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Kinetic and Kinematic Analysis of Landing a Grand Jeté between Barefoot and Pointe Shoe Footwear for Dominant and Non-Dominant Legs

Cara Giordani Daybré

Submitted to the Movement Arts, Leisure Studies, and Health Promotion Department at Bridgewater State University in partial fulfillment of Departmental Honors

May 2019

Kinetic and Kinematic Analysis of Landing a Grand Jeté between
Barefoot and Pointe Shoe Footwear for Dominant and
Non-Dominant Legs

Cara G. Daybré

Submitted in Partial Completion of the
Requirements for Departmental Honors in Physical Education

Bridgewater State University

May 14, 2019

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Abstract

Dancers wear pointe shoes while performing a Grand Jeté because the shoes produce an illusion that dancers are floating. Since dancers are required to absorb a significant amount of force in a small area on the toes during landing, this then causes a high incidence of injury. The question of how to perform a Grand Jeté safely for both feet remains unaddressed. Therefore, the purpose of this study was to examine the vertical ground reaction force and lower body joint angular displacements in the skill of a Grand Jeté between barefoot and pointe shoes for both dominant and non-dominant legs. Seven female experienced dancers performed a Grand Jeté and jumped and landed on top of a force plate barefoot and with pointe shoes for both dominant and non-dominant legs. Vertical ground reaction force was measured with a force plate and joint angular displacement was recorded using a high-speed camera. A two-way (2 sides of the body x 2 landing footwear conditions) repeated measure ANOVA was conducted at $\alpha = 0.05$. A t-test with a Bonferroni adjustment was then conducted to further investigate the statistical significance of all tested conditions. The results of this study showed an observable difference between the landing force of the dominant and non-dominant side, regardless of footwear, with the non-dominant side having a larger landing force than the dominant side. Additionally, a statistically significant difference in joint angular displacement was found as a result of the pointe shoe, regardless of landing side, during all three phases of landing. The results of this study indicate that dancers may benefit from addressing any bilateral asymmetries or deficiencies in muscular strength, technique, and joint stability and flexibility before beginning to dance in pointe shoes. Correcting any bilateral asymmetries may decrease some of the risks introduced by wearing pointe shoes by ensuring equal and proper strength and stability on both sides of the body when landing. This will allow the dancer’s joints to better withstand the joint angular displacements and high landing forces imposed. This study further investigated the difference in vertical ground reaction force between all the conditions and was able to identify the momentous joint angles that place dancers at a higher risk of injury. This study will provide a comprehensive understanding on the mechanics of performing a Grand Jeté; practitioners may utilize this information for teaching instruction and to prescribe a proper strength and conditioning program to reduce the risk of injury.

Dance has been a part of the history of human movement, culture, and communication since humanity began. As a result of its demanding nature, dance increases the knowledge of what the human body can achieve under stress. As an enjoyable form of physical activity, dance has been found to help improve quality of life by reducing symptoms of anxiety and depression, health issues resulting from inactivity and obesity, and improving the overall flexibility, strength, health, and mood of its participants (Brinson, 1996). Dancing became widespread in the third millennia BC when the ancient Egyptians started using dance as integral parts of their religious ceremonies ("Dance Facts," 2018). Today, there are numerous dance styles to explore and enjoy. Some of the most common performance dance styles are ballet, contemporary, modern, tap, jazz, and hip-hop. Ballet is a fluid and graceful style of dance that uses precise and highly formalized movements to tell a story; contemporary dance is an expressive dance style that abandons the rigid aspect of classical forms of dance and incorporates unconventional movements from styles around the world.

A dance skill movement that is primarily found in ballet and contemporary dance is called a Grand Jeté. A Grand Jeté is a jump in which a dancer springs from one foot to land on the other with one leg stretched forward of their body and the other stretched backward while in the air. The goal of the movement is to create the illusion that the dancer is floating through the air. From the moment of takeoff to the instant of landing, the dancer's center of gravity follows a parabolic trajectory. Thus, the movement can be considered a projectile motion. Unfortunately, dancers often experience lower extremity injuries, particularly the ankle sprain, resulting from the continuous jumping, leaping, and landing. Other common injuries dancers experience are tendonitis, muscle and ligament strains, stress fractures in the ankle and/or foot, flexible claw toes, hammer toes, and calluses over the prominent dorsal aspect of the knuckle or over the tip of the toe (Cheng-Feng et al., 2005). There is a dance-related injury incidence of 40-80% depending on the level of participation in dance, with a lifetime incidence of up to 90% for all dancers (Joy, 2000).

Ballet dancers commonly wear pointe shoe footwear when performing a Grand Jeté. These shoes have a wooden block inserted into the tip of the shoe to help dancers reach full extension of the ankle joint while on their toes. Pointe shoes have soft leather soles and a hard tip of paper, tissue, and hardened glue, with a small flat surface in the front. The shoes are not well suited for walking and are generally very slippery and stiff. Pointe shoes were first used at the beginning of the 19th century in the Romantic Age. At this time, ballerinas were meant to represent an almost illusionary female and an emblem of purity (Hoogsteyns, 2013). The pointe shoes were created to lift the dancer off the floor and produce the illusion that the dancer is floating (Hoogsteyns, 2013). Unfortunately, most dance shoes are designed for aesthetic reasons. Pointe shoes must be pliable, yet supportive. While wearing pointe shoes, the dancer’s foot is required to absorb a significant amount of force in a small area on the toes, which may lead to structural changes of the foot that may make the dancer more prone to injury (Kwon et al., 2008). The shoes also may throw dancers off balance, resulting in increased tension and stiffness in the knee and ankle joints. Several studies have shown that increased joint angular stiffness is associated with decreased joint angular displacement and increased moments, thereby increasing the risk of bony injury (Abernethy et al., 1978: Butler et al., 2003; Cavanagh et al., 1980).

Wyon, Harris, Brown, and Clark (2013) conducted a Grand Jeté study and found there was a significant difference in the vertical forces of landing a Grand Jeté between the dominant and non-dominant foot; however, the study did not examine the impact of footwear that may contribute to this difference in the vertical force and joint angles of landing. Limited research studies have been conducted to understand how the vertical landing force impacts the joints of dancers and how to land properly and safely with correct lower extremity joint angles to minimize chances of injury. These critical questions are yet to be answered, and the field of dance medicine is still in its infancy. As a result, many injured dancers do not receive the care that they require to heal properly. There needs to be a recognition that, like other sport injuries, dance injuries need particular understanding by medical professionals because of the extreme ranges of motion and high amounts of force that are placed on the bodies of dancers on a regular basis (Brinson, 1996). Performing and/or landing one move incorrectly can overload a joint with a substantial amount of torque, resulting in sudden and debilitating injuries. More importantly, it is imperative that researchers find ways to reduce the incidences of injuries acquired while dancing in the first place, rather than placing primary focus on how to treat the injuries once they have been obtained. Therefore, the purpose of this study was to examine the kinetics and kinematics of the vertical ground reaction force and joint angles of landing while performing a Grand Jeté in both barefoot and pointe shoe footwear between the dominant versus non-dominant side. The results will enable dancers, coaches, and health practitioners to have a comprehensive understanding of the mechanics of landing Grand Jeté, so proper teaching and coaching instruction and better muscular and joint strength and conditioning programs can be prescribed to prevent injury.

Review of Literature

History of Dance

Dance has been a part of the history of human movement, culture, and communication since humanity began. Dance is defined as the movement of the body in a rhythmic way, usually to music or chants within a given space, for the purpose of expressing an idea or emotion, releasing energy, or simply for enjoyment of the movement itself (Mackrell, 2018). Based on the earliest documented moments of dance history, dance was primarily used to accompany spiritual rituals, spiritual gatherings, and social events ("Dance Facts," 2018). To this day, dancing remains as one of the most expressive forms of communication in the world ("Dance Facts." 2018).

The first proof of the existence of dancing was found in 9000-year-old cave paintings in India. These paintings depicted people hunting, birthing children, religious ceremonies, burials, and communal drinking and dancing ("Dance Facts," 2018). During the first millennia, dance was used in Greece during important events. Dance was most noticeably used in Greece before the Olympian Games, the precursor for the Olympic Games that exist today ("Dance Facts," 2018). Dancing became widespread during the third millennia BC, when the Egyptians started using dance as an important part of religious ceremonies. At this time, dance was used to emulate important events, such as stories of the gods and the cosmic patterns of the moving stars and sun. Aside from religious ceremonies, people have been using dance for celebration, entertainment, and seduction to provoke the mood of exhilaration.

Dance is commonly utilized as a form of self-expression, communication, stress relief, and exercise. Dance is known to create a completely self-contained world for dancers in which they can exhibit a higher amount of physical effort, prowess, and endurance way beyond their normal capabilities (Mackrell, 2018). People commonly dance for the pleasure of experiencing their body and environment in new and special ways (Mackrell, 2018). The moves commonly performed while dancing may produce a state of mind and body that is different from a traditional every day experience.

Today, there are numerous forms of dance throughout the world. Some of the most common dance styles are ballet, contemporary, modern, tap, jazz, and hip-hop. The two dance styles particularly pertinent to this study are ballet and contemporary dance. Ballet is a fluid and graceful style of dance that uses precise and highly formalized movements to tell a story; contemporary dance is an expressive dance style that abandons the rigid aspect of classical forms of dance and incorporates unconventional movements from styles around the world.

Ballet has been the most dominant and popular form of dance in the Western Theater Dance since its creation during the Renaissance period around the year 1500 in Italy (Nedvigin, 2018). The term 'ballet" comes from the Italian word 'ballare' which means 'to dance.' Ballet still incorporates the positions and steps developed in the court dances of the 16th and 17th centuries (Mackrell, 2018). The earliest ballet dancers wore masks, numerous layers of brocaded costuming, pantaloons, large headdresses, and ornaments. This clothing was difficult to move in, resulting in traditional ballet choreography consisting of small hops, curtsies, promenades, and gentle turns (Nedvigin, 2018). At this time, the ballet dancers wore small heeled shoes, rather than traditional flat ballet shoes that are worn today. Ballet is characterized by an erect position of the dancer with the dancer's body maintaining a long, vertical line position during every dance move they perform. Ballet dancers always aim to conceal the stress of the choreography by performing with an air of grace and fluidity. The dancer's consistent poise and grace is responsible for maintaining the characteristic qualities of dignity and control that have been present in ballet since its creation. The official terminology for ballet was gradually created by the French over 100 years (Nedvigin, 2018).

Over the course of its existence, the ballet dance style has undergone numerous changes. During the Romantic Era in the early to mid-19th century, ballet was softer with fewer jumps and turns than in the later 19th and 20th centuries. Russian ballet resembles the more brittle and strenuous style of the Italians, as well as the vigorous athleticism of Russian folk dances. Although ballet still maintains many of its old traditions, ballet dancers have recently started to experiment with characteristics of modern dance, such as leaning away from the vertical line that is traditional in ballet, dancing closer to the floor, and using turned-in leg positions and flexed feet (Mackrell, 2018).

Jumping and Landing

Dance is a dynamic form of movement that typically requires flexibility, agility, poise, strength, endurance, and technical skill (Grealish et al., 2017). Researchers Wild, Grealish, and Hopper (2017) investigated the injury rate of Irish Dance, a form of dance that requires a lot of hopping, jumping, and leaping onto a singular leg, and the authors found that almost 80% of dancers sustain at least one musculoskeletal injury throughout the course of their dance career, especially right before a major performance or championship. The study defined injury as any incident that caused the dancer to be absent from dance practice or competition for at least two weeks. McNamara, Noon, Schmicke, and Zoch (2009) conducted a study that found that more than 90% of all reported dance injuries occurred to the lower limbs, with the foot and the ankle accounting for about 60% of all the injuries. For most dancers, overuse injuries account for most of the reported injuries. These overuse injuries may be the result of the numerous hours that dancers dedicate each day for dance practice and improving their technique. On average, skilled dancers dedicate about 10 to 18 hours to dance per week and have higher injury rates than less skilled dancers who only dedicate 2 to 3 hours per week to dance (McNamara et al., 2009). Other factors that contribute to an increase in injury risk are sudden increases in training, rehearsal hours, and performances.

In most forms of dance, dancers perform a series of repetitive high intensity leaps, hops and jumps that require them to land on a single limb. In Irish and ballet dance, these dancers must also sometimes land on the tip of their toes after these hops, leaps, and jumps which increase their risk of injury due to the unstable landing position of landing with an extended knee and hip with ankle plantar flexion and toe extension and an upright and rigid trunk. These motions often require immense strength and core stability. While jumping and landing, dancers must maintain postural control, which is the ability to control the center of mass with the synergistic performance of the neuromuscular and sensorimotor systems (Paillard, 2012).

One of the main injury risks of leaping and landing on one leg is the impact of muscular fatigue. Studies have also shown that performance and injury occurrence in a variety of athletes can be associated with single-leg balance and landing tasks (Munn et al., 2010). Dancers are required to constantly leap and hop landing on one leg, which can quickly result in fatigue of the impacted muscles and loss of balance. Fatigue can be defined as a reduction in the maximal force-generating capacity of a muscle that may lead to disruptions in neuromuscular function after strenuous exercise (Grealish et al., 2009). Fatigue has been found to have a negative impact on landing mechanics and contributed to a greater knee abduction load, reduced peak hip external rotation alignment, and greater forward and lateral trunk flexion (Grealish et al., 2009). In fact, fatigue brought about by isokinetic exercise reportedly reduces athletes' landing performance 5-17%, predisposing the athletes to a higher risk of injury as a result of poor landing form and fatigued muscles (Arab et al., 2007; Bizid et al., 2009; Powers et al., 2004). Fatigue resulting from variable-speed movements, such as dancing, has been found to decrease single-leg balance ability by 16-32% and single-leg landing performance by 4-35% (Ambegaonkar et al., 2010; Eckhardt et al., 2012; Hentschke et al., 2013). Aside from fatigue, injury while landing may result due to failure to assume the proper landing position or too high of a force exerted on the joints of the dancer.

Vertical Ground Reaction Force

According to Isaac Newton's Third Law of Motion, every action has an equal and opposite reaction. In accordance with this law, whenever someone walks, runs, or jumps, every time her foot lands, ground reaction forces are produced (Romanov, 2018). Ground reaction forces are external forces that act upon the human body in motion or at rest with the purpose of propelling the body to initiate and control movement (Romanov, 2018). Typically, human movements are subject to constant perturbations and constraints as a result of the anatomical construction of the body's joints. Despite these limitations, the human locomotor system tends to be strong and adaptable, which allows for quick and effective compensation for disruptions in stability allowing for the person to regain their stability as they move (Auyang et al., 2013).

For dancers, leaping through the air is often accompanied by a performance goal, such as leaping high, far, or fast. Unfortunately, the aesthetic constraints imposed on dancers challenge the performers to utilize limited strategies to modify their technique when trying to balance the bodily demands of leaping (Fietzer et al., 2011). A typical leap taking off from one leg and landing on the opposite leg is comprised of three phases: *take-off*, *flight*, and *landing*. The take-off and landing phases are the two phases that require ground contact and can be subdivided into two sub-phases consisting of *weight acceptance* and *propulsion* (Fietzer et al., 2011). The vertical ground reaction force is present during both the take-off and landing phases. The purpose of the vertical ground reaction force is to change the body's momentum. Studies completed by Ferris and Farley (1997) and McNitt-Gray (1993) have shown that the vertical ground reaction force is greater in jumping and leaping than running. In fact, numerous studies have found that the vertical ground reaction force during jumping and leaping can measure up to about 3.5-8.0 times the person's body weight (Farley et al., 1997; McNitt-Gray, 1993). The vertical ground reaction force combined with repetitive momentum changes that are common in dance prove the importance of controlling the vertical ground reaction force attenuation exhibited by dancers (Fietzer et al., 2011).

Leg stiffness, which is characterized by tissue compressibility, is a key component in vertical ground reaction force attenuation that is dependent upon kinematic and kinetic events (Butler et al., 2003). The angular joint stiffness of each individual joint plays an important role in determining the quality and characteristics of the leap, including the magnitude of the vertical ground reaction force, duration of ground contact, and the lower extremity joint angular displacement (Farley et al., 1997). The position of the femur and the tibia of the leg help to place the knee in the best position of all the lower extremity joints to help reduce the vertical ground reaction force (Kulas et al., 2006). The amount of stiffness in the joints required has been found to increase with the demands of the activity (Arampatzi et al., 1999; Cavanagh et al., 1980; Farley et al., 1998; Komi et al., 2002). Greater amounts of joint angular stiffness are associated with decreased joint angular displacement and increased moments which increases the risk of bony injury (Abernethy et al., 1978; Butler et al., 2003; Cavanagh et al., 1980). Contrarily, decreased joint angular stiffness results in greater joint angular displacement and less changes in moment, which also increases the risk of injuries, such as tendinopathies and sprains (Butler et al., 2003; Cavanagh et al., 1980; Kulas et al., 2006).

Vertical ground reaction force is an important factor in all sports that may increase athletes' risk of injury. The vertical ground reaction force present while landing dance leaps may measure up to 3.5 – 8.0 times the dancer's body weight (Farley et al., 1997; McNitt-Gray, 1993). Similarly, figure skaters performing a single leg landing generate a landing force of about 3.50 ± 0.47 times their body weight (Saunders et al., 2014). Comparatively, the average vertical ground reaction force generated by sport times body weight are: gymnastics 6.0x – 7.0x, basketball 4.3x – 8.9x, American football 4.8x – 5.5x, soccer 2.58x – 3.55x, walking 1.1x – 1.5x, and running 2.0x - 2.9x (Brock et al., 2014; McClay et al., 1994; Ortega et al., 2010; Seegmiller et al., 2003) Based on these comparisons, dancers sometimes generate landing forces that nearly double the forces generated from sports that are dubbed the most dangerous, such as American football and soccer.

Grand Jeté

A dance skill movement that is primarily common in ballet and contemporary dance is called a Grand Jeté. The term Grand Jeté translates to "big throw," relating to how the dancer throws herself into the air ("BalletHub," 2018). A Grand Jeté is a jump in which a dancer springs from one foot to land on the other with one leg stretched forward of their body and the other stretched backward while in the air, Figure 1. The goal of the movement is to create the illusion that the dancer is floating through the air. From the moment of takeoff to the instant of landing, the dancer's center of gravity follows a parabolic trajectory. Thus, the movement can be considered a projectile motion.

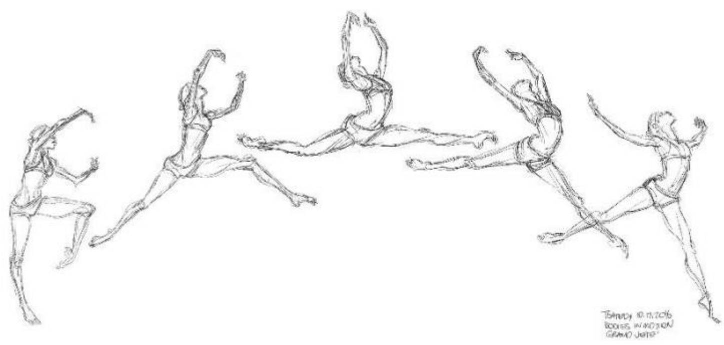

Figure 1: Flight phases of a Grand Jeté (Eaton, 2019)

Dominance and Ambidexterity

Leg dominance and non-dominance is important in the world of dance. Oftentimes, dancers tend to practice on their preferred leg which causes their non-dominant leg to not be as stable or trained as their dominant leg. This discrepancy between the skill level of the dancers' dominant and non-dominant sides may result in injury if they are not careful. When participating in choreography that the dancers themselves did not create, they may be required to perform a move on their non-dominant side. If that side of the body is not trained or strong enough, the movement may result in injury due to instability and lack of skill and force dissipation on that side. Leg dominance and non-dominance in dance, as well as other sports, is so important and relevant to the world of sports and injury that the Performing Arts Medical Association held an entire conference addressing the issue of leg dominance in June 2002 in Colorado (Martin, 2002). In addition, Robinson conducted a dance-medicine study in Canada and found that 312 out of 397 of the adolescent pre-professional ballet dancers in one residential program preferred using their left leg to turn away from and toward the right. This preference of the left leg may suggest that dance programs can influence dancers' chosen dominant leg, resulting in more discrepancy between the dominant and non-dominant sides due to the increased use of the preferred side in the dance program. Marika Molnar, a physical therapist from New York City Ballet, found that dancers tend to commonly use their preferred supporting leg for turning while warming up before class or any time after class (Martin, 2002).

Approximately 90% of the population is right-handed and right-footed (Martin, 2002). In most dance programs, combinations will start with the right leg. As a result, dancers typically spend more time marking and practicing the movements to the right. During advanced classes, choreography combinations are typically taught on the right and then are only quickly marked to the left, or not at all, before running through the combination on the left side. This causes there to be less time spent performing the movements to the left. Choreographers typically create movements from their own physical viewpoint, which would primarily be right dominant (Martin, 2002). In this traditionally right dominant dance world, dancers use their right leg to gesture and their left leg to support. Using the left leg constantly for support and the right leg for landing risks wearing out the ankle, knee, and hip joints on both sides (Martin, 2002). Due to the strain of supporting the dancer during all movements, Dr. Rietveld found that dancers' left hips were replaced more often than the right.

Structural differences between dancers can exacerbate the wear-and-tear on the hip joint during the moments of stress. For example, one dancer might have hip sockets that do not cover the entirety of the femoral head, while another dancer might have one femur that is longer than the other (Martin, 2002). Structural differences between the dominant and non-dominant sides can drastically change the stability, strength, and skill ability between the two sides, possibly resulting in injury. These structural differences may also be the result of individual dancer behavior. Repetitive movements or habits of the dancer may cause functional changes due to the overuse or underuse of the area or side of the body. For example, right handed individuals tend to have a lower right shoulder than those who are left handed. With regards to dancers, one side of a dancer's pelvis may be higher or lower, depending on which leg is dominant (Martin, 2002). Such functional differences develop over time instead of from at birth. With the use of stress-sensitive instruments, dance-medicine researchers Marijeanne Liederbach, PT (director of research and education of the Harkness Center for Dance Injuries at the Hospital for Joint Diseases in New York City), and Virginia Wilmerding, Ph.D. (a flamenco expert at the University of Mexico) discovered that dancers' dominant legs and hips take the brunt of their hard work (Martin, 2002). These dance-medicine researchers found that the supporting leg worked harder and the landing leg in jumps was more vulnerable to injuries (Martin, 2002). These studies emphasize the importance of equal training on both sides of the body to prevent injury. Dancers should focus on ambidexterity when building strength, balance, and technique. Ambidexterity will allow the dancers to perform movements on both sides, equally distributing the wear and tear associated with supporting and landing the movements. Dancers should be sure to equally train on both sides even if that means that they need to practice on the less-trained side before or after practices that are run by an instructor if the instructor does not prompt dancers to do so during rehearsal (Martin, 2002).

Footwear

Ballet dancers commonly wear pointe shoes when performing Grand Jeté. These shoes have a wooden block inserted into the tip of the shoe to help dancers reach full extension of the ankle joint while on their toes. Pointe shoes have soft leather soles and a hard tip of paper, tissue, and hardened glue, with a small flat surface in the front. The shoes are not well suited for walking and are generally very slippery and stiff.

Figure 2*:* **Pointe shoe footwear** ***(capezio.com)***

Pointe shoes were first used at the beginning of the 19th century in the Romantic Age. At this time, ballerinas were meant to represent an almost illusionary female and an emblem of purity (Hoogsteyns, 2013). Pointe shoes were created to lift the dancer off the floor and produce the illusion that the dancer is floating (Hoogsteyns, 2013). Unfortunately, most dance shoes are designed for aesthetic reasons. Pointe shoes must be pliable, yet supportive. While wearing pointe shoes, the dancer's foot is required to absorb a significant amount of force in a small area on the toes, which may lead to structural changes of the foot and a higher risk of injury (Kwon et al., 2008). The shoes also may throw dancers off balance, resulting in increased tension and stiffness in the knee joint. Several studies have shown that increased joint angular stiffness is associated with decreased joint angular displacement and increased moments, thereby increasing the risk of bony injury (Abernethy et al., 1978: Butler et al., 2003; Cavanagh et al., 1980).

Dancing on pointe requires complete plantar flexion of the foot and ankle to a combined minimum of 90 degrees. The ankle is believed to be stable in the full pointe position because the posterior lip of the tibia locks onto the calcaneus and the subtalar joint is locked with the heel and forefoot in varus (Shah, 2010). Unfortunately, the stability of the pointe position has no impact on the landing stability of a dancer in point shoes. This is because dancers do not land leaps in the pointe position. Dancers are required to land leaps on the bottom of their foot, which automatically decreases the stability of their ankle joint due to the lack of contact of the entirety of the bottom of the dancers' foot with the ground, as well as the shoe's design to provoke the dancer to spend as little time out of the pointe position as possible. Pointe shoes are designed to provide flexibility of the ankle joint to allow dancers to reach the peak pointe position, as well as complete inversion and eversion for aesthetic and functional reasons when on the balls or heels of their feet. Landing with their foot flat on the floor exposes the dancers to the risk of inversion or eversion of the ankle joint due to the instability of the shoe and the freedom of movement at the ankle joint provided by the shoe. Dancing barefoot allows dancers to make full contact with the floor when landing. Contrastingly, dancing in pointe shoes keeps the medial and lateral edges of the dancers' feet from touching the floor, which requires the dancers to land leaps balancing on the middle of their foot without using the edges of their feet for support. This lack of stability combined with increased landing force exposes the joints to a higher risk of injury.

Simply walking in pointe shoes doubles the peak pressures acting on the foot compared to barefoot (Shah, 2010). While in the full pointe position, the dancer's body weight is supported on the tips of the toes. The average pressure on the toe box while on pointe is 220psi (Shah, 2010). Pointe shoes absorb some of the impact from jump landings, but the load must also be dissipated throughout the foot and ankle complex. One study that compared five popular pointe shoe styles found that the compressive strength of the shoes was 4,300 Newtons or less. This means that a 60 kg ballerina landing on pointe from a height of one meter generates a force of impact of about 4,950 Newtons (Cunningham et al., 1998). This high force can be a risk factor for the development of injuries. The annual incidence of injuries in the ballet dance style alone is 75-85%, based primarily on retrospective studies. The most common injury locations are the foot and ankle, with ankle sprains being the most common. Other common injuries that occur due to the use of pointe shoes are bunions, traumatized toenails, corns and calluses, cortical hypertrophy of the first, second, and third metatarsals, posterior impingement syndrome, and injuries of the flexor hallucis longus and peroneal tendons (Anderson et al., 1993; Bayley et al., 1991; Bo et al., 2002; Bowling et al., 1989; Bronson et al., 1974; Leanderson et al., 2001; McGray et al., 1999; Miller et al., 1982; Ryan et al., 1987; Shah, 2010).

Due to the risks of dancing in pointe shoes, there are five requirements that one must meet before beginning their training on pointe. First, dancers must be at least 11 years old before they begin training on pointe. Although the proper age to start pointe work is controversial and many instructors only rely on ability to determine when their dancers can start, young dancers should refrain from beginning their pointe training until they are at least 11 years old. This is because the growth of the foot is about complete at age 11 or 12 so the introduction of dancing on pointe will no longer have the risk of interfering with the growth and development of the dancers' feet (Bedinghaus, 2018). Next, dancers must have at least three years of ballet training before they begin pointe training. This is because dancers must have enough time to achieve the form, strength, and alignment needed to make a successful transition into pointe work. Proper technique is essential in order to properly rise on the toes without increased risk of injury. Dancers should also consider being enrolled in at least three ballet classes each week before beginning their pointe training. In order to maintain the proper technique and flexibility needed for pointe work, it is imperative that all dancers practice ballet formally three days per week at a minimum. All added pointe training should be done towards the end of class to ensure that the entire body, especially the feet and ankles, are properly warmed up. Next, all dancers should be formally evaluated by their ballet instructor to determine if they are physically ready to meet the demands of pointe work. Instructors should evaluate dancers based on their body position and alignment, turnout, strength and balance, and mastery of basic ballet techniques. Finally, before beginning pointe training, dancers must be certain that they are emotionally ready for the task. Dancing on pointe is physically and mentally demanding, complicated, and time consuming. All dancers must be certain that they are willing to risk experiencing physical discomfort and dedicating numerous hours per week towards training and maintenance of their pointe shoes (Bedinghaus, 2018).

Aside from wearing pointe shoes, dancers also commonly dance barefoot or in shoes that focus on high flexibility and reduced cushioning to imitate barefoot situations while allowing the dancers to freely turn and move about the floor. In literature, shoes with minimal cushioning and weight and/or increased sole flexibility, which includes flimsy ballet shoes, foot undies, and jazz shoes, are referred to as minimalist shoes, lightweight shoes, or barefoot shoes (Hentschke et al., 2013). It is questionable, however, whether these shoes have beneficial effects or temporarily increase the risk for adverse effects. To this date, no evidence exists to prove that minimalist shoes provide enough stability during the complex movements required during dancing, such as dynamic stabilization following jumping, turning, and change of direction (Hentschke et al., 2013). Studies have shown that, compared to dancing barefoot, the use of footwear increases stiffness in the lower extremity during hopping and jump landing, joint excursion at the ankle, and lower extremity muscle activation during jump landing stabilization (Bishop et al., 2006; Kulas et al., 2012). These effects of dancing in shoes can be partly attributed to the different mechanical strategies employed for controlling peak impact forces during jumping and landing.

Although dancing in minimalist shoes has been shown to contribute to joint instability, there is also a notion that dancing barefoot comes with its own biomechanical challenges. Dancing barefoot requires strong foot and ankle supporter muscles, as well as increased joint stability and balance capabilities. When landing with and without shoes, dancers must be wary of the surface they are landing on to prevent slipping, landing on unexpected small items on the floor or stage, and prevent infection and cuts on the bottom of their feet. Without shoes, dancers' feet are not cushioned during landings and turns, which may result in severe bruising, calluses, or even bony damage of the foot from landing with high landing forces. Landing on one foot from a leap exposes dancers to high force moments that need to be dissipated by one limb, resulting in the risk of extreme ankle and/or knee instability, compression, and muscle failure. Landing in this manner has been found to be one of the main causes for accidental ankle inversion amongst dancers. However, there are some benefits of dancing barefoot, including increased control over motion due to increased contact with the ground, increased sticking to the floor due to the abrasion of the skin on the floor, and the ability to compensate for poor landings due to the flexibility allowed by not wearing shoes that inhibit the motion of the ankle joint. Due to the mixed reports of how footwear impacts dance landings, the intent of this study was to examine the effects of the pointe shoe on the vertical ground reaction force and joint angular displacements of landing a Grand Jeté. The results of this study provide instructors, practitioners, and dancers with critical information about how to prepare dancers' bodies to withstand the force and joint displacements imposed by pointe shoes.

Methods

Participants

Seven right leg dominant female college dancers (age: 20.4 ± 1.5 years old, height: 1.63 ± 0.06 meters, mass: 62.8 ± 4.5 kilograms, dance experience: 17.6 ± 2 years in a variety of disciplines) were recruited to participate in this study. All recruited dancers had numerous years of training in ballet, contemporary, hip hop, and jazz and had 1-2 years of experience dancing in pointe shoes. Leg dominance was determined by asking the dancers which leg they naturally choose to practice and perform movements on and then confirmed by having dancers fall forward and determine which leg they bring forward to catch themselves. Participants were recruited from the Bridgewater State University Dance Company. All participants were free of injury or illness that could impact their performance of the movement. Each participant's age, height, weight, years of dance and pointe experience, and dominant leg were recorded. Institutional Review Board permission was acquired and written informed consent was obtained from each participant prior to the study. A pair of new Capezio pointe shoes was provided for each dancer to prevent any skewing of the data resulting from the use of worn-out shoes. Capezio Ouch Pouches were provided for the dancers to cushion their toes to allow the dancers to perform the movement with full intensity without experiencing significant toe pain. A foot roller was also available for the dancers to use to stretch and massage the muscles in their feet after completion of their trials. Participants were briefed on the study protocol and were informed that they had the right to withdraw from the study at any time without penalty. All dancers were instructed to wear athletic clothing that did not limit their range of motion.

Protocols and Experimental Set Up

All participants were tested at the Biomechanics Laboratory in the Adrian Tinsley Center at Bridgewater State University. Participants had minimal experience with Capezio pointe shoes and were allotted five to ten minutes to warm-up and feel comfortable with the shoes. After their warm-up, dancers were given detailed instructions about the experimental protocol and required movement. Each participant was allowed 2-3 practice trials to mark where they needed to begin the movement to land directly on an AMTI force plate that was operated at 1000 Hz.

Five joint reflective markers were placed on each side of the dancers' bodies, at the shoulder (acromion), hip (greater trochanter), knee (lateral epicondyle of the femur), ankle (lateral malleolus), and toe (base of the fifth metatarsal), Figure 3.

Figure 3: Positioning of reflective joint markers on both sides of the body to allow tracking and analysis of joint angles.

All participants were instructed to perform a Grand Jeté at maximal effort, landing on one foot on the force plate. Maximal effort of the movement would indicate that the dancers reach their individual maximum height and split in the air before they land, and this effort was monitored and confirmed with the use of a Casio high speed video camera (Model: EX-FH25) that was positioned to capture the sagittal view of the Grand Jeté at 120 Hz. Each dancer performed the movement three times landing on the dominant foot, three times landing on the non-dominant foot, three times landing on the dominant foot wearing the pointe shoes, and three times landing on the non-dominant foot wearing the pointe shoes, Figures 4 & 5.

Figure 4: Phases of a Grand Jeté completed barefoot on participant's dominant leg.

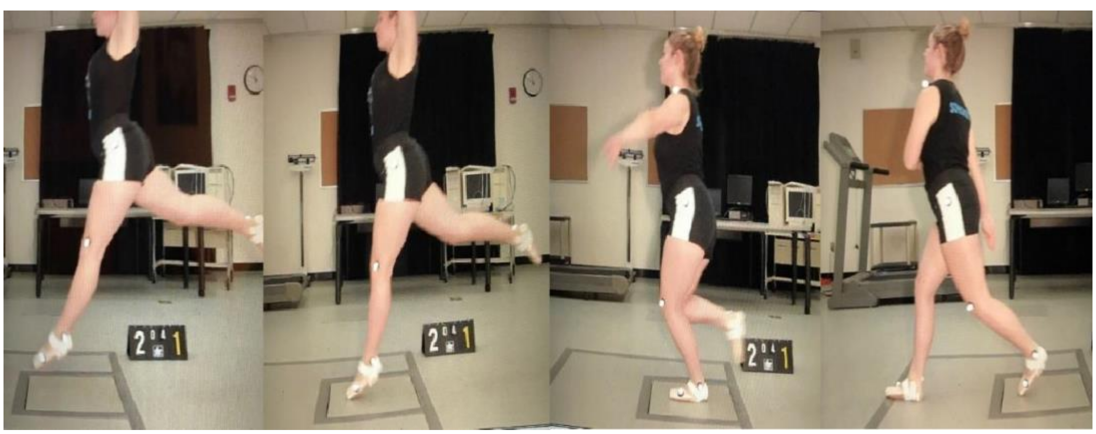

Figure 5: Phases of a Grand Jeté completed in pointe shoes on participant's non-dominant leg.

The order of the testing conditions was randomized to reduce any order effect. Dancers were allowed 30-60 seconds between each trial to reset their position and prepare for the next trial. A total of 12 trials were collected for each participant and a total of 84 trials were collected in the study.

Instrumentation and Statistical Analysis

A Casio high speed video camera (Model: EX-FH25) was positioned to capture the sagittal view of the Grand Jeté jumping and landing motion at 120 frames per second to identify the instant of impact on the force plate, Figure 6.

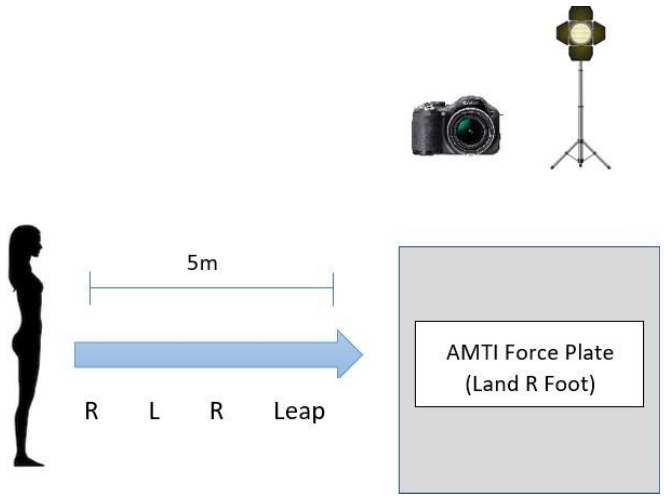

Figure 6: Set up of equipment during the testing procedure for dominant side.

A standard two-dimensional kinematic motion analysis of the lower extremity joints was conducted using the fractional linear transformation. The joint angular displacements were analyzed using the Ariel Performance Analysis System (APAS^{TM}). The force plate information was collected through Vicon Nexus (Version 1.8). A two-way (2 sides of the body x 2 landing footwear conditions) repeated measure ANOVA was conducted at $\alpha = 0.05$. A t-test with a Bonferroni adjustment was used to further investigate statistically significant differences. All statistical analyses were conducted using SPSS (Version 23).

Results

Vertical Ground Reaction Force

A two-way (2 sides x 2 footwear conditions) ANOVA repeated measure test was conducted at α = 0.05 of the vertical ground reaction force of each phase of landing a Grand Jeté. The results of this study yielded no statistically significant difference in vertical ground reaction force during the three phases (initial/maximum, minimum, or toe-off) of landing when completing a Grand Jeté at maximum effort/intensity between the barefoot and pointe shoe conditions, as well as between the dominant and non-dominant legs. From the ANOVA statistical analyses (statistically significant at $p < 0.05$), the main effect of side, dominant vs. non-dominant ($p = 0.078$), was approaching significance during the first phase of landing the Grand Jeté. This observable difference indicates that the initial landing force of the dominant (right) leg was consistently less than the initial landing force of the non-dominant (left) leg in both barefoot and shoe conditions, Table 1 & 2. Please note that the tables reflect the results from the t-test with a Bonferroni adjustment and not the two-way repeated measure ANOVA.

Table 1. Initial/maximum vertical ground reaction force between footwear and side conditions

Max GRF (N)	**Barefoot** Mean ± SD	**Shoe** Mean ± SD	***p***
Dominant (Right)	1837 ± 584	1895 ± 394	*0.819*
Non-Dominant (Left)	2033 ± 588	2227 ± 504	*0.353*
p value	*0.388*	*0.135*	

Statistically significant at $p < 0.013$

Table 2. Normalized body weight for maximum ground reaction force between footwear and side conditions

Max GRF of BW	Barefoot	Shoe	
	Mean ± SD	Mean ± SD	*p*
Dominant (Right)	3.01 ± 1.03	3.07 ± .61	*0.877*
Non-Dominant (Left)	3.35 ± 1.11	3.66 ± 1.01	*0.321*
p value	*0.353*	*0.113*	

Statistically significant at p < 0.013

With regards to the minimum force/maximum dorsiflexion in the second phase of landing a Grand Jeté, no significant differences were found in the force of landing for the dominant leg between barefoot (1,149 ± 265 N or BW: 1.86 ± .38) and pointe shoe (1,100 ± 297 N or BW: 1.77 ± 0.39) conditions. Similar findings were observed in the force of landing for the non-dominant leg between barefoot (1,190 ± 290 N or BW: 1.95 ± .56) and pointe shoes (1,208 ± 175 N or BW: 1.96 ± 0.28). For the last phase (toe-off) of completing a Grand Jeté, no significant differences were found in the force of landing for the dominant leg between barefoot (1,405 ± 342 N or BW: 2.66 ± 0.48) and pointe shoe (1,342 ± 232 N or BW: 2.17 ± 0.32) conditions. Similar findings were observed in the force of landing for the non-dominant leg between barefoot (1,451 ± 317 N or BW: 2.37 ± 0.54) and pointe shoes (1,355 ± 210 N or BW: 2.21 ± 0.40).

Joint Angular Displacement

Joint angular displacement data of the hip, knee, and ankle were calculated through APAS™ and then analyzed using SPSS (Version 23). A two-way repeated measure ANOVA test was conducted at $\alpha = 0.05$ of the joint angular displacements of the hip, knee, and ankle of all three phases of landing a Grand Jeté. The results of this study showed no statistically significant difference between the angles of the hip and knee during the three phases of landing a Grand Jeté at maximum effort/intensity between the barefoot and pointe shoe conditions, as well as between the dominant and non-dominant legs, Table 3 - 8. From the statistical analyses, a significant difference was found at the ankle joint during the initial, dorsiflexion, and toe-off phases of landing, Table 9-11. A post-hoc Bonferroni t-test adjustment was conducted at $\alpha < 0.013$ ($0.05 \div$ # of comparisons $= 0.05 \div 4 = 0.013$). Please note that the tables reflect the results from the t-test with a Bonferroni adjustment and not the two-way repeated measure ANOVA.

Table 3. Hip joint angular displacement during initial landing phase

Joint Angles (˚)	**Barefoot** Mean ± SD	**Shoe** Mean ± SD	***p***
Dominant (Right)	168.51 ± 4.81	167.64 ± 4.32	*0.422*
Non-Dominant (Left)	167.20 ± 7.86	166.71 ± 8.10	*0.279*
p value	*0.944*	*0.924*	

Statistically significant at p < 0.013

Table 4. Hip joint angular displacement during maximum dorsiflexion landing phase

Joint Angles (˚)	**Barefoot** Mean ± SD	**Shoe** Mean ± SD	***p***
Dominant (Right)	155.33 ± 7.77	152.01 ± 10.25	*0.422*
Non-Dominant (Left)	155.34 ± 8.57	151.57 ± 11.99	*0.279*
p value	*0.994*	*0.924*	

Statistically significant at p < 0.013

Table 5. Hip joint angular displacement during toe-off landing phase

Joint Angles (˚)	**Barefoot** Mean ± SD	**Shoe** Mean ± SD	***p***
Dominant (Right)	172.89 ± 2.75	174.34 ± 3.20	*0.488*
Non-Dominant (Left)	171.67 ± 4.09	173.34 ± 3.34	*0.369*
p value	*0.391*	*0.656*	

Statistically significant at p < 0.013

The results of the knee joint angular displacement showed no statistically significant difference between the footwear and side conditions during the initial and maximum dorsiflexion landing phases of the Grand Jeté, Table 6 & 7. However, the knee joint angular displacement data from the two-way repeated measure ANOVA test showed a statistically significant difference between the footwear in general ($p = 0.018$) during the toe-off phase of stepping off the force plate upon completion of the landing but was not found statistically significant (dominant: $p = 0.015$, non-Dominant: $p = 0.035$) during the t-test with a Bonferroni adjustment at $p < 0.013$, Table 8.

Table 6. Knee joint angular displacement during initial landing phase

Joint Angles (˚)	**Barefoot** **Mean ± SD**	**Shoe** **Mean ± SD**	***p***
Dominant (Right)	157.57 ± 5.27	158.37 ± 5.87	*0.543*
Non-Dominant (Left)	157.10 ± 6.19	157.52 ± 6.83	*0.534*
p value	*0.749*	*0.770*	

Statistically significant at p < 0.013

Table 7. Knee joint angular displacement during maximum dorsiflexion landing phase

Joint Angles (˚)	**Barefoot** **Mean ± SD**	**Shoe** **Mean ± SD**	***p***
Dominant (Right)	129.96 ± 6.13	131.37 ± 6.89	*0.502*
Non-Dominant (Left)	133.09 ± 5.80	130.30 ± 3.96	*0.075*
p value	*0.347*	*0.588*	

Statistically significant at p < 0.013

Table 8. Knee joint angular displacement during toe-off landing phase

Joint Angles (˚)	**Barefoot**	**Shoe**	
	Mean ± SD	**Mean ± SD**	***p***
Dominant (Right)	134.98 ± 10.09	146.23 ± 6.03	*0.015*
Non-Dominant (Left)	138.89 ± 7.56	146.78 ± 3.56	*0.035*
p value	*0.264*	*0.826*	

Statistically significant at $p < 0.013$

A two-way (2 sides x 2 footwear conditions) repeated measure ANOVA test was conducted at $\alpha = 0.05$ of the ankle joint of all three phases of landing a Grand Jeté. The statistical analyses of the ankle joint during the initial landing phase of the Grand Jeté showed no significant difference between the footwear conditions alone. Additionally, the data showed no significant difference between the footwear conditions compared with the dominant and non-dominant sides. There was a significant difference noted between the landing sides (dominant and non-dominant) not compared to footwear ($p = 0.028$) during the repeated measure ANOVA. During the maximum dorsiflexion phase of landing, the joint angular displacement ankle data showed a statistical significance between the footwear conditions at $p = 0.007$, while the differences between the landing sides and sides compared with footwear showed no statistical significance. Finally, during the toe-off phase of the landing, a statistical difference was again found between the footwear conditions ($p = 0.021$), but no statistical significance was found between the landing sides and footwear compared with landing sides.

Table 9. Ankle joint angular displacement during initial landing phase

Joint Angles (˚)	Barefoot Mean ± SD	Shoe Mean ± SD	*p*
Dominant (Right)	137.17 ± 6.45	136.18 ± 5.22	*0.679*
Non-Dominant (Left)	134.01 ± 6.63	129.51 ± 5.23	*0.007*
p value	*0.129*	*0.025*	

Statistically significant at p < 0.013

Table 10. Ankle joint angular displacement during maximum dorsiflexion landing phase

Joint Angles (˚)	Barefoot Mean ± SD	Shoe Mean ± SD	*p*
Dominant (Right)	72.48 ± 5.79	63.23 ± 5.62	*0.001*
Non-Dominant (Left)	75.51 ± 11.84	64.03 ± 6.62	*0.028*
p value	*0.468*	*0.848*	

Statistically significant at p < 0.013

Table 11. Ankle joint angular displacement during toe-off landing phase

Joint Angles (˚)	Barefoot Mean ± SD	Shoe Mean ± SD	*p*
Dominant (Right)	124.23 ± 9.54	112.96 ± 31.38	*0.306*
Non-Dominant (Left)	124.85 ± 10.06	99.25 ± 4.67	*0.000*
p value	*0.926*	*0.267*	

Statistically significant at p < 0.013

To further investigate the extent of the statistical significance, a t-test with a Bonferroni adjustment was performed at $p < 0.013$ for the footwear comparison of the knee joint angular displacement during the toe-off phase of landing, the ankle displacement during the initial landing phase between the landing sides, the ankle displacement during the maximum dorsiflexion phase between the footwear conditions, and the ankle displacement during the toe-off phase of landing between the footwear conditions. The results of the t-test showed that there is an approaching significant difference between the barefoot and pointe shoe conditions on the right side of the toe-off phase of the knee (p = 0.015), Table 8. The ANOVA statistical analyses of the ankle regarding the initial phase of landing showed a significant difference between the dominant and non-dominant sides of the body at p = 0.028. Contrastingly, the t-test showed a statistically significant difference between the footwear conditions, rather than the side conditions, on the left ankle displacement during the initial phase of landing at p = 0.007, Table 9. The repeated measure ANOVA of the ankle during the dorsiflexion phase of landing found a p value of p = 0.007 between the footwear conditions. The results of the t-test indicate that there is a statistically significant difference regarding the footwear conditions on the right side during the dorsiflexion phase of landing (p = 0.001), Table 10. The repeated measure ANOVA of the ankle during the toe-off phase showed a significant difference of p = 0.021. When investigating further with a t-test, a statistically significant difference was found between the barefoot and pointe shoe conditions on the left ankle side at p = 0.000, Table 11.

Discussion

The purpose of this study was to examine both the kinetic and kinematic measurements in the skill of a Grand Jeté between barefoot and pointe shoe footwear for dominant and non-dominant legs. Based on the statistical analyses of this study, two observations can be made. First, the effects of the pointe shoe footwear have a greater influence on the non-dominant leg than on the dominant leg. The pointe shoes may alter the ankle joint angular displacement to be greater or smaller depending on the phase of landing. Next, the footwear does not affect vertical ground reaction force. However, leg dominance may have a greater influence on the vertical ground reaction force.

The results of this study yielded no statistically significant difference during the three phases (initial/maximum, minimum, or toe-off) of landing in vertical ground reaction force when completing a Grand Jeté at maximum intensity between the barefoot and pointe shoe conditions, as well as between the dominant and non-dominant legs. However, the two-way repeated measure ANOVA indicated that the main effect of side, dominant vs. non-dominant, was approaching significance (p = 0.78) during the initial landing phase. This observable difference indicates that the initial landing force of the dominant (right) leg was consistently less than the initial landing force of the non-dominant (left) leg in both barefoot and shoe conditions.

The statistical analyses of the joint angular displacements yielded no statistically significant difference in the joint angular displacement of the hip during all three phases of landing, as well as in the knee during the first two phases of landing. The results did show an approaching significant difference of the joint angular displacement of the knee during the toe-off phase between the footwear conditions on the dominant (right) side of the body. The results also found a statistically significant difference in joint angular displacement of the ankle joint during all three phases of landing a Grand Jeté. Specifically, a difference was found between the footwear conditions on the non-dominant (left) ankle side during the initial phase of landing, the footwear conditions on the dominant (right) ankle side during the dorsiflexion phase of landing, and the footwear conditions on the non-dominant (left) ankle side during the toe-off phase of landing.

Previous research studies have shown that the ground reaction force upon landing a jump or leap can be as much as 3.5-8.0 times a person's original body weight (Ferris et. al., 1997; McNitt-Gray 1993), and this study showed between 3.0-3.7 times a person's body weight. The difference between the current study and previous literature may be due to the type of leaping and landing activity and as well as the intensity and the skill level of the participants. Also, this preliminary dance research study examined the vertical ground reaction force that occurred in the sagittal plane of the primary landing movement in three critical phases of landing a Grand Jeté at maximum effort between barefoot and pointe shoe and as well as between dominant and non-dominant legs. The effects of the pointe shoe did not show any significant change in the vertical ground reaction force of landing in both dominant and non-dominant legs in all three phases. A possible explanation may be that the influence of effort/intensity of jumping and landing is greater than the influence of footwear, so there was no significant difference observed since all dancers performed a Grand Jeté at maximal effort. Another possible explanation may be that the dancers were able to change their lower limb kinematic joint angles and velocities at landing when wearing pointe shoes with toes fully extended to enable them to absorb the landing force.

This study further investigated the effects of asymmetry between dominant and non-dominant legs. Even though no significant difference in vertical ground reaction force was found between dominant and non-dominant legs in all three phases of landing, a lower force of landing was consistently observed in the dominant leg when compared to the non-dominant leg in all three phases of landing in the barefoot and pointe shoe conditions. This difference in landing force may be attributable to a bilateral difference in technique and muscular strength, which may allow dancers to dissipate landing forces more effectively on the dominant (right) side, lowering the landing force on that side.

Wyon, Harris, Brown, and Clark (2013) conducted a Grand Jeté study that found a difference in landing force between the dominant and non-dominant leg over the course of three trials. However, this study did not find a significant difference between the dominant and non-dominant legs, but the data showed it was approaching significance in the initial/maximum landing phase. The difference in findings between this current and previous study may be due to the different skill levels of the examined populations since the previous study used 20 female dancers who were in their final year of the same pre-professional dance program at a contemporary conservatoire. Contrarily, the participants in this study were all young college dancers taught at different studios and taught by different instructors, which may contribute to the difference in technique and bilateral proficiency. Additionally, the results of the Wyon et al. study (2013) were collected from the best trial, rather than as a mean of all three trials as done in this preliminary study. It was also not indicated whether the dancers in their study were allotted a warm-up, which would impact the effort/intensity of each trial because some of the trials might have possibly been performed at a lower effort/intensity while the dancers were getting used to the movement and warming up, rather than performing at the same maximum effort for each trial and each condition as done in this current study. This could contribute to the observed increase in force over the course of three trials as seen is the Wyon et al. study (2013).

This study also observed the joint angular displacements during the three phases of landing a Grand Jeté of the hip, knee, and ankle joints with the intention of determining how footwear and leg dominance impact the degree of joint angular displacement. Extreme joint angular displacement while landing is proven to be a leading cause of acute injury amongst dancers due to the unstable landing positions that dancers are often required to assume. The tendency of dancers to land in positions consisting of unstable joint angles places dancers at a higher risk of injury because they are subjecting their joints to high forces in these moments that may surpass their joints' force withstanding threshold at that landing angle. Dancers must also maintain a degree of stiffness in their joints when landing to support their body to achieve and maintain the desired aesthetic, yet unstable, landing position, which will also predispose them to a higher risk of injury. In fact, several studies have shown that increased joint angular stiffness is associated with decreased joint angular displacement and increased moments, thereby increasing the risk of bony injury (Abernethy et al., 1978: Butler et al., 2003; Cavanagh et al., 1980). Since the dancers must achieve the desirable aesthetics of their landing by maintaining a degree of joint angular stiffness, they will be unable to allow their joints to naturally bend to a position that would allow for the greatest amount of force dissipation and the least amount of force directed on the joints themselves.

The introduction of pointe shoes further impacts joint angular displacement and stability by minimizing the contact of the dancers' feet with the ground. Pointe shoes also result in increased instability in any position other than full pointe position. The ankle is believed to be stable in the full pointe position because the posterior lip of the tibia locks onto the calcaneus and the subtalar joint is locked with the heel and forefoot in varus (Shah, 2010). However, since dancers do not land a Grand Jeté in full pointe position while wearing the shoes, they are considerably landing in an unstable position. The unstable landing position combined with the high forces of landing may be significant enough to overload the joint and result in a sudden and debilitating injury of that joint. Additionally, as the initial landing force of the non-dominant side was greater than the initial landing force of the dominant side, regardless of footwear, it can be inferred that dancers may have a higher risk of injury when landing on their non-dominant side rather than their dominant side. The higher force when landing on the non-dominant side may also be enough to overload the joints in their unstable positions to result in injury of the joint.

The statistical data analyses of this study also suggest that when landing on the non-dominant (left) side, footwear has a higher impact on ankle joint angular displacement during the initial and toe-off phases of landing. It was observed that on the non-dominant (left) side, the pointe shoes resulted in increased plantarflexion during the initial phase of landing and increased dorsiflexion during the toe-off phase of landing. The impact of footwear on the joint angular displacement of the non-dominant side may be especially profound amongst novice dancers, who tend to have more observable bilateral asymmetries due to an increased volume of training on their preferred side. Since joint angular displacement is impacted by footwear, it is important that dancers understand that their non-dominant leg may be at higher risk of injury due to a higher landing force and a significant difference between joint angular displacements of the ankle when landing on their non-dominant side. Dancers must understand that they must account for these differences instead of landing the leap the same way on both sides of the body in any footwear conditions.

The dominant (right) side of the body also proved to have a significant difference between the footwear conditions regarding the joint angular displacement of the ankle during the dorsiflexion phase of landing. It was observed that the pointe shoes resulted in increased dorsiflexion of the dominant (right) side ankle during the dorsiflexion phase of landing. This may be attributable to the greater flexibility and stability of the dominant side, which allowed the dancers to sink into a greater degree of dorsiflexion when landing to help dissipate the landing forces and support themselves more effectively during their landing. It is important to note that the dominant side ankle joint experienced a pointe shoe induced statistically significant difference in joint angular displacement during the maximum dorsiflexion phase of landing because it shows that although the dominant leg tends to be more trained, the dominant side is still not immune to factors that require a change in technique and training in order to protect against the risks posed by these changes. Although the greater degree of dorsiflexion observed on the dominant side may be beneficial for dissipating landing forces when wearing the pointe shoe, the ankle joint may be more susceptible to injury due to its unstable position. In fact, the ankle joint is believed to be in its most unstable position at maximum dorsiflexion compared to the full pointe position when wearing pointe shoes, which places dancers at an even higher risk of injury during the maximum dorsiflexion phase of landing when wearing the shoes because they are subjecting their ankle joint to a substantial amount of force when landing in a significantly unstable position.

A few observations can be made based on the results of this study. First, it can be determined that the non-dominant side may have less strength and ability, which may cause the greater impact forces during the initial landing phase of the Grand Jeté. If the non-dominant leg has had less training and conditioning compared to the dominant leg, it may lack the muscular strength, flexibility, and technique needed to dissipate the landing forces as effectively as the dominant leg. In order to achieve bilateral symmetry between the landing forces and joint angular displacements, instructors and dancers must be certain that they train both sides of the body equally in all aspects of their training (i.e. strength, conditioning, flexibility, and dance technique). It is of utmost importance that instructors encourage their dancers to practice and perform all skills and choreography on both sides in order to prevent any bilateral asymmetries that could contribute to a higher risk of injury over time. The prevention of bilateral asymmetry is of highest importance regarding the novice dancer population. If asymmetry is addressed early in the dancers' careers, it may protect novice dancers from bilateral asymmetry related injuries in the years to come.

Next, it is likely that the non-dominant side may have less strength and stability which could account for the statistical difference of joint angular displacements when wearing pointe shoes. The effect of footwear may cause the non-dominant leg to have greater plantarflexion while initially landing and greater dorsiflexion during the toe-off phase. The results of this study found a statistically significant difference on the non-dominant side when wearing pointe shoes during the initial and toe-off phases of landing at the ankle joint. These differences may be attributable to the lack of strength and stability on the non-dominant side as compared to the dominant side, which may impact the joint angular displacement of the ankle. It is possible that when landing on the non-dominant side, the dancers' ankle joints were not strong enough to support the force of landing in a dorsiflexed position that would allow for a greater degree of force dissipation. This would account for the greater degree of plantarflexion when landing on the non-dominant side when compared to landing on the dominant side. Without the strength and stability to withstand the higher landing forces of landing on the non-dominant side, the ankle joint would naturally employ greater joint stiffness in order to protect the ankle joint from transitioning into a more unstable position that may have a higher risk of a force-related injury. In this case, the dancers subconsciously push their foot into the floor to resist the landing force and maintain their balance, instead of sinking into a greater degree of dorsiflexion to help absorb the impact. Perhaps the lack of strength and stability on the non-dominant leg prevented the dancers from instantaneously undergoing a greater degree of dorsiflexion at the ankle joint. It is possible that the strength curve of the dancers' non-dominant ankle is unable to withstand the force of landing in extreme dorsiflexion, which could result in the dancer maintaining a greater degree of plantarflexion while landing on the non-dominant side. It is also possible that dancers tend to maintain a greater degree of plantarflexion when landing on the non-dominant side because plantarflexion is the most stable position of the ankle joint when wearing pointe shoes. The dancers may try to regain that stable position upon landing in order to protect their joint from any injury resulting from instability.

Some limitations should be considered in this study. This study had seven young college dancers and it demonstrated that the main effect of side (dominant vs non-dominant leg) with regards to vertical ground reaction force was approaching significance. Despite the lack of statistical significance found in this study regarding the landing force, there was an observed difference in initial ground reaction landing force between the dominant and non-dominant legs during both footwear conditions. With a greater sample size and/or less experienced dancer population, the significance may be observed. Additionally, this study did not evaluate the level of leg strength between the dominant and non-dominant legs, so the tendency towards greater landing forces on the non-dominant leg may be a result of a higher effort/intensity of the jump from the dominant leg, which may provide further understanding of the effects of jumping effort/intensity that is more critical than the footwear. This study also examined the kinematics of landing a Grand Jeté, which detected statistically significant differences between the joint angular displacements of the ankle when wearing pointe shoes. During the initial and toe-off phases of landing, a significant difference was found in joint angular displacements of the ankle between the footwear conditions on the non-dominant (left) side. A significant difference was also found at the ankle during the dorsiflexion phase of landing between the footwear conditions on the dominant (right) side. This study also found an approaching significant difference caused by the footwear conditions on the joint angular displacement of the knee on the dominant (right) side. Previous studies have shown that increased joint angular stiffness is associated with decreased joint angular displacement and increased moments, thereby increasing the risk of bony injury (Butler et al., 2003). Pointe shoes have a wooden block inserted into the tip of the shoe to help dancers reach full extension of the ankle joint while on their toes, and this wooden block may cause increased joint angular stiffness, resulting in a higher amount of force to be applied on joints that are prevented from displacing themselves freely to safely dissipate these high forces. Since a significant difference was found regarding the joint angular displacements of the ankle joint between the footwear conditions, it is presumable that the pointe shoes do, in fact, impact the joint angular stiffness and joint angular displacement of the ankle joint, which may prevent the joints from effectively dissipating the forces of landing in the joints and result in an increased risk of injury.

Future studies are warranted to further investigate the degree of joint angular stiffness imposed by the pointe shoes versus dancing barefoot in order to understand if any intervention is needed in order to protect and train dancers to combat the possible negative effect of this joint stiffness. Additionally, bilateral asymmetries and the effect of footwear may be more noticeable amongst a novice dancer population. Future studies should examine a novice dancer population and bilateral leg strength to truly determine the extent of these differences in order to develop comprehensive strength, conditioning, and training programs for novice dancers that may protect against these differences and increased risks of injury. Implementing these interventions early in dancers' careers is critical for preventing bilateral asymmetry and combating the effects of footwear that may contribute to an increased risk of injury.

This study provides a comprehensive understanding of the skill of a Grand Jeté. The information provided in this study can be utilized by practitioners, instructors, and other researchers to further increase their knowledge of the mechanics of landing a common dance leap and to learn about the effect of certain factors on landing in order to protect dancers from an increased risk of injury throughout their dance career.

Conclusion

This comprehensive study was the first to examine and quantify the effects of pointe shoes on landing force and joint angular displacement in all three phases of landing the skill of a Grand Jeté with young female college dancers. This study found no statistically significant difference between the landing legs or footwear conditions on vertical ground reaction force. However, the initial ground reaction force between the dominant and non-dominant legs was approaching significance. This study also found a statistically significant difference between footwear conditions (barefoot vs. pointe shoe) on the non-dominant (left) leg at the ankle joint during the initial and toe-off phases of landing and on the dominant (right) leg at the ankle joint during the maximum dorsiflexion phase of landing. This study suggests that dancers should identify, evaluate, and treat any bilateral asymmetries in leg strength, flexibility, and overall dance technique before wearing pointe shoes. Treating these differences and insufficiencies may lower the risk of injury associated with the effects of side and footwear. This study provides an important comprehensive understanding of the effects of pointe shoes and leg dominance on landing force and joint angular displacement when performing a Grand Jeté during three phases of landing. Future studies are warranted for further investigation of additional variables, such as leg strength, 3D landing forces, muscular fatigue, and internal joint stiffness, to provide a more comprehensive understanding of the biomechanics of a Grand Jeté and the impact of footwear and leg dominance on injury risk.

References

Abernethy, P., Chernack, R., Ehrlich, M. G., Paul, I. L., Radin, E. L., Rose, R. M. (1978). Effect of repetitive impulsive loading on the knee joints of rabbits. *Clinical Orthopedics and Related Research*, 131, 288–293.

Ambegaonkar, J. P., Brazen, D. M., Peterson, C., Todd, M. K., Wunderlich, R. (2010) The effect of fatigue on landing biomechanics in single-leg drop landings. *Clinical Journal of Sports Medicine,* 20, 286-292.

Anderson, I. F., Crichton K. J., Harrington T. (1993) Overuse ballet injury of the base of the second metatarsal. a diagnostic problem. *Am J Sports Med*; *21*(4), 591-598.

Arab, A. M., Ebrahimi, I., Moughadam, M., Salavati, M. (2007) Changes in postural stability with fatigue of lower extremity frontal and sagittal plane movers. *Gait & Posture*, 26, 214-218.

Arampatzi, A., Bruggemann, G. P., Metzler, V. (1999). The effect of speed on leg stiffness and joint kinetics in human running. *J. Biomechanics*, 32, 1349–1353.

Auyang, A. G., Chang, Y. H. (2013). Effects of a Foot Placement Constraint on Use of Motor Equivalence during Human Hopping. *PLoS ONE*, *8*(7), 1–9.

BalletHub (2018). Find, Talk, Share and Learn Ballet & Dance. Retrieved from https://ballethub.com/

Bayley, J. C., Tuckman, A. S., Werner, F. W. (1991) Analysis of the forefoot on pointe in the ballet dancer. *Foot Ankle*, 12(3), 144-148.

Bedinghaus, T. (2018). 5 Requirements to Begin Pointe Work. Retrieved from https://www.thoughtco.com/requirements-to-begin-pointe-work-1006948

Bishop, M., Brunt, D., Conrad, B., Fiolkowski, P., Horodyski, M. (2006). Athletic footwear, leg stiffness, and running kinematics. *Journal of Athletic Training, 41*(4), 387-392.

Bizid, R., Dupui, P., Francois, Y., Gonzalez, G., Jully, J. L., Margnes, E., Paillard, T. (2009) Effects of knee and ankle muscle fatigue on postural control in the unipedal stance. *European Journal of Applied Physiology*, 106, 375-380.

Bo, K., Byhring, S. (2002) Musculoskeletal injuries in the Norwegian National Ballet: A prospective cohort study. *Scand J Med Sci Sports*, *12*(6), 365-370.

Bowling, A. (1989) Injuries to dancers: prevalence, treatment, and perceptions of causes. *BMJ*; 298(6675), 731-734.

Brinson, P., Dick, F. (1996). Fit to dance? *The Report of the National Inquiry Into Dancer's Health and Injury*, 19-26.

Brock, E., Zhang, S., Milner, C., Liu, X., Brosnan, J., Sorochan, J. (2014). Effects of two football stud configurations on biomechanical characteristics of single-leg landing and cutting movements on infilled synthetic turf. *Sports Biomechanics*, *13*(4), 362-379.

Bronson, J. L., King, A. Y., Miller, E. H., Schneider, H. J. (1974) Stress injuries and developmental change of lower extremities in ballet dancers. *Radiology*, 113(3), 627-632.

en L'air." *Journal of Dance Medicine & Science*, *8*(4), 108-115.

Brown, D., Clarke, F., Harris, J., Wyon, M. (2013). Bilateral differences in peak force, power, and maximum Plié depth during multiple Grand Jetés. *Science & Medicine*, 28(1), 28-32.

Butler, R. J., Crowell, H. P., McClay Davis, I. (2003). Lower extremity stiffness: Implications for performance and injury. *Clinical Biomechanics*, 18, 511–517.

Cavanagh, P. R., Lafortune, M.A. (1980). Ground reaction forces in distance running. *Journal of Biomechanics*, 13, 397– 406.

Cheng-Feng, L. (2005). Ankle biomechanics of ballet dancers in relevé en pointé dance. *Research in Sports Medicine*, *13*(1), 23-35.

Cunningham B. W., DiStefano, A. F., Kirjanov, N. A. (1998). A comparative mechanical analysis of the pointe shoe toe box: an in vitro study. *Am J Sports Med*, *26*(4), 555-561.

Dance Facts (2019). History of dance.

Dance Facts (2019). Types of dance - Categories.

Eckhardt, H., Hentschke, C., Pfeifer, K., Steib, S., Zech, A. (2012) Effects of localized and general fatigue on static and dynamic postural control in male team handball athletes. *Journal of Strength and Conditioning Research*, 26, 1162-1168.

Farley, C. T., Ferris, D. P., (1997). Interaction of leg stiffness and surfaces stiffness during human hopping. *Journal of Applied Physiology*, 82, 15–22.

Fietzer, A. L., Kulig, K., Popovich Jr., J. M. (2011). Ground reaction forces and knee mechanics in the weight acceptance phase of a dance leap take-off and landing. *Journal Of Sports Sciences*, *29*(2), 125-131.

Grealish, A., Hopper, D., Wild, C. Y. (2017). Lower Limb and Trunk Biomechanics After Fatigue in Competitive Female Irish Dancers. *Journal of Athletic Training (Allen Press)*, *52*(7), 643–648.

Hentschke, C., Pfeifer, K., Steib, S., Welsch, G., Zech, A. (2013) Effects of fatiguing treadmill running on sensorimotor control in athletes with and without functional ankle instability. *Clinical Biomechanics*, 28, 790-795.

Hoogsteyns, M. (2013). Giving more weight to the ballerina: Material agency in the world of pointe shoes. *International Journal of Cultural Studies*, *16*(2), 119-133.

Joy, E., Macintyre, J. (2000) Foot and ankle injuries in dance. *Clin Sports Med*, *19*(2), 351–468.

Komi, P. V., Kuitunen, S., Kyrolainen, H. (2002). Knee and ankle joint stiffness in sprint running. *Med. Sci. Sports Exerc.* 34, 166–173.

Kulas, A. S., Perrin, D. H., Schmitz, R. J., Shultz, S. J., Watson, M.A. (2006). Energy absorption as a predictor of leg impedance in highly trained females. *Journal of Applied Biomechanics*, 22, 177-185.

Kwon, Y., Wilson, M. (2008). The role of biomechanics in understanding dance movement. *Journal of Dance Medicine & Science, 12*(3), 109-114.

Leanderson, J., Nilsson, C., Strender L. E., Wykman, A. (2001) The injury panorama in a Swedish professional ballet company. *Knee Surg Sports Traumatol Arthrosc*, *9*(4), 242-246.

Mackrell, J. R. (2018). What is Dance. Retrieved from http://www.academicroom.com/topics/what-is-dance

Martin, S. (2002). Righty? Lefty? Does it matter? *Dance Magazine*, *76*(12), 80.

McClay, I. S., Robinson, J. R., Andriacchi, T. P., Frederick, E. C., Gross, T., Martin, P., Cavanagh, P. R. (1994). A profile of ground reaction forces in professional basketball. *Journal of Applied Biomechanics, 10*, 222-236.

McGray, E. Jr., Micheli L. J., Solomon, J., Solomon, R. (1999) The ‘cost’ of injuries in a professional ballet company: a five year study. *Med Probl Perform Art*, 14(4),164-69.

McNamara, L., Noon, M., Schimke, J., Zoch, A. Z. (2009). Injury patterns in female Irish dancers. *PM R*, *2*(11), 1030– 1034.

McNitt-Gray, J. L. (1993). Kinetics of the lower extremities during drop landings from three heights. *Journal of Biomechanics*, 26, 1037–1046.

Miller, E. H., Sammarco, G. J. (1982) Forefoot conditions in dancers, part I. *Foot Ankle*, 3(2):85-92.

Munn, J., Schneiders, A. G., Sullivan, S. J. (2010) Evidence of sensorimotor deficits in functional ankle instability: a systematic review with meta-analysis. *Journal of Science and Medicine in Sport*, 13, 2-12.

Nedvigin, G. (2018). A Brief History of Ballet. Retrieved from https://www.atlantaballet.com/resources/brief-history-of-ballet

Ortega, D. R., Rodriguez Bies, E. C., Berral de la Rosa, F. J. (2010). Analysis of the vertical ground reaction forces and temporal factors on the landing phase of a countermovement jump. *Sports Science & Medicine*, *9*(2), 282-287.

Paillard, T. (2012) *Neuroscience and Behavior Review*, *36*(1), 162-76.

Powers, M. E., Tillman, M. D., Wikstrom, E. A. (2004) Dynamic stabilization time after isokinetic and functional fatigue. *Journal of Athletic Training*, 39, 247-253.

Romanov, D. (2018). Running: Ground Reaction Force and how to use it.

Ryan A. L., Stephens, R. E. (1987) The epidemiology of dance injuries. *Dance Medicine: a Comprehensive Guide*, 3-15.

Seegmiller, J., McCaw, S. (2003). Ground reaction forces among gymnasts and recreational athletes in drop landings. *Journal of Athletic Training*, *38*(4), 311-314.

Shah, S. (2010). Pointe shoes complicate biomechanics of ballet. *Lower Extremity Review*.