Comparison of Jump Landings in Figure Skaters While Barefoot and Wearing Skates

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Emily K. Griswold
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This thesis titled
Comparison of Jump Landings in Figure Skaters While Barefoot and Wearing Skates

by

EMILY K. GRISWOLD

has been approved for
the School of Applied Health Sciences and Wellness
and the College of Health Sciences and Professions by

Jeffrey A. Russell

Assistant Professor of Athletic Training

Randy Leite

Dean, College of Health Sciences and Professions
Abstract
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Director of Thesis: Jeffrey A. Russell

Background: Jump landing is a major contributor to overuse injuries in figure skaters. Previous research has examined the differences in barefoot jump landing biomechanics of figure skaters and nonskaters; however, differences between figure skaters landing barefoot and in skates has not been evaluated. Purpose: The purpose of this study is to compare landing mechanics among figure skaters while barefoot and in skates, and to describe the landing mechanics of figure skaters. Methods: A total of 10 female figure were asked to perform a backwards jump landing task and land on their dominant leg in the single-leg figure skater landing position. Inertial measurement units (IMUs) were secured to the landing leg and trunk of each participant. The task was performed under two conditions: barefoot and in skates. Main outcome measures: Peak vertical ground reaction force (vGRF), time-to-peak vGRF, and lower extremity joint angles at peak vGRF. Results: Time-to-peak vGRF was significantly faster during the in-skates condition when compared to the barefoot condition. All other variables were not significant between conditions. Conclusions: Figure skaters do not change their landing mechanics while barefoot compared to while wearing skates. Lack of articulation through the foot when in a skating boot can lead to a shorter time to dissipate vGRF, which can increase the risk of lower extremity injuries in figure skaters.
Preface

Chapter 3 contained within the thesis document serves as a prepublication manuscript. This manuscript has been formatted to meet the guidelines set forth by the *Journal of Athletic Training* and Thesis and Dissertation Services at Ohio University. The reference citation style follows the guidelines of the AMA Manual of Style (10th ed., 2007).
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Chapter 1: Introduction

Figure skating jumps are a major point of interest in biomechanical research of the sport. As figure skating evolves, skaters continue to attempt larger, more complex jumps in their practices and competitive programs.\(^1\) Research shows that figure skating jump landing is a serious contributor to overuse injuries in these athletes.\(^2\) According to an epidemiological study conducted by Dubravcic-Simunjak et al.,\(^2\) overuse injuries of the lower extremity are the most common injuries in freestyle figure skaters. Overuse injuries made up 78% of injuries sustained by male and female singles figure skaters throughout the course of the study.\(^2\) However, research pertaining to the biomechanics of this population is outdated.\(^3\)–\(^7\) There have been many significant changes to the sport over the last 12 years, and most research regarding jumping biomechanics was performed and published long before the implementation of these changes. The structure and design of figure skates have been altered, and there are manufacturers who now offer boots and blades made out of lighter weight materials.\(^8,9\) Another substantial difference in the sport is the implementation of a new, more objective judging system of figure skaters’ competitive performance.\(^10,11\) These fundamental changes in the sport were implemented in an attempt to reduce figure skaters’ risk of overuse injury. In order to mitigate the risk of overuse injuries in figure skating, more must be learned about the physical demands of the sport.

A contemporary study regarding jump landing biomechanics investigated lower extremity kinetics and vertical ground reaction forces (vGRF) of a single-leg drop-jump performed by figure skaters and nonskaters while barefoot and off the ice.\(^12\) This study
provided insight into the unique landing mechanics of figure skaters, however differences between landing barefoot and while wearing skates has not been examined. To better understand the mechanics of jump landing in figure skaters, it is important to identify potential differences in landing mechanics of skaters while wearing their skating boots as compared to barefoot.

The purpose of this study is to compare landing mechanics in figure skaters while barefoot and in their skates.

RESEARCH QUESTION AND HYPOTHESES

1. Are there differences in jump-landing biomechanics for figure skaters performing a jump-landing task while barefoot compared to when in skates?
   a. Figure skaters demonstrate similar peak vertical ground reaction force (vGRF) and time-to-peak vGRF when in skates compared to barefoot.
   b. Figure skaters demonstrate less ankle dorsiflexion, greater knee flexion, greater hip flexion, and greater lumbar flexion at peak vGRF when in skates compared to barefoot. Knee abduction is comparable between the conditions.

INDEPENDENT VARIABLES

1. Condition
   a. Barefoot
   b. In-skates

DEPENDENT VARIABLES

1. Force plate variables
a. Peak vertical ground reaction force (normalized to body weight)
b. Time-to-peak vertical ground reaction force (seconds)

2. Inertial measurement unit (IMU) variables
   a. Ankle dorsiflexion (degrees)
   b. Knee flexion (degrees)
   c. Knee abduction (degrees)
   d. Hip flexion (degrees)
   e. Lumbar flexion (degrees)

ASSUMPTIONS

1. Participants dropped from the box with no observable differences in technique.
2. Participants did not knowingly alter their jump-landing technique because they knew they were being analyzed.
3. The polyethylene covering on the force plate did not alter the data of the jump-landing task in the in-skates condition.
4. Evaluation of IMU data was consistent for every participant.

LIMITATIONS

1. The results of the study cannot be directly translated onto the ice.
2. The results of the study are not applicable to male figure skaters.
3. The evaluator for the jump-landing task is also the main researcher and could be biased due to not being blinded.
DELIMITATIONS

1. Participants were healthy female figure skaters in the Athens area.
2. No electromyography or muscle strength data was collected.
3. Barefoot and in-skates testing conditions was obtained in a single testing session rather than on separate occasions.
Chapter 2: Review of the Literature

Increased emphasis on jumping has become evident as figure skaters continue to attempt larger, more complex jumps in their competitive programs.\(^1\) Research demonstrates that figure skating jump landings are a serious contributor to overuse injuries in these athletes.\(^2\) Much of the research performed to evaluate landing biomechanics is outdated.\(^3\)–\(^7\) Over the last 12 years, there have been many changes to both the physical design of the skating boot and blade,\(^8\),\(^9\) as well as the implementation of a completely new, more objective judging system of figure skaters’ competitive performances.\(^10\) These fundamental changes in the sport have altered the focus of skaters’ practice regimens. They were incorporated for a variety of reasons, one of which was to reduce skaters’ risk of overuse injury. This literature review will focus on figure skating injuries, biomechanics, and differences among figure skaters of various levels, as well as on ways of measuring jump-landing biomechanics in figure skaters, such as evaluation of joint angles and force plate data.

**FIGURE SKATING Injuries**

Many researchers have studied the specific types of injuries that figure skaters endure. Injury classifications vary depending on the discipline in which the skater competes. A study conducted by Dubravcic-Simunjak et al.\(^2\) used a retrospective questionnaire to collect injury data over a course of 4 years in elite junior-level figure skaters. They separated figure skaters of different disciplines to determine injury type and
prevalence in elite skaters. Overuse injuries of the lower extremity were the most common type of injuries in freestyle figure skaters.

Another injury-prevalence study conducted by Fortin and Roberts\(^1\) found similar results. After examining the nature, frequency, and type of injuries sustained by the figure skaters competing at a national figure skating competition through medical history forms and on-site evaluations, the researchers found that lower extremity injuries were the most common. They also found that 64% of the injuries seen were due to exacerbation of a pre-existing injury, which further supports that overuse injuries are the most common type of injuries in the competitive figure skater population.

Stress fractures of the lower leg, tarsals, and metatarsals are also prevalent in figure skating\(^3\). For pairs skaters, acute injuries are more common than overuse, and head injuries become a greater concern\(^2\). Ice dancers suffer the fewest injuries, which could be due to the lack of jumping and overhead lifting involved in the discipline\(^2\).

Injuries to the foot and ankle are typically of concern due to the rigidity of the skating boot\(^1\). Injuries of the foot and ankle have been examined extensively, including metatarsal stress fractures, bursitis, Achilles tendinopathies, and extensor hallucis longus tendinopathies\(^1\).

**Equipment**

Figure skates are made of a leather boot and metal blade, and are known for their rigidity\(^1\). The boots have become increasingly more stiff as skaters attempt greater revolution jumps to accommodate the greater stress placed on them\(^1\). It is thought that
this increased rigidity of the skating boot has contributed to weakness in ankle musculature and an increased number of injuries in competitive figure skaters.\textsuperscript{16}

**Biomechanics**

Research regarding biomechanics in figure skaters is still developing after the major changes in the foundations of the sport. This research has focused on jumping in particular. One study analyzed figure skaters’ air position for single, double, and triple revolution jumps.\textsuperscript{17} The researchers provided a biomechanical description of each specific jump. Its main purpose was to provide helpful training strategies for figure skaters to improve their jumping abilities.

Other research has focused on comparing biomechanically correct jumping techniques with jumps that would be awarded the highest scores by accredited figure skating judges.\textsuperscript{18} This research was performed after the implementation of the new judging system, where every jump has a base point value, and fractions of points are added or subtracted based on the judges’ perception of the execution.\textsuperscript{11} More optimal jump landings—as determined by the biomechanists—were awarded higher scores by the judges. This is helpful because it supports that skaters are striving toward jump executions that win the highest scores, and the aesthetics of the jumps appear to match what is desirable biomechanically.

Other biomechanical research has evaluated figure skaters’ balance abilities by assessing postural control on a force plate.\textsuperscript{19} Figure skaters who trained using a neuromuscular training program had improved postural control scores after a 6-wk intervention period compared to the skaters who performed a basic off-ice protocol. This
information also contributes to the knowledge of biomechanics in the sport, and will help coaches and strength trainers to create training programs that involve more appropriate neuromuscular training exercises.

**Differences in Skill Levels**

Studies have compared the biomechanics of figure skaters of differing skill levels. Skaters of differing skill levels have different biomechanics, muscular strength, cardiovascular capabilities, and respond differently to neuromuscular training programs. Figure skaters at higher levels of skill in the sport must complete jumps with more revolutions, which means they need to attain higher vertical jumps and be explosive in their jump takeoffs. Differences in muscular strength may account for these differences in jumping and rotational ability.

Differences in cardiovascular endurance may be attributed to the length of the skating program for skaters of different skill levels. As figure skaters progress through the levels, the freestyle program increases in length. Skaters at lower levels skate programs that are around 2 min in length, whereas the highest level of figure skating requires that skaters perform for 4 to 4.5 min, depending on whether the skater is female or male.

Differences in postural control and balance are not as easily explained with regard to skill level. One study evaluated postural control in skaters who could and could not perform multiple revolution jumps. At baseline there were no differences between groups. Following the intervention of the same 6-wk neuromuscular training program, the higher level group showed significant improvement in single leg landing when compared
to the lower level group. Because of these discrepancies in biomechanics among figure skaters of differing levels, it is important to make sure that research is completed on skaters at low and high levels to determine if the results in skaters of one level apply to other levels.

**MEASURING JUMP LANDING MECHANICS**

**Joint Kinematics**

Various studies have examined jump landing biomechanics by measuring lower extremity joint angles of figure skaters in the jump landing position. One study compared hip, knee, and ankle joint angles of pairs figure skaters during a repeated jumps test.\(^1\) Kinematic data of the jumps were obtained using a standard digital video camera and video analysis system. Circular reflective markers were placed at the greater trochanter, knee joint line, lateral malleolus, xiphoid process, inferior angle of the eleventh rib, and the lateral side of the fifth metatarsal head. The researchers examined the joint angles during both takeoff and landing during three consecutive trials.

In another study, participants performed a series of squat jumps. Landmarks were placed on the acromion, greater trochanter, lateral femoral epicondyle, lateral malleolus, and fifth metatarsal.\(^2\) Participants were filmed in the sagittal plane with a camcorder on a tripod, and the images were digitized frame-by-frame. Squat jumps were performed under three conditions: barefoot, while wearing a weight around the ankle, and in skating boots. The researchers found that the skate significantly reduced jump performance due to reduced joint angles at the ankle and subsequent reduction in vertical jump height.
Retroreflective markers were used in another study to measure joint angles of figure skating jumps. Markers were placed on 19 standardized anatomical landmarks. Biomechanists and accredited figure skating judges analyzed the jumps, and the analyses were compared. Two digital video cameras were positioned at two oblique views and were used to achieve three-dimensional videography. These measures were computed then profiled biomechanically into four categories. It was found that the skaters whose jumps were considered biomechanically correct or safe were the skaters who received higher marks from the judges on technical merit.

Previous research shows differences in lower extremity kinematics in runners who run barefoot compared to running in shoes. The literature agrees that lower extremity joint angles are decreased when running in shoes compared to when running barefoot. No published literature could be found that compared lower extremity landing kinematics in figure skaters while barefoot versus wearing skates.

The 3D video system Vicon is considered the gold standard of motion capture. A study conducted out of Arizona State University examined the validity of the Noraxon MyoMotion IMU system by comparing it to Vicon during a knee flexion exercise. The researchers found no significant differences between Vicon and the Noraxon MyoMotion IMU system for measuring anatomical joint angles.

**Time to Stabilization**

A previous study conducted by Wikstrom et al. examined the differences in time to stabilization after holding a jump landing for 3, 5, and 10 s of data collection. It was
found that holding the single leg landing for 3 s produced reliable data that was comparable to the data collected after 10 s.

**Drop Landing**

The drop landing test onto a force plate has been used by several different biomechanical studies. Center of pressure (CoP), peak vertical ground reaction force (vGRF), time-to-peak vGRF, time to stabilization (TTS), and impulse have been measured previously. In a recent study conducted by Saunders et al., a group of figure skaters were compared to nonskaters in a barefoot drop landing test. Participants were asked to stand barefoot on a 20-cm platform and drop backwards onto a force plate into the single-leg skater landing position, and remain still for 15 s of data collection. Peak vGRF, time-to-peak vGRF, TTS, CoP, and impulse were all measured in this study. The researchers found that figure skaters exhibited greater peak vGRF with shorter time-to-peak vGRF, as well as a longer TTS than the nonskater group. Also, it was found that the skater group overall had a significantly more confined CoP in both the medial-lateral and anterior-posterior directions.

Using similar methods, Bruening and Richards compared figure skaters in a drop-landing test in their traditional skating boots to the same test in prototype articulated skating boots. The off-ice component of their research consisted of hopping backward off a 30-cm box onto a force plate covered with 3-mm-thick sheet of acrylic (artificial ice surface) into the single-leg skater landing position. This procedure was tested in both the traditional skating boot as well as the new articulated skating boot. Peak vGRF at heel strike, peak vGRF at toe strike, and the loading rate were measured. It was found that the
peak heel strike and loading rate both significantly decreased when the skaters wore the articulated boot when compared to the traditional skating boot.

Another study included a landing jump test onto a force plate to collect information regarding postural control.\textsuperscript{19} Figure skaters were tested, then randomly assigned to either a neuromuscular training group or a traditional off-ice training group, then retested. The procedure included hopping backward from a 46-cm platform onto a force plate and landing in the single-leg skater position. The participants performed this procedure with their eyes open and with their eyes closed, and their CoP path length was measured using the force plate. The researchers found that skaters who underwent the neuromuscular training program exhibited greater postural control through a significantly more contained CoP measure during the eyes-closed landing procedure.

In a more recent study, a new, instrumented blade was being tested to determine its validity by performing the landing procedure onto a force plate covered in a 0.1 m thick rubber mat in the instrumented blade.\textsuperscript{29,30} This procedure was performed from both 18-cm and 27-cm boxes. It was found that the data from the instrumented blade had good to excellent agreement with the force plate data, suggesting that the instrumented blade may be effective in measuring peak vGRF in a more sport-specific setting, such as landing multiple-revolution jumps on the ice. Once the instrumented blade is better understood and validated, the opportunities for biomechanics research in the figure skating setting will greatly increase. This tool could help provide a more comprehensive look at the physical impact that jumping has on figure skaters, and may lead to positive changes in training, as well as a potential decrease in overuse injuries.
**Force Plate Cover**

Previous studies have used a thin plastic cover over the force plate to protect the equipment from damage and provide a simulated ice surface.\(^{28,31}\) In a recently published thesis out of Sweden, two different brands of skating boots were compared in a jump landing task.\(^{31}\) The researcher used artificial ice to cover the force plate to protect the blades and simulate a true ice surface environment during the jump landing task. Artificial ice has been proven to be analogous to traditional ice surfaces for short duration skill execution, making it acceptable for examining skaters in a laboratory environment.\(^{32,33}\)

**Box Height**

Previous research examined jump landings from differing heights to determine whether box height would affect kinetic data enough to differentiate between a group of gymnasts and a group of recreational athletes.\(^{34}\) They found that a forward 2-ft drop landing from a 30-cm box was not high enough to distinguish between the groups. However, a later study determined that kinetic differences between skaters and nonskaters could be seen when using a box height of 20 cm.\(^{12}\) The task for the skaters was a backward, single leg drop landing task. The substantial difference in landing task of these two studies could explain the lower box height’s ability to differentiate between groups when a higher box height could not.

**CONCLUSION**

Overuse injuries in figure skating are a common issue, and more research needs to be done to develop a plan to reduce this injury rate. Previous research supports that the
repetitive nature of the sport and the large ground reaction forces are major contributors to this problem. Previous studies have also shown that figure skaters of differing levels have different biomechanics. Drop-landing tests for measuring landing forces and biomechanics have been used in previous studies; however, little is known about the differences in forces between skaters of lower and higher levels. Jump landing research in the skating boot is still in its early stages of research, and more information must be gained to understand skaters’ exact landing mechanics.
Chapter 3: Comparison of Jump Landings in Figure Skaters While Barefoot and Wearing Skates

**Context:** Landing from jumps is a major contributor to overuse injuries in figure skaters. Previous research has examined the differences in barefoot jump landing biomechanics of figure skaters and nonskaters; however, differences between figure skaters landing barefoot and in skates has not been evaluated.

**Objective:** To compare landing mechanics among figure skaters while barefoot and in skates.

**Design:** Within-subjects repeated-measures.

**Setting:** University laboratory setting.

**Participants:** Ten competitive female figure skaters (age = 19 ± 1.3 yrs, height = 164.7 ± 4.7 cm, weight = 64.4 ± 9.6 kg), volunteered to participate in the study. None had sustained any injury that kept them from practice within the last 3 months.

**Data Collection:** Participants were asked to perform a backwards jump landing task and land on their dominant leg in the single-leg figure skater landing position. Inertial measurement units (IMUs) were secured to the landing leg and trunk of each participant. The task was performed under two conditions: barefoot and in skates.

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1 This chapter represents a prepublication manuscript to be submitted to the *Journal of Athletic Training* (May 2017). Authors are: Emily K. Griswold, AT (School of Applied Health Sciences and Wellness, Ohio University, Athens); Dustin Grooms, PhD, AT, CSCS (School of Applied Health Sciences and Wellness, Ohio University, Athens); Jae Yom, PhD (School of Applied Health Sciences and Wellness, Ohio University, Athens); Charlotte Elster, PhD (College of Arts and Sciences, Ohio University, Athens); and Jeffrey A. Russell, PhD, AT, FIADMS (School of Applied Health Sciences and Wellness, Ohio University, Athens).
**Data Analysis:** A total of 7 repeated measures ANOVA were conducted for peak vertical ground reaction force (vGRF), time-to-peak vGRF, and lower extremity joint angles at peak vGRF (dorsiflexion, knee valgus, knee flexion, hip flexion, and lumbar flexion) to compare the barefoot and in-skate conditions. A Bonferroni correction was used, and the resulting $P$-value was set at $P < 0.007$.

**Results:** Time-to-peak vGRF was significantly faster during the in-skates condition when compared to the barefoot condition ($P = 0.002$). All other variables were not significant between conditions.

**Conclusions:** Figure skaters do not change their landing mechanics while barefoot compared to while wearing skates. Lack of movement through the foot when in a skating boot can lead to a shorter time to dissipate vGRF. This may contribute to increased risk of lower extremity injuries in figure skaters.

**Key Words:** figure skating, biomechanics, inertial measurement units, kinetics, kinematics, vertical ground reaction force

**Word Count:** 297

**Key Points**

- Time-to-peak vGRF was significantly shorter while wearing skates when compared to barefoot landings.

- No differences were found in jump landing kinematics between the barefoot and in-skates conditions.
Figure skating jumps are a major point of interest in biomechanical research of the sport. Increased emphasis on jumping has become evident as skaters continue to attempt larger, more complex jumps in their competitive programs.\textsuperscript{1} Research shows that figure skating jump landings are a substantial contributor to overuse injuries in these athletes.\textsuperscript{2} According to an epidemiological study conducted by Dubravcic-Simunjak et al.,\textsuperscript{2} overuse injuries of the lower extremity are the most common injuries in freestyle figure skaters. Overuse injuries were cited in 78\% of injuries sustained by male and female singles figure skaters throughout the course of the study. However, research regarding jumping biomechanics is generally outdated, showing publication dates between 1990 and 1997.\textsuperscript{3–7} Over the last 12 years, there have been many changes to both the physical design of the skating boot and blade,\textsuperscript{8,9} as well as the implementation of a new, more objective judging system of figure skaters’ competitive performance.\textsuperscript{10,11} This grading system resulted in point values being assigned to specific jumps, with the opportunity to increase points with more difficult jump entries and near-perfect landings. Thus, the change has necessitated greater attention to specific mechanical aspects of jumping. More must be learned about the physical demands of the sport to be able to develop ways to improve technique and training, as well as limit the frequency of overuse injuries.

A contemporary study regarding jump landing biomechanics investigated lower extremity kinetics and vertical ground reaction forces (vGRF) of a backward, single-leg drop-jump performed by figure skaters and nonskaters while barefoot and off the ice.\textsuperscript{12} While this provided some insight into the differences between figure skaters’ and
nonskaters’ landing mechanics, differences between landing barefoot and while wearing skates has not been examined. To better understand the mechanics of jump landing in figure skaters, it is important to identify potential differences in landing mechanics of skaters while wearing their skating boots as compared to barefoot. Therefore, the purpose of this study was to compare landing mechanics among figure skaters while barefoot and in skates.

**METHODS**

**Participants**

Participants included competitive figure skaters of all levels from a Midwestern state. Flyers were posted and emails were sent to coaches and skaters in the area with contact information to volunteer for the study. Informed consent was obtained from all participants over the age of 18; and parental consent and participant assent were obtained from minors. The study was approved by an Institutional Review Board.

To be considered for this study, participants were required to meet the following inclusion criteria: female between the ages of 10 and 28 yr with at least 1 yr of competition experience and an on-ice practice schedule of at least 2 hr per week. Volunteers were excluded from the study if they missed a practice or competition due to injury within the preceding 3 mo or at the time of data collection, had any physical or physiological deficiencies affecting balance (eg, ear infection), or had a known pregnancy. Ten competitive female figure skaters (age = 19 ± 1.3 yr, height = 164.7 ± 4.7 cm, weight = 64.4 ± 9.6 kg, competition experience = 10.9 ± 1.8 yr, practice time per week = 3.3 ± 0.8 hr) fit these criteria and volunteered to participate in the study.
Procedures

**Questionnaire.** Participants were given a questionnaire to determine their eligibility for the study. Height and weight measurements were obtained for each participant.

**Equipment.** Testing procedures were conducted in a university biomechanics lab. Ground reaction forces were obtained with a Bertec 600 x 1200 mm force plate (Bertec, Inc., Columbus, Ohio). Kinematic measures were collected with Noraxon inertial measurement units (IMUs) and processed using the Noraxon MyoMotion system and MR3.8 software (Noraxon, Inc., Scottsdale, Arizona).

**Drop jump.** Before beginning the testing procedures, the researcher attached 7 IMUs to the participant at the following locations: upper thorax, lower thorax, pelvis, free leg thigh, landing leg thigh, landing leg shank, and landing leg foot. These locations are shown in Figure 1. The IMUs were calibrated for each participant while she stood in anatomical position before the jump landing procedure began.
Participants were asked to stand barefoot on a 20-cm-high box placed 10 cm from the force plate. This height was previously used successfully in a study comparing skaters to nonskaters in a backward one-foot drop landing task. They were instructed to drop backwards off the box from both feet and land on their typical landing foot in the skater landing position (see Figure 2). They landed on a sheet of 3 mm thick polyethylene plastic. This surface was selected primarily to protect the force plate from the skaters’ blades; it is the same material commonly used for artificial ice surfaces. The participants were told to hold their landing position for as long as possible. To diminish a learning effect, practice trials were allowed until the participants felt comfortable with the procedure. Participants performed an average of $4.9 \pm 2.02$ (range = 2–8) barefoot practice trials before beginning the collection of data.
Following the practice trials, participants performed the jumps until they attained three successful stabilized landings. The best of the three successful trials was used for analysis. The analyzed trial was chosen by watching the video replay of the landings and selecting the landing that had the most correct and stable technique. Landings were excluded as unsuccessful if they included hops or gross loss of balance that required stabilization assistance from the other foot. Participants performed an average of $3.6 \pm 0.84$ (range = 3–5) recorded trials to obtain three successful landings.

The participants performed the same procedures with their skates on and no guard covers over the blades (see Figure 3). An average of $10.3 \pm 7.21$ (range = 5–29) practice trials were performed by the skaters in their skates, and an average of $8.2 \pm 3.94$ (range = 4–16) recorded trials were required to obtain three successful landings in skates. The two conditions were performed in random order, as determined by a coin flip.

*Figure 2*. Barefoot single-leg skater landing position. The skater dropped backward off the 20-cm box while barefoot from two feet onto the force plate, landing in the single-leg skater landing position.
Figure 3. Drop landing procedure in skates. The participants also performed the procedures in their figure skates.

**Outcome Variables**

The independent variable of this study was the testing condition (barefoot or in skates). Dependent variables were peak vertical ground reaction force normalized to body weight (vGRF), time-to-peak vGRF in s, and lower extremity joint angles in degrees at peak vGRF, including ankle dorsiflexion, knee abduction, knee flexion, hip flexion, and trunk flexion.

**Statistical Analysis**

Means and standard deviations were calculated for all dependent variables. Seven repeated measures ANOVAs were conducted for each dependent variable (vGRF, time-to-peak vGRF, dorsiflexion, knee valgus, knee flexion, hip flexion, and lumbar flexion) with the independent variable condition (barefoot and in-skate). A Bonferroni correction
set $\alpha$ at $P < 0.007$ to reduce the chance of a Type I error when running multiple ANOVAs.

RESULTS

Six of the seven dependent variables did not exhibit significant differences between conditions. These were peak vGRF ($F_{(1,9)} = 1.49$, $P = 0.25$, $1-\beta = 0.19$), dorsiflexion ($F_{(1,9)} = 0.06$, $P = 0.82$, $1-\beta = 0.06$), knee valgus ($F_{(1,9)} = 1.07$, $P = 0.33$, $1-\beta = 0.15$), knee flexion ($F_{(1,9)} = 2.88$, $P = 0.12$, $1-\beta = 0.33$), hip flexion ($F_{(1,9)} = 1.67$, $P = 0.24$, $1-\beta = 0.21$), and lumbar flexion ($F_{(1,9)} = 1.21$, $P = 0.30$, $1-\beta = 0.17$). ANOVA for time-to-peak vGRF did indicate significant differences between the skate and barefoot conditions ($F_{(1,9)} = 17.42$, $P = 0.002$, $\eta^2_p = 0.659$) with a mean difference of 0.019 s. Table 1 shows the means and standard deviation for each dependent variable by condition.
Table 1. Results by Condition, Presented as Mean ± SD

<table>
<thead>
<tr>
<th></th>
<th>Barefoot</th>
<th>In Skates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak vGRF (% of BW)</td>
<td>2.60 ± 0.39</td>
<td>2.72 ± 0.42</td>
</tr>
<tr>
<td>Time-to-Peak vGRF (s)</td>
<td>0.11 ± 0.02*</td>
<td>0.09 ± 0.02*</td>
</tr>
<tr>
<td>Dorsiflexion (degrees)</td>
<td>21.65 ± 5.23</td>
<td>22.09 ± 3.28</td>
</tr>
<tr>
<td>Knee Valgus (degrees)</td>
<td>0.33 ± 5.13</td>
<td>-0.66 ± 5.99</td>
</tr>
<tr>
<td>Knee Flexion (degrees)</td>
<td>34.34 ± 5.36</td>
<td>32.39 ± 4.48</td>
</tr>
<tr>
<td>Hip Flexion (degrees)</td>
<td>29.15 ± 11.42</td>
<td>26.20 ± 10.17</td>
</tr>
<tr>
<td>Lumbar Flexion (degrees)</td>
<td>10.96 ± 5.96</td>
<td>12.78 ± 7.16</td>
</tr>
</tbody>
</table>

*Significantly different (P = 0.002).

DISCUSSION

The purpose of this study was to compare landing mechanics among figure skaters while barefoot and in skates. This comparison involved examining the kinetic and kinematic variables of drop landings performed during each condition. Specifically, the study sought to test the hypotheses that there would be significant differences in the kinetic variables, peak vGRF and time-to-peak vGRF, between barefoot and in-skates trials, as well as in the kinematics of the lower extremity, pelvis, and trunk. Our results suggest that the only differences between barefoot and in skate conditions occurred in the time-to-peak vGRF.
**Time-to-Peak Vertical Ground Reaction Force**

We found significant differences between the barefoot and in-skates condition for time-to-peak vGRF. Time-to-peak vGRF was significantly shorter while wearing skates than while barefoot. These results are similar to those found by Saunders et al.,\textsuperscript{12} where figure skaters had a significantly shorter time-to-peak vGRF than nonskaters. The authors suggested that the skaters continued to act out of habit of wearing a stiff boot even though they were barefoot, and, thus, resisted full range of motion at the ankle. This may indicate a training effect that is present in skaters based on the nature of their specific task.

Our data indicate that landing in a stiff skating boot creates an even shorter time-to-peak vGRF than when the skaters are barefoot. This may be related to the lack of motion throughout the joints of the foot while wearing the boot, which does not allow for the longer dissipation of forces that landing barefoot allows. Future research should investigate this dissipation of forces during loading to further understand why this occurs.

Similarly, Bruening and Richards\textsuperscript{15} found that while using articulated boots, loading rate decreased by 31% when compared to traditional boots. Our results agree with this increased loading rate in traditional skating boots. Because the body has less time to dissipate forces while wearing skates, the joints of the lower extremity are taking the same amount of force over a shorter period of time. This decrease in time to decelerate from landing may be a contributor to lower extremity overuse injuries in this population.
Peak Vertical Ground Reaction Force

We found no differences in peak vGRF between the barefoot and in-skates conditions. This finding is not consistent with that of Bruening and Richards\textsuperscript{15} in their study examining the differences between jump landings in a traditional figure skating boot and an articulated skate. They reported no differences in peak toe force, but there were significant differences in peak heel force. Furthermore, they found that while wearing the articulated boot, skaters had significantly less vGRF than while wearing the traditional skating boot. During the present study, there were no differences between jump landing in a traditional skating boot and landing barefoot. This discrepancy may be due to the lack of landing instruction in the present study. Bruening and Richards instructed the skaters to land with as much plantarflexion as possible, while no such instruction was given to the participants of the present study. Also, the differences in box heights between the studies may have contributed to the differences in findings of the two studies, as the box height of the present study was 10 cm shorter than that used by Bruening and Richards.

A similar study performed in gymnasts further supports the theory of box height affecting the peak vGRF results.\textsuperscript{16} The researchers did not find significant differences in peak vGRF in a forward drop landing from a 30-cm box height. They concluded that the lower height was not sufficiently challenging enough to distinguish between groups of gymnasts and recreational athletes. However, this study did not have a large sample size, which may have affected the peak vGRF results.
Contrary to the gymnast study, Saunders et al.\textsuperscript{12} concluded that a 20-cm box height was high enough to distinguish differences in vGRF between figure skaters and nonskaters, though the task was much more challenging than that of the gymnasts. Based on these results we elected to utilize a 20-cm box height. The same jump-landing task was executed as that used by Saunders et al., but our smaller sample size may contribute to the discrepancies between theirs and the present study. Saunders and colleagues suggested that the differences between skaters and nonskaters could be attributed to the skaters landing out of habit of wearing the stiff skating boots. Our findings support this hypothesis, suggesting that figure skaters land with the same amount of peak vGRF while barefoot as they do while wearing skates.

**Lower Extremity Joint Angles**

No significant differences were found in any of the lower extremity joint angles at the moment of peak vGRF between barefoot and in-skates conditions. There is minimal published literature regarding the joint angles of figure skating jump landings. Much of it aims to analyze in-air jump positions or jump takeoffs.\textsuperscript{1,5,17,18} Bruening and Richards\textsuperscript{15} conducted the only known study of the kinematics of figure skater jump landings. They found that ankle angular velocity at peak vGRF was significantly greater while wearing a traditional skating boot than while wearing an articulated skating boot. This indicates that the ankle was moving faster at the time of peak vGRF while wearing the traditional skates. We discovered no differences in lower extremity joint angles at peak vGRF, yet time-to-peak vGRF was decreased while wearing skates compared to landing barefoot. This means that our study corresponds to Bruening and Richards’ findings, as the ankle
would have to be moving more quickly in order to reach the same position in a shorter amount of time while wearing skates versus while barefoot.

However, Bruening and Richards credited their slower time-to-peak vGRF in the articulated boot to the increased range of motion provided by the articulated boot at the ankle. Based on our findings in the present study, there were no differences in ankle dorsiflexion angle at peak vGRF while in skates when compared to barefoot, which means that the increased time-to-peak vGRF could be attributed to the range of motion likely occurring at the joints within the foot.

While barefoot, these joints are able to move, thus slowing down the loading rate and allowing the skater to reach peak vGRF more slowly. In skates, the metal blade acts as a rigid bar below the sole of the foot, restricting these joints from allowing any motion, and thus making toe and heel contact occur much closer together. Therefore, the ankle joint is the first joint to move during a figure skating jump landing. This may be why the time-to-peak vGRF was significantly shorter in the traditional skating boot, where stiffness and design make it more difficult to move quickly through the full range of motion.

Furthermore, this lack of difference between barefoot and in-skates conditions in lower extremity joint angles at peak vGRF contradicts research comparing barefoot running to shod running.\textsuperscript{19,20} Prior reports suggest significant differences in lower extremity running kinematics between barefoot and shod running. The lack of differences found between barefoot and in-skates landings in our study could be attributed to a training effect in figure skaters. This would support the theory presented
by Saunders et al.\textsuperscript{12} that the differences in landing kinetics between skaters and nonskaters was attributed to the skaters acting out of habit of wearing a stiff skating boot.

**Limitations**

The primary limitation of this study is the small sample size. It is possible that we observed no differences in peak vGRF and jump landing kinematics due to the small sample size and a lack of skating ability differentiation. Further research should focus on recruiting more skaters to assess further differences, as well as differences in jump landings between beginner and elite groups.

Some of the participants struggled to properly perform the drop jump task, and instead stepped off the box, which affected their starting height and thus, their peak vGRF scores. Clearly the task is not a natural activity for a figure skater. Because some of the participants stepped off the box instead of dropping from it, some of their body weight was distributed to the nonlanding lower extremity longer than it was in those who properly dropped off the box.

Almost every participant struggled to hold the backwards jump landing in-skates for longer than 1 s, so no stabilization data were recorded. Also, instead of taking 3 successful trials and averaging them, only 1 of the 3 successful trials was analyzed because of inconsistent jump landings across each participant’s 3 trials.

Due to the difficulty inherent in the landing task, we selected a box height of 20 cm, the lowest height reported in the literature.\textsuperscript{12} While high enough to highlight vGRF differences between skaters and nonskaters, this height may not be high enough to
identify differences in jump landing performance in figure skaters while barefoot and wearing skates.

Furthermore, though the set box height was used for purposes of standardizing the landings and eliminating a confounding variable of jump height, it is not realistic that figure skaters will land their jumps on the ice from a height of only 20 cm. Future research should examine the jump landing differences from varying heights, including heights that better resemble those reached when performing jumps on the ice. Moreover, while we tried to create as realistic a laboratory setting as possible, we recognize the remaining dissimilarities between any assembled landing surface compared to the ice surface on which skaters are accustomed to landing.

It is also important to address the time at which we collected our kinematic data. Because we examined the joint angles at the time of peak vGRF, we were only examining the joint angles at that exact moment. Future research should compare the total joint displacement between barefoot and in-skates trials to examine potential differences in the full range of motion of the ankle, knee, hip, and lumbar spine.

**Clinical Implications**

Because of the decreased time-to-peak vGRF in skates, the body has less time to dissipate forces, resulting in the joints of the lower extremity absorbing the same amount of force over a shorter period of time. This is a potential contributor to lower extremity overuse injuries in figure skaters. To reduce the risk of overuse injuries, coaches and skaters should limit the number of on-ice jumps they perform. Skaters also should work on landing with greater hip flexion and knee flexion to help absorb the forces transmitted
to their joints. It is unlikely that they will achieve greater ankle dorsiflexion due to the stiff nature of their skating boots; however, increasing the other joint angles of the lower extremity may help to dissipate the landing forces and potentially reduce the risk of overuse injury in this population. Coaches can encourage this biomechanical change by giving verbal feedback to their students, and taking video of the skaters during practice for visual feedback. If future research reveals differences in jump landing techniques in skaters of different skill levels, coaches will be better equipped to tailor their feedback appropriately for each skater’s skill level. In short, teaching skaters proper landing techniques to better dissipate the forces and limiting the number of jumps skaters perform during practices may reduce the risk for overuse injury.

CONCLUSION

This study aimed to compare differences in jump landings of figure skaters while barefoot and wearing skates. While there were no significant differences between barefoot and in-skate landings for peak vGRF and lower extremity joint angles, time-to-peak vGRF was significantly shorter when landing in skates. The results of our study suggest that the joints of the lower extremity receive the same landing impact forces over a shorter duration when landing in skates than they do when landing barefoot. The fact that the joint angles of the lower extremity were statistically the same between the conditions meant that the joints had less time to decelerate during the in-skates landing than they did during barefoot landing. This decrease in time to dissipate the forces could be a potential cause for overuse injuries that are commonly seen in the lower extremities of figure skaters. Therefore, coaches and skaters should adjust their training regimen to
decrease the number of jumps performed during practice, and learn how to appropriately dissipate forces throughout the body when landing figure skating jumps to limit the occurrence of lower extremity overuse injury.

REFERENCES


11. U.S. Figure Skating. International Judging System.


Chapter 4: Conclusion

This study aimed to compare differences in jump landings of figure skaters while barefoot and wearing skates. While there were no significant differences between barefoot and in-skate landings for peak vGRF and lower extremity joint angles, time-to-peak vGRF was significantly shorter when landing in skates. The significant differences in time-to-peak vGRF agree with the limited literature, supporting the conclusion that traditional figure skates alter landing biomechanics in figure skaters. The results of our study suggest that the joints of the lower extremity receive the same landing impact forces over a shorter amount of time when landing in skates than while barefoot. Because there were no significant differences in the measured joint angles of the lower extremity between the conditions, it is possible that the slower time-to-peak vGRF could be attributed to increased range of motion in the joints of the foot while barefoot. Due to the decreased time-to-peak vGRF while wearing skates and comparable kinematics of the lower extremity between conditions, these joints had less time to decelerate during the in-skates landing. This decrease in time to dissipate the forces could be a potential cause for overuse injuries in the lower extremity that is commonly seen in figure skaters.

Coaches should adjust their skaters’ training regimens to decrease the number of jumps performed during practice. Skaters must learn how to appropriately dissipate forces throughout the body when landing figure skating jumps as a means to mitigate the risk of lower extremity overuse injury. Future research should focus on the differences in jump landing kinetics and kinematics in figure skaters of different levels to help coaches determine the appropriate feedback for their skaters based on skill level.
References


31. Spiegl O. *The Effects of Different Figure Skating Boots on the Human Body During the Landing Impact* [master's thesis]. Stockholm, Sweden; Swedish School of Sport and Health Sciences; 2016.


33. My Backyard Ice Rink. Synthetic ice.

Appendix A: Specific Aims

Figure skating jumps are a major point of interest in biomechanical research of the sport. Increased emphasis on jumping has become evident as skaters continue to attempt larger, more complex jumps in their competitive programs.\(^1\) Research shows that figure skating jump landing is a serious contributor to overuse injuries in these athletes.\(^2\) According to an epidemiological study conducted by Dubravcic-Simunjak et al.\(^2\), overuse injuries of the lower extremity are the most common injuries in freestyle figure skaters. Overuse injuries made up 78% of injuries sustained by male and female singles figure skaters throughout the course of the study.\(^2\) However, most research regarding jumping biomechanics is outdated.\(^3-7\) Over the last 12 years, there have been many changes to both the physical design of the skating boot and blade,\(^8,9\) as well as the implementation of a completely new, more objective judging system of the figure skater’s competitive performance.\(^10\) These fundamental changes in the sport were brought about in an attempt to reduce the skater’s risk of overuse injury. More must be learned about the physical demands of the sport to be able to develop ways to improve technique and limit frequency of overuse injuries.

A contemporary study regarding jump landing biomechanics investigated lower extremity kinetics and vertical ground reaction forces (vGRF) of a single-leg drop-jump performed by figure skaters and nonskaters while barefoot and off the ice.\(^12\) While this provided some insight into the differences between figure skaters’ and nonskaters’ landing mechanics, differences between landing barefoot and in skates has not been examined. To better understand the mechanics of jump landing in figure skaters, it is
important to identify potential differences in landing mechanics of skaters while wearing their skating boots as compared to barefoot. The goals of this study are to compare landing mechanics among figure skaters while barefoot and in skates.

To identify differences in jump landing biomechanics, skaters performed the same backwards drop-jump single-leg landing procedure onto a force plate as outlined by Saunders et al. In addition to these procedures, the participants wore inertial measurement units (IMUs) on their trunk and landing leg to allow for a full-body analysis of the landing mechanics. Participants performed the task under 2 separate conditions: barefoot and in their figure skates. This was to examine the differences in biomechanics when the skater is barefoot versus in their skating boot. The specific aim of this study is as follows.

**Aim 1: To compare biomechanical differences in jump landings of figure skaters when landing barefoot versus landing in-skates.** To achieve this aim, skaters performed the jump landing procedure onto a force plate while barefoot and in their skates, as outlined by Saunders et al. Additional IMU data of the trunk and landing leg was recorded.

1.1 barefoot and in-skates landing data examined 7 dependent variables:

1.1.1 peak vGRF and time-to-peak vGRF as measured by a force plate covered in a sheet of polyethylene plastic

1.1.2 ankle dorsiflexion, knee flexion, knee abduction, hip flexion, and lumbar flexion at peak vGRF as measured by the IMUs
Appendix B: Data Procedures Checklist

Participant Code: 
Date: 

<table>
<thead>
<tr>
<th>BIOMECHANICS LAB SESSION</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consent Form</td>
<td>2 min.</td>
</tr>
<tr>
<td>Questionnaire</td>
<td>4 min.</td>
</tr>
<tr>
<td>• Measure height</td>
<td></td>
</tr>
<tr>
<td>• Measure weight</td>
<td></td>
</tr>
<tr>
<td>Randomization of Conditions</td>
<td>30 sec. (+5 min.)</td>
</tr>
<tr>
<td>• Change into skates if necessary</td>
<td></td>
</tr>
<tr>
<td>Attach IMUs</td>
<td>4 min.</td>
</tr>
<tr>
<td>• Upper thoracic, lower thoracic, pelvis, free leg thigh, landing leg thigh, landing leg shank, landing leg foot</td>
<td></td>
</tr>
<tr>
<td>Calibration of Equipment</td>
<td>2 min.</td>
</tr>
<tr>
<td>• IMUs</td>
<td></td>
</tr>
<tr>
<td>• Force Plate</td>
<td></td>
</tr>
<tr>
<td>Explanation of Procedures</td>
<td>1 min.</td>
</tr>
<tr>
<td>Drop Jump Practice Trials (Condition 1)</td>
<td>5 min.</td>
</tr>
<tr>
<td>• Practice until comfortable</td>
<td></td>
</tr>
<tr>
<td>• Feedback on technique</td>
<td></td>
</tr>
<tr>
<td>Drop Jump Data Collection (Condition 1)</td>
<td>8 min.</td>
</tr>
<tr>
<td>• Explanation of task</td>
<td></td>
</tr>
<tr>
<td>• Collect trials until 3 are completed successfully</td>
<td></td>
</tr>
<tr>
<td>• Feedback limited</td>
<td></td>
</tr>
<tr>
<td>Change Skates</td>
<td>5 min.</td>
</tr>
<tr>
<td>Drop Jump Practice Trials (Condition 2)</td>
<td>5 min.</td>
</tr>
<tr>
<td>• Practice until comfortable</td>
<td></td>
</tr>
<tr>
<td>• Feedback on technique</td>
<td></td>
</tr>
<tr>
<td>Drop Jump Data Collection (Condition 2)</td>
<td>8 min.</td>
</tr>
<tr>
<td>• Explanation of task</td>
<td></td>
</tr>
<tr>
<td>• Collect trials until 3 are completed successfully</td>
<td></td>
</tr>
<tr>
<td>• Feedback limited</td>
<td></td>
</tr>
<tr>
<td>Take Off Skates (if necessary)</td>
<td>1 min.</td>
</tr>
</tbody>
</table>

Total: 45-50 min
Appendix C: Data Collection Forms and Surveys

Recruitment Flyer

Participate in Figure Skating Research!

We are conducting a study to look at the way figure skaters of different levels land their jumps. We are doing this to identify possible risk factors for injuries of the landing leg in figure skaters.

Do I qualify to participate?

- Females age 10 to 28 years old
- Practice on-ice at least 2 times per week
- At least 1 year of competition experience
- No current or recent injuries that caused absence from practice or competition within the last 3 months
- No diagnosed balance problems

What Will I be Asked to Do?

Participants will be asked to jump backwards off an 8-inch box while barefoot and in their skates so that we can measure the jump landing forces.

Where? Off-ice at Bird Arena, Athens, OH

If you are interested, or know someone who would be interested in participating, please contact the lead researcher, Emily Griswold at eg027915@ohio.edu to set up an appointment.
Figure Skater Questionnaire

Age: ____________

Skating Status
Please list your hardest jumps that you can consistently land (at least 7 times out of 10 attempts):
__________________________________________________________

How many hours on average do you skate per week? ____________

Which leg do you use as your landing leg? ____________

How many years have you been competing in figure skating? ____________

Health Status
Do you currently have an injury, or have you had an injury within the last 3 months that has prevented you from practicing or competing?  □ Yes  □ No

Do you currently have a common cold, ear infection, or other infection?  □ Yes  □ No

If yes, please specify what body region is affected. ____________________________

Have you been diagnosed with any type of balance disorder, or do you have a condition of your inner ear that disrupts your equilibrium?  □ Yes  □ No

Are you currently pregnant?  □ Yes  □ No

For Researcher Use Only:
Eligible to participate?  Yes  No  Height: ____________
Participant Code: ____________  Weight: ____________
Determined Group Level:  Low  High
Appendix D: Power Analysis

A minimum of 25 participants for each group (low-level skater and high-level skater) were required for sufficient power. A total of 50 participants should have been analyzed during this study. This is based on having a small effect size 0.4, alpha level 0.05, and power (1-β) 0.95.