ACL RISK DATA COMPARISON AND TURNOUT ANALYSIS OF FEMALE DANCERS TRAINED IN BALLET AND FEMALE TRADITIONAL JUMPING SPORT ATHLETES

A Thesis
presented to
the Faculty of California Polytechnic State University,
San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Biomedical Engineering

by
Samantha Campbell
March 2022
COMMITTEE MEMBERSHIP

TITLE: ACL Risk Data Comparison and Turnout Analysis of Female Dancers Trained in Ballet and Female Traditional Jumping Sport Athletes

AUTHOR: Samantha Campbell

DATE SUBMITTED: March 2022

COMMITTEE CHAIR: Michael D. Whitt, Ph.D.
Professor of Biomedical Engineering

COMMITTEE MEMBER: Jared W. Jones, MD
Orthopedic Non-Operative Physician

COMMITTEE MEMBER: Christiane O’Hara, M.S.
Lecturer of Kinesiology
ABSTRACT
ACL Risk Data Comparison and Turnout Analysis of Female Dancers Trained in Ballet and Female Traditional Jumping Sport Athletes
Samantha Ann Campbell

INTRODUCTION: An increase in participation in females sports has created an increase of female athletes at risk for injuring their Anterior Cruciate Ligament (ACL)[12,21,29,44]. Traditional jumping sports have the highest rate of non contact ACL injuries, due to the use of movements of cutting, pivoting and landing on one foot[5,8,32,33,38]. ACL injuries can also be attributed to neuromuscular deficits such as the 'Ligament Dominance Theory', 'Quadriicep Dominance Theory', 'Trunk Dominance Theory' and the 'Leg Dominance Theory'[24,33]. The neuromuscular deficits are muscle strength, power or activation patterns that can cause an individual to have an increased risk of ACL injury[33]. Female traditional jumping sport athletes have been associated with being at a higher risk of ACL injury than their male counterparts due to anatomical, hormonal and neuromuscular differences[2,8,24,28,32,37,38,44,47]. However, female dancers trained with ballet have a lower risk of ACL injury than their female athlete counterparts, but also have a similar ACL injury to their male dancing counterparts[28,37,45,47].

METHODS: This study analyzed six papers that compared the lower body biomechanics of female traditional jumping sport athletes to female dancers trained in ballet. The results of the measurement of this study will be placed into a chart to compare the results of each study to each other, to confirm the results of the comparison between the two populations. The next part of this study will examine unused turnout angle data collected from a previous thesis performed by Ashley Tornio. The data was taken from 20 participants, 15 female traditional jumping sport athletes and 5 female dancers trained in ballet. The averages of these two groups will be compared using an f test to determine differences in the turnout capabilities of each group.

RESULTS: The results of the data comparison found only six comparable measurements between the 6 papers. The papers were in agreement that female traditional jumping sport athlete had greater hip adduction moments and trunk forward flexion than female dancers trained in ballet. The papers were also in agreement that there was no statistically significant difference in the knee stiffness between the two populations. There was no consensus for the results of knee valgus angle, knee rotation, muscle activation or leg stiffness between the six papers. For the turnout angle f test, female traditional jumping sport athletes had an average turnout angle of 120.5 degrees and the female dancers trained in ballet had an average turnout angle of 141.2 degrees. It was found that the there was no statistically significant difference between the two populations at the 95% confidence level. However, there was a statistically significant difference between the two populations average turnout at a reduced confidence level of 80%. The
DISCUSSION: The limiting number of studies which compare female traditional jumping sport athletes and female dancers trained in ballet, were unable to form consensus on the difference between the biomechanics of each group during a landing task. The turnout angle data was also limited in the number of participants and a valid conclusion was unable to be made determining the ability to use the turnout angle as an indicator for risk of ACL injury. There needs to be continued research on the comparison of the female traditional jumping sport athletes and female dancers trained in ballet to determine the biomechanical advantages female dancers have for protection of the ACL.

Keywords: Female Athlete, ACL, Jumping Sport, Female Ballet, Landing task, Turnout Angle
ACKNOWLEDGMENTS

I would like to acknowledge Ashley Tornio, who allowed me to assist with her thesis in 2018 and proceed to give me guidance to continue building upon her work. I would like to thank Jasmine Janisch, Sally Thurman, Maya Jain, Aditi Sriram, and Tori Barrington for their help and assistance in the completion of this thesis.

Special thanks to my friends and family for all their support during my time as a student at Cal Poly. Thanks to Dr. Whitt for his support and guidance as I have gone through the many twist and turns of performing a thesis through the COVID-19 pandemic. I would also like to thank my grandparents Dr. Bert and Muriel Heoflich and Dr. Oscar and Virginia Campbell who have installed a love of science and education in me from a young age.
# TABLE OF CONTENTS

LIST OF TABLES ........................................................................................................ viii
LIST OF FIGURES ...................................................................................................... ix

CHAPTER

1. INTRODUCTION ................................................................................................................ 1
  1.1 ACL Anatomy and Function .................................................................................. 2
      1.1.1 ACL Anatomy .......................................................................................... 2
      1.1.2 ACL Function ......................................................................................... 7
  1.2 Mechanics of ACL Injury ....................................................................................... 7
      1.2.1 Non Contact ACL Injuries ...................................................................... 7
      1.2.2 Neuromuscular Control Deficits ............................................................. 10
      1.2.3 Effect of Leg Stiffness ............................................................................ 14
      1.2.4 Hip Extension-Knee Flexion Paradox ....................................................... 16
      1.2.5 Fatigue ..................................................................................................... 18
      1.2.6 Turnout Angle/Hip Range Of Motion ....................................................... 20
  1.3 Background of Populations ..................................................................................... 23
      1.3.1 Female Traditional Jumping Sport Athletes ............................................ 23
      1.3.2 Female Dancers Trained in Ballet ............................................................ 25
      1.3.3 Comparison of Dancers Trained in Ballet and Traditional
          Jumping Sport Athletes .............................................................................. 28
  1.4 Gender Disparities ................................................................................................. 29
      1.4.1 Traditional Jumping Sport Athletes Gender Disparities ......................... 30
      1.4.2 Dancers trained in Ballet Gender Disparities ......................................... 33
  1.5 Hypothesis .............................................................................................................. 33

2. METHODS .................................................................................................................... 35
  2.1 Initial Plan .............................................................................................................. 35
  2.2 Meta Analysis ........................................................................................................ 37
  2.3 Data Comparison .................................................................................................. 40
  2.4 Turnout Angle Comparison .................................................................................. 41

3. RESULTS ...................................................................................................................... 43
  3.1 Initial Plan Results ............................................................................................... 43
  3.2 Meta Analysis Results .......................................................................................... 43
  3.3 Data Comparison Results ..................................................................................... 43
      3.3.1 Article Search Results .......................................................................... 43
      3.3.2 Table of Papers ...................................................................................... 44
      3.3.3 Comparison of Results of Papers ......................................................... 44
  3.4 Turnout Angle Comparison Results ..................................................................... 48

4 DISCUSSION ................................................................................................................. 52

BIBLIOGRAPHY ............................................................................................................. 56
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. A breakdown of the 6 papers used in the Data Comparison with a description of the participants and exposure of each paper.</td>
<td>44</td>
</tr>
<tr>
<td>2. All the measurable outcomes, the paper which outcome was seen in, how the measurements were made and how each measurement effects the risk of ACL injury.</td>
<td>45</td>
</tr>
<tr>
<td>3. A combination of the measurable results that had two or more papers with results pertaining to the measurements. The results for each paper is shown below and a comparison can be made from this table. FA: Female Athlete and FD: Female Dancer</td>
<td>46</td>
</tr>
<tr>
<td>4. The 20 participants with their athletic activity and the turnout angle they performed</td>
<td>49</td>
</tr>
<tr>
<td>5. The Means, SD and results of the f-test comparing the two populations turnout results</td>
<td>50</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Diagrams which show the location of the ACL in terms of the other ligaments and muscles within the knee (left) also shows the lateral condyle from which the ACL originates (right) [49, 50]</td>
<td>3</td>
</tr>
<tr>
<td>2. An example for how the posterior tibial slope (PTS) is measured using an x-ray of a patient's knee [51]</td>
<td>5</td>
</tr>
<tr>
<td>3. A visual comparison of the tangents lines utilized in measuring the posterior tibial slope (PTS) and the meniscal slope of the knee [59]</td>
<td>5</td>
</tr>
<tr>
<td>4. Shows the insertion points of the posterolateral bundle (PL) and anteromedial bundle (AM) in contrast to the medial meniscus (MM), lateral meniscus (LM) and the posterior cruciate ligament (PCL) [52]</td>
<td>6</td>
</tr>
<tr>
<td>5. A diagram which indicates movements that can place the ACL in an unstable environment at higher risk of injury [53]</td>
<td>8</td>
</tr>
<tr>
<td>6. Diagram which shows the differences between a soft landing and a stiff landing [54]</td>
<td>15</td>
</tr>
<tr>
<td>7. An example of a dancer performing a proper turnout [55]</td>
<td>21</td>
</tr>
<tr>
<td>8. An example of a dancer dancing on en pointe (left), demi pointe (middle) and en dehors (right) [56, 57, 58]</td>
<td>28</td>
</tr>
<tr>
<td>9. The foot tracing of participant #3, the three x's denote the three points used to determine the measurement of the turnout angle of a traditional jumping sport athlete</td>
<td>48</td>
</tr>
<tr>
<td>10. The foot tracing of participant #5, the three x's denote the three points used to determine the measurement of the turnout angle of a ballet dancer</td>
<td>49</td>
</tr>
</tbody>
</table>
Chapter 1

1. INTRODUCTION

Participation in women’s sports has been expanding, estimated to be doubling every 10 years, with this increase in participation, comes the increase in the risk of female Anterior Cruciate Ligament (ACL) injury[12,21,29,44]. Though males account for the majority of ACL injuries in the general population, when the numbers are normalized to populations of individuals that partake in high risk activities, females are at higher risk of injuries to their ACL[15]. High risk activities are those that include deceleration, lateral pivot, landing task, contact force on the knee, and any twisting movements, these movements are found in traditional jumping sports such as soccer, basketball, volleyball and field hockey[5,8,38]. It is estimated that 200,000 to 250,000 ACL injuries occur each year in the US, with an estimated 38,000 of these injuries occurring in female athletes[21,38]. The cost of these ACL injuries at a national level is approximately 646 million dollars for surgery and rehabilitation, but this cost does not take into account the decrease in physical activity, loss of athletic scholarships, and decrease in athletic performance[5,21,38]. Injury to an ACL can also have long term effects such as loss of ability to play at the participant’s previous level, and a higher risk of development of knee osteoarthritis[5, 11, 17, 29, 38, 41]. Even if the patient receives a surgical reconstruction of the ACL, most patients with an ACL injury will develop knee osteoarthritis 10-20 years following the injury[5, 11, 17, 29, 38, 41].
Most ACL injuries in female athletes are through non contact mechanisms. Some studies report that over 70% of ACL injuries are due to non contact episodes[5, 7, 8, 10, 13, 20, 21, 24, 27, 33, 44]. Noncontact ACL tears are caused by deceleration, lateral pivoting, and landing tasks which cause high loads on the knee joint[5, 8, 33, 38]. These movements are found in traditional jumping sports and multidirectional team sports but are also found in ballet[36]. Dancers trained in ballet are different to their athlete counterparts; not only are the ACL injuries risk of dancers not dependent on sex, but they are also lower than the athletes[28, 37, 44, 45, 47]. Dancers have an ACL injury incidence rate of around 0.009 ACL injuries per 1000 exposures, while traditional jumping sport athletes have an ACL injury incidence rate of around 0.07-0.31 ACL injuries per 1000 exposures[28, 37, 44, 45].

Due to the similarities of the movements and differences in the ACL injury rate between female jumping sport athletes and female dancers trained in ballet, lower body biomechanics of dancers may provide insights to mitigating the risk of ACL injury to female athletes. An understanding of the anatomy and function of the ACL, mechanics of noncontact ACL mechanics, an understanding of the differences of genders, and the training of each group will help to decipher the insight obtained through experimentation.

1.1 ACL Anatomy and Function
1.1.1 ACL Anatomy
The ACL connects the femur and tibia, located within the synovial membranes of the tibiofemoral articulation in the femoral notch, known as the intercondylar
fossa[3, 8, 47]. The ACL originates at the medial side of the lateral femoral condyle, a condyle is a large protrusion of bone, and inserts at the medial tibial eminence, an elevated region of bone located between the lateral and medial tibial condyles[3, 47]. The ACL fans towards its insertion point, with the narrowest part of the ACL at the midsubstance area, which has an area of about 36 mm^2 and 44 mm^2 for females and males respectfully[47]. The intercondylar fossa is wider in the posterior of the knee than the anterior of the knee, which allows for this fanning, or widening, at the insertion of the ACL. It should be noted that the intercondylar fossa is reported to be smaller in females than males [47].

![Figure 1](image)

**Figure 1**: diagrams which show the location of the ACL in terms of the other ligaments and muscles within the knee(left) also shows the lateral condyle from which the ACL originates(right)[49, 50]

The tibial plateau is the flat proximal(top) portion of the tibial bone, on which the femur rests[47]. The tibial plateau has a posterior to anterior inclination in the sagittal plane that is termed the posterior tibial slope or PTS[8]. The PTS is measured by the angle formed between a line perpendicular to the longitudinal axis of the tibia and a line along the sagittal plane inclination of the tibial
plateau[8]. The PTS has an effect on the dispersion of forces on the knee[17]. It has been shown that athletes with a steeper PTS can have a larger shear force during load transmission in the knee joint, which results in potentially higher anterior tibial translation[17]. If an athlete has a milder PTS when load transmission occurs the milder PTS may innately avoid excessive tibial translation[17]. The protective nature of milder PTS works by utilizing the change of knee flexion during a landing maneuver. When the knee flexion increases, the combined movement of the tibia and femur will cause the plateau to angulate behind the femoral condyles, resulting in the joint contact forces (JCF)( which are perpendicular to the plateau) to be directed posteriorly causing a posteriorly directed shear force. The posteriorly directed shear force will work to resist anterior tibial translation[17]. The tibial plateau is also the location of the meniscus, which is a semilunar-shaped fibrocartilaginous structure[8]. This structure plays a critical role in shock absorption and helps to reduce friction forces experienced by the knee during landing[8]. The slope of the meniscus, which is the angle formed between the tangent line of the border of the ipsilateral anterior and posterior meniscus and the longitudinal axis of the tibia, is shown to have an effect on the stability of the knee joint[8]. Studies have shown that the men and women with noncontact ACL injuries had measurements of greater lateral meniscus slopes[8].
Figure 2: An example for how the posterior tibial slope (PTS) is measured using an x-ray of a patient's knee [51].

Figure 3: A visual comparison of the tangents lines utilized in measuring the posterior tibial slope (PTS) and the meniscal slope of the knee [59].

The ACL is a band of connective tissue, however the ACL does not function as a simple band of fibers with a constant tension as the knee flexes and extends [40, 47]. With the differentiation of tension of the ACL in different angles, one theory for the difference in tensions is that this band can be divided into bundles [47, 40].
The division of the ACL into bundles is a controversial idea, many studies vary the number of bundles in the ACL[40, 47]. Though the number varies study to study, most studies agree that the posterolateral and anteromedial bundle are the major functional bands of the ACL[40, 47]. The terminology of these bands is attributed to their tibial insertion points, the anteromedial bundle originates at the most proximal part of the femoral insertion and inserts at the anteromedial tibial insertion, while the posterolateral bundle originates distally at the femur and inserts at the posterolateral part of the tibial insertion[40]. The function of the anteromedial and posterolateral bundles are in opposition to each other. When the knee is extended the posterolateral bundle is tight and the anteromedial bundle is moderately lax, and when the knee is flexed the anteromedial bundle is tight and the posterolateral bundle is loose[40]. However, it should be noted that these fibers do not behave isometrically with each other [40].

**Figure 4:** Shows the insertion points of the posterolateral bundle (PL) and anteromedial bundle(AM) in contrast to the medial meniscus(MM), lateral meniscus(LM) and the posterior cruciate ligament(PCL) [52]
1.1.2 ACL Function

The ACL’s anatomical function is to add passive stability of the knee joint in multiple planes, which makes it an integral player in the mechanical stability of the knee joint[5,11]. In the sagittal plane, the ACL constrains forward translation of the tibia and the resulting anterior forward pull on the ACL decreases with increased knee flexion[5]. During this maneuver of the knee joint, quadriceps reaction forces are a major contributor to this anterior shear force[5]. Due to the patella ligament angular attachment to the tibia, the quadriceps muscle contraction force contribution to the anterior shear force is most prominent at a more extended knee joint angle(0-35 degrees of flexion)[5]. In the frontal plane, the ACL restrains knee abduction and adduction moments. This can be shown by increased ACL strain when the knee is placed in loading at either valgus or varus direction in combination with anterior tibial force production[5].

The ACL serves as primary restraint to anterior tibial translations, it is the primary restraint to sagittal plane tibial displacement and provides restraint to frontal and transverse plane movements[17, 47]. The ACL also serves to restrain internal rotation of weight-bearing and non weight-bearing knees[47]

1.2 Mechanics of ACL Injury

1.2.1 Non Contact ACL Injuries

The simplest explanation of an ACL injury is that it occurs when stress on the ligament exceeds its failure strength[17]. A noncontact ACL injury is an injury that
occurs without physical contact between athletes or physical structures[46]. Most ACL injuries in females athletes occur during non contact episodes, some studies even cite numbers as high as 78% of injuries are by noncontact episodes[5, 7, 8, 10, 13, 20, 21, 24, 33, 44, 46]. Unlike the ACL injuries caused by contact injuries, non contact ACL injury risk can be related to neuromuscular factors influenced by the biomechanical loading of the knee[5]. The neuromuscular factors of the knee can affect the magnitude and timing of muscular force that can serve to stabilize the knee, or if the production is not adequate, the knee is unstable and risk of injury is increased[5].

![Diagram showing movements that can place the ACL in an unstable environment](image)

**Figure 5:** A diagram which indicates movements that can place the ACL in an unstable environment at higher risk of injury[53]

Multidirectional team sports, such as traditional jumping sports, have the highest rate of noncontact ACL tears as compared to single-direction sports[32]. The movements of cutting, pivoting, and landing on one knee have all been associated with high loads on the knee joint, which put the ACL at risk of injury[5,
Advanced biomechanical analyses of individual injury cases have shown that ACL injury occurs within the first 50 ms after ground contact in a noncontact injury[5].

Through the study of tasks associated with increased risk of an ACL tear, it was found that the position of the lower body affects the amount of risk these movements have to causing an ACL injury[5, 29]. It was found that performing landing and cutting tasks with the hip and knee joints in an extended position (straight) are predictive of elevated anterior shear forces, which will most likely result in increased strain on the ACL[5]. Landing and cutting movements with more extended knee increases the magnitude of vertical ground reaction impact forces, which causes an increase of compression of the knee joint and if the subject has a steeper PTS, the forces can induce tibial rotations leading to increased strain of the ACL[5, 17]. Whereas the landing and cutting movements with more flexed knee joint angles have been reported to reduce the magnitude of anteriorly directed strain in the ACL, but this allows for the activation of the hamstrings to work as synergists for the ACL[5]. In addition to the hip and knees, it was found that the hyperpronation of the foot and ankle can also increase the risk of ACL injury[29].

Non contact ACL injuries can be produced by knee knee external rotations and hip internal rotations or forced tibial rotation, but the body postures that allow these positions to occur may also increase stress to the ACL and lead to injury.
Static positions consist of anterior pelvic tilt, anteverted hips, tight hamstrings, genu recurvatum (hyperextended knees), and subtalar joint pronation[29]. Static positions put the lower body in a position of knee hyperextension and increased tibial rotations which cause stress at the ACL and cause forceful stretching of the ACL[29]. Noncontact ACL injury risk is affected by anthropometric, neuromuscular, and biomechanics of a subject's lower body, depending on the body posture during which a high risk movement is performed causing the risk to either increase or decrease.

1.2.2 Neuromuscular Control Deficits

Neuromuscular control deficits are muscle strength, power, or activation patterns that can lead to an increase in knee joint and ACL loading that take effect during certain high risk maneuvers[33]. When the neuromuscular control of joints decreases it can place stress on the passive ligament structures that can exceed their strength limits and lead to mechanical failure of the ligament[33]. Neuromuscular control is necessary to maintain knee stability during landing and pivoting. When neuromuscular control is decreased during an execution of sports movements, one result is abnormal joint mechanics[33]. When female athletes have suffered ACL injuries in competition, they have demonstrated altered neuromuscular control as evident by their lower limb biomechanics during the maneuver which injured them[21]. The examination of athletes in studies have supported the theory that neuromuscular imbalances are potential explanations for ACL injury mechanisms[21]. The four neuromuscular theories for ACL
ligament risk are the ‘Ligament Dominance Theory’, ‘Quadriceps Dominance Theory’, ‘Trunk Dominance Theory’ and the ‘Leg Dominance Theory’[24, 33].

The ‘Ligament Dominance Theory’ is when the ligaments are relied upon excessively to absorb the high landing forces being transmitted through the lower body, this is more apparent when the lower body is in a misaligned position of excessive knee abduction, hip abduction, and hip internal rotation[24, 33, 37, 38]. The absence of muscle control of the mediolateral knee motion allows the ground reaction force (GRF) to control the direction of motion of the lower extremity joints, which in turn will place more stress on the ligaments to absorb a percentage of the ground reaction force[17, 33].

The ‘Quadriceps Dominance Theory’ is when a subject has preferential utilization of the quadriceps muscle to stiffen and stabilize the knee joints during landing or cutting maneuvers[24, 33, 37]. The preferential activation of the quadriceps muscle may result in excessive anterior translation of the tibia and excessive strain on the ACL[37]. This utilization of the quadriceps becomes even riskier with low flexion angles of the knee which can then cause reduced recruitment and activation of the hamstring muscles[24, 37, 38]. Quadriceps and hamstring muscle forces contribute to the net shear force at the tibiofemoral joint and have important implications for ACL injury during functional tasks[6]. A description of the relationship in recruitment of the hamstring (H) and the quadriceps (Q) is the H:Q ratio, which can be used to determine the risk of ACL ligament injuries[7, 24].
The H:Q ratio and muscular activity can be related to the majority of the factors involved in dynamic joint stability[24]. When the H:Q ratio is low, it signifies that the quadriceps are activated without sufficient strength of the hamstrings, this is a limitation of the prospect of muscular co-contraction which serves to protect the ACL[24].

The ‘Trunk Dominance Theory’ is when a subject is unable to control or stabilize the position of their trunk during a landing maneuver[24, 33, 37] This deficit can be characterized by excessive trunk tilt over the supporting leg, which is related to an increase in hip adduction and knee abduction, which creates large external moments about the subject’s knee[37]. This deficit is also known as ‘core dysfunction’ and it can be simplified to an imbalance between the inertial demands of the trunk and control/coordination to resist it[33]. During landing, pivoting or deceleration female athletes have been shown to have more motion that is often excessive and directed by a greater extent by the trunk’s inertia, than by the counter forces that would come from control of the athlete’s core muscle function[33]. This shows that females have shown weaker core control than their male counterparts[33]. This weaker core control and ability to dissipate force result in excessive trunk motion, high GRFs, and high knee joint abduction torques(knee loads)[33]. This theory shows that movements of the trunk can affect the load dissipation in the lower body when performing high risk movements[33].
The final neuromuscular theory is the ‘Leg Dominance Theory’[24, 33]. This theory is when a subject shows differences in the side-to-side kinetic and kinematic asymmetries of their legs, generally shown by subjects favoring one leg over the other[37]. These asymmetries tend to result in one leg consistently absorbing more of the impact force compared to the other leg, which can lead to one ACL taking more force than the other and can result in an ACL tear[37]. If a subject shows large favoritism between legs, there has been evidence this can increase their risk of an ACL injury[38, 45]. This imbalance of reliance on one leg can also be exhibited as an imbalance in muscle strength and recruitment patterns in the opposing leg[31]. Muscle strength imbalances are measured by the isokinetic strength of the knee flexors and extensors, which have been associated with higher injury rates[31]. Studies have shown that female athletes exhibit landings with significant side-to-side differences in movement patterns and landing forces, which has been associated with increased injury risk to the ACL[31].

Many studies have been performed to verify the theories and also try to determine which neuromuscular deficit theory is the best indicator. One prospective study analyzed the landing biomechanics of 205 high school female basketball and soccer players[38]. These athletes performed a baseline landing task and then were followed for 1 to 2 seasons, this study found through observation measurements of ligament dominance and leg dominance were strong predictors of future ACL injury[38]. Another study followed 277 collegiate
athletes and found that deficits in trunk control were strong predictors of risk for future ACL injury[38]. Current literature has observed that athletes have deficits that are consistent with more than one neuromuscular deficit theory[38]. There is evidence of overlap between trunk, leg and quadricep dominance theory in athletes at risk of ACL injury[38].

A study performed by Lim et al., looked to compare ACL injury risk factors between female dancers and female soccer players during a single and double leg drop landing vertical jump task[28]. The results of this study showed that athletes had higher incidence of trunk flexion, trunk external rotation angle, higher knee external rotation and higher knee valgus moments than ballet dancers[28]. This study shows that when examining the female athletes and female dancers, non ballet trained athletes showed to have more of a deficit in the trunk dominance and ligament dominance theories.

1.2.3 Effect of Leg Stiffness

ACL injuries are at higher risk to occur under conditions of high dynamic loading of the knee joint, when active muscular restraints are unable to compensate and dampen joint loads adequately[33]. This combination is more likely to appear during landing. Landing impact can be quantified using measures of mechanical stiffness[2, 45]. Mechanical stiffness is the body’s ability to resist deformation against an applied force, under the assumption that the body acts as a spring[45].
Figure 6: Diagram which shows the differences between a soft landing and a stiff landing[54]

A stiff landing technique could transmit a greater load to the knee joint and expose the ACL to an increased risk of injury[45]. Leg stiffness cannot be applied uniformly, it has to be regulated by modulating stiffness at individual joints[45]. This stiffness of each joint can be controlled by altering the joint range of motion and the associated muscle activity[45]. No optimal joint stiffness is known; but it was found that an increase in lower limb stiffness can cause an increase in the risk of bony injuries, and a decrease in lower limb stiffness can cause an increase in the risk of soft tissue injuries in the leg, not connected to the risk of ACL or the posterior cruciate ligament(PCL) injury[2, 45].

Ambegaonkar et al. performed a study that compared knee muscle activation, leg spring stiffness, and knee joint stiffness of female dancers and basketball players[2]. The study looked at the initial landing of a drop jump off a 45 cm box[2]. This study found that dancers had higher spring stiffness, but similar knee
joint stiffness to athletes during the initial landing of the drop jumps[2]. The study showed that dancers had trends towards earlier onset of muscle activity and higher muscle activity in the medial hamstring and lower lateral quadriceps[2]. During post landing, dancers show higher gastrocnemius activity[2]. The findings of this study show that there is a possibility of neuromuscular differences in landing across the hip and ankle joints between these two groups[2]. The findings lean toward a difference in joint stiffness affecting the lower body biomechanics of the female dancers and basketball players. The ability to alter the joint stiffness could be utilized to protect the lower body extremities during landings from injury.

1.2.4 Hip Extension-Knee Flexion Paradox

The hip extension-knee flexion paradox is a convergence of factors that create an unstable environment for the knee joint and increase the risk of injury to the ACL. The factors begin with a delayed or slowed co-activation of the quadriceps and hamstring muscles[17]. This factor may occur at any critical time during athletic endeavors when quadriceps and hamstring muscle groups are either not activated, or are activated but at inadequate levels[17]. This deficit of the activation will result in a joint that is reliant on passive restraint, or ligaments, and also inadequately compressed at the time of ground contact[17].

The next factor is a dynamic ground reaction force applied to the lower body while the knee is near full extension[17]. If there is a deficit in co-contraction prior
to foot contact, it will ensure that the ground reaction force becomes the key force in loading the tibia in all planes[17]. When the knee is at full extension, the joint contact forces(contact forces that act perpendicular to the medial/lateral tibial plateau) act on the posteriorly tilted tibial plateau creating a large component[17]. This large component induces anterior tibial rotation, which is unconstricted by the hamstring[17].

The anatomical factor is a combination of a shallow medial tibial plateau and a steep PTS[17]. This is when the posterior slope of the tibial plateau(PTS) is different in the medial and lateral aspects, with differences ranging from -1 to 14 degrees[17]. The shear anterior force component produces tibial translation in conjunction with the anterior component of the quadriceps forces acting on the patella tendon[17]. Subjects with a steeper PTS will have a larger shear force resulting in potentially higher anterior tibial translation[17]. The shallow medial tibial plateau depth may be a more critical risk to ACL injury than the PTS[17]. Subjects that have shallow or flat medial tibial plateaus are at three times greater risk of injury[17]. This is because the flatter medial tibial plateaus do not provide stable seating of the medial femoral condyle on the tibial plateau[17]. This is because a flat medial plateau is unable to angulate behind the femur at large flexion angles or provide a locking mechanism between the femur and tibia, and allows for more tibial translation[17].
The final factor of the hip extension-knee flexion paradox is a stiff landing due to incompatible hip and knee flexion velocities[17]. The incompatibility happens when the co-flexion of the hip and knee is interrupted or impaired, such that the knee will flex but the hip flexes more slowly than the knee[17]. This will further force the tibia to undergo translation with resistance solely on the ACL[17]. This instability of hip and knee flexion velocities can happen if the quadriceps and hamstring muscles have delayed coactivation and then due to instability, there is a strong application of the gluteus maximus[17]. Another situation that can cause this incompatibility is the position of the trunk at the time of ground contact[17]. IF the trunk is in a position where the center of mass is positioned posterior to the knee, the ground reaction force of landing will encourage more knee flexion than hip flexion, even possibly acting to extend the hip[17].

The convergence of a delayed co-activation of the quadriceps and hamstring muscles, ground reaction force applied to a fully extended knee, a shallow medial tibial plateau with a steep PTS, and a stiff landing creates an unstable environment for the knee that can cause injury to the soft tissue of the joint, which includes the ACL[17].

1.2.5 Fatigue
Numerous studies have found that ACL injuries tend to occur with a higher frequency at the end of the day or even towards the end of the season when athletes are fatigued[26]. Fatigue is known to contribute to the risk of altering
neuromuscular control for the trunk, lower limbs, and an individual's ability to stabilize their own knee joint effectively[26, 27, 41]. Fatigue can also significantly decrease muscular force development and contraction velocity, which in turn can increase the forces on passive tissues such as the ACL[26].

When experiencing fatigue an individual is more at risk of ACL injury especially when performing unanticipated movements[26]. Fatigue can create a delay in knee flexor/extensor muscle activation, which can create unsafe knee valgus angles and moments about the knee joint which increases the risk of ACL injuries[17, 26]. Individuals suffering from fatigue are also more prone to ACL injury due to hip adduction and an observed increase in faulty trunk posture[26].

Fatigue has been shown to cause changes that can alter the lower body biomechanics and put the lower body into positions that have an increased risk of ACL injury. In a study performed by Quammen et al., 15 NCAA Division 1 athletes were put through both functional agility short-term fatigue protocol and a slow linear oxidative fatigue protocol[41]. It was shown after each fatigue protocol was performed that participants exhibited changes to their lower extremity biomechanics during landing tasks[41]. The participants presented with a more erect or extended lower body position during landing after being fatigued, and also exhibited a decrease in knee and hip flexion during landing[41]. The more extended position has been associated with an increased anterior shear force on the proximal end of the tibia, due to an increased patellar tendon-tibia shaft
angle[41]. Decreased joint angles make a mechanical disadvantage for the hamstring muscles to activate, by decreasing their angle of pull and reducing the amount of posterior force that can be applied to the tibia which increases the anterior tibial translation and ACL loading[41].

Dancers trained in ballet have also been shown to be affected by fatigue similar to nonballet trained athletes. After fatigue dancers are found to have a decrease in their jumping height capabilities and an increase in faulty alignment of their lower body extremities[26]. In studies performed by Ekrgen et al. and Costa et al. dancers were found to have an increased risk of injury when they had an increase in training durations[9]. In another study performed by Liederbach et al, it was found that of the 0.02% ACL injuries that were reported 75% of the injuries happened in the second half of performance season and 67% happened after several hours of activity from the dancer[27]. Fatigue creates misalignment and improper landing technique which in turn creates conditions that increase the risk to the ACL.

1.2.6 Turnout Angle/Hip Range of Motion

A turnout is a ballet position which focuses on the external rotation of the legs with an aim of exhibiting optimal range of motion, especially abduction of the hips, as well as increasing an individual's static and dynamic balance[23]. The active aspects of the turnout require high levels of inter- and intra- muscular coordination, body awareness, strength and strength endurance to allow for
functional dynamics of alignment of the legs in the turnout position[23]. The turnout is considered to be one of the most important technical and stylistic aspects of classical ballet[23].

![Image](image.png)

**Figure 7:** An example of a dancer performing a proper turnout[55]

An individual's passive anatomical abilities will determine the amount of turnout a dancer or athlete will be maximally able to present while maintaining efficient alignment and balance[23]. Professional ballet dancers display an average functional turnout of 133.6 deg, with a passive hip external rotation of 50.2 deg and an active hip external rotation of 35.3 deg[23]. Passive movement is a movement that can be performed while the body is relaxed, while active movement utilizes contraction of muscles to perform movements. The ideal turnout for these dancers is to perform a turnout with 90 degrees of external rotation from each foot, to form an angle of 180 degrees[16, 34]. The minimum requirements to perform this level of optimal flexibility is 70 degrees of hip external rotation bilaterally, 5 degrees of tibial external rotation bilaterally and 15 degrees of foot external rotation bilaterally[16]. Dancers will work to obtain the
optimal turnout out, and if they are unable to do so may compensate with either lumbar hyperlordosis, forced tibial external rotations(screwing of the knee) and/or hyperpronation/abduction of the feet to force the body into a bigger angled turnout[16, 23].

Injury in dancers has been associated with forcing turnout angles past the dancer’s ability to be closer to the ideal turnout or a poor turnout angle that has to do with inflexibility in the individual[23,34]. A study performed by Caplan found that in a study between dancers with and without injury, the average compensated turnout was 20.8 degrees higher in dancers that suffered injuries[34]. The findings of this study were not statistically significant, but it was found that 90% of dancers with compensated turnouts of 25 degrees and more had self-reported injury[34]. This shows that though the amount of compensated turnout was not statistically significant in determining which of the dancers will get injured, the act of forcing a bigger turnout is a key to determining if a dancer will get injured[23, 34].

The turnout relies heavily on the hip’s external range of motion, though athletes do not perform turnouts in their athletic endeavors, some movements do require internal and external hip range of motion[16, 34]. In a study performed by Escudiero et al., a total of 154 athletes were analyzed for their hip range of motion[14]. The athletes in this study were a mix of men and women, 94 athletes had an ACL injury while 60 athletes(control group) had other muscular injuries
not related to the ACL or the lower body[14]. When the hip motion was analyzed, it was found that the hip range of motion of the ACL injury group was significantly less than that of the control group[14]. This shows that there is a possible correlation between hip joint limitations and risk of an ACL injury[14].

Though studies have been limited, the turnout and hip internal and external range of motion may be a step to determine the risk of ACL injury in populations deemed at high risk of ACL injury.

1.3 Background of Populations

1.3.1 Female Traditional Jumping Sport Athletes

Females in athletics have been linked to a higher risk of ACL injury[47]. Female athletes are also more prone to excessive exercise without paying attention to the possibility of damage that can be done due to such exercise[24]. Researchers agree that this could be harmful in the long term[24] Overall skilled athletes have a higher tolerance of pain and may not limit themselves to suitable amounts of exercise[24]. This tendency makes athletes more vulnerable to sustaining injuries in sports activities[24].

Jumping sports are multidirectional sports that utilize movements in all directions including vertical[32]. These sports involve lateral movements, cutting, and landings which place the body at an increased risk for ACL injury[8,38]. The volume of demands between the multitude of jumping sports athletes is widely
variable, each sport fluctuating in the amount of running, lateral shuffling/cutting, and jumping[42]. In a study performed by Taylor et al., the amount of time of multi-directional movements for a plethora of jumping sports during competition was measured and then analyzed to define categorical movements[42]. Female elite soccer players were found on average to run 6900 to 8500 meters, of those 160 to 615 meters of sprinting, and 608 to 2452 meters of high intensity running[42]. For both genders in this study, soccer players were found to perform cutting maneuvers over 300 times and traveling laterally 217 to 549 meters per game. Female basketball players were found to move 5576 to 7039 meters, of those 952 to 1329 meters of sprinting with an average of 18-105 sprints per game. Female basketball players were found to perform lateral shuffles about 62 to 298 times and perform an average of 19 to 43 jumps per game[42]. Female volleyball players were found to perform lateral movements for 50.9% of movements on offense and 6.9% of movements on defense, this study also found that females performed an average of 22.9 jumps per game[42]. This study was unable to calculate the number of movements that were unanticipated. The unanticipated movements create more of a risk during competition because they are split second changes and the athlete may not be able to concentrate on performing the task correctly, but only able to think of quickly performing the task which in turn can put the body into misalignment[42].

These movements increase the risks that an athlete will have an incident resulting in an ACL injury[47]. Also the combination of the movements within
competition increases fatigue, which has shown to decrease an individual’s form and increases the risk of an injury[26, 27, 41].

1.3.2 Female Dancers Trained in Ballet

Ballet dancers perform artistic movements, with their body in position that are designed to create aesthetically pleasing clean lines and some if not most of these movements at the elite level are done so en pointe on a fully extended leg, with force on the toes of the dancer. Ballet dancers undergo extensive training starting from a young age to develop technical skills, as well as achieve the strength necessary to perform the movements with high levels of technical execution[9, 27, 37]. Formal Ballet training focuses on the alignment of body and lower extremities to be in an aesthetically pleasing position, which requires a high level of neuromuscular control and balance[44].

Ballet dancing is dependent on the proper technique and movements to achieve the aesthetically pleasing and fluid movement. The turnout is an important aspect of classical ballet, an ideal turnout is achieved by the formation of both limbs at a 90 degrees turnout of each leg[16, 34, 44]. This ideal turn out requires the dancers to have specific anatomical relationships with their lower extremities (which includes skeletal alignment, joint mobility and soft tissue flexibility) to be able to contort their bodies into this position[16, 34]. This will take many years of training, and even then there are few dancers that are able to perform this maneuver without compensations of the spine, knee or ankle[16]. If
A dancer is unable to perform an ideal turnout, their turnout is considered a functional turnout[34]. A functional turnout is the angle of an external rotation of the lower extremities that is able to be done with proper technique and without forcing the body to perform the ideal turnout, which raises the risk of injury to the lower extremities[16]. The functional turnout has three qualitative criteria to promote the stability of the lower body. The first is that the center of the knee must be over the midline of the foot, this criteria limits excessive tibial rotation[16]. The second criteria is the dancer must keep equal weight over both feet, this is intended to limit the dancer from forcing a turnout in the legs unequally[16]. The third criteria is that weight must be evenly distributed over all of the phalanges and metatarsals(toes), this helps to limit pronation of the feet.[16]. More information on the turnout can be referenced back to section 1.2.5.

Technique classes are a necessary aspect of ballet, in these classes dancers can perform up to approximately 200 jumps per 1.5 hours[26, 27, 36, 44, 45]. The amount of jumps can also be more, depending on if the dancer has rehearsals, performances or other classes[26, 27, 36, 44, 45]. Many of these jumps include maximal plantar flexion within the air and, for aesthetic reasons, an appearance of an effortless and smooth landing[36, 44]. The dancers are trained to land with lower extremities near full extension, with a vertical spine and full use of plantar flexion at initial contact[36]. This landing style results in a large force being transmitted through the leg, this is combated by a unique landing technique.
which involves rolling through the feet[36, 45]. This landing technique involves a
controlled toe strike followed by the ball of the foot with a delayed controlled
lowering of the heel and sequential flexion of the lower limb joints[45]. This
landing technique requires control of the lower extremities during landing, with an
emphasis placed on keeping the patella directly over the midline of the foot and
works to dissipate the forces through the stiffness that is trained into the
dancers[36, 45].

The placement of feet during movements play an important role within ballet.
Ballet dancers perform movements in a multitude of feet positions, these include
en pointe(on the toes), demi pointe(on the balls of feet) and en dehors(feet
turned outwards)[9]. These various positions are performed in pointe shoes[39].
A pointe shoe is a stiff shoe that contains a box on the front of the shoe, this box
works to lift the dancers off the ground and help to dissipate pressure across all
toes[1]. The shoe also contains a shank, which is a stiff insole of the shoe that
provides support for the bottom of the foot when en pointe[1]. Pointe shoes are
an extension of dance limbs and with many brands and styles to choose from,
dancer’s will work to try and find pointe shoes that are the best fit for them[1].
Though each dancer can wear a different pointe shoe, all pointe shoes are made
from stiff material in order to support the dancer during maneuvers both en pointe
and demi pointe[39]. These materials have low shock absorbent properties,
which places higher demand on the foot structures and lower body biomechanics
to dissipate the force throughout the lower extremities[39]. Due to this excessive
force, studies have found that the ankle is the most common injury site for ballet dancers[9].

![Figure 8: An example of a dancer dancing on en pointe(left), demi pointe(middle) and en dehors(right)[56, 57, 58]](image)

Though ballet dancers are found to have low overall frequency of injury to the ACL, the frequency of sprains and muscle injury of their lower limbs is high[9]. Approximately 86% to 97.48% of injuries in ballet occur in the lower limbs, and 64% of these are caused by micro-trauma from repetition[9].

**1.3.3 Comparison of Dancers Trained in Ballet and Traditional Jumping Sport Athletes**

Ballet and traditional jumping sports have similar movements, but distinct differences exist between the two activities. Even though the groups have similar movements ballet dancers have an ACL incidence rate of 0.009 ACL injuries per 1000 exposure, which is significantly less when compared to female athletes with an ACL injury rate of 0.07-0.31 ACL injuries per 1000 exposures[28, 37, 44, 45]. Through intensive training of movements dancers have developed heightened body awareness and controlled movement patterns when compared to
athletes\cite{44}. In a study performed by Ward et al., forty dancers and forty team athletes performed three single-leg drop landings from a 30 cm platform\cite{45}. This study found that dancers had a lower vertical leg, knee joint and ankle joint stiffness when compared to athletes\cite{45}. During the landings dancers had greater center of mass vertical displacement per height, lower peak ground reaction forces, as well as increased landing time compared to athletes\cite{45}. This is due to the dancers relying more on the ankle joint to dissipate the landing than athletes\cite{45}. Dancers rely more on rolling through the foot during landing, and exhibit a more controlled landing than that of athletes\cite{45}.

A major difference between ballet dancers and athletes is that for dancers the movement is the final objection and requires extensive repetition while athletes use movement to get to their final objection\cite{9}. Dancers are also not generally exposed to unanticipated environmental events which would force the dancer to perform a movement when not in full control of their body\cite{44}.

1.4 Gender Disparities

Females tend to have slightly different anatomical constructs than their male counterparts, which may place females at an increased risk for ACL injury\cite{8}. Women have been identified as being more prone to have a larger PTS than men\cite{8}. Since women have greater PTS than men, this also means that they have greater internal rotation of the tibia\cite{8}. The meniscus slope has also been found to be greater in females than males\cite{8}. Together the magnitude of the PTS
and meniscus slopes have been shown to influence the biomechanics of the knee during load transmission and can increase the incidence of ACL injury[8].

Various studies have shown that women have smaller ACLs than males[8]. A 2012 study performed by Lipps et al. reported a size difference between male and female ACL, but also found female ACL’s exhibit lower strain stress and modulus of elasticity at failure when compared to males[8]. This study also reported findings that the cross sectional area, length, mass and density of the female ACL is comparably smaller than that of the males[8].

Hormonal factors have also been linked to gender disparity in ACL risk[21]. Females' follicular and ovulatory phases of the menstrual cycle have been associated with ACL injury risk[21]. After puberty it has been found that female athletes show an increase in faulty landing patterns[37]. The risk and extent of the hormonal contribution to ACL injury is currently unknown[21].

1.4.1 Traditional Jumping Sport Athletes Gender Disparities

Female athletes are more likely to have an injury to the ACL when compared to their male counterparts[2, 7, 11, 19, 20, 24, 28, 29, 31, 32, 37, 44]. The NCAA performed an injury survey from the years 1990-1993 of approximately 15% of the NCAA member institutions[7]. The results of this study found an average knee injury rate greater than one injury for every ten female athletes[7]. In any given year more than 10,000 knee injuries were expected to occur in female
athletes within the organization, including more than 2200 ACL ruptures[7]. The NCAA also has an injury surveillance system which institutions may opt to participate in[7]. The surveillance program found from the years 1990-2002, ACL injuries from the participating institutions showed in basketball there were 682 ACL injuries, with 514 of the injuries sustained by female athletes[7]. For soccer players there were 586 ACL injuries, with 394 of the injuries sustained by female athletes[7]. Differences in lower extremity biomechanics have been a presented theory to account for the gender disparity in ACL injuries[20]. This is supported by accounts of longitudinal studies which have shown that male traditional jumping sport athletes demonstrate neuromuscular adaptations after puberty when compared to female traditional jumping sport athletes and female athletes that suffer an ACL injury demonstrated altered neuromuscular control characteristics[37].

The presence of a low H:Q strength ratio has been linked to increased incidence of overuse knee injuries among female athletes[7]. Research has suggested that female athletes have higher levels of quadricep muscle activity and lower levels of hamstring muscle activity[6, 7]. The slower response of the hamstring activation after quadricep muscle activation has been shown to increase anterior stress on the ACL[7]. Studies have presented evidence that supports a theory that female hamstring muscle are substantially weaker than their quadricep muscle[6].
Female athletes have been found to exhibit a pattern of landing with more extended knee and hip joints during vertical and horizontal landings, as well as in lateral cutting maneuvers when compared to their male counterparts[5, 12]. Landing with the knee joint in an extended position has been associated with causing elevated anterior shear force and an increased risk of ACL injury[5, 12]. Female athletes had greater leg to opposite leg discrepancies in normalized hamstring peak torque when compared to male athletes, this is evidence to show that there is insufficient neuromuscular control of lower limbs[33].

In a study conducted by Ford et al., biomechanical differences between genders were reported during the performance of a drop vertical jump[33]. Female athletes were shown to land with greater maximum knee valgus angle and greater total knee valgus motion during their maximum knee valgus angles[33]. Female athletes demonstrated significant biomechanical differences between their non-dominant leg and dominant leg in performance of maximum valgus knee angle[33]. The result of the leg to leg difference reflect neuromuscular deficits that are more heavily present in the population of female athletes[33].

Females have been shown to perform movements that put the ACL at risk more often than their male counterparts.
1.4.2 Dancers Trained in Ballet Gender Disparities

Female and Male dancers have shown no sign of gender disparities in the rate of incidence of ACL injuries[28, 37, 45, 47]. It has also been observed that male and female dancers trained in ballet do not exhibit differences in their biomechanics during a landing task[26, 28, 37]. In a study performed by Orishimo et al., the results found similar values for knee flexion and peak vertical ground reaction forces among male and female dancers[12].

1.5 Hypothesis

Female traditional jumping sport athletes have a higher incidence of ACL injuries than both male traditional jumping sport athletes and female dancers trained in ballet. Considering the anatomical and hormonal differences that naturally predispose females to ACL injuries, female dancers trained in ballet have been able to obtain a lower rate of ACL injury than female traditional jumping sport athletes, but also have a similar ACL injury rate to male dancers trained in ballet. This study will analyze published studies to identify differences in the lower body biomechanics between the population of female dancers trained in ballet and female traditional jumping sport athletes, in order to determine the biomechanical changes in which female traditional jumping sport athletes can initiate to decrease their risk of ACL injury. This study will also examine the turnout angle of female dancers trained in ballet and female traditional jumping sport athletes to determine if there is a significant difference in turnout angle between the two populations. I hypothesize that the published studies will show that there is a
muscular differences in the activation of the gluteus maximus and vastus lateralis since these muscles are associated with valgus moment, as well as differences in the neuromuscular deficits between the two groups. I also hypothesize that there will be significant differences in the turnout angles between the female ballet dancers and female jumping sport athletes.
Chapter 2

2 Methods

The methods of this thesis have been affected by the development of the COVID-19 pandemic and other outside influences that have been out of my control. An initial plan was created that would involve human testing and ongoing observation of the participants, this plan was put on hold and canceled as it was approved a month before the pandemic shut down Cal Poly. The next option was an meta analysis, which was unable to be performed due to the low number of studies of this comparison, the differences in how the studies were performed and discrepancies in which the lower body biomechanics were measured. The turnout angle and data comparison are the two aspects of this thesis which were able to be performed successfully. The data comparison was done by using the papers that were initially found through the meta analysis. The turnout data was data that was collected for Ashley Tornio's thesis 'Biomechanical Study of Jumping & Landing Techniques: Ballet VS Non-ballet Athletes' and was not used for her thesis[43]. I was able to get this data because I had helped collect this specific piece of data and had access to the data as part of the data acquisition research team on the project.

2.1 Initial Plan

In this study, noninjured female team sport athletes (i.e. basketball, volleyball, and/or soccer) will perform an entrance protocol of double-leg drop vertical jumps (DVJ) and traditional body squats from which biomechanical measures will be
captured. Subjects will perform three DVJ exercise from a 40-cm platform dropping off the box with both feet leaving at the same time, and then immediately performing a maximum vertical jump, tucking their knees to their chest. Additionally, the subjects will perform three traditional bodyweight squats while additionally being instrumented with 4 wireless Heel-Toe Strike force transducers.

Each subject will be instrumented with electromyography (EMG) surface electrodes (skin-mounted) on the vastus medialis, vastus lateralis, bicep femoris, and the gluteus maximus. Each subject will also be instrumented with ~16 reflective markers placed bilaterally over the lateral femoral condyle, midshank, anterior superior iliac spine, acromion, lateral humeral epicondyle, distal radius, on the sacrum and left posterior superior iliac spine per the Helen Hayes system. Electromyography during DVJ will be recorded for differences. Two-dimensional video kinematics of the lower extremity during DVJ task will be collected to utilize the sixteen reflective markers for tracking the body segments.

The subjects will then be randomly placed into either a control group or a ballet training group. For five weeks following the entrance protocol, the control group athletes will be asked to continue their normal training regime and the ballet training group will be asked to continue their normal training regime and add 15 minutes of ballet exercise.
The ballet training is based on a collaboration between the Royal Academy of Ballet and the Amatuer Athletic Association. This collaboration was documented in the book “Ballet for Athletes”[48]. The exercises from this book were taken and updated according to the current ballet training, as well as exercises deemed outdated or high risk of injury due to movements where exempt from the study. The book requires that the first two exercises be done daily, while the rest of the exercises are randomized for a total of 4 exercises per day.

At the conclusion of the five-week period, the subjects will be asked to return to perform the exit protocol. The exit protocol will be a repeat of the entrance protocol. This will allow for there to be a direct comparison of before and after the training regime is added.

This study was approved by the California Polytechnic State University: San Luis Obispo Institute Review Board(IRB) under the name ‘Biomechanical Study of Jumping & Landing Techniques: Ballet vs Classical Jumping sports’, study number 2018-017 on February 11th, 2020.

2.2 Meta Analysis

This study will be a systemic review of studies that have data which can be used to prove the hypothesis that there is a difference in the lower body biomechanics between ballet dancers and jumping sport athletes during a landing. The steps of
the meta analysis where taken from the paper ‘How to conduct a meta-analysis: A basic tutorial’ by Basu[4].

For this analysis, the question of lower body biomechanics between ballet dancers and jumping sport athletes was divided into phrases that will be searched through search platforms that produced scientific papers. These keywords for this search are ‘female athlete’, ‘female jumping aport athlete’, ‘female dancer’, ‘female ballet dancer’, ‘ACL’, and 'landing’. Each phrase is combined with other phrases to maximize the number of papers which are found in each search. Combining the phrases also helps to collect papers that only focused on one subject group, therefore maximizing the amount of data that can be combined for analysis. The abstract and title of each paper will be read and compared to a beginning set of criteria to filter out papers that are found to have participants under 18, have only participants of the male gender, or not include traditional jumping sport athletes or dancers trained in ballet.

The papers will be analyzed through an initial screening, and then the quality of information will be determined. To determine the quality of the information, the information pertaining to the hypothesis, sample size, selection bias, and the confounding variables for each study are extracted and analyzed [4]. If the paper is determined to be of good quality, then the information will continue through the
meta analysis, if the data is found to be of low quality the data is then disposed of.

The next step is to determine the extent of heterogeneity of the studies, how different the studies are from each other. The idea behind determining heterogeneity is that each study in a meta analysis should be a sample representative of the population, therefore each paper should be able to give similar and comparable results or a homogeneous result; if the paper cannot give similar results then it is heterogeneous and therefore cannot be directly compared[4]. Heterogeneity will be determined using Cochran’s Q statistic, which is a chi-square statistic.

After heterogeneity is determined and the data is found to be homogeneous, effect is to be determined. Effect is found through estimating the summary effect assuming both fixed and random effects ratios. The fixed-effect model assumes that the population of these studies is uniform enough to allow a determination that the sets of studies are sufficient enough to compare, while random effects models assume that there can be a relaxation of the assumption that the studies are from the same population to allow a determination that the sets of studies can be compared. The effect size plotted against the inverse of the variance of the study creates a forest plot. On the forest plot, two diamonds will be imposed to represent the summary effect estimate of the fixed and random effects meta-
analysis final. The area of the diamonds corresponds to the 95% confidence interval[4].

The next step is to determine publication bias. This is to test whether omitted studies should have been included due to smaller studies potentially being unpublished. This is achieved by plotting the effect estimates by the standard deviation of the study. This graph should resemble a funnel, with a base created from small-sized studies and a point created by large sample size studies[4]. If a quadrant of this funnel is missing then studies included in the meta-analysis represent a publication bias.

After these steps have been completed, subgroups of data are analyzed which include differences in height of the jump, years of training, and age of participants. Next, a subgroup analysis is performed to determine the effects of the study on these differences and allows for a creation of a summary estimate of the diverse studies included within the meta-analysis.

2.3 Data Comparison

For this comparison, Data has been taken from published papers.

To find the papers, the question of lower body biomechanics between ballet dancers and jumping sport athletes is divided into phrases that will be searched through search platforms that produced scientific papers. These keywords for
this search are ‘female athlete’, ‘female jumping sport athlete’, female dancer’, ‘female ballet dancer’, ‘ACL’, and ‘landing’. Each phrase is combined with other phrases to maximize the number of papers that are discovered in the search.

The abstract and title of each paper were read and compared to a beginning set of criteria to filter out papers that were found to have participants under 18, have only participants of the male gender, not include traditional jumping sport athletes or dancers trained in ballet, or is not a comparison study of dancers trained in ballet and traditional jumping sport athletes.

The results of these studies will be extracted from the papers and placed into a chart that will allow for the results to be compared to each other. These results will be dependent on whether a result from a paper will be able to be in agreement or disagreement to other results from other papers.

2.4 Turnout Angle Comparison

In a previous study performed by Ashley Tornio, female dancers trained in ballet and jumping sport athletes were asked to stand on a piece of paper with their heels together and their legs externally rotated to provide a foot tracing that indicated an active range of external rotation. The feet placement is then traced onto the piece of paper.

The feet tracing is then analyzed to find the middle of the feet and a line is traced from the middle to the place where the heels touch. This step is repeated for both
sides creating an angle and the angle is measured using a protractor. The measurement is repeated for the turnout angles of each participant is then recorded as an active range of external rotation.

The angles are then separated into Ballet trained and Non-Ballet trained groups. These groups are compared to each other using an f-test.
3 RESULTS

3.1 Initial Plan Results

No results were able to be produced from the initial plan, because due to COVID this study was unable to be conducted.

3.2 Meta Analysis Results

No results were able to be produced from the Meta-Analysis, due to the inability to find enough papers on the subject to be able to perform the necessary steps of a Meta-analysis.

3.3 Data Comparison Results

3.3.1 Article Search Results

A search was conducted for papers that compare jumping sports athletes’ and ballet dancers’ lower body biomechanics. From the search papers were selected if the age of subjects were above 18, the subjects were performing a landing task, and if the subjects did not have any lower extremity injuries or previous surgeries. Of the search results, six papers were able to fulfill the parameters of the study.
### 3.3.2 Table of Papers

**Table 1:** A breakdown of the 6 papers used in the Data Comparison with a description of the participants and exposure of each paper.

<table>
<thead>
<tr>
<th>Title</th>
<th>Paper</th>
<th>Authors, Year</th>
<th>Participants</th>
<th>Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison of Landing Biomechanics Between Male and Female Dancers and Athletes, Part 1</td>
<td>1</td>
<td>Onishama et al., 2009</td>
<td>40 dancers, 40 team sport athletes</td>
<td>Three single-legged drop landings from a 30 cm box</td>
</tr>
<tr>
<td>Lower extremity Biomechanical Differences Between Female Dancers and Soccer Players</td>
<td>2</td>
<td>Ericksen et al., 2020</td>
<td>17 collegiate female dancers and 14 female athletes</td>
<td>Rebound jump landing task from a 30 cm box</td>
</tr>
<tr>
<td>Lower body Stiffness and Muscle Activity Differences Between Female Dancers and Basketball Players during Drop Jumps</td>
<td>3</td>
<td>Ambegoankar et al., 2010</td>
<td>35 female dancers and 20 female basketball players</td>
<td>Double leg jump landing from a 45 cm box</td>
</tr>
<tr>
<td>Comparison of lower limb stiffness between male and female dancers and athletes during drop jump landings</td>
<td>4</td>
<td>Ward et al., 2018</td>
<td>40 dancers and 40 team sport athletes</td>
<td>Performed three single leg drop landings from a 30 cm platform</td>
</tr>
<tr>
<td>Differences in anterior cruciate ligament injury risk factors between female dancers and female soccer players during single and double-leg landing</td>
<td>5</td>
<td>Lim et al., 2021</td>
<td>15 female athletes and 45 female dancers</td>
<td>Single leg drop landing and double leg drop landing from 45 cm</td>
</tr>
<tr>
<td>Biomechanical Study of Jumping &amp; Landing Techniques: Ballet VS Non-Ballet Athletes</td>
<td>6</td>
<td>Tomio, 2019</td>
<td>5 collegiate athletes and 5 collegiate ballet dancers</td>
<td>Double legged drop landing from 30 cm and MVC</td>
</tr>
</tbody>
</table>

### 3.3.3 Comparison of Results of Papers

Each paper had different has different measurable outcomes for which the results are reported for.
Table 2: All the measurable outcomes, the paper which outcome was seen in, how the measurements were made and how each measurement effects the risk of ACL injury.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Paper</th>
<th>How</th>
<th>effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Valgus Moment</td>
<td>5</td>
<td>combining three dimensional motion data and ground reaction force data[28]</td>
<td>increased knee valgus moment, and increased risk of ACL injury[28]</td>
</tr>
<tr>
<td>Knee Valgus Angle</td>
<td>1,6</td>
<td>shank reference frame vs the thigh reference frame[37,46]</td>
<td>Increased Knee valgus Angle, Increase risk of ACL tears[37,46]</td>
</tr>
<tr>
<td>Knee Rotation</td>
<td>1,2,5</td>
<td>shank reference frame vs the thigh reference frame[13,28,37]</td>
<td>Increased knee rotation, decrease in risk of ACL injury[13, 28, 37]</td>
</tr>
<tr>
<td>Knee Flexion</td>
<td>2</td>
<td>comparison of four IMU sensors in the sacrum, thigh, shank and foot at the moment of initial contact during a landing( point in which participant exceeds 10N force on landing)[13]</td>
<td>decreased knee flexion, decreases risk of ACL injury[13]</td>
</tr>
<tr>
<td>Knee Abduction</td>
<td>2</td>
<td>comparison of four IMU sensors in the sacrum, thigh, shank and foot at the moment of initial contact during a landing( point in which participant exceeds 10N force on landing)[13]</td>
<td>Increase in knee abduction, increase in risk of ACL injury[13,18]</td>
</tr>
<tr>
<td>Ankle Aversion</td>
<td>2</td>
<td>comparison of four IMU sensors in the sacrum, thigh, shank and foot at the moment of initial contact during a landing( point in which participant exceeds 10N force on landing)[13]</td>
<td>Current studies have shown no statistical significance in ankle movement on ACL injury risk, however there have been some connections to ankle movement on knee position[25]</td>
</tr>
<tr>
<td>Ankle Dorsiflexion</td>
<td>2</td>
<td>comparison of four IMU sensors in the sacrum, thigh, shank and foot at the moment of initial contact during a landing( point in which participant exceeds 10N force on landing)[13]</td>
<td>Current studies have shown no statistical significance in ankle movement on ACL injury risk, however there have been some connections to ankle movement on knee position[25]</td>
</tr>
<tr>
<td>Ankle Abduction</td>
<td>2</td>
<td>comparison of four IMU sensors in the sacrum, thigh, shank and foot at the moment of initial contact during a landing( point in which participant exceeds 10N force on landing)[13]</td>
<td>Current studies have shown no statistical significance in ankle movement on ACL injury risk, however there have been some connections to ankle movement on knee position[25]</td>
</tr>
<tr>
<td>Hip Rotation</td>
<td>2</td>
<td>comparison of four IMU sensors in the sacrum, thigh, shank and foot at the moment of initial contact during a landing( point in which participant exceeds 10N force on landing)[13]</td>
<td>increase in hip rotation, decrease in risk of ACL injury[13]</td>
</tr>
<tr>
<td>Hip Adduction Moment</td>
<td>1,2</td>
<td>combining three dimensional motion data and ground reaction force data[13, 37]</td>
<td>Increase Hip adduction moment, increase risk of ACL injury[13,37]</td>
</tr>
</tbody>
</table>
Trunk Forward Flexion 1,5 global reference frame vs the trunk reference frame[37,28] increased trunk forward flexion, increased risk of ACL injury[37,28]

Trunk External Rotation 5 global reference frame vs the trunk reference frame[28] increased trunk external rotation, increased risk of ACL injury[28]

Trunk Side Flexion 1 global reference frame vs the trunk reference frame[37] Increased trunk side flexion, increased risk of ACL injury[37]

Muscle Activation 3,6 muscle activity measured using electrodes placed on the skin and normalized with the absolute peak RMS(root mean square) amplitude[2,43]

Leg Stiffness 3,4 force and position data from the initial landing were used to calculate leg stiffness[2,45] Increased leg stiffness, increased risk of ACL injury[2,45]

Knee Stiffness 3,4 force and position data from the initial landing were used to calculate knee stiffness[2,45] Increased knee stiffness, increased risk of ACL injury[2,45]

### Table 3:
A combination of the measurable results that had two or more papers with results pertaining to the measurements. The results for each paper is shown below and a comparison can be made from this table. FA: Female Athlete and FD: Female Dancer

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee Valgus Angle</td>
<td>FA &gt; FD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FA = FD</td>
</tr>
<tr>
<td>Knee Rotation</td>
<td>FA &gt; FD</td>
<td>FA = FD</td>
<td></td>
<td></td>
<td></td>
<td>FA &gt; FD</td>
</tr>
<tr>
<td>Hip Adduction Moment</td>
<td>FA &gt; FD</td>
<td>FA &gt; FD</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk Forward Flexion</td>
<td>FA &gt; FD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FA &gt; FD</td>
</tr>
<tr>
<td>Leg Stiffness</td>
<td></td>
<td></td>
<td>FA &lt; FD</td>
<td>FA = FD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Stiffness</td>
<td></td>
<td></td>
<td>FA &gt; FD</td>
<td>FA = FD</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Knee valgus angle was a measured outcome for papers 1 and 6. These papers have conflicting results; for paper 1 female athletes have statistically greater knee valgus angles, while paper 6 found that there was no statistically significant difference between the two populations.
Knee rotation was a measurable outcome for papers 1, 2, and 5. These results show that papers 1 and 5 were in agreement that female athletes had higher knee rotation when compared to female dancers. However, paper 2 disagrees with this finding.

For hip adduction moment at the point of landing, there was data from the study in papers 1 and 2. These papers are in agreement and the studies show that female athletes have bigger hip adduction moments than female dancers.

Trunk forward flexion was measured by papers 1 and 5. The results were consistent between the two studies, and it was found that female athletes had larger trunk forward flexion than the Female dancers.

Muscle activation was a measurable outcome for papers 3 and 6. The results of this comparison was unable to be made due to the differences in muscles examined for each measurement. The other aspect of this comparison is that muscle activation has been shown to have different effects determined by the velocity for which muscles are activated, as shown in the quadricep dominance theory.

Knee stiffness was measured by papers 3 and 4. These studies came to the same results that leg stiffness of female athletes had no statistically significant difference from female dancers.
The leg stiffness was measured in studies reported on in papers 3 and 4. These studies results did not agree over leg stiffness. Paper 3 found that female dancers had greater leg stiffness than female athletes. Paper 4 found that there was no statistically significant difference in leg stiffness between female athletes and female dancers.

The biomechanical results of knee valgus moment, knee valgus angle, knee flexion, knee abduction, ankle aversion, ankle dorsiflexion, ankle abduction, hip rotation, trunk external rotation, and trunk side flexion were only available in one paper each. Therefore there are no studies to be compared for these results. Muscle activation was studied in two papers, but the outcomes were not comparable to each other.

3.4 Turnout Angle Comparison Results

Figure 9: The foot tracing of participant #3, the three x’s denote the three points used to determine the measurement of the turnout angle of a traditional jumping sport athlete
Figure 10: The foot tracing of participant #5, the three x’s denote the three points used to determine the measurement of the turnout angle of a ballet dancer.

Table 4. The 20 participants with their athletic activity and the turnout angle they performed.

<table>
<thead>
<tr>
<th>Participant number</th>
<th>Activity</th>
<th>Turnout angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basketball</td>
<td>112</td>
</tr>
<tr>
<td>2</td>
<td>Basketball</td>
<td>145</td>
</tr>
<tr>
<td>3</td>
<td>Basketball</td>
<td>114</td>
</tr>
<tr>
<td>4</td>
<td>Basketball</td>
<td>120</td>
</tr>
<tr>
<td>5</td>
<td>Ballet</td>
<td>155</td>
</tr>
<tr>
<td>6</td>
<td>Basketball</td>
<td>N/A</td>
</tr>
<tr>
<td>7</td>
<td>Basketball</td>
<td>N/A</td>
</tr>
<tr>
<td>8</td>
<td>Basketball</td>
<td>135</td>
</tr>
<tr>
<td>9</td>
<td>Soccer</td>
<td>139</td>
</tr>
<tr>
<td>10</td>
<td>Soccer</td>
<td>105</td>
</tr>
<tr>
<td>11</td>
<td>Volleyball</td>
<td>150</td>
</tr>
<tr>
<td>12</td>
<td>Soccer</td>
<td>99</td>
</tr>
<tr>
<td>13</td>
<td>Soccer</td>
<td>130</td>
</tr>
</tbody>
</table>
Of the twenty participants of this study, three participants were excluded from the final results. Subject 6 did not sign the release forms to allow for her data to be used in the study, subject 7 had previous surgeries to her knee and subject 19 did not perform a proper turnout. The results of this study were based upon the remaining seventeen participants.

Table 5. The Means, SD and results of the f-test comparing the two populations turnout results

<table>
<thead>
<tr>
<th></th>
<th>Athletes</th>
<th>Dancers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>120.5</td>
<td>141.2</td>
</tr>
<tr>
<td>Variance</td>
<td>359.9091</td>
<td>139.7</td>
</tr>
<tr>
<td>Observations</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>df</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>F</td>
<td>2.5763</td>
<td></td>
</tr>
<tr>
<td>P(F&lt;=f) one-tail</td>
<td>0.18716</td>
<td></td>
</tr>
<tr>
<td>F Critical one-tail</td>
<td>5.935813</td>
<td></td>
</tr>
</tbody>
</table>
There was no statistically significant difference at the 95% confidence level in the turnout between female ballet dancers and female jumping sport athletes (Table 4). There is a statistically significant difference when the means are compared at an 80% confidence level. The variance for female athletes is higher than the variance found for the female ballet dancers.
Chapter 4

4 DISCUSSION

Through analyzing the published studies for the comparison of the lower body biomechanics of female traditional jumping sport athletes and female dancers trained in ballet, some biomechanical aspects were found to be in agreeance among the multiple studies. Papers were able to come to a consensus that female athletes had greater hip adduction moment, trunk forward flexion, and knee stiffness than female dancers (table 3). The published studies were unable to come to a consensus if the knee rotation, muscle activation and leg stiffness of female dancers were greater than female athletes or if the difference was not statistically significant (table 3). Due to the lack of studies and the differences in data between the published papers, the comparison did not allow for consensus between any papers on the results of knee flexion, knee abduction, ankle aversion, ankle dorsiflexion, ankle abduction, hip rotation, trunk external rotation, trunk side flexion or muscle activation (table 2). Due to the specificity of the comparison, the number of studies available of comparison between two populations was very limited and each study primarily had different measurements.

The accepted theory is that female dancers trained in ballet have a lower risk of ACL injury when compared to female traditional jumping sport athletes[28, 37,
Through biomechanical experiment consensus between studies has been somewhat lacking. The limited comparison studies and the difference in the protocol and output measurements for each study limit the ability to verify any study findings of the biomechanical differences between the groups that could affect the ACL risk of the populations.

Though consensus of the biomechanical differences between the populations is affected by the limited studies available, the importance of discovery rises as the population of female athletes rises[2, 21, 29, 44]. The cost of an ACL injury to an athlete is more than the monetary value of medical assistance, it can cause long term issues, such as osteoarthritis, that will affect the athlete throughout their life[5, 11, 17, 29, 38, 41]. The difference between the two populations may also be attributed to other factors such as extensive rehearsal, repetition of movements, the effect of pointe shoes on the lower body biomechanics, and the difference of materials between the stage and athletic playing surfaces[28, 36]. Continual studies should be conducted to determine biomechanical differences between the populations, as well as if any of the factors previously listed can be attributed to the decreased risk of ACL injury.

The second goal of this study was to compare turnout angles of female dancers trained in ballet and female traditional jumping sport athletes to determine if there is a significant difference between the two populations. Though the average between the groups is different, female athletes had a turnout average of 120.5
degrees and female dancers had an average of 141.2 degrees, it was found that the difference was not statistically significant at the 95% confidence level (table 4). The difference of the turnout average between the two groups was statistically significant at approximately the 80% confidence level. The variance of ballet dancers was 139.7 and the variance of the female athletes was 359.9, which shows that the ballet trained dance group had a smaller range of the turnout data (table 4). The smaller range can be linked to more training of this position compared to the more sporadic female athlete group. This study was unable to determine if turnout angles can be used as a determinant of ACL injury risk.

The findings of the turnout study are supported by a study performed by Negus et al., in which 29 dancers were measured for turnout and hip external rotation range of motion [34]. The turnouts of participants were measured and then observed for the next two years for injury [34]. After two years it was determined that the correlation between turnouts and injury was low and not statistically significant [34]. However, still many injuries in dance have been attributed to technical faults with poor turnout [34].

The lack of findings of the study of turnout may be due to the low number of dancers that were included compared to the number of athletes. Another issue may be that athletes are not trained in the proper technique of a turnout. Athletes may turn to compensations of excessive pelvic tilt, lumbar lordosis and/or
excessive subtalar joint pronation[16]. Therefore, the results of this study will require further research to verify any findings.

Future studies should continue to examine the biomechanical differences between female dancers trained in ballet and female traditional jumping sport athletes in their landing mechanics as well as the movement of the lower body extremities in relation to each other. The future studies of female dancers and female athletes should also examine the use of pointe shoes and athletic shoes in the lower body biomechanics of the two groups during a landing sequence. Another aspect that is rarely examined in studies is the hormonal aspects of the risk of ACL injury, and whether hormonal birth control increases or decreases the risk of ACL injury. The differences in performance of similar movements may be able to help explain the differences in ACL injury rate between the two populations.
BIBLIOGRAPHY


