Musculoskeletal effects and injury risk in collegiate Indian classical and ballet dancers

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ABSTRACT

Dancers of all forms often engage in aesthetic yet challenging movements. Their training, choreography, and performances require strength, stamina, flexibility, grace, passion, and emotion. Ballet and Bharatanatyam (an Indian classical dance form) dancers utilize two movements in each of their dance forms that are similar—a half-sitting pose and a full-sitting pose, both requiring external rotation of the legs and bending at the knee joints. The purpose of this study was to examine and compare the biomechanics of joint reaction forces and knee angles in both styles of dance for these particular poses. The study included nine female ballet dancers and seven female Bharatanatyam dancers. Hamstring and gastrocnemius flexibility were measured for each dancer. Knee angles, vertical peak forces, and moments were determined for dancers at the lowest point of their bending positions. Mann-Whitney U tests found significant differences in hamstring flexibility, right gastrocnemius flexibility, and knee angles for the full-sitting poses between ballet and Bharatanatyam dancers. No significant difference was found in the vertical peak forces as a ratio to total body weight and moments between the two styles of dance. Further research can be done to more directly assess a difference in injury risk between the ballet and Bharatanatyam dancers.
INTRODUCTION

Dance may have originated in early human prehistory for reasons including communication, emotional expression, ritual, tradition, bonding, exercise, or mating. Today, it is practiced by all cultures throughout the world and has differentiated into many different forms (Hanna 1987). Dancers of all styles often engage in aesthetic yet challenging movements. Their training, choreography, and performances require strength, stamina, flexibility, grace, passion, and emotion. As dancers perform the poses and steps necessary for their art form, it is important that proper training and injury prevention measures are taken so that dancers do not compromise their health and wellbeing. Two of the most widely practiced dance forms in the world are ballet and Bharatanatyam (an Indian classical dance form). Practice in both forms commonly begins at a very young age, thus becoming an important part of the physical development of the dancers. The purpose of this study is to better understand 1) differences in these dance forms in the incidence of injury; 2) differences in training regimes that might have had an effect on injury risk; and 3) differences in the stresses placed on the knee (a joint commonly injured by dancers) in both styles of dance during similar poses.

BACKGROUND

The study of dance-related injuries has long focused on the practice of ballet (Russell 2013). A systematic review of musculoskeletal injury in ballet, modern, and theatrical dancers found that most reported injuries are mild or minor, are chronic or overuse in nature, and affect the back and lower extremities. Of the twenty-nine studies included in the review, twenty-two of them studied ballet (Hincapié et al. 2008). Although ballet is a standardized and widely practiced dance form, research on other styles of dance can lead to a more thorough understanding of injury-
causing movements among dancers. Exploring Bharatanatyam provides the opportunity to investigate the potential causes of injury among Indian classical dancers, a less studied population of dancers. The similarities between dance poses in Bharatanatyam and ballet offer a chance to explore the relationship between the biomechanical stresses placed on the knees in both forms of dance.

Bharatanatyam

History

Bharatanatyam is one of many forms of Indian classical dance that originated in Tamil Nadu, a region of southern India (Pillai 2002). The dance was historically named sadir and performed in the nineteenth century by devadasis (female temple dancers) who danced for the statues of deities in the Hindu temples (Meduri 2004). Traditionally, the temple dancers were young girls who had inherited the occupation from their mothers and were expected to dedicate themselves to the deities. While the dancer was required to be unmarried, she would sometimes become intimately involved with a patron. This became a point of contention for British and Indian reformers who viewed the devadasi as a type of prostitute that had no control over her own lifestyle—an argument structured around Christian ideals of morality. By the early twentieth century, the once ritualistic dance was tarnished, and consequently abolished (Srinivasan 1985). In the mid-1930s, classical artist, freedom fighter, and lawyer E. Krishna Iyer and dancer and choreographer Rukmini Devi Arundale led the revivalist movement to save, refine, and institutionalize the traditional dance form as well as to dispel the negative connotations associated with it. They repurposed the original sadir dance form and named the slightly altered and more sophisticated version Bharatanatyam (Barba and Savarese 2006). Today, the dance form is extremely popular and is taught and practiced across
the world. While competitive college dance teams have incorporated fusion music into the Carnatic music that is traditionally used, the dance form is considered to retain value as a practice of religious and cultural expression (Khandelwal and Akkoor 2014).

Form

The term *Bharatanatyam* is broken up into four components: Bha for *Bhava* (expression), Ra for *Raga* (music), Ta for *Tala* (rhythm), and *Natya* (dance) (“History of Bharatanatyam” 2007). Bharatanatyam is often used to tell religious stories, so the technique of the steps and postures representative of Hindu deities are based on a half-squatting position (aramandi) or a full-squatting position (muzumandi) along with rhythmic stamping of the feet and a multitude of crisp and meaningful hand gestures (Figure 1). In order to correctly execute aramandi, the dancer has to sit as deeply as she can while still keeping her back straight, feet together in a V-formation, heels on the floor, legs rotated outwards, and knees spread apart. In muzumandi, the same posture is maintained, but the heels come off the floor as the dancer fully squats.
**Figure 1.** The primary pose of Bharatanatyam called aramandi is shown on the left. Another frequently used pose in Bharatanatyam is muzumandi, shown on the right.

**Ballet**

*History*

Ballet originated from the Italian Renaissance courts in the fifteenth century as an elaboration of court pageantry, and classical ballet was popularized in the seventeenth century when King Louis XIV of France brought French Ballet into his courts. The dance was reintroduced during World War I to Western Europe. Classical ballet was refined, but other styles such as romantic, post-romantic, Imperial Russian, and contemporary ballet arose as well (Lee 2002).

*Form*

Ballet as another form of classical dance shares several motions with Bharatanatyam. Both dances feature movements that require turnout, deep bending of the knees, and an erect spine (Figure 2). The demi plié (which corresponds to aramandi in Bharatanatyam) and grand plié (which
corresponds to muzumandi) are two movements performed in ballet that serve as transition steps in exercises and choreography.

![Ballet Dancer](image)

**Figure 2.** The ballet dancer performs a first position demi plié. Photo from Star Bulletin.

Given the brief origins and forms of Bharatanatyam and ballet, it is important to look at the injury risk and associated factors surrounding the poses that are used in these dance and art forms.

**Anatomy of the Knee**

In both of the dance forms, knee injuries are commonly reported among dancers (See *Injury in Bharatanatyam Dancers* and *Injury in Ballet Dancers* below). Thus, knowing the anatomy of the knee is crucial to understanding what kinds of knee injuries are developed from dancing.
Osteology

The knee joint is a hinge type synovial joint that allows for flexion and extension. It involves the articulation of the distal portion of the femur with the proximal tibia and the patella (Figure 3). The convex condyles of the femur fit with the concave condyles of the tibia, forming a rocking chair-like formation. In order to bear the necessary weight, the femoral condyles are less curved anteriorly; to allow for flexion, the femoral condyles are more curved posteriorly. The movement of flexion occurs through a combined sequence of rolling and gliding movements, while the movement of extension involves gliding followed by rolling. This bending motion at the knee joint is also possible due to the knee joint capsule, a structure that surrounds the knee and contains the synovial fluid. The patella is a sesamoid bone embedded within the distal end of the quadriceps muscles that protects the knee joint and the quadriceps tendon, moves laterally during active extension or slight flexion of the knee, and increases the moment arm and thus the amount of torque created by the quadriceps (Calais-Germain and Anderson 1993). Movements in dance often require closed chain knee flexion, in which the leg is still in contact with the ground, but the knee is bent (Ellenbecker 2009).
Figure 3. The knee joint consists of the femur, patella, and tibia. Photo from Michigan State University.

Musculature and Ligaments

Many of the muscles associated with the knee joint also have an action at the hip joint. The rectus femoris muscle crosses two joints because it originates at the anterior inferior iliac spine at the hip and inserts on the common tendon on the knee. The vastus medialis and lateralis originate from the linea aspera on the femoral shaft and meet on the anterior side of the femur while the vastus intermedius runs deep to these two muscles. These four muscle bodies compose the quadriceps femoris, generally acting to extend the knee. The sartorius muscle attaches at the anterior superior iliac spine at the hip and inserts on the tibia, acting to flex the knee when the femur is not fixed. On the posterior side of the leg, the hamstrings are composed of the semimembranosus, semitendinosus, and the biceps femoris and act to flex the knee and extend the thigh (Calais-Germain and Anderson 1993). In dance, certain muscles are used more heavily than others for achieving knee-bending movements such as the demi plié or aramandi poses. The grand
plié, for example, involves the adductors, quadriceps, hamstrings, and tibialis anterior muscles (Trepman et al. 1998).

C-shaped discs of cartilage called menisci sit between the femur and tibia and attach to the intercondylar eminences and edges of the tibia. The menisci serve to spread synovial fluid within the knee joint during movement and to allow for greater stability and a better distribution of forces at the knee joint. The ligaments provide a majority of the stability in the knee joint. The anterior cruciate ligament and posterior cruciate ligament cross in the intercondylar fossa; the ligaments work to resist anterior and posterior displacement of the tibia on the femur and to play a role in medial and lateral rotation of the knee. Acting to further stabilize the joint, the collateral ligaments run on the sides of the knee. The medial collateral ligament runs from the medial femoral epicondyle to the medial tibial condyle and shaft, and prevents lateral movement of the tibia. The lateral collateral ligament runs from the lateral femoral epicondyle to the fibular head, and prevents medial movement of the tibia (Calais-Germain and Anderson 1993).

At the knee joint, the musculature and ligaments are highly interrelated. Injury prevention at the knee joint primarily relies on stability, which can be accomplished through strengthening exercises for specific muscles such as the quadriceps, hamstrings, and gastrocnemius muscles (Ellenbecker et al. 2009).

**Injury in Bharatanatyam Dancers**

Based on anecdotal and experimental evidence provided in studies, it has been found that Bharatanatyam dancers can experience several forms of lower limb injury. The literature on Indian
classical dance injuries, however, is not abundant; a Google Scholar search for studies with the words “ballet injuries” in the title yields 112 results, while a search for studies with “Bharatanatyam injuries” in the title yields one result. Paul and Kapoor (1998) found that knee injuries (specifically chondromalacia patellae, torn menisci, and other patellar injuries) were the most common type of injury among Indian Classical dancers. Because of the nature of many of the dance positions, the knee experiences torque from a large amount of twisting and rotation, which can cause tenderness and swelling. According to the study, 29% of the dancers in their sample were diagnosed with a torn meniscus due to their constant attempts to achieve the ideal form of aramandi. This dance pose can also place severe stress on the medial structure of the knee, cause excessive rotation of the tibia underneath the femoral condyles, and lead to a torn medial meniscus. The authors attributed the pain and injury experienced by Indian classical dancers to a lack of warm-up routines, overcompensation for inflexibility, hyperlordosis of the back, hyperextension of the knees, or a lack of core strength (Paul and Kapoor 1998). Another possible explanation for the high rate of injury in the knee joints is that many Bharatanatyam poses involve the extension of the knee far beyond the toe, a position that puts an excessive amount of shearing stress on the knee joint (Fry et al. 2003). An ideal squat is performed with both feet on the ground, the knees not extending past the toes, and an erect trunk (Canizares, pers. comm). Therefore, any position that is held for a long time with the knees extended past the toes can put a large amount of stress on the knee joints.

In a more recently published paper, Anbarasi et al. analyzed the lower limb muscle flexibility of Bharatanatyam dancers with the purpose of encouraging dance teachers to implement stretching exercises in their teaching routines for this dance form. The sample of injured
Bharatanatyam dancers frequently demonstrated muscle flexibility issues in the lower extremities, iliotibial band muscle tightness, and quadriceps tightness—all concerns that lead to applied stress on the knee joints, as discussed in the paper. The importance of stretching was also highlighted in the study as a method of preventing overuse injury caused by wear and tear in weight-bearing joints such as the knee (Anbarasi et al. 2012). While knee injuries are defined as being the most common type of injury among this population of dancers, Bharatanatyam has also been shown to cause foot, ankle, and back pain (Paul and Kapoor 1998). These studies focus on injury using self-reported measures and flexibility, so there is a need for specific tests to be done on the stress and strain placed on the knees during Bharatanatyam.

Based on the arguments made in Pillai 2002, it can be assumed that injuries experienced by Bharatanatyam dancers were not common when training and the dance form were conducted in customary manners, but became more of a risk as newer interpretations and hybrid forms of the dance arose. If strict attention is not paid to correct positioning during deep sitting (outward rotation of the legs and a straight back), it is likely that the young dancer is overcompensating for a lack of muscle strength and flexibility by hyperextending, hyperflexing, or increasing lordosis. As a physical therapist that has worked with Indian dancers, Dr. Rosalinda Canizares (Duke University Medical Center) explained that she often suggests warm-up exercises that help find and wake up certain muscles in isolation, so that they will be more inclined to fire when the student is dancing. She has found that dancers that perform the positions correctly and utilize the necessary muscles for the movements often do not encounter pain or injury (Canizares pers. comm).
Injury in Ballet Dancers

According to Mr. Tyler Walters, Associate Professor of the Practice of Dance at Duke University, knee injuries in ballet, in contrast, are well studied and often are due to movements that are performed at extreme ranges of flexion and from jumping into or out of these types of positions. Additionally, a large amount of torque can be placed on the knees if movements that require an ideal outward rotation of 180 degrees are performed incorrectly. In his extensive work with ballet dancers, Walters identifies the major knee injuries for ballet dancers as meniscus cartilage tears, sprains, and ligament tears (Walters pers. comm).

Several studies have looked at potential factors that could be associated with dance-related injury in the lower extremities for ballet dancers. A 2013 experimental study utilized electrogoniometers to determine knee angular displacement in amateur ballet dancers and found that there was a high incidence of valgus peaks during the ascending and descending phases of a demi plié, often in dancers that did not have extensive hip rotation or strong hip muscles (Faria et al. 2013). It was also determined that external longitudinal rotation at the knee is a serious predisposing factor to knee injury, and that grand pliés (particularly in the third and fourth positions) cause high values of external longitudinal rotation and danger of compromising knee joint stability (Barnes et al. 2000). In these two studies, it is shown that dancers who do not have the necessary muscle strength in their limbs are more at risk for dance-related injury. For elite adolescent ballet dancers, their risk for overuse injury in the lower extremities is associated with the dancer’s rate of growth (Bowerman et al. 2014). A correlation between iliotibial band tightness and patellofemoral pain in female ballet dancers was also found (Winslow and Yoder 1995). These studies show that factors such as muscle or ligament tightness, low levels of flexibility, technique
of ballet positions, and growth rate all influence injury among dancers.

**Biomechanics**

A few of the fundamental concepts in physics are Newton’s second and third laws: the acceleration of an object is proportional to applied force and that every action has an equal and opposite reaction (Scheck 2010). Because dancers are constantly accelerating and have contact with the ground, the ground reaction force that is generated between the floor and feet can act on the body and its joints (Shippen and May 2012). Therefore, looking at ground reaction forces in dancers can help provide information on the forces that specific joints of the body endure. When compared to typical joint loading forces, excessive ground reaction forces from dance that are acting on the body’s joints can offer information on potential injury risk.

When looking at ground reaction forces, there are three axes that must be considered: vertical, anteroposterior, and mediolateral (Nilsson and Thorstensson 1989, Figure 4). In the static postures of aramandi, muzumandi, demi plié, and grand plié, there is a minimal amount of side-to-side (mediolateral) and front-and-back (anteroposterior) movement. Therefore, this study focused solely on the vertical component ($F_z$) of the ground reaction force. Looking at the vertical component of the ground reaction force will allow for a relative quantification of the force that goes through the knee joint in terms of the dancer’s body weight.
Stress is difficult to measure quantitatively, so moments and knee angles can be used to relate ground reaction forces to the knee joint. The moment arm is the distance between the line of force acting on a joint and the joint axis. This length can be multiplied by the peak ground reaction force to determine the moment or torque at the knee joint in particular positions. When the leg is fixed, excessive amounts of torque at the knee joint can contribute to shearing forces, which are related to injury risk (Bose et al. 2008).

**Additional Considerations**

*Flexibility*

Based on the poses that need to be performed in both Bharatanatyam and ballet, flexibility in specific muscles and tendons is highly valued for injury prevention. In the hip area, tightness in hip muscles can hinder the dancer from performing an ideal or acceptable degree of turnout for
either of the dances (IADMS 2011). Additionally, injured female Bharatanatyam dancers have shown more hamstring tightness and a lower tendoachilles range of motion when compared to uninjured female Bharatanatyam dancers (Anbarasi et al. 2012). Although injury prevention exercises are not a standardized practice for many Bharatanatyam classes, some dance teachers encourage stretching and strength training as pre-class routines. Using this information, it is important to consider the flexibility of the dancers when making conclusions about a dancer’s injury risk. The movement and technique of the dance pose itself could contribute to dance-related injury, but the flexibility of the dancer could also play a role in the risk of injury. In order to test the alternative hypothesis of flexibility having a primary influence on differential forces at the knee joint, the collected data on flexibility from the participants can be used to compare subjects performing the same dance form, but demonstrating differing flexibilities. If the forces generated at the knee joint vary greatly, this provides evidence that flexibility could be a major factor in affecting force generation and injury risk. Because of the small sample size of the current study, this test was not done.

Training

Training in Bharatanatyam varies depending on the Guru (dance teacher) and the region in which the classes are taught. Generally, children above the age of five can begin training by learning adavus—the basic steps involved in all of the dances. The hand gestures, neck movements, and deliberate eye movements are also learned in this time frame. The students are trained to hold the aramandi position for long periods of time in order to build the strength and stamina necessary to perform longer dances (Bharatanatyam Syllabus Outline 2013). After the dancer undergoes basic training, she begins learning the choreography for several simple, standard dances that are
learned by all beginning Bharatanatyam dancers. After the customary postures and hand gestures are well developed, years of learning more advanced compositions follow until the dancer is deemed ready to perform by her teacher.

Ballet training regimes vary by institute. Similarly to Bharatanatyam, ballet academies and schools exist in a variety of places across the country. As outlined in the Joffrey Ballet School handbook, young girls can begin ballet training around the age of four or five years, and they often start by exploring the coordination of simultaneous movements. Later, dancers learn simple ballet steps, the dynamics of their movements, and balance techniques. By age seven or eight, ballet students begin body conditioning and learn how to access hip rotation as well as foot-ankle articulation in certain postures. Poses, allegro steps, weight transfer, and postural alignment are emphasized during this stage. Steps are then linked together, poses that use more parts of the body simultaneously are introduced, and strength, precision, and flexibility are highlighted (Matos 2013). With the amount of literature published on ballet injuries and the factors that have been identified as contributory to injury risk, dance educators have recently developed altered training methods that incorporate anatomically-based techniques for injury prevention such as emphasizing the correct alignment of the trunk and legs, reducing the number of grand pliés performed, and ensuring that the outward rotation of the legs comes from the hip joint (Walters pers. comm).

A study by Hamilton et al. investigated whether intense training during the ages of 11 to 14 can lead to femoral torsion, or an inwardly pointed and forward inclination of the femoral head. They found that the starting age of dancers was not significantly correlated with turnout measurement, but that the number of years of practicing ballet was significantly correlated with
turnout measurement (Hamilton et al. 2006). Moreover, based on the concept of overuse injury from the wearing of joints that hold weight over long periods of time, dancers that have performed stressful positions for more years should present with a higher risk of dance-related injury (Anbarasi et al. 2012). Therefore, the participants in this study who have had a significantly higher number of years of active dance experience could demonstrate a higher risk for injury.

Additionally, injury risk can be higher when dancers learn dance postures in incomplete or varying ways. Because of the increasing popularity of Bharatanatyam among Indian-Americans and other foreigners, however, experts argue that the dance that is practiced globally today lacks the precision and meaning that it once had. Shanti Pillai—a dancer and scholar—contends that dance training is now less intensive and significant because students often take dance classes during time off from school, rather than learning in a traditional gurukul system in which the teacher and student constantly interact for several years. She maintains that stylistic differences such as the distance between feet in aramandi are fundamental aspects of the dance that currently vary from teacher to teacher, and are not properly standardized among all dancers (Pillai 2002). If training has become less intensive and proper technique is not as emphasized as it once was, it is possible that these changes are contributing to the dancer’s vulnerability to injury because she may not be able to properly perform the pose in a safe and intentional way. When a dancer attempts to achieve a certain aesthetic in a dance posture or step, compensatory strategy becomes a factor by which the dancer can use either the correct muscles in risky ways or merely use the incorrect muscles (Hamilton et al. 2006).
**BMI and Weight**

Several studies have shown that weight is implicated in injury risk. In a study done on running injuries, it was found that a lower body weight reduced risk of the development of plantar fasciitis (a type of heel pain) in women; the authors attributed this lower risk to reduced stress or force in the musculature in the foot (Taunton et al. 2002). Furthermore, body weight was positively associated with dance-related injury in jazz and contemporary dancers (Campoy et al. 2011).

Because body weight has an effect on force generation, participant populations that have significantly differing body mass indices (BMI) could exhibit varying risks for dance-related injury. In this study, the influence of weight was accounted for through the force outcome measures, which are reported in terms of the participant’s body weight. In order to test the role that body weight could have on forces, force data from participants trained in the same dance form with similar levels of flexibility and dance experience but different BMIs could be compared. Because of the small sample size of the current study, this test was not done.

**Broader Implications**

Dance medicine as a field aims to enhance the performance and fitness of dancers (IADMS). Information from this study may help dancers and instructors of ballet and Bharatanatyam to better understand the stresses placed on the knee during common poses, and inform them about how training regimes might affect their risk of injury. It is my hope that this study will be a valuable contribution to the dance medicine literature.
Study Expectations

Because the technique of Bharatanatyam involves more sustained and deeper knee bending than that of ballet, dance-related injury risk among Bharatanatyam dancers differs from injury risk among ballet dancers when comparing corresponding postures between the dances. I predict that the peak vertical force as a percentage of body weight and moment at the knee joint in Bharatanatyam dancers will exceed those of ballet dancers and that the angle at the knee joint will be more acute in the Bharatanatyam dancers’ poses when compared to those of the ballet dancers.

MATERIALS AND METHODS

Study Subjects and Site

A total of sixteen participants were recruited for the study: seven Bharatanatyam dancers and nine ballet dancers. The participants were all female undergraduates at Duke University, ranging in age from 18 to 22 years and with a mean (± SD) of 20.375 ± 1.408 years. The subject was included in the study if she had formally trained in the dance form (ballet or Bharatanatyam) for at least 5 years. The data was collected in the Duke Locomotion Lab run by Dr. Daniel Schmitt.

The participants were recruited through announcements in an advanced ballet class taught at Duke and an Indian Classical Dance team practice, emails sent out to Duke University Ballet and several Indian dance teams, word of mouth, and flyers placed around campus (Appendix A). The participants were volunteers and received no compensation for being involved in the study. Before participating, the participants were required to sign a consent form and fill out an online dance history questionnaire (Appendix B, Appendix C), and were requested to wear black leggings. The protocol, consent form, questionnaire, and recruitment materials were approved by Duke University Health System’s Institutional Review Board.
**Protocol**

When the participant arrived at the Duke Locomotion Lab, she removed her shoes before her full height, leg length, and foot length were taken with a tape measure. I also performed hamstring and gastrocnemius flexibility tests using a goniometer on the right and left legs of each participant (Figure 6). Small pieces of visible, brightly colored tape were placed over the dancer’s leggings on the toes, heels, ankles, knees, and hips.

![Figure 6. Measurement of hamstring and gastrocnemius flexibility. Images from Norkin 2009](image)

A PASPORT 2-Axis force platform was placed on a level surface less than one inch away from a wooden platform of the same height. The force data were recorded at 1 kHz using the PASCO Capstone™ software, which measured the normal force in Newtons and time in seconds for each run (Appendix I, Appendix II). A Canon Rebel T2i was set up on a tripod at a lateral angle for video recording at a maximum of 60 frames per second.

I started the video recording and then bounced a tennis ball on the PASPORT force plate in order to synchronize the video and force plate data. The participant was asked to place her left foot on the wooden platform and right foot in the center of the force plate from which her weight
for one foot in Newtons was recorded. For some of the trials, the participant also stood on a standard scale to confirm her weight. The participant was asked to perform a total of two dance poses unique to her dance, and repeat each of these stances three times (Figure 7, Figure 8). For the Bharatanatyam dancers, I gave the participants a general time frame of twenty to thirty seconds for the pose, since the posture can be held for longer in the dance itself. Each participant had a total of four runs on the PASCO Capstone™ software and one video clip.

![Figure 7. Two of the comparable poses between ballet (left) and Bharatanatyam (right). Left photo from Star Bulletin.](image-url)
Figure 8. A study participant demonstrating a demi plié (left) and grand plié (right) on the force plate-wood platform set up.

Data Processing

I used iMovie to split the video file from each participant into four separate clips for each run: the tennis bounce, weight measurement, half-sitting sequence, and full-sitting sequence. These videos were watched in conjunction with the force trace data for each run from the PASCO Capstone™ Software. I analyzed the graphs of each run and used an embedded tool to determine the vertical peak force value in Newtons, which represented the instant at which the dancer reached her lowest point for the specific pose (Appendix I, Appendix II). The peak force was generally taken from the second of the three trials within one run. In addition, I used Excel to calculate the average body weight of each participant in Newtons either from the PASCO Capstone™ graphs or reported weights to provide a reference point for the maximum force values. Any drift was accounted for in the calculations.
To determine the angle of the knee joint for the two poses each participant performed, the hip to knee length and knee to ankle length were either measured in person or taken from a still image in ImageJ32. Then, the length from the hip to ankle was taken from images of the half-sitting and full-sitting poses for each dancer. These three lengths were used to calculate the angles inside of the triangle. Using standard trigonometric formulas, I used the limb lengths and angles to determine the moment arm in meters (Figure 9). The moment of the force generated at the knee joint was calculated by multiplying the vertical peak force in Newtons by the moment arm in meters.

Statistical Analysis

R Studio and Microsoft Excel were used to obtain means and standard deviations for moment, moment arm, knee angle, and peak force measurements. A total of twelve non-parametric Mann-Whitney U tests were run. Eight tests were run to determine whether there was a statistically significant difference between the two styles of dance in each of their poses—four tests for the half-sitting positions in ballet and Bharatanatyam and four tests for the full-sitting positions in ballet and Bharatanatyam (Table 1, Table 2). Four more tests were run to analyze differences in flexibility between the groups. A linear regression was used to analyze the relationships between vertical peak forces, years of training, and number of injuries for each dance style.
Figure 9. A diagram of the triangle method for determining the moment arm distance in meters from limb lengths and angles.

RESULTS

The study included seven Bharatanatyam dancers and nine ballet dancers. On average, the Bharatanatyam dancers had $9.5714 \pm 3.1547$ years of experience in Bharatanatyam and ballet dancers had $16 \pm 4.0620$ years of experience in ballet. The Bharatanatyam dancers also started dance training on average at $6.9286 \pm 3.2201$ years of age while the ballet dancers started their training on average at $3.4444 \pm 0.5271$ years.

Knee Angle

The knee angle measurements were calculated for the similar poses in each dance. For the
half-sitting position, the average angle at the knee for Bharatanatyam participants was 107.6201 ± 12.85405 degrees and the average angle for ballet participants was 106.2461 ± 14.8593. There was no significant difference between these measurements (p = 0.9182). In the full-sitting positions for each dance, the Bharatanatyam dancers had an average knee angle of 35.0801 ± 7.1183 degrees while the ballet dancers had an average knee angle of 51.4273 ± 9.3979 degrees. The difference in knee angle measurements for the two groups of dancers in the full-squatting positions was significant (p = 0.00122).

*Peak Force*

The vertical peak forces through one leg as a ratio to total body weight were also compared between the dance styles. For Bharatanatyam dancers, the average peak force as a percentage of body weight for the half sitting position was 56.334 ± 5.1051%. For the half-sitting position in ballet, the average peak force as a percentage of body weight was 54.3447 ± 2.0150%. For the full-sitting position of Bharatanatyam, dancers on average exerted a peak force 64.1294 ± 8.3460% of their body weight. Ballet dancers exerted an average peak force that was 56.5188 ± 5.1704% of their body weight. The differences in the percentages between the two dance populations was not significant (half-sitting poses, p = 0.4698; full-sitting poses, p = 0.0907).
Figure 10. A boxplot showing the knee angles for ballet dancers in the grand plié and for Bharatanatyam dancers in the muzumandi pose.

Moment

The average moment of the vertical peak force in Bharatanatyam dancers in aramandi (half-sitting position) was $80.5758 \pm 20.1389 \text{ N} \cdot \text{m}$, and that for the ballet dancers for the demi plié was $81.2383 \pm 25.2021 \text{ N} \cdot \text{m}$. For the full-sitting positions, the average moment of the peak force for Bharatanatyam participants was $145.7484 \pm 29.9 \text{ N} \cdot \text{m}$ and $124.3031 \pm 23.2437 \text{ N} \cdot \text{m}$. The differences in moments between the two groups of dancers were not significant (half-sitting poses, $p = 0.9182$; full-sitting poses, $p = 0.1738$).
Table 1. Participants’ knee angle, peak force as a percentage of body weight, moment arm, and moment of force in their dance form’s half-sitting pose. Mean ± SD and p-values provided.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ballet Dancers (n = 9)</th>
<th>Bharatanatyam Dancers (n = 7)</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee angle (deg)</td>
<td>106.2461 ± 14.8593</td>
<td>107.6201 ± 12.85405</td>
<td>0.9182</td>
</tr>
<tr>
<td>Peak force in terms of body weight (%)</td>
<td>54.3447 ± 2.0150</td>
<td>56.334 ± 5.1051</td>
<td>0.4698</td>
</tr>
<tr>
<td>Moment Arm (m)</td>
<td>0.2485 ± 0.05839</td>
<td>0.2359 ± 0.04346</td>
<td>1</td>
</tr>
<tr>
<td>Moment (N·m)</td>
<td>81.2383 ± 25.2021</td>
<td>80.5758 ± 20.1389</td>
<td>0.9182</td>
</tr>
</tbody>
</table>

Table 2. Participants’ knee angle, peak force as a percentage of body weight, moment arm, and moment of force in their dance form’s full-sitting pose. Mean ± SD and p-values provided. Significant value <0.05 indicated with ***.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ballet Dancers</th>
<th>Bharatanatyam Dancers</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee angle (deg)</td>
<td>51.4273 ± 9.3979</td>
<td>35.0801 ± 7.1183</td>
<td>0.00122***</td>
</tr>
<tr>
<td>Peak force in terms of body weight (%)</td>
<td>56.5188 ± 5.1704</td>
<td>64.1294 ± 8.3460</td>
<td>0.0907</td>
</tr>
<tr>
<td>Moment Arm (m)</td>
<td>0.3693 ± 0.03922</td>
<td>0.3740 ± 0.02704</td>
<td>0.8371</td>
</tr>
<tr>
<td>Moment (N·m)</td>
<td>124.3031 ± 23.2436</td>
<td>145.7484 ± 29.9</td>
<td>0.1738</td>
</tr>
</tbody>
</table>

Flexibility

The average hamstring flexibility measurement for Bharatanatyam dancers was 76.213 ± 4.950 degrees and that for the ballet dancers was 107.8333 ± 2.6713 degrees. The average gastrocnemius flexibility measurement for Bharatanatyam dancers was 16.2857 ± 1.010 degrees and the measurement for ballet dancers was 11.7847 ± 2.347 degrees. There was a significant difference between the dance groups for three of the four flexibility measurements: right hamstring flexibility (p = 0.0035), left hamstring flexibility (p = 0.0015), and right gastrocnemius flexibility (p = 0.0327). There was no significant difference between the ballet and Bharatanatyam dancers for the left gastrocnemius flexibility (p = 0.7481).
A linear regression was run to analyze relationships of the peak force as a percentage of body weight with years of experience in the dance form and the number of lower limb injuries per participant. For either dance form, there was no significant relationship between these variables (Ballet Demi Plié R-squared = 0.03593, p = 0.896; Bharatanatyam Aramandi R-squared = 0.3374, p = 0.439; Ballet Grand Plié R squared = 0.2839, p = 0.3672; Bharatanatyam Muzumandi R-squared = 0.4899, p = 0.2602).

DISCUSSION

The ballet positions of the demi plié and grand plié in first position require turnout, or an external rotation of the legs and feet, and bending at the knees. Bharatanatyam involves two similar positions called aramandi and muzumandi that also involve turnout and knee bending. The purpose of this study was to investigate the differences between the stress at the knee joints for each dance style through measurements of ground reaction forces, moments of forces, and knee angles. The study’s results did not provide evidence to support a significant difference between the Bharatanatyam and ballet dancers in peak forces, moments of force in the half- and full-sitting positions, or knee angles in the half-sitting position, but demonstrated a significant difference in the knee angles in the full-sitting position.

Although the poses in the two dances are similar, the technique behind each position varies greatly. The knee angle measurements provide a quantitative perspective on this variation; in the full-sitting positions for each dance, the Bharatanatyam dancers had a significantly more acute angle at the knee once they reached their lowest position. The knee joint’s extreme bent angle in Indian classical dancers could contribute to higher strain on the joint, in addition to factors such as
muscle engagement. Because the Bharatanatyam dancers fully squat until they come to a resting position on their calves, they are likely not engaging their gluteal, quadriceps, and hamstrings muscle groups to hold the position. Instead, they engage these muscles upon sitting before stabilizing into the pose and upon straightening. The ballet dancers, on the other hand, perform the grand plié without touching their thighs to their calves, indicating an engagement of the gluteal muscles, quadriceps, and hamstrings to maintain the posture. Since knee injury can be caused by a weakness in quadriceps, it is possible that a lack of muscle engagement in stabilizing the knee joint can contribute to a large amount of strain on the knee joint (Hart et al. 2010).

Because of the link between flexibility and injury, the results in this study provided more information on potential injury risk among the dancers. There was a significant difference between the Bharatanatyam and ballet dancers for right and left hamstring flexibility and right gastrocnemius flexibility. The ballet dancers’ hamstring flexibility exceeded that of the Bharatanatyam dancers, which could be due to an emphasis on stretching and warm-up as well as population differences. The first twenty to thirty minutes of a typical advanced ballet class at Duke University consist of warm-up exercises; the dancers stretch and perform varied sequences of steps before beginning the choreography portion of the class. Based on anecdotes and interviews with professional dance teachers, Bharatanatyam and other forms of Indian classical dance classes do not standardize a warm-up or stretching routine. Nevertheless, the Bharatanatyam participants had more flexibility in their right gastrocnemius muscle than the ballet participants did. This increased flexibility could be explained by differences in the length of the Achilles tendon, although extensive stretching of the Achilles tendon can present another set of potential injury issues with the ankle and foot (Cheung et al. 2005).
In regards to the peak force percentages of body weight and moments, it is possible that the small sample size (Ballet, n = 9; Bharatanatyam, n = 7) could have contributed to the statistical insignificance of these measurements. A heavy presence of previous injury among the sample could have also had an effect on the results; 14 out of the 16 participants had experienced at least one lower limb injury in their past. The testing environment could also explain variation in the way the dancers performed their poses, since one foot was on a force plate and the other was on a light colored wooden board of equal height. The participants are accustomed to dancing on solid and uniform floors, so a different surface could have altered the way they completed their movements.

The average peak force for one foot in percentage of body weight was slightly over 50% for both the Bharatanatyam and ballet dancers in their respective half-sitting positions. This demonstrates that the instant at which the dancer hit her lowest point for the dance pose, she was exerting a force slightly higher than half her body weight through one leg. In the full-sitting position, a similar pattern was found true, but the average percentage of the peak force in terms of body weight was higher in the Bharatanatyam dancers than in the ballet dancers. This difference, however, was not significant. The moments calculated were higher in the full-sitting positions compared to the half-sitting positions. A study examining moments in squatting supported this result because the researchers found that knee moment increased as knee flexion increased (Zwerver et al. 2007).

Although the differences for a majority of the measurements between the two groups of dancers were insignificant, it is important to consider the duration of these poses in the dance forms
as well. Demi pliés in ballet are used primarily as transition movements and are often held for several seconds between other movements. Aramandi in Bharatanatyam, on the other hand, can be sustained for thirty seconds or longer at a time, depending on whether the particular dance is of a step-based or more expressive form. As the results of this study have shown, all four poses between both dance forms require forces that exceed body weight and bent knees. While these poses may not cause immediate damage, holding them for sustained periods of time over many years could increase risk of wear and tear injury at the knee joint.

Considerations

There are several aspects of the study that could be further investigated or changed if the study is repeated. Because of the scale of the study’s purpose in attempting to find differences between two dance styles, it would be beneficial to have a larger sample size. The limited sample size was primarily due to availability of subjects, presence of Bharatanatyam dancers on campus, and perhaps a lack of compensation. In order to obtain clearer force trace patterns during the dance sequences, participants’ upper body motions and foot placement on the force plate should be standardized. Similarly, accurate synchronization of video and force data could have been more efficiently conducted if participants were asked to step on the force plate prior to each run. In terms of the testing environment, it would be interesting to see how participants react to a wooden board that was painted to look like the force plate, in case the obviously different surfaces for each foot encouraged them to put more weight on one leg than another. Finally, a more careful placement of markers on the joints and ensuring that they do not move with the dancer’s clothes would allow for more accurate knee angle measurements.
If the equipment was accessible, this study would be an ideal one to carry out with three-dimensional analysis. Markers placed on the joints and a multiple camera set up would allow the principal investigator to more accurately determine every movement made by the dancer and analyze the exact angles at the knee joints. Further research could include a larger number of participants with standardized dance histories and also incorporate an educational component on injury risk and injury prevention for dancers.

CONCLUSION

Published literature related to dance science is steadily growing, but there is a large gap in the presence of studies on dance forms other than ballet. This study investigated the joint reaction forces at the knees for ballet and Bharatanatyam dancers through measurements of peak forces, moments, and knee angles. The results did not show significant differences between the forces or moments, but did demonstrate a significant difference in the acuteness of the knee angle in the full-sitting poses between the Bharatanatyam and ballet dancers. While there were several limitations, this study is among the first to provide quantitative information on measurements linked to lower limb injuries among Bharatanatyam dancers. More studies like this one are valuable and necessary in addressing potential injury risk among all styles of dance, and could also have a positive influence on training for these dance forms to include more injury prevention techniques.
AKNOWLEDGEMENTS

First, I would like to thank Dr. Blythe Williams for inspiring me to take a random idea that I had and run with it. You have been a wonderful mentor to me and I sincerely appreciate all the support, encouragement, and patience that you have given me. Your passion for your work is inspiring and continues to motivate me as I begin to pursue my career as well.

I would also like to thank my committee members. Dr. Schmitt—thank you for never failing to make me laugh at least once during the stressful moments that I was in your lab. Dr. Ildari—thank you for inspiring me to pursue Evolutionary Anthropology as a major by capturing my interest through the two classes I took with you, and for showing me how class material can be applied in the real world. Dr. Canizares—thank you for being so patient as I attempted to learn the basics of anatomy and dance medicine from you.

I also thank Dr. Angel Zeininger and Dr. Michael Granatosky for their enormous amount of help with this project. Thank you both for answering my never-ending questions and for sharing your expert knowledge on biomechanics, force traces, and joint angle measurements with me. I truly appreciate everything you have done for this project.

Thank you to all the dancers who volunteered to participate in my study and to everyone who showed interest in the idea; knowing that others were interested in my work helped motivate me to continue working on this research. Last but not least, thank you to my amazing friends and family who have provided all the love and encouragement that I needed through this process. Every hug and word of support meant so much to me.
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Appendix I. A force trace (y-axis=normal force (N), x-axis=time (sec)) for the Bharatanatyam half-sitting sequence from the PASCO Capstone™ Software with annotations. Pictures that demonstrate the positions for each annotation are presented.

a) Dancer demonstrates the aramandi position.

b) Dancer stands still.

c) Dancer hits her lowest point, at which a peak is seen on the trace.
Appendix II. A force trace (y-axis=normal force (N), x-axis=time (sec)) for the Bharatanatyam full-sitting sequence from the PASCO Capstone™ Software with annotations. Pictures that demonstrate the positions for each annotation are presented.

b) Dancer demonstrates the muzumandi position.

a) Dancer stands still.

c) Dancer hits her lowest point for this pose, at which a peak is seen on the force trace.
Dance science study: Email rop3@duke.edu

The flyer that was used for recruitment.

Appendix A

Bharatanatyam (Indian classical dance) to participate in a 30-minute study on dance science.

SEEKING: undergraduates with training in ballet or

Your movement?

Want to learn about the science behind

Interested in dance?
Appendix B. The consent form that was given to each participant prior to her involvement in the study.

Contact: Roshni Prakash  
Email: rop3@duke.edu  
Phone: (941) 350-2765

Informed Consent Form  
Address: Box 96189, Duke University, Durham, NC 27708

This consent form asks you to take part in a research study. The study is being conducted by Roshni Prakash, an undergraduate student in the Department of Evolutionary Anthropology, under the advisor, Dr. Blythe Williams.

Reasons for the study: This research study aims to explore the musculoskeletal effects of Bharatanatyam (Indian Classical Dance) on the lower limbs, and the similarities and differences of turnout biomechanics in female Bharatanatyam dancers and ballet dancers ages 18-22.

What you will be asked to do: Your participation in the study involves taking a 5 minute survey where you will be asked about your dance background, experiences in the dance classroom, and previous injuries. Next, your foot turnout will be traced on a piece of paper. Then, you will be asked to perform two specified stances specific to the dance form in which you are trained on a force plate and in front of two video cameras, and go in and out of this stance three times. If you feel discomfort during any parts of this physical examination, you should immediately let the primary researcher or student assistant know. With your consent, photos (excluding the face) will be taken for evaluation.

Total time for participating in this study should not exceed 35 minutes. Your participation is completely voluntary. You may withdraw consent and discontinue participation in this study at any time for any reason.

How your confidentiality will be maintained: If you choose to participate, your name will never be linked to your survey responses. We do not collect your name in the survey and there is no link between this consent form and your responses. Researchers analyzing the data will not know who provided any specific test results.

Benefits and Risks: There are no risks and no benefits to you for participating in this study.

If you have any questions, please feel free to ask me them. If you would like to speak to someone besides me about this research, you may contact my advisor, Dr. Blythe Williams, at blythe@duke.edu. If you have any questions regarding your rights as a participant in a research study, you may contact the Duke University IRB Office at +01 (919) 684-3030.

If you would like to participate, please fill in the lines below. Keep the extra copy of this form that you are given so that you have this information.

Name: _____________________________  
Signature: _____________________________  
Date: ________

Appendix C. The online dance history questionnaire that was completed by each participant.
Study ID
(Researcher will provide this for you)

Current age

Age you started dancing

Dance background: Please list any dance styles you have trained in and the number of years trained in each style.
E.g. Ballet (10 years), Bharatanatyam (5 years), Kathak (1 year), Tao (3 years)

Previous injury: Please list any past injuries to back and lower extremities (hip, knee, ankle, foot, etc.). Provide a brief description of how the injury happened.
E.g. Torn ACL (from skiing), Sprained ankle (from tripping on the sidewalk), Broke toe x2 (from pointe shoes)
From a scale of 1 to 5, with 1 being never and 5 being always, how often have your past teachers emphasized:
For ballet dancers - turnout of the lower extremities?
For Bharatanatyam dancers - turnout (or similar term) to achieve aramandi?
1 = never, 2 = rarely, 3 = sometimes, 4 = often, 5 = always


How have your dance teachers (previous or current) talked about turnout (for ballet) or aramandi (for Bharatanatyam)? Please choose the answer that fits for most of your experiences if multiple apply.

- They simply tell me to do it
- They describe the stance with imagery (e.g. "knees should face opposite directions, envision a diamond" or "turnout by using the undercurve")
- They explain the stance with anatomical terms (e.g. "rotate leg so that femur fits into the ball of the hip socket")
- They fix my stance without a verbal explanation
- I do not have to perform the stance in class

For ballet dancers: In your opinion, what do you think is the best way to achieve the 180 degree turnout in first position?
For Bharatanatyam dancers: In your opinion, what do you think is the best way to achieve the ideal aramandi?

Have you ever had a turnout-related or aramandi-related dance injury?
If so, please describe the nature of the injury. If not, enter N/A.