FUNCTIONAL ANALYSIS OF THE
ARTICULATING FIGURE SKATE

by

Scott Coleman

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science with a major in Exercise Science

Fall 2005

Copyright 2005 Scott Coleman
All Rights Reserved
FUNCTIONAL ANALYSIS OF THE

ARTICULATING FIGURE SKATE

by

Scott Coleman

Approved :

James G. Richards, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved :

Susan J. Hall, Ph.D.
Chairperson of the Department of Health, Nutrition, and Exercise Sciences

Approved :

Betty J. Paulanka, Ed.D., R.N.
Dean of the College of Health Sciences

Approved :

Conrado M. Gempesaw II, Ph.D.
Vice Provost for Academic and International Programs
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>v</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>vi</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>METHODS</td>
<td>4</td>
</tr>
<tr>
<td>RESULTS</td>
<td>8</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>14</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>18</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>32</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1. Prototype figure skate boot used in the analysis ................... 5
Figure 2. Subject A ............................................................................. 9
Figure 3. Subject B .............................................................................10
Figure 4. Subject C .............................................................................11
Figure 5. Subject D .............................................................................12
Figure 6. Subject E .............................................................................13
Figure 7. Segmental contribution to vertical force curve ................. 29
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Calculations for total body reaction forces</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>Ankle, knee, and hip angles at landing</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>GRF, ankle, knee, and hip resultant peak forces</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>Peak knee and hip moments</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>Jump Height</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>Effect of ankle bracing on performance in vertical jumps</td>
<td>24</td>
</tr>
<tr>
<td>7</td>
<td>Ground reaction forces measured in body weight</td>
<td>25</td>
</tr>
</tbody>
</table>
ABSTRACT

The frequency of injuries in singles and pairs figure skaters coincides with the number and difficulty of jumps performed on a daily basis. Medical experts working with figure skaters agree that the design of the skate boot also plays a substantial role in the injury process. Specifically, the primary point of concern has been the constrained ankle mobility characteristic of the modern boot. Literature has shown that the ankle plays a key role in attenuating the shock from the landing impacts. If ankle mobility is restricted as it is in the figure skate, loads in the knee, hip, and spine will significantly increase. The advent of the articulated figure skate permits ankle flexion and extension in the sagittal plane, theoretically allowing the ankle to attenuate some of the force at landing. The purpose of this study was to determine differences between the traditional and articulated figure skates with respect to ground reaction forces, knee, and hip moments. It was hypothesized that the articulated figure skate would result in higher ground reaction forces and lower hip and knee moments.

This study involved five competitive female figure skaters. Subjects completed 3 successful double toe loops in each of the two skates. Video data collected at 240 frames/sec was used to estimate lower extremity kinematics and vertical ground reaction forces. Inverse dynamics were used to estimate moments at the knee and hip. Two different landing techniques were observed: one with the landing leg approximating a
straight position and the other with the landing leg approximating a “seated” position. The subjects’ landing technique appeared to dictate whether or not they could take advantage of the articulated figure skate. Skaters landing with a straighter leg produced lower ground reaction forces, knee, and hip moments in the AFS. Skaters landing in the seated position had increased ground reaction forces, knee, and hip moments in the AFS.
INTRODUCTION

Ice skating has a long, rich history dating back over 5,000 years. The first ice skates were used by Northern Europeans as a means of survival. The skate "blades" were made from wood or bone and were attached to common shoes with leather straps. Today, ice skates have steel blades attached to machine manufactured boots (Gutman, 1995) and skating has become a form of sport and entertainment.

The interest in figure skating today continues to grow. United States Figure Skating (USFS), the national governing body for figure skating, has recently reported a membership of over 12,700 athletes. The United States Parcels Service/USFS “Skate with U.S.” program was developed to bring figure skating to more people across the country. Over 350,000 people have enrolled in the past 15 years (Figure Skating, 1999).

Training today for competitive skaters has become demanding. Skaters are faced with an increased demand for training time, spending up to six hours a day on the ice, six or seven days a week. The devotion of skaters to their sport even takes them away from traditional schooling. They opt for private tutoring, which allows them to spend more hours at the ice rink (Litman & Davis, 1984). The move to more training hours occurred in response to a rules change that eliminated the compulsory figures from world and
Olympic competition in 1990. Skaters began placing a heavier emphasis on skate jumps, attempting between 20 and 100 jumps each day (Smith, A., 1990).

The level of performance in figure skating competition has also risen. More athletes now have the ability to complete triple jumps. For example, Kurt Browning, a Canadian figure skating champion who has completed the quadruple jump, believes “there will probably be a quintuple; five revolutions in full flight” (Gutman, 1995).

Ice skaters are at risk for numerous overuse and acute injuries. With the increased participation by skaters today and the greater emphasis placed on difficult and dangerous jumps, injuries seen in figure skating have increased. The majority of these injuries are occurring in the ankle, knee, and hip (Smith, A, 1990).

The skate boot is the only equipment that the figure skaters utilize, and it is crucial to their performance. The boot itself has been cited as a major source of injuries (Ferstle, 1979). The ideal skating boot needs to “support the ankle and subtalar joints while allowing the ankle to dorsi-flex enough to provide power for jump take-offs and to plantar-flex it enough to give the skater an aesthetically pleasing line” (Smith, A., 1990). A recently designed skate boot, the articulated skate, exhibits these characteristics. This development “abandons the traditional concept of the one-piece leather boot in favor of a new lined plastic boot that is hinged at the ankle” (Smith, A, 1990).

"A new plastic skate boot that is hinged at the ankle could revolutionize skate design and reduce injuries" (Smith, A., 1990). This skate will allow the skater to plantar-flex and dorsi-flex the foot, which will assist the skater in attenuating the shock at impact. It may also enable the skater to generate more power in the ankle to help at take-off,
resulting in higher jumps. Higher jumps translate into a longer time in the air, which leads to more revolutions.

The biomechanical study of figure skating using current technology has not been utilized, despite the recent increased popularity of the sport. Because measures such as ground reaction forces are difficult to obtain on-ice, attempts have been made to simulate skating jumps off-ice, but they do not accurately represent the skaters actual on ice motion. Most figure skaters do not give much thought to parameters such as ground reaction forces, joint angles, center of gravity, or joint powers, although these measures are crucial to proper technique and figure skating success.

The purpose of this study was to determine biomechanical differences between an articulated figure skate (AFS) and a standard traditional figure skate (SFS) during landings. Ground reaction forces, joint forces, and moments were investigated at the ankle, knee, and hip of 5 USFSA ranked female figure skaters. It was hypothesized that 1) the articulated figure skate would produce greater vertical ground reaction forces (GRFs) and compressive hip and knee forces when compared to the standard figure skate and 2) the articulated figure skate would produce lower moments in the knee and hip when compared to the standard figure skate. Increased ankle mobility will allow the skater to land with a straighter leg, resulting in higher GRFs and lower moments in the knee and hip. Increased motion at the ankle joint should allow the skater to more effectively attenuate the downward acceleration of the heel by increasing the moment at the ankle.
METHODS

Five female figure skaters from the University of Delaware training facility participated in this study. Each subject was informed of the testing procedures and signed an informed consent form prior to the study. For the athletes under the age of 18 years, parental consent was obtained. All athletes were told that their cooperation was voluntary and that they could terminate their participation in the investigation at any time. Skaters wore their own clothing, although they were instructed to wear skin-tight garments to facilitate marker visibility as well as to minimize marker movement. Subjects completed successful double toe loops, three with their own skate, and three wearing the articulated skate. Each subject was weighed while wearing the marker set and figure skates. The mass of each figure skate boot was measured and added to the mass of the foot. This value represented the mass of the foot during inverse dynamics calculations.

Data from each skater’s jump were collected using an EVa RealTime Motion Capture System from the Motion Analysis Corporation consisting of six Hires video cameras with 6 mm focal length. The cameras were mounted above the ice rink in one corner of the ice above a hockey face-off circle. The cameras were set 20m from the center of the circle to provide a sufficient volume to record both take-off and landing of
singles jumps. Motion data were recorded at 240 Hz and smoothed with a 2nd order Butterworth filter at 12 Hz.

The articulating figure skating boot was designed utilizing two pairs of skates. A pair of skates was designed to be the lower part of the boot, covering the malleoli and protecting the achilles tendon. The remaining upper portion of the cuff was cut off. The other pair of skates was made into the cuff. This cuff was designed to cover both malleoli. (Drewlinger, 1992). A metal brace with a pin hinge to allow for sagittal plane movement, was fixed to each side of the boot with the hinge axis of rotation located inferior to the medial and lateral malleoli (Foti, 1991).

![Figure 1. Prototype figure skating boot used in the analysis.](image)

The skaters warmed-up and stretched independently as part of their daily routine. They were recorded for three successful double toe loops in each of the skate boots.
Retro-reflective markers, 1.5 inches in diameter, were placed on appropriate anatomical landmarks in order to estimate body segment limb positions and accelerations. Each subject’s limbs included the head, the trunk, thigh, shank, foot, upper arm, and forearm, which included the hand.

Each skater landed double toe loops within the area defined by the face-off circle in the northwest corner of the ice surface. A double toe loop is a toe pick assisted jump that requires the skater to take off and land on the same back outside edge of the skate, revolving 1.5 times during flight. King (1994) found horizontal distance traveled in double axels to range between 10 and 13 feet. The hockey circle is 30 feet in diameter, giving the skater ample room for take-off and landing.

Marker data can be used to predict ground reaction forces of the skaters’ landing without the use of a force plate, because ground reaction forces are the algebraic summation of all mass-acceleration products of all body segments’ center of mass (Winter, 1988). However, when utilizing the acceleration data from each of the segment center of masses, the transient peak forces that occur during heel and toe contact are missed due to the limited collection rate of 240 Hz, and by the damping that occurs within the body. The transient forces are critical in determining peak loads. Without these transients, peak GRFs may be under-reported by as much as 50%. In this study, the transient forces were estimated by using the effective mass constants of the foot, lower leg, and upper as reported by Pagano (2002). These values were 1.00, 0.75, and 0.75 for the foot, lower leg, and upper. These estimated ground reaction forces were then
propagated to the knee and hip joints using inverse dynamics to determine joint forces for
the ankle, knee, and hip, and joint moments for the knee and hip.

Table 1. Calculations for total body reaction forces

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_x = \sum_{i=1}^{n} m_i a_{xi} + C_1(a_{toex}) + C_2(a_{heelx}) + C_3(a_{heelx}) )</td>
<td>where ( m = ) mass of ( i )th-segment ( a = ) acceleration of ( i )th-segment in the x direction</td>
</tr>
<tr>
<td>( F_y = \sum_{i=1}^{n} m_i a_{yi} + C_1(a_{toey}) + C_2(a_{heely}) + C_3(a_{heely}) )</td>
<td>where ( m = ) mass of ( i )th-segment ( a = ) acceleration of ( i )th-segment in the y direction</td>
</tr>
<tr>
<td>( F_z = \sum_{i=1}^{n} (m_i(a_{zi} + g) + C_1(a_{toez}) + C_2(a_{heelz}) + C_3(a_{heelz}) )</td>
<td>where: ( m = ) mass of ( i )th-segment ( a = ) acceleration of ( i )th-segment in the z direction ( g = ) acceleration due to gravity ( C_1 = 100% ) of foot mass ( C_2 = 75% ) of shank mass ( C_3 = 75% ) of thigh mass ( a_{toex} = ) acceleration of toe marker in X direction ( a_{heelx} = ) acceleration of heel marker in X direction ( a_{toey} = ) acceleration of toe marker in Y direction ( a_{heely} = ) acceleration of heel marker in Y direction ( a_{toez} = ) acceleration of toe marker in Z direction ( a_{heelz} = ) acceleration of heel marker in Z direction</td>
</tr>
</tbody>
</table>

RESULTS

Subjects’ ages ranged between 18 and 21 years with a mean age of 18.6 years. Mass ranged between 46.4 and 59.0 kg with a mean of 52.4 kg. Of the five participating subjects, 3 subjects (Subject A, Subject B, and Subject C) had lower GRFs in the AFS.

The 5 subjects Resultant Peak Forces at the ankle, knee, and hip increased or decreased uniformly with their respective increase or decrease in GRF.

Table 2. Ankle, Knee, Hip angles at landing (units in degree)

<table>
<thead>
<tr>
<th>Subject</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AFS</td>
<td>SFS</td>
<td>AFS</td>
<td>SFS</td>
<td>AFS</td>
</tr>
<tr>
<td>Ankle Angles</td>
<td>3.7 p flx</td>
<td>11.8 p flx</td>
<td>11.5 p flx</td>
<td>8.6 p flx</td>
<td>9.7 p flx</td>
</tr>
<tr>
<td>Knee Angles</td>
<td>4.7 flx</td>
<td>12.6 flx</td>
<td>3.5 flx</td>
<td>8.9 flx</td>
<td>5.7 flx</td>
</tr>
<tr>
<td>Hip Angles</td>
<td>9.3 ex</td>
<td>8.6 ex</td>
<td>5.1 flx</td>
<td>7.1 flx</td>
<td>2.4 flx</td>
</tr>
</tbody>
</table>

Key: p flx = plantar flexion; d flx = dorsi flexion; flx = flexion; ex = extension

Table 3. GRF, Ankle, knee, and hip resultant peak forces

<table>
<thead>
<tr>
<th>Subject</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AFS</td>
<td>SFS</td>
<td>AFS</td>
<td>SFS</td>
<td>AFS</td>
</tr>
<tr>
<td>GRF (BW)</td>
<td>8.30</td>
<td>12.56</td>
<td>5.24</td>
<td>7.10</td>
<td>10.48</td>
</tr>
<tr>
<td>Ankle Resultant Peak Force (BW)</td>
<td>8.24</td>
<td>12.46</td>
<td>5.21</td>
<td>7.06</td>
<td>10.41</td>
</tr>
<tr>
<td>Knee Resultant Peak Force (BW)</td>
<td>8.10</td>
<td>12.21</td>
<td>5.11</td>
<td>6.93</td>
<td>10.22</td>
</tr>
</tbody>
</table>

Table 4. Knee and hip moments

<table>
<thead>
<tr>
<th>Subject</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AFS</td>
<td>SFS</td>
<td>AFS</td>
<td>SFS</td>
<td>AFS</td>
</tr>
<tr>
<td>Knee Moments (Nm/Kg)</td>
<td>5.45</td>
<td>14.31</td>
<td>5.93</td>
<td>9.66</td>
<td>10.90</td>
</tr>
<tr>
<td>Hip Moments (Nm/Kg)</td>
<td>5.61</td>
<td>14.66</td>
<td>6.10</td>
<td>10.91</td>
<td>12.68</td>
</tr>
</tbody>
</table>
Subject A presented the greatest decrease in GRF, a 34% decrease (4.26 BW), landing with 12.56 BW in the SFS and 8.3 BW in the AFS. Hip and knee moments also decreased significantly. Knee moments decreased from 14.31 Nm/kg to 5.45 Nm/kg, a 62% (8.86 Nm/kg) drop. Hip moments also decreased 62% in the AFS. Hip moments went from 14.66 Nm/kg in the SFS to 5.61 Nm/kg in the AFS resulting in a 9.05 Nm/kg difference. Subject A landed the double toe loops with a relatively straight leg. The angles included 3.7° plantar flexion in the ankle, 4.74° flexion in the knee, and 9.38° extension in the hip while in the AFS and 11.8° plantar flexion, 12.6° flexion in the knee, and 8.63° extension in the hip landing in the SFS.

Figure 2. Subject A
Subject B experienced a 26% (1.86 BW) GRF reduction while landing in the AFS. Subject B presented peak loads of 7.1 BW in the SFS and 5.24 BW in the AFS. Knee and hip moments decreased significantly again, by 39% (3.74 Nm/kg), going from 9.66 Nm/kg to 5.93 Nm/kg and 49% (4.81 Nm/kg), going from 10.91 Nm/kg to 6.1 Nm/kg respectively. Subject B landed with a relatively straight leg. Ankle, knee, and hip angles were 8.6° plantar flexion, 8.99° flexion, and 7.18° flexion in the SFS and 11.56° plantar flexion, 3.52° flexion, and 5.18° flexion in the AFS.

![Figure 3. Subject B](image)

Subject C showed a decrease in GRF while landing the jump in the AFS, although only by 6% from 11.12 BW to 10.48 BW. Knee and hip moments did however show greater decreases posting a 29% decrease in the knee and 17% in the hip. Subject C
landed with a relatively straight leg. The SFS consisted of angles 5.13° plantar flexion, 0.54° flexion, and 2.61° flexion, while the AFS posted 9.72° flexion, 5.78° flexion, and 2.46° flexion.

Subject D showed a 3% increase in their GRF landing in the AFS. Subject D landed 10.95 BW in the SFS and increased to 11.25 BW in the AFS. Knee moments increased 18% (2.47Nm/kg) going from 13.41 Nm/kg to 15.88 Nm/kg. Hip moments showed no significant change, only .15 Nm/kg, or 2%. Subject D lands with a much less extended leg, more in the seated position. In the SFS, angle positions of the leg included

![Figure 4. Subject C](image)

Subject D showed a 3% increase in their GRF landing in the AFS. Subject D landed 10.95 BW in the SFS and increased to 11.25 BW in the AFS. Knee moments increased 18% (2.47Nm/kg) going from 13.41 Nm/kg to 15.88 Nm/kg. Hip moments showed no significant change, only .15 Nm/kg, or 2%. Subject D lands with a much less extended leg, more in the seated position. In the SFS, angle positions of the leg included
3.80° plantar flexion, 31.81° flexion, and 24.63° flexion. In the AFS, angles included 14.59° plantar flexion, 27.76° flexion, and 20.53° flexion.

Subject E had the greatest increase in GRF landing with 12% more force in the AFS. There was a 1.29 BW increase, going from 10.34 BW in the SFS to 11.63 in the AFS. Knee moments were identical, both skates producing 12.86 Nm/kg. Hip moments increased by 20% (1.87Nm/kg) going from 9.29 Nm/kg to 11.16 Nm/kg. Subject E landed more in the seated position. The angles of the ankle, knee, and hip in the SFS

![Graph showing GRF comparison between SFS and AFS for Subject D.](image)

**Figure 5. Subject D**

Subject E had the greatest increase in GRF landing with 12% more force in the AFS. There was a 1.29 BW increase, going from 10.34 BW in the SFS to 11.63 in the AFS. Knee moments were identical, both skates producing 12.86 Nm/kg. Hip moments increased by 20% (1.87Nm/kg) going from 9.29 Nm/kg to 11.16 Nm/kg. Subject E landed more in the seated position. The angles of the ankle, knee, and hip in the SFS.
were 9.43° dorsi flexion, 27.12° flexion, and 18.44° flexion and in the AFS they were 4.1°
dorsi flexion, 21.05° flexion, and 21.50° flexion.

Figure 6. Subject E
DISCUSSION

Each subject’s landing technique appeared to dictate whether or not the skater could take advantage of the articulated figure skate. Two different landing techniques were observed: one with a straight leg consisting of ranges of $0.5^\circ$ to $12.6^\circ$ flexion in the knee and $9.4^\circ$ extension to $7.2^\circ$ flexion in the hip, and the other technique approximated a “seated” position with knee flexion ranging from $21.1^\circ$ to $31.8^\circ$ and hip flexion ranging from $18.4^\circ$ to $24.6^\circ$. Skaters landing with a straighter leg, Subjects A, B, and C, produced lower GRFs in the AFS. Skaters landing in the seated position had increased GRFs. Regardless of the type of skate, knee and hip moments decreased as the leg became straighter at landing. The lower knee and hip moments coupled with an allowance for a straighter leg at landing support hypothesis #2 for these three subjects. The decrease in compressive forces for these subjects fails to support hypothesis #1. The remaining two subjects, Subject D and Subject E, had increased compressive forces, as well as increased moments while landing with more of a bent leg.

Only 3 of the 5 skaters landed with increased ankle plantar-flexion. The hinges in the AFS should have allowed each skater to plantar flex to a greater degree. The failure of the subjects to use this ability may be due to the lack of experience in the AFS and the years of repetitive landing in a SFS. Another possibility is skaters may have weak ankle muscles that did not allow them to use the articulation in the skate. Their heels may have
collapsed on contact with the ice. Due to the stiffness of the leather boot, skaters may be trained not to use these muscles effectively. With more practice time in the AFS, these skaters may re-learn how to land most effectively.

Negative hip angles reported in two of the subjects represent hip extension at landing. Extension of the hip is not practical in a landing, and it’s likely that the angles were affected by the placement of the sacral markers on these subjects. If the sacral marker is placed too low, the estimated hip joint centers are translated forward and the pelvic coordinate system is tilted backward, resulting in excessive estimates of hip extension. In this study, skaters were tested without removing markers between trials in each of the skates, so any errors in estimation of hip joint centers were identical for both skates.

Limitations of this study included:

1) Unfamiliarity of subjects with the articulating skate. Skaters have countless hours of training in their own boots. While they were given as much time as possible to train in the articulating skate prior to testing, it is unlikely that they trained enough to fully adapt their landing mechanics to the new boot.

2) It is also possible that there was marker movement during impact with the ice. While the markers on the boot likely remained stable, markers on the skaters’ landing leg may have moved with the soft tissue during impact. This would affect the calculation of the segment accelerations, but not the calculations associated with the effective mass. This motion may or may not have been the same for both boots.
3) Figure skaters also do not regularly jump in the corners of the ice rink. There was concern with some subjects having to adopt a different approach angle to the jumps, which may have affected their technique. Their focus may have been aimed more at the approach and takeoff rather than at the landing, distracting them from utilizing the ankle motion available in the articulated boot.

4) The number of subjects recruited for this study was limited to five.

5) Jump heights were different between boot types. Each subject jumped higher in the SFS. The AFS should allow the skaters to generate more power at take-off resulting in higher jumps. This may lead back to lack of training time in the AFS. Another consideration is that the skaters may not need to jump higher. They may be spinning with a faster rate of rotation. This should be considered in interpreting this study’s results.

<table>
<thead>
<tr>
<th>Subject</th>
<th>SFS (cm)</th>
<th>AFS (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>24.5</td>
<td>21.5</td>
</tr>
<tr>
<td>B</td>
<td>33.3</td>
<td>31</td>
</tr>
<tr>
<td>C</td>
<td>37.8</td>
<td>30.8</td>
</tr>
<tr>
<td>D</td>
<td>28.8</td>
<td>24.5</td>
</tr>
<tr>
<td>E</td>
<td>33.8</td>
<td>27.2</td>
</tr>
</tbody>
</table>

Delimitations of this study included:

1) Female figure skaters between the ages of 18 and 21 years skaters that could successfully complete double toe loops in competition.
2) Female figure skaters that wore a size five skate because the only working models of the articulating skate that had been custom manufactured were a size five.

This study has identified a number of methodological weaknesses that should be addressed in future studies. First, it is recommended that each subject’s effective mass constants be determined on an individual basis rather than using the group coefficients recommended by Pagano (2002). Individual coefficients will likely provide a significant improvement to the accuracy of on-ice GRF estimates. Second, articulating figure skates should be manufactured in a variety of sizes to permit the testing of both male skaters and female skaters. Third, different types of jumps should be explored to determine whether landing positions and GRFs are affected by different takeoff mechanics.
APPENDIX A

REVIEW OF LITERATURE

Boot History

The evolution of the ice skate has taken an interesting path through time. Ice skating was an invention of early Northern Europeans. The first pair of ice skates was discovered at the bottom of a Swiss lake dated approximately 3000 B.C. (Gutman, 1995). Skating was at this time a means of survival as it was a fast form of travel, a way to hunt for food, and an escape from enemies. Skate blades have progressed from wood and bone to the steel used today (Milton, 1996).

The first materials used for blades were flat pieces of wood and long bones of large animals, such as horse, deer, elk, and sheep. Walrus teeth and frozen corncobs were also used (Travers, 1980). Holes were bored or drilled into these bones in order to allow leather straps to fasten the bone to the shoe. These pioneers also greased the bottoms with hog lard to make the bone more slippery. Sticks were used to help skaters push off acting as ski poles do today. During the 1800s, straps were built into the skate itself, similar to today's sandals. Iron blades were later developed, giving skaters the ability to grab the ice and be able to push off (Milton, 1996).

The ice skating craze hit the United States during the nineteenth century with the help of Jackson Haines. In 1850, E.V. Bushell revolutionized ice skates with the
invention of the strapless skate, which was first to allow skaters to twist, turn, and spin without losing their blades. As skating grew in popularity, so did the pace of development. American inventors were issued 149 patents during the 1860s for new skate designs. Another major adjustment came in the 1880s with the development of the toe pick. The conventional ice skate appeared at the turn of the twentieth century and within the past 100 years, skate development has remained relatively stagnant, with only minor adjustments being made (Gutman, 1995).

Figure skating boots today restrict the flexion of the foot, not allowing the skater to point their toes. This design is used for protection from ankle strains and sprains by not allowing lateral movement of the ankle upon landings from jumps. Although designed to help the skater, this design limits the ankle extension necessary to generate enough power at take-off in order for skaters to reach their maximum height. Sufficient ankle flexion is also needed at landing to absorb the repeated high impact (King, 1998).

The skate boot has been the subject of blame by physicians as the primary cause for foot injuries in figure skating during the late 70s. Skaters wanted more support as they increased the number of jumps and jump difficulty increased. These heavier boots, stiffer and thicker than before, were being blamed for a majority of skating injuries. Tenley Albright, MD, a former Olympic figure skating champion and member of the USFSA's sports medicine committee, reported, "stiffer boots cause an increase in acute and chronic tendonitis" (Ferstle, 1979, p132). Dr. Duane Nelson, a podiatrist, discovered that 80% of injuries in skater's feet resulted from these heavier designed boots. Both men have suggested that skaters turn to thinner, more flexible boots (Ferstle, 1979).
Skating Injuries

Figure skating is a physically demanding sport. With an increased participation in skating over past years, the number of figure skating injuries has increased. The majority of injuries seen in figure skating are located in the foot, ankle, and lower leg. (Smith, A., 1990) Most competitive figure skating injuries are a result of over training and poor fitting boots. Common boot-related injuries include pump bump, malleolar bursae, tenosynivitis, and Achilles tendonitis. Knee pain, stress fractures, and spondololysis are frequently seen overuse problems (Smith, A., 1997). Foot and ankle injuries “stem from ill-fitting boots and jarring jump landings” (Smith, B., 1997).

Changes in performance standards demand an increased difficulty of maneuvers from figure skaters, which may be directly related to the increased number of injuries. A rules change eliminating the compulsory figures from world and Olympic competition in 1990 has placed a heavier emphasis on the free skate. As a result, skaters are now spending more time on the free skate in practice, attempting between 20 and 100 jumps daily (Smith, A., 1990). Changes in performance standards have led to an increased level of competition, as more and more skaters are attempting triple and quadruple jumps. There has also been an increase in the number of competitions and shows.

Competitive figure skaters sustain acute and overuse microtrauma injuries. The musculoskeletal system of the athletes is exposed to enormous impacts, particularly upon landings from jumps. Overuse injuries result from an overload placed on the body. This “overload can occur due to one force being above the critical limit or a number of cyclic forces below that limit producing a combined fatigue effect” (Nigg, 1985, p369).
Brock and Striowski (1986) examined 60 nationally ranked Canadian figure skaters involved in singles, pairs, and ice dancing, over a one-year period. They found that 47% of national level skaters suffered injuries, 50% being acute and 43% overuse. They also found that ice dancers had fewer injuries due to the lack of jumps involved in their discipline.

During the 1997 World Figure Skating Championship in Lusanne, Switzerland, the International Congress on Medicine and Science in Figure Skating convened. This committee is composed of leading doctors that exchange ideas and recent findings among each other. Boot-related injuries were a major focus of this particular meeting. “Shoemakers torture our skaters with their skating boots,” said Dr. Wolf-Dieter Montag, an orthopedic surgeon and member of the medical commission of the International Olympic Committee (Smith, B., 1997). The committee suggested that skaters need to find boots that actually fit. When boots do not fit correctly, the leather can crease causing a pressure point against the skin. This may lead into an abrasion that can possibly become infected. This happened to Canadian champion Susan Humphreys. She had to withdraw from the free skate in Lusanne, which eventually cost Canada a spot at the 1998 Olympics.

A study conducted at the Olympic Training Center in Dortmund, Germany examined boot-related injuries. It was suggested "the manufacturers of figure skating boots should think of better ways to get an isolated additional stability for the ankles to prevent turning during the landing"(Smith, B., 1997).
It is possible to apply mechanical strategies to reduce overloading in the body. Nigg (1985) noted these strategies to reduce load and stress on the body and consequently reduce the frequency of injury in sport. These strategies include altering the movement, the surface, the shoe, and the frequency of repetition. In figure skating, changing the surface is not practical. All jumps are performed on-ice. The frequency of repetition can be altered, although it is difficult, as skaters need sufficient practice in order to be proficient. The landing movements of multi-rotational jumps have relatively small margins of error and therefore difficult to adjust. Adjustments in the shoe, or skate, may help reduce loading to the body.

Ankle Restrictions

Many athletes believe that increased ankle support is restricting their athletic performance (Pienkowski et al, 1995). A restriction of the ankle's range of motion, in particular plantar-flexion, can affect the function of the ankle as a shock attenuation mechanism, limiting its effectiveness. This leads to increased impact forces upon jump landings, and likewise the body will receive an increased transmission of shock. Upon landing, if the foot is not allowed plantar-flexion, time to peak vertical impact will be generated quicker (Brizuela et al, 1997).

If greater ankle support reduces the normal range of motion of the ankle, the shock attenuation capability of the joint will be reduced. This could lead to increased risk of overuse injuries in athletes and hinder athletic performance (Brizuela et al, 1997).
The ankle is an important shock attenuation mechanism. Previous studies have been conducted examining the effects of increased ankle support on ground reaction forces and athletic performance. Many of these studies were designed to provide increased lateral support, although sagittal plane motion may also be compromised. Devices used in these studies included ankle taping, ankle braces, and high-top basketball shoes. Mixed results have been reported in literature by a number of investigators.

Brizuela et al (1997) conducted a study on the influence of basketball shoes with increased ankle support on shock attenuation and jumping performance. The group tested high top and low top basketball shoes. It was concluded that ankle support did increase while wearing the high top shoe by decreasing ankle eversion, however, they also discovered that with the high top shoe, there was an increased shock transmission through the body and jump performance was hindered. The increase in impact forces and decrease in performance "are particularly influenced by limitations of ankle flexion-extension" (Brizuela et al, 1997, p514).

Burks et al (1991) studied athletic performance with prophylactic ankle devices and found a decrease in performance when the ankle was both taped and when it was braced. Burks cited Mayhew (1972) and Juvenal (1972) as also discovering a performance decrease with ankle taping in their respective studies.

Robinson et al (1986) found that decreased range of motion in the ankle affected subject performance. They used high top basketball shoes. They placed plastic strips and positioned them in specially designed pockets anterior and posterior to the lateral and medial malleoli. Four shoe conditions were used. One condition included no plastic
strips, while the other three were of varying stiffness. It was found that as stiffness increased, performance and range of motion decreased. Paris (1992) concluded that subjects with "New Cross" taped ankle had a 5.4% decrease in vertical jump height (Bot, 1999).

Table 6. Effect of Ankle Bracing on Performance in Vertical Jump

<table>
<thead>
<tr>
<th>Study</th>
<th># of Participants</th>
<th>Type of Brace</th>
<th>Vertical Jump</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greene &amp; Hillman (1990)</td>
<td>7 (F)</td>
<td>Ankle ligament protector</td>
<td>No Effect</td>
</tr>
<tr>
<td>Bocchinfuso (1994)</td>
<td>15 (M/F)</td>
<td>Aircast Sport-Stirrup</td>
<td>No Effect</td>
</tr>
<tr>
<td>Gross et al (1994)</td>
<td>16 (M/F)</td>
<td>Ankle ligament protector</td>
<td>No Effect</td>
</tr>
<tr>
<td>Macpherson et al. (1995)</td>
<td>25 (M)</td>
<td>Aircast Sport-Stirrup</td>
<td>No Effect</td>
</tr>
<tr>
<td>Paris (1992)</td>
<td>18 (M)</td>
<td>Swede-o Universal</td>
<td>No Effect</td>
</tr>
<tr>
<td></td>
<td></td>
<td>New Cross</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>McDavid</td>
<td>No Effect</td>
</tr>
<tr>
<td>Pienkowski et al. (1995)</td>
<td></td>
<td>Swede-O Universal</td>
<td>No Effect</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kallasy</td>
<td>No Effect</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aircast Air-Stirrup</td>
<td>No Effect</td>
</tr>
<tr>
<td>Verbrugge (1996)</td>
<td></td>
<td>Aircast Sport-Stirrup</td>
<td>No Effect</td>
</tr>
<tr>
<td>MacKean et al.</td>
<td></td>
<td>Aircast Air-Stirrup</td>
<td>No Effect</td>
</tr>
<tr>
<td>Burks et al. (1991)</td>
<td></td>
<td>Swede-O Universal</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kallasy</td>
<td>Negative</td>
</tr>
<tr>
<td>Brizuela et al. (1997)</td>
<td></td>
<td>High top Shoes</td>
<td>Negative</td>
</tr>
</tbody>
</table>


Pienkowski et al (1995), however, provided contradictory results. They studied twelve male high school basketball athletes that wore three varieties of ankle braces for four basketball-related activities, including the vertical jump. They concluded that prophylactic ankle bracing does not affect athletic performance, particularly jumping.
Other studies (Greene, 1990, Bocchinfuso, 1994, Gross, 1994, Macpherson, 1995, Verbagge, 1996, Mackean, 1995) discovered no significant difference when athletes were wearing an ankle brace on performance (Bot, 1999). Bot (1999) stated that "it is possible that ankle bracing has a negative effect on vertical jump performance, although the evidence is not conclusive" (Bot, 1999).

Jump Studies

Joint kinematics can attenuate ground reaction forces. Jumping is a key component in a number of sports, including figure skating. When an athlete executes any type of jump, a landing will follow exerting external forces upon the body. These forces are absorbed by the musculoskeletal components of the lower extremities. In figure skating competition, the participant is permitted to land on one foot only, causing these forces to be absorbed through one leg instead of two (Dufek, 1989). Dufek & Bates (1989) found that a reduction in vertical impact forces was accompanied with a toe-heel landing, rather than landing flatfooted.

Table 7. Ground Reaction Forces Measured in Body Weight (BW)

<table>
<thead>
<tr>
<th>Activity</th>
<th>Vertical Forces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking(^a)</td>
<td>1.1 – 1.5</td>
</tr>
<tr>
<td>Running(^a)</td>
<td>2.0 – 2.9</td>
</tr>
<tr>
<td>Basketball Landings(^b)</td>
<td>4.3 – 8.9</td>
</tr>
<tr>
<td>Drop Jump Landings(^c)</td>
<td>9.1 – 11.0</td>
</tr>
<tr>
<td>(1.28m)</td>
<td></td>
</tr>
<tr>
<td>Gymnastics(^d) (somersault)</td>
<td>6.0 – 7.0</td>
</tr>
</tbody>
</table>

Valiant and Cavanagh (1983) studied the landings from basketball rebounds. Two different landing techniques were observed, toe-heel and flatfooted. The heel-toe landing graphs report two peak forces. The first peak was caused by forefoot contact. The forces decreased slightly before rising rapidly with heel strike to a much higher peak. Forces reached averages of 1.3 times body weight (BW) for the first peak occurring 10 ms after contact, and 4.1 BW for the second peak, 37 ms after landing. Flatfooted subjects exhibited one peak vertical ground reaction force that was 6 BW, occurring 12 ms after contact.

McNitt-Gray (1993) examined kinematics of the lower extremities of gymnasts and recreational athletes upon landing from three different heights. Peak moments and work in the ankle, knee, and hip significantly increased as impact velocity increased. It was discovered that the gymnasts distributed increases in work more evenly among the ankle, knee, and hip than the recreational participants. Peak moments in the ankle were measured at 7.69 Nm kg$^{-1}$ for gymnasts and 6.25 Nm kg$^{-1}$ for recreational athletes.

Gross and Nelson (1988) noticed two landing styles during their study investigating the shock attenuation role of the ankle during landing from a vertical jump. Seven of the eleven subjects landed with heel contact, while the remaining four landed without any heel contact. The forefoot landing increased the joint range of motion, and the time the body took to come to rest. This reduced exposure to skeletal transients by nearly 50% (Gross, 1988).
Mizrahi and Susak (1982) attempted to discover parameters affecting the attenuation of impact forces following a freefall from two different heights, 0.5m and 1m. They studied landings on the balls of the feet and flatfooted. They concluded that during landings from a jump, joint movement plays a key role in minimizing peak forces.

Lees (1981) investigated impact absorption during vertical jump landings. Again, two landing techniques were present. Lees termed the landings "hard" landings and "soft" landings. The hard landings had greater ground reaction forces, over 3 BW, and the impact absorption only lasted 150ms. The soft landings were 2 BW for 200ms. “It is reasonable to assume that a shorter rise time to peak force is associated with greater stresses experienced by the body” (McClay et al, 1994).

Ozguven & Berme (1988) examined impact forces on gymnasts. They found peak forces ranging from 8.2 to 11.6 BW. McClay et al (1994) studied ground reaction forces among 24 professional basketball players. Lay-up landings resulted in the highest forces, with 8.9 BW. The jump shot had forces of 6.0 BW and vertical jump landings with 4.3 BW.

Panzer (1987) studied the loads in the lower extremities while landing from a double back somersault. Peak ground reaction forces ranged between 8.8 and 14.4 BW. Vertical force reduction in the lower leg averaged 14%. The greatest decrease was found to be between the knee and hip. At hip level, the vertical ankle joint force was reduced by an average of 41%. Maximum compressive knee joint force averaged 2106 N ranging between 547 and 4422.5 N (1.48 to 5.75 BW). The hip joint was found to be receiving 50 to 68% of the vertical impact force. The average peak compressive force at
the hip was 1593 N and ranged from 632 to 3285 N (1.88 to 4.87 BW). Peak joint moments occurred 70 to 90 ms after ground contact with peak forces occurring 30 to 50 ms after contact. Average peak ankle joint moments were found to be 317 Nm for plantar-flexion and 352 Nm for dorsi-flexion. The vertical ground reaction force was found to increase proportionally with multi-rotations as multi-rotation requires greater angular velocity in flight to complete the somersaults.

Lees (1981) described impact landing in mechanical terms. When the body is rigid, it acts like a pole dropped on its end. All the body segments decelerate together. Total body deceleration time will be small causing a high force level. The body could also act as a damped spring, by becoming flexible. This causes the time for deceleration to increase and a smaller force level. The body is a multi-linked system. Force reduction is a direct result of the complex interaction between the links of the system.

Lees (1981) noted that differences in force curves are a result of segment interaction in the multi-linked system. Each segment of the body contributes differently to the vertical force curve. Acceleration measurements can be used in load analysis (Nigg, 1985). Using Newton's second law, force is equal to the product of mass and acceleration, it is possible to discover segment contributions to the total vertical force. Proportional contributions of each major segment of the body can be calculated (lees, 1981).
Articulating Skate Studies

Three masters’ thesis were conducted at the University of Delaware after development of the articulating figure skate. Investigation into the kinetics and landing leg kinematics were the focus of the three studies.

In the first study Foti (1991) simulated low-level landings in the articulating skate and the traditional figure skate. The study was conducted in a laboratory setting, using a

Figure 7. Segmental Contribution to Vertical Force Curve
force plate covered with an artificial ice surface. Ten subjects dropped backwards from a height of 0.3 meters onto the artificial surface. Foti concluded that peak vertical impact force was significantly lower upon landings with the articulating skate, although the force reduction mechanism was not determined. Time to peak force between the two variables was consistent. Lateral support for the ankle also showed no significant differences. Foti also noted that the landing leg was more extended upon landing with the articulating skate. Foti recommended that skaters need training time in the articulating skate after data showed that ankle angle measurements showed large variability.

In another off-ice study Henley (1992) examined the effects of the articulating ice skate on the attenuation of joint forces and moments while landing from a jump. Again, subjects dropped from a height of 0.3 meters onto artificial ice surface covering a force plate. Henley also found a decrease in ground reaction forces, with the traditional skate producing forces ¾ body weight greater than the articulating skate. Joint range of motion increased for the ankle, knee, and hip. There was no significant difference among ankle moments. Range of motion in the ankle and knee increased significantly, with a small increase in the hip angle. The articulating skate produced “more favorable kinematic and kinetic profile than the standard skate” (Henley, 1992,).

The third study was conducted on-ice. An F-scan foot pressure insole was used to measure forces under the foot. Drewlinger (1992) examined the effects of the articulating ice skate on the attenuation of joint forces and moments and discovered that the findings were contradictory to those of Foti (1991) and Henley (1992). There was an increase in ground reaction forces when the athlete used the articulating skate. Forces and moments
in the ankle and knee were also attenuated more successfully with the newly designed boot. The articulating skate was not utilized to its fullest potential, however. Plantarflexion at the ankle did not change between boots, although dorsiflexion increased with the articulating boot. Skaters did not use the articulation until after ground contact. They landed from each jump as if they had their own non-articulating boots on. This may have been due to the lack of training time in the articulating skate.

Summary

The continued rise in figure skating injuries has been blamed on the loads caused by the increased number of jumps attempted by skaters. Medical personnel have also identified the standard figure skate as another contributing factor to the injury rate. Specifically, the problem of restriction in ankle mobility has been the primary point of concern. In addition, participation in figure skating has risen and more skaters are completing triple and quadruple jumps, which are causing greater loads on the body. Literature has shown that the ankle plays a key role in attenuating the shock from the ground impact following a jump. If ankle mobility is hindered or eliminated, as it is in a figure skate, loads in the knee and hip will significantly increase. This can become more of a problem as skaters increase the number of triple, quadruple, and quintuple jumps that they execute daily. The advent of the articulating figure skate permits ankle flexion and extension in the sagittal plane, allowing ankle attenuation. This mechanical feature should lead to lower on-ice shear forces occurring in the knee and hip joints at impact following a jump.
REFERENCES


Ferstle, J. (1979). Figure Skating: In Search of the Winning Edge. The Physician and Sportsmedicine.


Henley, J.D. (1992). Three Dimensional Evaluation of the Moments at the Ankle, Hip, and Knee While Landing in a Standard and Articulated Figure Skate. Unpublished Master’s Thesis, University of Delaware, Newark, DE.


Pagano, M. (2002). The Use of Kinematics in Estimating the Vertical Ground Reaction Forces of Impact Landing During Jumps in Figure Skating. Unpublished Master’s Thesis, University of Delaware, Newark, DE.


Smith, A.D. (1990). Foot and Ankle Injuries in Figure Skaters. The Physician and Sports Medicine. 18(3), 73-86.

Smith, B. (1997). Talking Figure Skating. McClelland & Stewart, Inc., Toronto.

