

A Review of the Biomechanics of ACL Injuries in Ballet, Bharatanatyam, and Modern Dance

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ABSTRACT: Anterior cruciate ligament (ACL) injuries are a significant concern in various physical activities, particularly for dancers. The forces placed on the knee during dance put dancers at a high risk for knee-related injuries. Developing injury-reduction strategies that can be readily incorporated into an existing dance training program is highly desirable but challenging. It requires understanding the biomechanics of dance movements and their relationship to knee anatomy. In addition, newly developed strategies need to allow dancers the freedom to maintain essential aspects of their current training regimens. In this review, we use a combination of biomechanical research and anatomical understanding to elucidate how forces incurred during dance affect the knee joint. We also discuss how dancers can optimize their training to reduce incidents of ACL injuries. For this study, ballet, Bharatanatyam, and modern dance were chosen as representative styles. We review the available literature, analyze relevant data, and present strategies that dancers can use to reduce the risk of ACL injury.

KEYWORDS: Biomedical Engineering, Biomechanics, Injury Prevention, ACL, Dance EMG.

■ Introduction

Dancing, like many sports, is associated with various types of injuries, and more often, lower limb injuries.¹⁻⁶ The prevalence of sudden changes in direction, deep knee flexion, and high-impact landings in dance makes knee injuries a particularly common type of injury for dancers. In fact, among all types of injuries sustained by dancers, knee injuries typically account for 14-20%, and within those knee injuries, tearing of the anterior cruciate ligament (ACL) is particularly common.⁷ For example, in a study monitoring classical dancers over 10 years, the risk of rupturing the left ACL was approximately 7%.⁸ An ACL injury can have severe consequences for a dancer's career. ACL injuries in dancers have most likely been studied less than in athletes because dance is often viewed as an art form rather than a sport, leading to fewer biomechanical studies within this population. Additionally, standardized performance conditions and injury reporting systems, which are common in sports, are often lacking in dance. ACL tears typically require surgery and a lengthy rehabilitation period post-surgery.⁹ Moreover, even after recovery, many people exhibit a reduced range of motion and a higher risk of re-injury. Despite these commonalities among all ACL injuries, two features specific to dance make ACL injuries particularly intriguing. First, in most sports, the incidence of ACL tears in women is significantly higher than that occurring in men. However, this gender disparity of ACL injuries does not seem to hold for dancers.¹⁰ seconds, the risk of an ACL injury in dance depends on a complex interplay of intrinsic and extrinsic factors that are often difficult to distinguish. For example, the type of flooring, footwear, and variable training loads are examples of extrinsic factors that can often affect the propensity for injury.⁸

The collection of biomechanical data in dancers can be used to identify muscle fatigue, muscle imbalances, or inefficient ac-

tivation patterns that may contribute to injury. A large body of literature exists that reports biomechanical data on dancers. However, little focus is placed on how dancers can use that data. These limitations have prompted us to review existing biomechanical data on dancers and their training to identify methods for reducing injury risk. In particular, we examine ACL injuries in dancers through the lens of five common movement culprits: knee valgus, lack of lower limb strength, hip immobility, and faulty landing mechanics. We hope dancers can use this information to adjust their training programs in ways that improve strength, flexibility, and coordination—ultimately enhancing performance while minimizing the likelihood of injury.

■ Discussion

Methodology:

A comprehensive literature search was conducted to identify studies on ACL injuries in dancers. Databases including PubMed and Scopus were systematically searched using the following keywords: "ACL injury", "dance", "modern dance", "ballet", "bharatanyam", "biomechanics", "training", and "prevention". The choice of papers included in our review was limited to peer-reviewed articles published in English. Additionally, we aimed to review studies that had at least 15 participants, when applicable. For this study, ballet, Bharatanatyam, and modern dance were chosen because of the availability of biomechanical data in each style. For instance, we have found a large body of literature comparing the prevalence of ACL injuries in ballet and modern dance, in addition to the large amount of data found in each dance style individually. Moreover, to demonstrate the generality of our analysis, a well-established and traditional dance style, Bharatanatyam, was selected. Although Bharatanatyam is a dance that dates back centuries and changes to the dance style itself are not plausible, we show that it can

benefit from additions to the training program. Finally, whenever data for a specific dance style was unavailable, we chose to use biomechanical data for other non-contact ACL injuries and drew conclusions based on what was found.

Knee Anatomy:

ACL injuries are among the most common injuries impacting the knee, often resulting from movements such as pivoting or landing from a jump. The ACL plays a large part in controlling the forward motion of the tibia relative to the femur, preventing excessive rotation of the knee.¹¹ When the ACL is injured, either by tear or rupture, the stability of the knee is compromised, leading to pain, swelling, and instability of the joint. This can lead to further injuries, including tears of the menisci and increased wear on the cartilage structures. Treatment often includes surgery followed by extensive rehabilitation. However, even with treatment, returning to physical activities can be extremely difficult, often taking between six and nine months to fully heal. Therefore, taking preventative measures is crucial in protecting the knee for any athlete.¹²

The knee is a compound joint that connects the three bones: the femur (thigh bone), tibia (shin bone), and the patella (kneecap), as shown in Figure 1. Because of its geometric complexity, the nature of forces that can be incurred on the knee can be very complicated. The knee consists of three main joints: the tibiofemoral joint (between the tibia and femur), the tibiofibular joint (between the tibia and fibula), and the patellofemoral joint (between the patella and femur). These joints allow for flexion and extension. This joint is then strengthened by a combination of ligaments – the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL), and the lateral collateral ligament (LCL) – that provide resistance to abnormal movement of the joint. Additionally, the knee consists of two cartilage structures, the medial and lateral menisci, which act as shock absorbers for the knee, reducing friction as well. Synovial fluid in the joint cavity lubricates the structures, enhancing smooth movements. The quadriceps and hamstrings are muscles surrounding the knee, and they play a crucial part in the stability and movement of the joint, contributing to the functionality.¹³

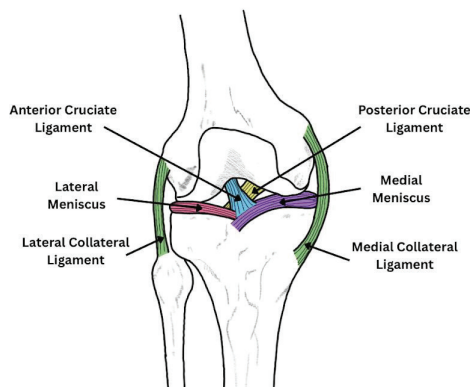


Figure 1: Adapted from.⁴³ Schematic of the knee joint

Bharatanatyam:

Bharatanatyam is one of the eight classical dances that originated in the subcontinent of India. The dance form focuses

on abhinaya, facial expressions, and adavus, the basic steps. One of the fundamental postures in Bharatanatyam is called ‘aramandi’, in which a dancer stands with heels together and toes pointing outwards, squatting halfway to form a diamond shape with their legs, as illustrated in Figure 2(a).¹⁴ In this position, the hip joints are externally rotated and abducted, while the knees are under significant flexion. This combined loading pattern on the lower limb joints places increased stress on the ACL, due to the rotational and shear forces involved. This becomes particularly concerning when dancers transition into and out of aramandi without adequate muscular support or optimal joint alignment.¹⁵ Another of the three main postures in Bharatanatyam is “mandi,” which is like a grand plié in ballet. In this position, the dancer transitions from aramandi and fully squats down, lowering until the thighs are parallel to the floor, with their heels lifting off the ground, as illustrated in Figure 2(b). The flexion of the knees required in mandi, coupled with the external rotation at the knee joint, increases the strain on the joint and may elevate the risk of ACL injury. When these movements are performed repetitively, especially with light misalignments or under muscular fatigue, the cumulative stress can contribute to injury over time. A study on Bharatanatyam dancers found that poor aramandi technique was the cause of 28.57% of ligament-related injuries. The authors also discuss how improving a dancer’s flexibility can reduce the risk of knee injuries. They concluded that lower levels of flexibility in the dancers were a leading cause for knee-related injuries and that incorporating yogic stretches and warmups can help reduce injury risk.¹⁶ While several studies have examined the prevalence of ACL injuries during aramandi, there is comparatively less data on mandi. We attribute this difference to the biomechanics of ACL loading during knee flexion. Specifically, the ACL is most mechanically engaged between 0° and 30° knee flexion and becomes progressively less loaded as the knee moves into deeper flexion.¹⁷

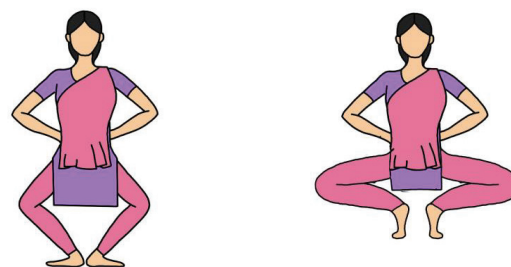


Figure 2: Dancer in Bharatanatyam postures (a) Dancer in aramandi (b) Dancer in mandi

Ballet:

Ballet is a classical dance form that originated during the Italian Renaissance and evolved in France and Russia, known for its emphasis on precision, posture, and technique. A foundational aspect of ballet technique is the five basic positions of the feet. In “first position”, the dancer’s heels touch with the toes pointed outwards, forming a straight line. “Second position” is similar in how the feet are turned out, but the dancer’s heels are shoulder-width apart. In “third position”, one foot is placed in front of the other with the heel of the front foot

touching the arch of the other foot. “Fourth position” is similar, but the dancer moves the front foot in third position in front of the other foot, still angled the same way. “Fifth position”, the most turned-out and closed of all, has one foot directly in front of the other so that the toes and heel of each foot are touching.¹⁸ These positions not only help train turnout and alignment but also create the clean lines and elegant shapes that define ballet’s aesthetic. These positions rely heavily on external rotation of the hip, often referred to as turnout. While turnout is aesthetically central to ballet, it can be biomechanically problematic if the rotation is forced at the knees or ankles rather than initiated from the hips. Improper or excessive turnout places significant stress on the ACL, particularly during landing, pivoting, or directional changes. A study done using electromyography analyzed which of the five positions causes the most strain on a dancer’s body. They found that the fourth position was the most demanding, requiring the greatest pelvic anterior tilt. The repetitive jumping, landing, and directional shifts in ballet, especially from turned-out positions, can exacerbate instability in the knee joint, increasing the likelihood of ACL strain or tear. According to a study by Fotaki et al., the grand plie, a key movement in ballet, mimics the mechanism of meniscus injuries because it leads to the knee experiencing a strong impact from the ground and excessive forward movement at the knee joint.¹⁹ Moreover, the demand for hyperextension and rigid alignment may reduce natural shock absorption, compounding the risk of joint injury.

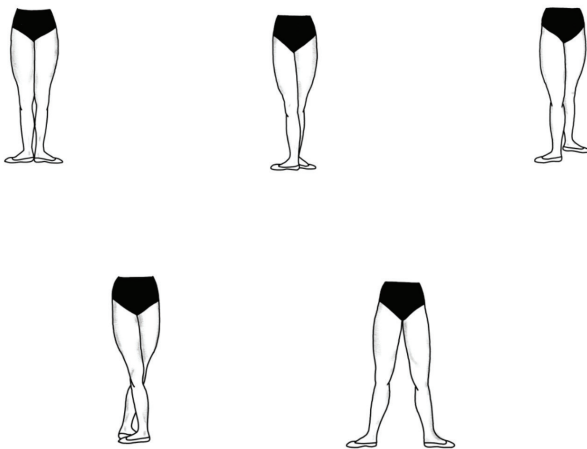


Figure 3: Adapted from.⁴² Dancer in ballet postures (a) Dancer in first position (b) Dancer in second position (c) Dancer in third position (d) Dancer in fourth position (e) Dancer in fifth position

Modern Dance

Modern Dance is a broad genre of dance that was formed in the 20th century as a reaction against the structure found in classical ballet. Unlike other forms of dance, modern dance does not rely on a codified set of positions but instead explores the body’s natural lines and movement patterns. Modern dancers use positions like parallel feet (where the toes point forward and the feet are hip-width apart) instead of turned-out feet, emphasizing a more natural stance. These forms reflect modern dance’s focus on individual interpretation over formal structure. This alignment is generally more anatomically neutral and can reduce strain on the knee joint. However,

modern dance also frequently incorporates unpredictable or improvisational movements, floor work, and off-axis balance, which may challenge knee stability.²⁰ While the parallel stance may offer better baseline support for ACL safety, the dynamic shifts, sudden directional changes, and non-linear choreography of modern dance can still pose a risk, especially if a dancer has insufficient control or strength. Modern dance presents several unique biomechanical challenges that may increase susceptibility to ACL injury. One concern is the lack of consistent turnout or structured alignment training, which can lead to variation in lower limb mechanics during high-demand movements. This can result in inconsistencies in knee alignment, such as increased dynamic knee valgus or internal tibial rotation during landings, leaps, or floor recoveries, known contributors to ACL stress.⁸

Biomechanical data and its limitations in dance:

The degree of muscle activation in a dancer can be assessed using electromyography (EMG).²¹ In an EMG, electrodes are placed on the skin, above a specific muscle, or inserted into the skin through a needle. As a muscle contracts, it generates electrical signals, whose amplitude correlates with the intensity of the contraction. By placing electrodes over several muscles, researchers can determine the activity of each of those muscles during a specific movement.²² It is often the inactivation of certain muscles that is of primary interest in ACL injuries. For example, reduced or delayed gluteus medius activation is associated with an increased incidence of ACL injuries. Incorporating EMG into dance research can therefore explain why certain movements can increase the risk of ACL injuries. However, its application in dance has many limitations.

One limitation in EMG research is the impact of sweat on signal quality. As dancers exert themselves, perspiration can reduce electrode adhesion and increase skin impedance. In turn, this decreases the reliability of recorded muscle activity.²³ This presents a challenge in dance studies, where continuous, high-intensity movement can lead to dancers perspiring. Another limitation stems from how EMG protocols are applied in research studies. Dancers are typically asked to repeat the same movement multiple times for data collection, not aligning with how they would typically train or perform choreography. This methodological choice, often necessary to average EMG signals, may limit validity and restrict the applicability of findings to real dance settings. To mitigate this limitation, researchers will often specify that dancers do not perform the same movement more than a set number of times without a break in between, to create a closer simulation of how dancers realistically train. Furthermore, EMG interpretation in dance is complicated by the fact that many muscles are activated simultaneously during complex movements. This leads to overlapping electrical signals and cross-talk between electrodes.²⁴ These technical challenges highlight the difficulty of using EMG as a stand-alone tool to understand ACL injury mechanisms in dancers and suggest that training programs informed by biomechanical data must carefully account for the unique conditions of dance performance. Nevertheless, EMG

can still be used to uncover general trends that dancers can follow to mitigate injury risk.

■ Injury Mechanisms in Dance

Knee valgus:

Knee valgus, or medial collapse of the knee joint during movement, is a well-established biomechanical risk factor for non-contact ACL injuries.²⁵ It typically occurs when the knee falls inward relative to the hip and foot. This misalignment is most commonly observed during dynamic activities, such as landing, cutting, or squatting. When excessive knee valgus occurs, large rotational forces are generated across the joint, which increases strain on the ACL. This mechanism was studied by Withrow et al., who used cadaveric knee specimens to investigate the effect of knee valgus angle on peak ACL strain. In the first trial, the force was directed posterior to the knee joint center in the sagittal plane. In the second trial, the force was directed 15 degrees lateral to the knee sagittal plane. A differential variable reluctance transducer was used to measure the relative ACL strain. The study found that when impulsive compression was applied to a knee in flexion and valgus, the strain on the ACL increased by 30% compared to flexion alone. They concluded that reducing the knee valgus of the joint will lower ACL strain during a jump landing and therefore reduce the risk of ACL injury.²⁶ These forces that cause strain can gradually weaken the ligament or cause a sudden ACL tear.

To better understand the biomechanical factors contributing to knee valgus, Turner et al. conducted a study examining the relationship between knee valgus angle, hip strength, joint mobility, and muscle activation.²⁷ The researchers used three methods to collect data regarding muscles and range of motion: a dynamometer to measure hip muscle strength, a goniometer to measure the hip external range of motion, and an EMG system to measure gluteus maximus and gluteus medius activation. They assessed how dancers and non-dancers landed from a jump, both naturally and when instructed to prevent knee contact and to land with toe-first foot placement before the heels. They found that after being given instructions, non-dancers saw a greater increase in the measured knee valgus angle, while the value in dancers did not show a significant change. These results are compelling because they offer insight into movement training and how that relates to injury prevention. For instance, the study recruited participants with a mixed background of ballet and modern dance. This may bias the results in favor of dancers as a whole because of variations in training approaches and emphasis. For instance, in ballet dance, every position (Figure 3) has dancers point their toes outwards, creating “turnout.” This technique is heavily enforced in classical ballet and is a part of most movements in ballet. Consequently, the knees of a ballet dancer do not fall inward when they land. This pattern of landing is so deeply ingrained in a ballet dancer's motor memory that even when given instructions to land with their feet in a neutral position, it is difficult for them to do so. This consistent method of landing leads to less variation in knee valgus angle, ultimately reducing the risk of ACL injuries. Notably, this preventative

mechanism is not seen in other physical activities. For example, female soccer players show a higher rate of ACL injuries compared to female dancers.²⁸ In another study, video analysis showed that female soccer players tended to place their knees in increased knee valgus angles when making sudden changes of direction. This significantly increases the stress placed on the knee and can explain the large incidence, approximately 80,000, of ACL injuries among female high school soccer players alone. Compared to their male counterparts, instances of ACL injuries are 2-10 times higher in female soccer players.²⁹ This discrepancy in frequency of ACL tears between female and male soccer players is not as prevalent in dancers. For instance, Karl Orishimo et al. analyzed 40 professional dancers, 20 men and 20 women of similar backgrounds, and their knee valgus angle when performing single-leg drop-landings from a platform. The data indicated that in dancers, there was no discrepancy in ACL injuries in females vs males, contrasting most other sports.¹⁰

Lack of lower-body strength:

Insufficient lower-body strength is a well-recognized biomechanical risk factor for non-contact ACL injuries.³⁰ Weakness or an improper distribution of muscle strength in key muscle groups, such as the quadriceps, hamstrings, glutes, and calves, can impair joint stability and neuromuscular control during dynamic movements. This lack of strength often becomes evident during high-impact activities like jumping, landing, or cutting, where the muscles are unable to adequately absorb forces or maintain proper alignment. As a result, the knee may experience abnormal movement patterns, such as excessive valgus or rotational stresses, which significantly increase the strain on the ACL. Over time or during a single high-load event, this can lead to ligament rupture. This issue is particularly critical in athletes, where muscle imbalances or inadequate strength training can leave the knee vulnerable to injury.³¹

There are several techniques that researchers can use to measure lower-body strength. In a wall sit test, for example, participants lean their back against a wall with their knees in line with their ankles and thighs parallel to the floor. A researcher then measures the time during which the position is held. Longer times are typically associated with greater lower-body strength. Another test involves participants performing hops on a single leg for six meters, followed by the same hops with the other leg. The time taken to perform the action is also correlated with lower-body strength, where decreasing times are associated with greater lower-body strength. A study used those tests to compare the lower-body strength of Bharatanatyam dancers and non-dancers.³² The data show that Bharatanatyam dancers were able to hold a wall sit position for approximately 2.5 times longer than non-dancers, revealing increased quadricep, glute, and hamstring strength relative to non-dancers. In addition, Bharatanatyam dancers were able to hop 6 meters at relatively the same speed with their right and left legs, while non-dancers showed a preference for one leg. Those findings were explained by the dance training profile of Bharatanatyam dancers. Those findings were attributed to the time Bharatanatyam dancers spent in the aramandi posi-

tion (Figure 2a). For example, in a typical 60-minute training session, a Bharatanatyam dancer spends 30-40 minutes in the aramandi position, which seems to greatly improve their lower body strength. This empirical observation is consistent with biomechanical findings on the quadriceps and hamstring muscle activation during the aramandi position.¹⁵ Although the scope of the study by Jyothi and Sujaya did not include ACL injuries, one can infer from biomechanical data the protective benefit the aramandi position can have for a Bharatanatyam dancer. It is well known that a larger degree of lower-body muscle activation is associated with a lower incidence of ACL injury.^{33,34} The findings we discussed corroborate the idea that prevention efforts should focus not only on alignment cues but also on strengthening the stabilizing muscles.³² This prolonged muscular engagement, in addition to repetitive movements like adavus, functions similarly to isometric strength training and builds endurance in the hamstrings and hip stabilizers over time.

The emphasis on static holds observed in the training program of Bharatanatyam dancers is in stark contrast to other forms of dance, such as ballet. In ballet, for example, more focus is put on increasing flexibility and developing aesthetic lines rather than improving muscular load or endurance. Due to this difference in dance training, ballet dancers may not consistently engage the lower body in ways that develop strength sufficient to withstand high biomechanical stress. This lower-body strength deficiency can make them more vulnerable to ACL injury. This hypothesis is consistent with the study of Jeffery A. Russell, where the addition of targeted physical conditioning in female dancers was associated with a drop in injury rates from 4.14 to 1.81 per 1,000 hours over 3 years.⁵ This suggests that injury risk can be mitigated by addressing muscular deficiencies directly. Moreover, it demonstrates that dancers in disciplines with less emphasis on lower limb strength—such as ballet and modern dance—would especially benefit from supplemental strength training outside of traditional technique classes.

Hip immobility:

While limited data is investigating the effects of hip immobility on risk of ACL injury in the ballet, modern, and Bharatanatyam dancers, there is ample data on the biomechanical link between hip immobility and ACL injuries. A study done by Tainaka et al. has linked poor hip mobility, especially in extension and external rotation, to an increased risk of ACL injuries.³⁵ Limited range of motion or poor neuromuscular control at the hip, particularly in hip extension, abduction, and external rotation, can alter lower limb alignment and movement patterns. When the hips are restricted in motion or lack stability, the body compensates for the increased movement and stress at the knee. This compensation often presents as excessive knee valgus, internal femoral rotation, or lateral trunk lean, biomechanical patterns consistently associated with non-contact ACL injuries. Because knee valgus can be caused by hip immobility, many of our conclusions and recommendations in section 3.1 are relevant to hip immobility-related ACL injuries.

There are a couple of reasons to conclude that the risk of hip immobility-induced ACL injuries for dancers may not be so high. First, the data reporting such injuries is very limited. Second, consider the discrepancy mentioned earlier about ACL injuries in male versus female athletes. Female athletes experience ACL injuries at a rate 3.5 times greater in basketball and 2.8 times greater in soccer than male athletes.³⁶ One proposed explanation is that many female athletes display lower hip strength and mobility relative to male athletes, and without targeted training to address these deficits, the knee becomes the point of compensation during rapid movement. Remarkably, this discrepancy does not hold between male and female dancers. Therefore, it is likely that the training of external rotation and controlled hip abduction that is present in Bharatanatyam and ballet dancers could reduce the risk of ACL injury.

Ground Reactive Forces:

Ground reaction forces (GRFs) represent the load transferred from the ground into the body during movements like landings. In dance styles like ballet, peak vertical GRFs can reach 2.8-3.8 times a dancer's body weight during landings in leaps like a grand jete.³⁷ These elevated forces place great amounts of mechanical stress on the knee joint and surrounding soft tissues. When coupled with limited joint flexion, stiff landing technique, or poor shock absorption strategies, high GRFs can significantly elevate the strain on the ACL, increasing the risk of non-contact injuries. Understanding the magnitude and dynamics of GRFs in dance-specific movements thus informs targeted training interventions to improve force attenuation, optimize landing mechanics, and thereby mitigate ACL injury risk.

Ballet dancers may be especially vulnerable to GRF-related injury risks due to the aesthetic demands of the discipline. Frequent jumps and directional changes, combined with stylistic requirements like external rotation and an upright torso, alter natural force absorption strategies. These biomechanical constraints often reduce the contribution of stabilizing muscles in the lower limbs, leaving the ACL to absorb a larger share of the force.³⁸ A study done by Yayoi Jones shows that certain leaps, like a calypso, lead to higher GRFs, meaning there is more force applied from the ground when a dancer lands, leading to a higher risk of ACL injury. In the study, different leaps had significant differences in the resulting GRFs, with the most basic leaps having the lowest GRF and the most advanced leaps having the highest.³⁹ It can be concluded that as dancers become more advanced, the emphasis on the aesthetics of the jumps is prioritized, leading to the high GRFs as dancers choose to focus on hip rotation and upright posture instead of engaging hamstrings, quadriceps, and glutes. There was a lack of biomechanical data found regarding Bharatanatyam dancers, but we can conclude that since they possessed higher lower-body strength, they would be more likely to engage their muscles. This would lead to a decreased load being placed on the ACL. Similarly, a lack of biomechanical data regarding ground reactive forces during landings was found in modern dancers. However, we can assume that because modern danc-

ers focus less on the precision and aesthetics of their jumps, they would also activate their muscles more than ballet dancers. This increased muscle activation would remove strain from the ACL and reduce the risk of injury.

Additionally, the number of jumps expected from ballet dancers is higher than that of modern dancers. In a study analyzing the landing mechanics of dancers, 6 dancers in a classical company had ACL injuries, while no dancers in the 2 modern dance companies' studies had ACL injuries. Outside factors such as floor type and dancing hours have been ruled out as they were very similar between the two companies. In a classical dance company, the number of jumps is far greater than in a more modern company, and these landings will be in the classical turned-out position of the leg. Due to this, the amount of strain on the ACL in ballet dancers will be higher over an extended period, leading to an increased risk of ACL injuries.⁸ For example, during a sudden change of direction or landing from a jump, inadequate muscle activation may prevent proper absorption of forces and lead to faulty joint alignment, dramatically increasing ACL strain. While a lack of data was found comparing Bharatanatyam to the other dance styles, we can conclude that, because, like modern dance, the frequency of jumps is minimal in Bharatanatyam compared to ballet, the high ground reactive forces would be lower, leading to less strain on the ACL. Further research should be done to collect data regarding ground reactive forces in certain adavus in Bharatanatyam to conclude if there is less strain on the ACL in Bharatanatyam.

■ Discussion and recommendations

The data we have analyzed (summarized in Tables 1 and 2) shows that every dance style form offers unique protective mechanisms, but no single style provides complete coverage of all the necessary elements for ACL injury prevention. By integrating elements from other dance styles and physical conditioning protocols, dancers can strengthen vulnerable areas, enhance joint control, and reduce the likelihood of ACL injuries. For example, classical ballet emphasizes elevation, flexibility, and aesthetic alignment but often neglects strength development. This lack of strength is most notable in the posterior chain and stabilizing muscles around the knee. Therefore, ballet dancers will benefit from integrating lower limb strength training into their routine. Ballet dancers also spend significant time on turnout (Figure 3a) and line formation, which often comes at the expense of muscular conditioning. To counter this, ballet dancers would benefit from borrowing strength-focused additions from other dance styles to help reduce their injury risk. For example, our analysis shows that the prolonged time Bharatanatyam dancers spend in aramandi (Figure 2a) leads to increased hamstring strength. This type of isometric strength development is particularly effective in stabilizing the knee joint and absorbing ground reaction forces during dynamic movement. Studies have shown that a lack of strength in the hamstrings compared to the strength of the glutes significantly increases the risk of ACL tears.⁴⁰

Modern dancers, in contrast to ballet dancers, often prioritize fluidity, improvisation, and natural movement. Our review of the data shows that modern dancers have a greater change in knee valgus angle during landings, compared to ballet dancers. This variance in knee valgus angle makes modern dancers more susceptible to ACL injuries. Consequently, modern dancers would benefit from training consistent joint alignment, particularly to address variability in the knee valgus angle. Unlike ballet or Bharatanatyam, modern dance does not rely on fixed positions or turnout, which means dancers often lack a standardized reference for joint alignment. This variability can lead to inconsistent joint movements during landing or changing directions, where uncontrolled knee valgus is a well-established risk factor for ACL injury. Ballet dancers, by comparison, train in consistent external rotation and often land with similar lower limb alignment across movements, resulting in less variation in the knee valgus angle. Adopting a similar focus on alignment, through exercises that develop consistent hip-to-knee-to-foot coordination, would help modern dancers reduce valgus-related injury risk.

Another key factor in injury prevention we reviewed is hip mobility. Ballet places heavy emphasis on external rotation of the hip and deep hip abduction. This emphasis trains dancers to initiate movements from the hip rather than compensating them through the knee or ankle. This consistent use of the hip joint not only enhances performance but also protects the knee from absorbing excessive rotational or valgus stress. In contrast, Bharatanatyam dancers, and especially athletes in non-dance sports, often neglect structured hip mobility training. Data collected comparing the range of hip motion in ballet and modern dancers to Bharatanatyam dancers shows that when Bharatanatyam dancers incorporated stretching into their training routine, their range of motion improved and consequently, their hip mobility increased.¹⁶ As mentioned earlier, this increase in hip mobility directly results in a decrease in ACL strain. Moreover, a study has found that female athletes, particularly in sports like soccer and basketball, are disproportionately affected by ACL injuries linked to poor hip mobility and lack of neuromuscular control.⁴¹ Incorporating hip-focused mobility and control drills into training routines could offer critical protection, especially for dancers or athletes whose movement practices do not already include these components.

Given the distinct strengths and weaknesses of various dance disciplines (summarized in Table 1), we recommend that dancers incorporate techniques and conditioning strategies from multiple styles, along with supplemental physical training, to address biomechanical gaps that contribute to ACL injury risk.

Ultimately, the most effective approach to ACL injury prevention in dancers involves a multidisciplinary strategy that blends the strength and mobility benefits of Bharatanatyam, the alignment precision of ballet, and the expressive, adaptive movement patterns of modern dance. By addressing individual biomechanical vulnerabilities, such as muscle weakness, joint misalignment, or hip immobility, through targeted cross-training, dancers can better safeguard their bodies against the long-term risks of repetitive strain and acute ligament injuries. This integrative approach not only supports injury prevention

but also enhances overall performance and longevity in a physically demanding art form.

Table 1: Risk Factors, Protective Mechanisms, Recommended Additions, and Areas for Further Research of three styles of dance (ballet, Bharatanatyam, and modern)

Dance Style	Risk Factors	Protective Mechanisms	Recommended Additions	Areas Requiring Further Research	Sources
Ballet	Weak supporting muscles	Consistent knee alignment	Strength trainings, specifically targeting the hamstrings	Lower limb muscle strength of ballet dancers compared to dancers of other styles	19, 26, 27
Bharatanatyam	Lack of flexibility	Strong supporting muscles	Incorporate a variety of lower limb stretches into training	Knee alignment in aramandi and mandhi positions	15, 16, 32
Modern	Inconsistent knee alignment	Reduced strain	Add consistent alignment training into routine	How modern training differs from classical training	8, 20, 27

Table 1 shows the strengths and weaknesses of each dance style, in addition to what we recommend could be added to their training. This table highlights areas for future research to be conducted.

Table 2: Population, Protective Method, Key Metrics, and Main Finding Relative to ACL of studies presented throughout the paper.

Study	Population	Method	Key Metrics	Main Finding Relevant to ACL	Source
Withrow et al.	Cadaver Knees	Applied load in flexion with valgus	ACL Strain	ACL strain increases when valgus is added vs flexion alone	26
Eriksen et al.	Female soccer players and dancers	Analyzing biomechanical data regarding knee and ankle flexion	knee and ankle flexion	Female soccer players have a higher incidence of ACL injuries because they have less flexion in their knees due to differences in training programs	28
Evans et al.	Female and male soccer players	Reviewed various studies	Knee valgus angle	Unlike dancers, female soccer players are at a higher risk for ACL injuries than their male counterparts	29
Orishimo et al.	20 professional male and 20 professional female dancers	group-by-sex multivariate analysis of variance	Knee Valgus Angle	No significant difference between male and female dancer's knee valgus angles when landing	10
Jyothi S. et al.	Bharatanatyam dancers from various dance schools and non dancers from the general population	Wall Sit and Single-legged Hop Tests	Lower Limb Strength	Bharatanatyam dancers had a higher level of lower limb muscle activation when compared to the general population because of their training regimens.	32
Zazulak et al.	13 female and 9 male Division I collegiate athletes	Surface EMG	Lower Limb Strength	delayed gluteal activation is associated with higher ACL injuries	34
Russel	Professional dancers of various styles	Reviewed various studies	Lower Limb Strength	Additional strength training in ballet dancers is associated with a drop in the amount of ACL injuries dancers have.	5
Tainaka et al.	patients with non-contact ACL injuries	adjusted odds ratio of hip range of motion	Hip Mobility	poor hip mobility, especially in extension and external rotation, is linked to an increased risk of ACL injuries	35
Jones	16 female dance students enrolled in a university	Force plates and EMG	GRF and muscle activation	More advanced leaps in ballet that would be performed by dancers with more training show higher GRFs, leading to a higher risk of ACL injuries.	39

Table 2 displays studies conducted across various sports and dance styles that prove that each dance type has unique strengths and weaknesses.

Conclusion

In this study, we used both biomechanical research and anatomical understanding to explore how forces imposed during dance affect the knee joint of a dancer. We have analyzed data from three representative dance styles: ballet, Bharatanatyam, and modern dance. When there was a lack of biomechanical data in a particular dance, we analyzed data from other non-contact ACL injuries and connected them to the dance style in question. Our research shows that modern dancers can benefit from the structured positions of ballet and Bharatanatyam. Additionally, Bharatanatyam dancers can benefit from the flexibility that ballet dancers have, while ballet dancers should focus on lower limb strength, as Bharatanatyam dancers train during their rehearsals. Ensuring that all dancers implement strengthening, flexibility, and consistency regimens in their training will reduce the risk of ACL injury. Dance schools could add a stretching or yoga section to their class to improve dancers' flexibility. Additionally, repetition of steps could build a more consistent form in modern dancers if implemented. Finally, strength training should be prioritized through weightlifting or similar exercise methods to reduce the risk of muscles not being activated in dance. By creating a more well-rounded and balanced training program, dancers would ideally gain injury prevention mechanisms that were explored in this paper across the three styles of dance. We also present general training guidelines that dancers can implement to reduce the risk of ACL injury. While dance follows techniques that date back many years, biomechanical analysis is a relatively new field and has not been fully employed in the field of dance. We hope this review can be used to improve the training program of dancers and initiate further research into the biomechanics of dance to reduce injury risks.

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