during flight as was observed for the single loop. As mentioned in this section of the loop, the skaters start the flight phase with a more opened position, brought their arms closer to rotate faster and then open back up to prepare for a smoother landing.

**Upper Extremity.** Both the right and left shoulder exhibited the same motion as the shoulder in the loop. Both shoulders started in an abducted position and by mid-flight, the skaters brought their arms closer to their body, adducting at the shoulders. Near landing, the skaters moved their arms outward, returning to a more abducted state. The average range of motion was $47^\circ \pm 14$ for the right shoulder and $50^\circ \pm 28$ for the left shoulder (Table 4.20).

Generally all but one skater held their arms such that the shoulders were in a flexed position. The single skater who did not do this kept her arms alongside her body, with around shoulder flexion (or extension) angle of $0^\circ$. The overall motion during this phase was one of shoulder extension, whereby the skaters would bring their arms towards their body, from a flexed position. Upon landing, some skaters held their arms in more flexion than others. Both elbow motion varied greatly during the flight phase. However, all skaters extended their elbows just prior to landing.
Table 4.20 ROM, max and min joint angles for the upper extremity of the loop toe jump in the flight phase.

<table>
<thead>
<tr>
<th>Shoulder Flexion/Extension</th>
<th>Right</th>
<th>Mean ° (±SD)</th>
<th>Left</th>
<th>Mean ° (±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM</td>
<td>45.10 (±21.31)</td>
<td></td>
<td>55.22 (±35.65)</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>42.14 (±31.69)</td>
<td></td>
<td>57.90 (±23.34)</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>-2.96 (±29.56)</td>
<td></td>
<td>2.68 (±41.28)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shoulder Adduction/Abduction</th>
<th>Right</th>
<th>Mean ° (±SD)</th>
<th>Left</th>
<th>Mean ° (±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM</td>
<td>46.68 (±13.94)</td>
<td></td>
<td>49.60 (±27.88)</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>75.90 (±17.25)</td>
<td></td>
<td>81.46 (±20.10)</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>29.22 (±19.42)</td>
<td></td>
<td>31.86 (±22.29)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elbow Flexion</th>
<th>Right</th>
<th>Mean ° (±SD)</th>
<th>Left</th>
<th>Mean ° (±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM</td>
<td>48.95 (±15.86)</td>
<td></td>
<td>49.82 (±19.64)</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>112.12 (±21.05)</td>
<td></td>
<td>110.75 (±18.09)</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>63.17 (±18.53)</td>
<td></td>
<td>60.93 (±23.11)</td>
<td></td>
</tr>
</tbody>
</table>

**Trunk Flexion** It is interesting to note that the trunk was in a more upright position for the toe loop than the loop, thereby decreasing its contribution to the total moment of inertia. It was observed that the right side of the trunk was more erect, than the left side, especially after mid-flight. However, one skater did not exhibit this trend and thus is not reflected in the averaged data of Table 4.21. A more erect posture may help the skater for a more balanced and more controlled landing.

Table 4.21. ROM, max and min joint angles for the trunk of the toe loop jump in the flight phase.

<table>
<thead>
<tr>
<th>Trunk Flexion</th>
<th>Right</th>
<th>Mean ° (±SD)</th>
<th>Left</th>
<th>Mean ° (±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM</td>
<td>19.88 (±6.13)</td>
<td></td>
<td>18.06 (±3.69)</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>82.05 (±7.02)</td>
<td></td>
<td>81.90 (±3.64)</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>62.17 (±6.25)</td>
<td></td>
<td>63.84 (±4.25)</td>
<td></td>
</tr>
</tbody>
</table>
Lower Extremity. Generally, after take-off, the skater brings his/her left leg from a more extended position at the toe pick, to a more flexed position, from $-5^\circ$ ($\pm 12$) to $47^\circ$ ($\pm 14$). However, the opposite movement occurred for the right leg. Their right leg started from a more flexed position, $38^\circ$ ($\pm 19$), at the beginning of flight, then extend it out to $8^\circ$ ($\pm 12$) and reach for landing (Table 4.22).

As for hip adduction/abduction, the left hip was in greater abduction, especially near landing. The right hip would near an adducted position. The right leg was the landing leg, therefore, the skaters positioned their right leg in and under their hips while the left leg is brought out and forward for landing.

Both knees were somewhat extended, $124^\circ$ ($\pm 28$) to $158^\circ$ ($\pm 9$) for the right and $152^\circ$ ($\pm 10$) to $169^\circ$ ($\pm 7$) for the left. However, two skaters held their right knee around $100^\circ$ of flexion in this phase of the toe loop.

The right ankle, during flight, showed a recovery from the dorsiflexed position at take-off towards a more neutral position whilst in the air. Both ankles plantar flexed to about mid-flight then dorsiflexion afterward. The right showed a range of motion almost twice as much as the left, $42^\circ$ ($\pm 15$) compared with $24^\circ$ ($\pm 8$). The right ankle had more extreme positions, from $8^\circ$ ($\pm 12$) to $-34^\circ$ ($\pm 16$), than the left, $-7^\circ$ ($\pm 5$) to $-31^\circ$ ($\pm 6$).
Table 4.22. ROM, max and min joint angles for the lower extremity of the toe loop jump in the flight phase.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Right</th>
<th>Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Flexion/Extension</td>
<td>Mean ° (±SD)</td>
<td>Mean ° (±SD)</td>
</tr>
<tr>
<td>ROM</td>
<td>30.15 (±7.71)</td>
<td>52.05 (±17.23)</td>
</tr>
<tr>
<td>Maximum</td>
<td>38.37 (±19.39)</td>
<td>47.32 (±13.53)</td>
</tr>
<tr>
<td>Minimum</td>
<td>8.21 (±12.46)</td>
<td>-4.73 (±12.08)</td>
</tr>
<tr>
<td>Hip Adduction/Abduction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>31.84 (±10.91)</td>
<td>43.38 (±22.76)</td>
</tr>
<tr>
<td>Maximum</td>
<td>21.64 (±9.81)</td>
<td>16.90 (±5.58)</td>
</tr>
<tr>
<td>Minimum</td>
<td>-10.20 (±10.20)</td>
<td>2.20 (±5.09)</td>
</tr>
<tr>
<td>Knee Flexion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>33.12 (±20.27)</td>
<td>17.26 (±4.87)</td>
</tr>
<tr>
<td>Maximum</td>
<td>157.74 (±9.39)</td>
<td>169.38 (±7.43)</td>
</tr>
<tr>
<td>Minimum</td>
<td>124.62 (±28.20)</td>
<td>152.12 (±10.15)</td>
</tr>
<tr>
<td>Ankle Plantar Flexion/Dorsiflexion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM</td>
<td>42.07 (±15.20)</td>
<td>23.67 (±8.49)</td>
</tr>
<tr>
<td>Maximum</td>
<td>7.95 (±12.16)</td>
<td>-7.44 (±4.50)</td>
</tr>
<tr>
<td>Minimum</td>
<td>-34.12 (±16.33)</td>
<td>-31.11 (±6.32)</td>
</tr>
</tbody>
</table>

Hypothesis Testing of the Two Jumps

The angular momentum during flight of the toe loop was -6.3 (±1.1) kg m²/s and -7.4 (±1.2) kg m²/s for the loop (Table 4.23). Standard errors were used for the hypothesis parameters because the sample size was very small. For the calculated p-value of 0.3667, the differences were not significant when tested at an alpha of 0.0167. For single jumps, it takes less effort to complete a jump than for multiple revolutions. So the skaters may perform each jump with greater ease than for two revolutions.

The single loop and the single toe loop only require only a half of revolution more to the flight phase than the toe loop, so the angular momentum would not
significantly differ. The moment of inertia tends towards a slightly less value, 1.81
(+0.34) kg m², for the loop, than the toe loop 1.88 (+0.47) kg m². This unimpressive
difference does show that the skaters were in a “tighter” position, which is also
hinted in the angular velocity. In the loop, the skaters average around -4.2 (+1.6)
rad/s as opposed to the toe loop, -3.2 (+1.0) rad/s. Here, the skaters angular velocity
is slightly higher in the loop than the toe loop. It was originally thought that the toe
loop would have greater angular momentum since elite skaters are using the toe loop
to complete four revolutions. It is now clearly not the case and there are other
elements to the toe loop that gives the skater the advantage to completing a four
revolution jump.

Table 4.23. Tested Hypothesis Variables

<table>
<thead>
<tr>
<th>Tested Variable</th>
<th>Loop Mean (+SE)</th>
<th>Toe Loop Mean (+SE)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular Momentum (kg m²/s)</td>
<td>-7.4 (+1.2)</td>
<td>-6.3 (+1.1)</td>
<td>0.3667</td>
</tr>
<tr>
<td>Radial Velocity (m/s)</td>
<td>0.68 (+0.1)</td>
<td>0.12 (+0.3)</td>
<td>0.0868</td>
</tr>
<tr>
<td>Maximum Jump Height (m)</td>
<td>0.11 (+0.02)</td>
<td>0.08 (+0.02)</td>
<td>0.1618</td>
</tr>
</tbody>
</table>

1. P-value obtained from a heterogeneous T-test due to the substantial difference in standard
deviations between the two jumps.

The radial velocity of the right leg in the take-off phase of the loop was 0.68
(+0.1) m/s (Table 4.23). This was not significantly different than the radial velocity
of the right leg in the take-off phase of the toe loop, 0.12 (+0.3) m/s. A
heterogeneous T-test was used since the standard error of the right radial velocity of
the toe loop was more than three times that of the standard error of the loop. The
calculated p-value, 0.0868, shows that this difference is approaching the level of
significance at an alpha of 0.0167. The radial velocity of the right leg in the loop
does tend towards a greater value than the radial velocity of the single toe loop. In the loop, the skater used the edge of the right skater to press against the ice and lifted herself by extending the right leg. In the toe loop, the skater plants the left toe pick of the skate into the ice and extended her right leg, pushing her body up and over the left toe. Therefore, the skater is moving through a more circular path whereby the fixed point is the left toe. Thus, the skater can use the combine extension of both the right and left leg to lift herself into the air for the toe loop whereas, in the loop, the skater derives all her extension from the right leg alone.

The maximum jump height during flight for the toe loop was 0.08 (±0.02) m and, 0.11 (±0.02) m for the loop (Table 4.23). This did not significantly differ with a p-value of 0.1618 and tested at an alpha of 0.0167. In King et al. (1994) the results of their study found that there was no difference between the jump height of the single Axel as compared with the double and triple Axel. Although this Axel study focused on increasing revolutions, jump height, too, does not seem to discern between the single toe loop and the single loop of novice skaters. It seems that jumps height is not the essential key to complete a more difficult jump, whether it is due to an increase in the number of revolutions or the type of jump.

A post hoc analysis was made on the left leg radial extension velocities of the take-off phase in the single loop and single toe loop jump in this study. It was found that the average radial velocity of -0.17 (±0.71) m/s for the loop and 0.59 (±0.21) m/s for the toe loop. It is evident that the left leg in the toe loop is contributing to the upward velocity of the skater by assisting the right leg in take-off. However, in the loop, the skaters, on average, were flexing their left leg during take-off. These
results warrant further analysis into understanding the mechanisms of the right leg in the loop versus both the right and left leg in the toe loop.

**Wrapping of the Free Leg in the Single Loop Jump**

During the single loop, every skater demonstrated a “wrapping” of their left leg (Figure 4.10). Wrapping is defined as the free leg, the left, crossed over the right leg and the knee in flexion. During a properly completed jump, the skater should not exhibit wrapping.

![Figure 4.10. Wrapping of the left leg.](image)

Recall from the loop flight phase of the lower body that the left knee of the loop was in a greater state of flexion and underwent greater range of motion. Also, at the left hip, the left leg tended to be in a greater abducted position than the right leg. This excessive positioning of the left leg is not only aesthetically displeasing
but may also be problematic for the left knee. Strain on the lateral side of the left knee may cause injury and/or discomfort. Wrapping may affect the tensor fasciae latae (TFL) which crosses both the hip and the knee on the lateral side and abducts at the hip. So, in a “wrapped” position, the TFL is contracting across the left hip while slightly stretching across the left knee. Therefore, repeated and unnecessary strain at the knee may cause tendonitis or sore muscles. The problem may be attributed to weak legs and/or lack of skill in their jump.

**Variability of the Data**

The seemingly large variability in the kinematic data sets was noticed throughout the phases of both jumps. There was some speculation as to how this variability may be explained. First, the more experienced skaters may take advantage of upper body strength and/or lower body strength and demonstrate larger ranges of motion through those appropriate joints. This would help them attain greater heights, possibly, and greater angular velocities during the flight phase. The second possibility highlights the less experienced skater. These skaters may use excessive motions, indicative of an awkwardness in their technique. These skaters may unnecessarily swing their arms in a counterproductive way such that it hinders their ability for more skilled elements in a skater’s repertoire. Novice skaters may also limit their range of motion where they are unable to utilize their potential for greater techniques.
Bernstein documented the progression of motor learning for a sport technique. His theory explains the above mentioned dynamics of novice athletes and states that there are stages of motor learning in which an athlete progresses. At first, the degrees of freedom are frozen whereby the motions of a movement are restricted to a few degrees of freedom. The athlete then "unfreezes" the degrees of freedom and is able to use all motions of a skill. Finally, the athlete can exploit the dynamics of the skill, optimizing the movement by progressing though the correct sequencing (Shumway-Cook & Woollacott, 1995). It seemed that the skaters in this study were at various learning levels, with respect to the single loop and toe loop jumps. Therefore, the skaters exhibited wide range of abilities in their techniques.

At this point it is hard to determine the variability of one novice skater versus the variability of one elite skater. The more accomplished skaters have comparatively perfect forms and techniques. The novice skater tends to experiment with their techniques or possibly revamp their old ways later in their career. Without variability data of elite skaters it is hard to discuss the degree at which a novice skater varies.

Within the field of sport psychology, researchers understand some of the main underlying differences between the cognitive level of elite and novice athletes. One of the motor learning theories is that athletes learn skills through practice and experience as opposed to maturation or instinct (Kluka, 1999). Elite athletes must not only have superior strength over novice athletes, they must also have superior motor coordination to orchestrate a series of coordinated events. An elite skater does not require the same deliberate thought process that a novice skater undergoes when
attempting a figure skating jump. The novice skater must remind themselves of the sequencing in a jump, more so than an elite skater. Fitz and Postner’s theory included three stages of motor learning. The first stage or the cognitive stage in learning a technique requires a highly verbal component where the skater must carefully think about each element in a jump. The second stage or associative stage is when the skater does not need to think about the jump as thoroughly. The final stage or the autonomous stage, the skater approaches a jump without thinking and their efforts lie in improving the movement (Shumway-Cook & Woollacott, 1995).

There is another important reason why there was this potentially excessive variability in the data sets. Only six skaters were used in these analyses. These six skaters seemed to show a difference in their skill level. Their skill level was not precisely determined in study, however, upon observation, these skaters exhibited a distinct range of technical ability. A more homogeneous population would ideally reduce variability.

In the results of this study, the data reflects the novice ability of the figure skaters. The hypotheses did not proved to be the differentiating characteristics of the jumps. Therefore, there are other parameters that can better show the differences between the loop and the toe loop. Finally, these skaters demonstrated a wrapping of the left leg which can hinder their performances and should be rectified.
In conclusion, the novice skaters from Great Falls have demonstrated several differences between the single toe loop and the single loop as well as some unique characteristics that may be attributed to their skill level. The tested hypothesis resulted in no significant differences. Angular momentum of the flight phase, maximum jump height achieved during flight phase and radial velocity of the right leg during the take-off phase did not show any significant differences between the two jumps. These variables were not the answer to differentiating between the single loop and the single toe loop.

However, the techniques between the two jumps are different. Aside from the differing lift-off techniques, there were other differences discovered between the two jumps. First, the angle of the trunk throughout the two jumps indicated that the skaters’ postures were not the same. In the single toe loop, the skaters showed a more erect posture as compared to the loop. Therefore, the skaters were not as polished in the loop as they were with the toe loop. The tendency of the skaters to lean forward, away from the spin axis, was highlighted in the segmental contribution to moment of inertia. The trunk and head had a greater radius of gyration in the loop as compared to the loop, assuming trunk and head mass to be constant. Erect posture
is one of the most aesthetically pleasing aspects of skating (Woch, 1977). Even though an erect posture can use up to 20% more energy than standing, the novice skaters in this study have shown that within the toe loop, a skater can better utilize extra energy to maintain a more upright position. Quite possibly, the loop requires more of a skater’s energy than the toe loop.

Another outstanding feature between the two jumps was the excessive wrapping of the left leg in the single loop. This wrapping has been seen at the elite level, although not to the degree seen in this study. By extending the entire left leg (hip, knee, ankle), a skater could potentially increase their angular velocity, minimizing the moment of inertia of the left leg. Thus, not only could a correction of the left leg help a skater with faster angular velocities, it may also serve to enhance the gracefulness of their jump.

More importantly with the results of this study are the strategies used by the novice athletes to perform a jump versus an elite athlete. This is beyond the scope of this study; however, it is probably the most critical difference between a novice athlete and an elite athlete of any sport. Well developed musculature, pertinent to a given sport, is essential to well developed sport techniques. Just as important if not more is the motor coordination of the athlete to carry out a sequence of moves to perform a sporting element. In a study conducted by Bard et al. (1994), their more significant findings were that elite athletes, as compared with novice athletes, reduce visual search time and select more meaningful information, which resulted in the elite athlete making more accurate and faster decisions, as applied to a sporting element. The elite athlete has superior cognitive ability to process the available
information and to do so efficiently. Novice athletes tend to process the information at a semantic level and concentrate more on the motor aspect of a given task. This offers an explanation as to why novice skaters are more awkward in their maneuvers than an elite figure skater.

Implications for Further Research

This study has aroused more directions of necessary research to better understand the kinematics and kinetics of novice figure skaters. Certainly a more expansive study should include not only greater numbers of subjects, but also more skaters that are grouped to a better hierarchy of skill classification.

Synchronizing video data remains a difficult task. In this study, two out of the three cameras were synchronized. The third camera was then excluded from further analyses. It is hard to explain why the third camera did not work, however the main difference was the perspective of that third camera view. This camera recorded the events whereby the skaters moved from left to right. The other two cameras recorded the events from right to left. Therefore, it is necessary to find a method in which all cameras from many views can be synchronized.

One particular element from this study, wrapping of the left leg, deserves further attention. It is symptomatic of an improper technique adopted by these skaters. By observing comparisons with skaters who do not wrap their leg with those that do, it may be easier to determine the advantages of extending the left knee and adducting the left leg.
It is common knowledge that an elite athlete is far superior than a novice athlete. However, it is more interesting to understand the progression from novice to elite athlete in figure skating. In this study, the skill level among the athletes was not fully examined or documented. It would be very informative to document skill level of an athlete and compare that with the kinematics of a figure skating jump.

Another more pressing issue is understanding the key elements of the toe loop that provide the distinct advantage over most other jumps to completing four revolutions. The quad toe is the most impressive jump in elite competitions today. It is thought that within the toe loop, the skater is able to make a more controlled transition from a horizontal motion to a vertical motion. This transition is accomplished by the skater planting their skate into the ice and redirecting the ground reaction forces which “pushes” the skater into the air. Figure 5.1 illustrates the upward motion of one skater and the contribution of the right and left radial velocities of the toe loop.

![Graph](image)  

**Figure 5.1.** Vertical COM and radial velocities of both legs in the toe loop.
There is a shift, about halfway through the take-off phase, from contribution of the right leg to the left leg. However, in Figure 5.2, the same skater shows that the contribution is not shifted rather both legs show a decrease of extension velocity at the end of take-off.

Figure 5.2. Vertical COM location and radial velocities of both legs in the toe loop.

The velocity profile is very different between the two jumps during the take-off phase. The transition in the loop could possibly be more difficult by using the broad side of the skate as opposed to the toe loop, a pick jump. By further investigating how the skater makes the upward transition, the real dynamics of the toe loop will be understood. Therefore, a comprehensive analysis of this jump could help Olympic figure skaters take the gold.
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APPENDIX
Subject Consent Form
Kinematic Analysis of Figure Skating Jumps

PURPOSE
You are being asked to participate in a research study of figure skating jumps. We hope to obtain a better understanding jumping techniques of the single toe loop and the single loop jump in figure skating.

PROCEDURES
If you agree to participate, you will be asked to arrive at the Four Seasons Ice-Skating rink at 4:30pm on Monday, March 15, 1998. The entire preparation and filming should take no longer than one hour. The skater is instructed to wear dark, form fitting clothing that will allow her/him to perform their jumps without restriction. Prior to the filming, we will put reflective tape on the joints to determine their location in the video. The skater will be asked to do three single toe loop jumps and three single loop jumps. These jumps will be performed in a specific order. Each skater will be instructed when and what jump to perform. We will treat the skater’s identity with professional standards of confidentiality. The skater’s identity will not be revealed.

RISKS AND BENEFITS
There are no additional risks other than those inherent to the sport of figure skating. There is no direct benefit to the skater. If the skater would like to see their individual results, they may contact Carolyn Sharp, Department of Health and Human Development, MSU, Bozeman, MT (994-4001).

INJURY AND COMPENSATION
In the event your participation in this research directly results in injury to you, medical treatment consisting of standard first aid and/or emergency response will be available, but there is no compensation for such injury available. Further information may be obtained by calling: Dr. Debbie King at 994-4001.

Authorization
I have read the above and understand the discomforts, inconvenience and risk of this study. I (name of parent or guardian, if under 18 years of age) ____________________________, related to the subject as ____________________________, agree to the participation of (name of subject) ____________________________ in this research. I understand that the subject or I may later refuse participation in this research and that the subject, through his/her own action or mine, may withdraw from the research at any time. I have received a copy of this consent form for my own records.

Signed:
Witness:
Investigator:
Date:
Video Release Form
Kinematic Analysis of Figure Skating Jumps

By signing this video release, this will allow the researchers to present video images of the subject for educational purposes. This video may be used as a teaching tool for students at a university or figure skating coaches and athletes. The subject’s name would not be used in association with the video. If you choose not to sign this release form, the subject’s information will remain confidential and will in no way affect his/her participation in this study.

I (name of parent or guardian, if under 18 years of age)
__________________________________________, related to the subject as
__________________________________________, agree to the participation of (name of subject)
__________________________________________ in this research. I acknowledge that the researchers may use the videotape of the subject for educational purposes, such as training university students, coaches and athletes. By signing this release form, I give my permission for such use of the subject’s videotape. I have received a copy of this for my own records.

Signed:

Witness:

Investigator:

Date: