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THREE-DIMENSIONAL BIOMECHANICAL ANALYSIS OF LANDING FROM GRAND JETE: THE EFFECT OF BALLET FOOTWEAR ON SELECTED KINETIC AND KINEMATIC VARIABLES

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# THREE-DIMENSIONAL BIOMECHANICAL ANALYSIS OF LANDING FROM GRAND JETÉ: THE EFFECT OF BALLET FOOTWEAR ON SELECTED KINETIC AND KINEMATIC VARIABLES

By

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# ABSTRACT

## THREE-DIMENSIONAL BIOMECHANICAL ANALYSIS OF LANDING FROM GRAND JETÉ: THE EFFECT OF BALLET FOOTWEAR ON SELECTED KINETIC AND KINEMATIC VARIABLES

By

Ethel Ruth Leslie

This project was a case study which examined the effect of ballet footwear on the three-dimensional sagittal plane kinematics and three-dimensional kinetics of landing from grand jeté. The following variables were measured: (1) angular displacement, velocity, and acceleration of the ankle and knee joints, (2) peak vertical ground reaction force (GRF) and rate of loading, and (3) force-time characteristics of GRF components. One ballet student was filmed landing onto a force plate under three foot conditions: pointe shoes, ballet slippers, and barefoot. There was no apparent difference between conditions for the pattern or magnitude of angular displacement of the knee and angular velocity and acceleration of knee flexion and ankle dorsi-flexion. Average dorsi-flexion angular displacement was lower for the barefoot condition. Peak vertical GRF ranged from 3.06 to 5.12 BW. On average, all three components of GRF and peak rate of loading vertical GRF were highest for the pointe shoe condition.

"Dance is the only art of which we ourselves are the stuff of which it is made."

Ted Shawn

"Think of the magic of that foot, comparatively small, upon which your whole weight rests. It's a miracle, and the dance ... is a celebration of that miracle."

Martha Graham

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# Chapter 1

## Introduction

Ballet is a challenging form of movement which has its roots in the court dances performed by European royalty during the Renaissance (Hammond, 1974). The physical and aesthetic requirements of ballet technique make it one of the most demanding forms of physical activity, yet there has been relatively little scientific study of actual ballet movements.

Probably the most widely recognized and intriguing characteristic of ballet is the use of special shoes that allow the ballerina to dance on her toes, or "en pointe". While female ballet dancers traditionally perform en pointe, male dancers have been known to dance in pointe shoes as part of a character role or as training to strengthen their feet. Since feet and toes were not designed to bear weight in this fashion, dancing en pointe may contribute to a number of injuries and pathologies seen in ballet dancers. Sprained ankles, bunions, calluses, and bruised toenails are common among ballet dancers (Kravitz et al., 1986; Milan, 1984; Quirk, 1994; Sammarco, 1982; Weiker, 1988) as are structural adaptations of the bones in the feet (Kravitz, Fink, Huber, Bohanske & Cicilioni, 1985; Sammarco, 1982; Schneider, King, Bronson & Miller, 1974). Tissue damage that results in injury and/or structural adaptation can be caused by one or more of the following: 1) a single maximum load, 2) repetitive loading, and 3) the rate of loading (Nordin & Frankel, 1989). The injuries and adaptations experienced by a dancer's body are in response to the extreme demands inherent to dance movement and the repetitive nature of dance practice.

One of the more frequently performed movements in ballet, and dance in general, is grand jeté. Grand jeté is a spectacular leap that demands the dancer jump high into the air and form a 180 degree sagittal split of the legs. Upon landing, grand jeté has been known to generate peak vertical ground reaction forces of at least three times body weight (Becker, 1984; Miller, Paulos, Parker & Fishell, 1990). Take-off and landing kinematics have been given some study (Murgia, 1995; Ryman, 1976) as has the effect of body configuration on the illusion of suspension (Midgett, O'Bryant, Stone & Johnson, 1993; Rasmussen & Hay, 1993). Miller et al. (1990) found pressure more evenly distributed upon landing from grand jeté wearing the ballet slipper as compared to landing barefoot; however, they offered no explanation to account for this finding. The influence of pointe shoes on landing from jumping movements, such as grand jeté, has not yet been investigated.

To date, scientific study of ballet movements, and dance movement in general, has been scarce. Minimal attention has been given to the investigation of dance shoes and the influence of the shoes on movements dancers perform daily, as well as the effects of these movements on joint mechanics and stressors. While most athletes have specially designed shoes developed to protect their body from physical stress, ballet dancers have used the same footwear design for over a century (Barringer & Schlesinger, 1998). Made of little more than fabric and leather, ballet slippers and pointe shoes provide the dancer with little, if any, protection from potential injury. The current study was necessary in order to better understand landing movements from aerial movements in dance and the effect of dance footwear on the performance of these movements. Increased understanding of movements such as grand jeté may lead to the development of footwear and other equipment that can provide protection and support for dancers' feet.

The purpose of this study was to examine the effect of ballet footwear on landing from grand jeté using three-dimensional sagittal plane kinematics and three-dimensional kinetics. For the purposes of this study, landing was defined by the time the dancer was in contact with the force plate, from toe down to toe off. One advanced level ballet student performed grand jeté under three foot conditions: 1) barefoot, 2) wearing pointe shoes, and 3) wearing ballet slippers. Three-dimensional high-speed videographic and force plate data were used to investigate the following: (1) angular displacement of the knee and ankle joints, (2) angular velocity of the knee and ankle joints, (3) angular acceleration of the knee and ankle joints, (4) peak vertical ground reaction force and rate of loading, and (5) force-time characteristics of ground reaction force components (FX, FY, FZ).

## Chapter 2

## Review of Literature

### Description of the Pointe Shoe

Marie Taglioni commonly is credited with being the first major ballerina to dance on her toes as an essential choreographic element by performing the title role in the ballet La Sylphide in 1832 (Barringer & Schlesinger, 1998). To dance en pointe,[1] the ends of her shoes were darned and she probably padded the ends of her ballet slippers with cotton wool. As ballerinas were asked to perform more difficult feats en pointe, the toes of ballet slippers were darned and stiffened with glue and the insole was reinforced with light cardboard to provide support (Barringer & Schlesinger). Pointe shoes today are heavier than in the past (Lawson, 1983), yet are still little more than satin, glue, and leather even as the choreographic demands of ballet become more and more challenging. A more complete description of the pointe shoe is provided in Appendix B.

### Kinetic Analysis of Dancing in the Pointe Shoe

A handful of studies (Albers, Hu, McPoil & Cornwall, 1992; Dozzi & Winter, 1993; Galea & Norman, 1985; Kravitz et al., 1986; Teitz, Harrington & Wiley, 1985; Torba & Rice, 1993; Tuckman, Werner & Bayley, 1991) have investigated various kinetic aspects of dancing in the pointe shoe. Several of the authors of these studies explored occurrences inside the pointe shoe, while other authors utilized information of external forces and pressure distribution to examine the mechanical demands on the foot when en pointe. Pressure distribution inside pointe shoes have been investigated quantitatively using transducers (Kravitz et al., 1986; Teitz et al., 1985) and qualitatively

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[1] Definitions of dance terms are provided in Appendix A.

using a molding technique (Tuckman et al., 1991). Torba and Rice (1993) combined the use of quantitative (force sensing resistors) and qualitative (molding and pressure sensitive film) techniques in an effort to assess pressure distribution of the foot while en pointe. External force and pressure data have been used in the exploration of bone-on-bone forces at the ankle (Galea & Norman, 1985), plantar pressures (Albers et al., 1992), and energetics of the foot and ankle (Dozzi & Winter, 1993) during a rise onto pointe.

Teitz et al. (1985) studied the pressure distribution on the foot in pointe shoes using Kulite pressure transducers. Transducers were placed on the tips of the first and second toes and on the medial aspect of the metatarsophalangeal (MTP) joint. All 13 participants wore a new pair of the same brand and style of pointe shoe. Each performed plié-relevé two different ways. First they did relevé properly, rising through the center of the foot, keeping their weight equally distributed over all the toes as the rise onto pointe was completed. The movement was then done in an everted position, shifting most of the dancer's weight forward onto the big toe at the completion of relevé. Dancing with the foot everted is thought to be a contributing factor to bunion formation. Although eversion was found to increase the pressure on the first MTP joint for most subjects, the authors of this study were not able to document the pressure's contribution to the formation of bunions. Those participants whose second toe was shorter than their great toe, placed a cap onto their second toe and performed an additional set of relevés. From the data, the authors revealed that the first toe took at least as much, if not more, pressure than the second toe regardless of relative toe length or whether the second toe was capped. This finding contradicted a common belief among dancers and their doctors that the best foot shape for dancing en pointe is one with the first two toes of equal length to provide better pressure distribution (Barringer & Schlesinger, 1998; Contompasis, 1986; Kravitz et al., 1985; Sammarco, 1982; Weiker, 1988). Dancers with shorter second toes frequently put a cap on it to conform to this assumption.

Pressure transducers also were used in a pilot study by Kravitz et al. (1986) to examine the pressures at several locations on the foot inside the pointe shoe. Sensors were placed on ten landmarks of the foot: seven on and around the first and second toes, one on the plantar aspect of the first MTP joint, and two on the calcaneus. Sixteen dancers participated in this study and the researchers used an electrodynogram computer system to analyze the forces produced on the foot during relevé onto one and two feet. Because the electrodynogram was able to record pressures over time, relative pressures during the movement could be examined. The greatest percentages of peak force and peak shock occurred on the plantar aspect of the first MTP joint during the transitional period of the rise onto pointe. The authors did not indicate how peak shock and pressure were calculated. Pressures were greater when the dancers rose to a position on one foot than to the relevé on both feet. This finding was not surprising since the dancers would be transferring full body weight onto one foot rather than dividing their body weight, as occurred when rising to balance on two feet. Forces were generated through the medial aspect of the forefoot as the dancer reached full pointe and settled into position. This pattern of force during the rise onto pointe confirmed the visual observation made by these researchers in preparation for the study: that as the dancer rose onto pointe, the foot supinated, then pronated slightly as the final position was reached. When the dancers balanced in their final position on one foot, the three highest pressures were recorded by transducers located on the distal aspect of the hallux, the medial aspect of the first MTP joint, and the dorsal aspect of the first interphalangeal joint, respectively. In the final position on two feet, the three highest pressures, in order, were recorded by transducers placed on the distal aspect of the hallux, the dorsal aspect of the first interphalangeal joint, and the lateral tubercle. As was shown in comparison, the highest pressure for both the one foot and two feet conditions were the same, while the second and third highest pressures were completely different. As would be expected, as the dancers balanced on one foot, the pressure recorded at the distal aspect of the hallux was greater than when the dancers balanced on two feet. It was not made clear in the report whether the dancers were: 1) tested wearing their own pointe shoes, 2) if the pointe shoes were standardized in some way, or 3) whether the shoes were broken in. These factors are important because of their influence on the stiffness of the pointe shoe box. Stiffness of the box would influence the measurements taken, especially on the first MTP joint, and should be considered when interpreting the data.

Qualitative assessment of the forefoot while en pointe was done by Tuckman et al. (1991) using a molding technique. An alginate mixture was poured into the box of the pointe shoe and the dancer balanced en pointe for about one minute with minimal support as the mixture solidified leaving a negative impression of the forefoot. Plaster was then poured into the shoe and, once hardened, the shoe was cut away leaving a positive impression of the positioning of the toes en pointe. The nine student dancers who participated were given their preference of new pointe shoes and were asked to break in their shoes prior to testing. Pressure on the medial aspect of the foot was evident because of hallux valgus and flattening of soft tissue, both attributed to the unrelenting shape of the box. All molds except one demonstrated pressure on more than one toe and about half of the molds showed toenail deformations. There did not appear to be any relationship between the configurations of the toes en pointe and relative toe length, pain while en pointe, or toenail problems. This finding was in agreement with other research (Ogilvie-Harris, Carr & Fleming, 1995; Teitz et al., 1985) which found no relationship between toe length and performance en pointe. Based on the results of this study, the authors suggested that the shape of the foot outside the pointe shoe may not be as important as the position of the foot inside the shoe. Tuckman and colleagues hypothesized that the pressures on the forefoot may best be distributed if the toes are aligned while en pointe. These researchers recommended further study to investigate this assertion. Although the method used in this study was qualitative in nature, it presented visual evidence of pressure distribution over the entire forefoot that may provide direction for quantitative studies.

Torba and Rice (1993) used the alginate molding technique developed by Tuckman et al. (1991) along with pressure sensitive film and force sensing resistors to examine pressure distribution on the foot while en pointe. Neither the number of subjects nor the technical ability of the subjects was provided; however, the brand and style of pointe shoe worn by the subject(s) was noted. To assess the contribution of friction to supporting body weight, the foot was covered with plastic food wrap, which acted as a lubricant, and pressure was measured at bony prominences. Upon examination of the plaster moldings, Torba and Rice (1993) found that flattening of soft tissue and other adaptations were necessary to allow the foot to fit inside the shoe, similar to the findings of Tuckman et al. (1991). Although pressure distribution varied among subjects, higher peak pressures and higher readings from the force sensor resistors were consistently recorded where the foot was flattened or touched the side of the shoe. The pressure data of one subject from sampling with a force sensing resistor showed the first toe took greater pressure than the second toe and was in general agreement with the results of Teitz et al. (1985). Torba and Rice (1993) determined that 85% of the dancer's weight was accounted for by normal forces. The remaining percentage of body weight, 15%, was attributed to friction between the foot and shoe because lubrication of the foot was found to increase normal forces at all bony prominences examined. The findings of this study make sense because a normal force is defined as the force holding two objects together. The findings also make sense when it is considered that a normal force is proportional and perpendicular to friction.

Measurement of pressures inside the pointe shoe has led to a better understanding of what happens inside the shoe. Pressure transducers provided measurement of the pressures at a particular location, but they were not capable of recording the pressure distribution across the entire forefoot or expressing values for the force components that comprised pressure. The molding technique allowed a better understanding of the formation of the foot while in the shoe. Combining these quantitative and qualitative methods provided a more complete picture of occurrences inside the pointe shoe. The authors of two of these studies (Teitz et al., 1986; Tuckman et al., 1991) have suggested and agreed that the relative length of the toes may not be as important as the configuration of the foot inside the shoe.

Galea and Norman (1985) used force plate and surface electromyographic (EMG) data to estimate the bone-on-bone forces at the ankle joint during two footed relevé onto full pointe. Bone-on-bone forces were the result of joint reaction force as well as muscle and ligament forces acting at the joint. Bone-on-bone forces were calculated using a model that combined the joint reaction force and the force of contraction of the muscles crossing the ankle joint. Horizontal and vertical ground reaction forces, as measured by a force plate, were used to determine joint reaction force. EMG data recorded during relevé served as a measure of muscle activity. Muscle force and EMG outputs of a maximum isometric contraction were measured for the muscles around the ankle. These measurements provided a standard from which relative muscle forces during the movement were determined. The model also took into account changes in muscle length and velocity of muscle contraction. Peak bone-on-bone forces were calculated to be as high as ten times body weight and usually occurred when the dancer was on full pointe. The authors pointed out this amount of force alone is not necessarily destructive, but rather the repetitive loading of the joint surface. It should be added that the rate of loading would affect the potential for injury (Nordin & Frankel, 1989).

The relative contribution of the ankle extensor and metatarsal-phalangeal flexor muscle groups to the energetics of rising onto pointe were investigated by Dozzi and Winter (1993). Two female professional dancers, performers with a world class ballet company, performed elevé onto pointe. Time-history of the rise onto pointe showed that during the first part of elevé, the foot segment raised while the phalangeal segment remained stationary then, as the movement was completed, the phalangeal segment moved upward. A distinct pause associated with the transition from raising the foot segment to raising the phalangeal segment was noted. Calculations of the mechanical work done by both subjects showed that 22% and 33% of work was done at the metatarsal-phalangeal joint. It should be considered that the mathematical equations used to calculate the amount of work done at the two joints took into account vertical ground reaction force but not medial-lateral or anterior-posterior reaction forces (Winter & Robertson, 1978). Nonetheless, the percentage of work is noteworthy because, based on cross-sectional area, the muscles crossing the metatarsal-phalangeal joint are much smaller than the muscles crossing the ankle joint and therefore were estimated to work 2.5 to 3 times harder.

Using a pressure platform, Albers et al. (1992) compared plantar pressures during walking barefoot and in pointe shoes, peak pressures of relevé and elevé, peak pressures of walking in the pointe shoe and the two ways of rising onto pointe. These researchers showed that plantar pressure was higher while walking in pointe shoes compared to walking barefoot. This higher pressure was due to the constrictive nature of the pointe shoe which physically limits the plantar surface permitted to contact the ground. Not surprisingly, these researchers also found that peak pressure en pointe was greater than peak pressure while walking in the pointe shoe. Greater peak pressure en pointe was to be expected given that the surface area in contact with the ground while en pointe was greatly reduced when compared to the plantar surface contacting the ground while walking, for the same relative body weight. The researchers found no difference in the plantar pressures during relevé and elevé.

<u>Kinematic and Kinetic Studies of Aerial Movement in Dance</u>

Of all the movements in dance, aerial movement has received the most attention and is of interest because of the high ground reaction forces upon landing due to the effect of gravitational acceleration. Simple dance jumps were studied by Clarkson, Kennedy and Flanagan (1984) as well as McNitt-Gray, Koff and Hall (1992). These researchers compared the effect of training on the performance of sauté. Clarkson et al. (1984) compared how dance students and non-dancers performed sauté with the legs externally rotated from the hip and heels together in first position. Measuring knee angle with an electrogoniometer, these researchers found that the dance students used greater knee flexion than non-dancers in the demi-pliés that preceded and followed the jump. Furthermore, they found that those with dance training used a similar degree of knee flexion to perform relevé. Non-dancers, on the other hand, varied their degree of knee flexion with the different requirements of each movement. The authors attributed this finding to a learned motor pattern that sets the depth of the demi-plié. A reasonable explanation given was that demi-plié is learned on the first day of ballet class and is used thereafter in the performance of a variety of movements.

McNitt-Gray et al. (1992) used two-dimensional videographic and force plate analysis to compare dancers, dance students, and non-dancers in the performance of sauté with the feet in first and parallel positions. Because kinematic data for first position were deemed unacceptable, only data from the parallel condition were examined. Dancers and dance students used more knee flexion upon landing in demi-plié than non-dancers, in agreement with the findings of Clarkson et al. (1984); however, no difference in minimum ankle dorsi-flexion between groups was found. Dancers took longer than non-dancers to reach maximum knee flexion and maximum dorsi-flexion upon landing from the jump. Vertical ground reaction force peak magnitudes at impact ranged from 2.81 to 3.82 times body weight and no significant differences were found between subject groups or foot positions. These peak values were similar to those of Becker (1984) who found impact peaks of 3.36 and 3.51 for male and female dancers, respectively. While not statistically significant, dancers tended to delay time to peak vertical reaction force; and dancers, as well as dance students, tended to have longer landing phase times and took longer to reduce the center of gravity's vertical velocity to zero than non-dancers. Dancers are trained to land from jumps softly, with a great deal of control and Becker (1984) suggested that adaptations learned as part of dance training allow impact forces to be attenuated upon landing from a jump.

Ballet dancers are easily identified by their erect posture and regal carriage of the upper body. "Pulling-up" the abdominal muscles, or pull-up, as it is referred to in dance vernacular, is a concept used in ballet training which allows the dancer to achieve the correct postural alignment. Fu et al. (1994) investigated the effect of pull-up on the performance of sauté using two-dimensional motion analysis and force plate data. To compare the pull-up and non-pull-up conditions, six female advanced level students performed sauté in first position five consecutive times under both conditions. The dancers were instructed to jump maximally. Upon analysis of the data, two factors were reported prior to initiation of the first jump: 1) the seventh cervical vertebrae (C7) was higher when the subject was pulled-up and 2) the height of the second sacral vertebrae (S2) showed no difference between the two conditions. In the air, the vertical displacements of C7 and S2 were higher with pull-up than without. The dancers jumped higher with pull-up and suspension time increased under the pulled-up condition. Because the subjects were advanced dancers, they were probably more familiar with the pull-up condition and may have felt more secure executing a maximal jump in that condition. Additionally, the pull-up jumps were performed after the non-pull-up jumps and practice effect may have influenced the height of the jumps as the dancers became warm and they became more comfortable in the test space. Fu et al. (1994) found no significant differences in the landing force or maximal ground reaction force between the two conditions, although the dancers felt they landed more softly while jumping with pull-up. Again, this finding may have had to do with their familiarity with the pull-up condition.

A series of studies by Simpson and colleagues (1996, 1997, 1997) utilized two-dimensional inverse dynamics analysis to evaluate the effect of jump distance on the forces acting at the knee and ankle upon landing from a simple dance leap (Simpson, Jameson & Odum, 1996; Simpson & Kanter, 1997; Simpson & Pettit, 1997). The protocol was the same for all three studies and the data for the same six dancers were used in the analyses. The leap began from a stationary position, the subject extended a leg forward, and leapt onto it. With the use of a metronome, flight time was held constant as the dancers leapt horizontal distances equal to 30, 60, and 90 percent of their predetermined maximum leap. The magnitude of peak anterior/posterior ground reaction force increased as leap distance increased. Maximal peak vertical ground reaction force was nearly three times body weight upon landing from the longest leap, similar to the impact peak magnitudes measured by McNitt-Gray et al. (1992) in the performance of sauté. The difference between a sauté and a leap is that with a sauté, the dancer lands on two feet so both legs share the forces of landing, while with a leap, the dancer lands on one foot and one leg must accept and attenuate the forces.

In their investigation of occurrences at the knee during a simple leap, Simpson et al. (1996) analyzed maximum magnitudes and derivatives for quadriceps force, patellofemoral compressive force, and patellofemoral contact pressure. With increased leap distance, quadriceps force, peak compressive force, and maximum patellofemoral pressure increased. At landing, knee angular displacement increased as leap distance increased, allowing the distribution of force through a greater number of patellofemoral contact regions. Additionally, at longer leap distances, peak knee flexion velocity also increased, allowing pressure to shift rapidly from one contact region to another. Thus, no one patellar or femoral region was subjected to high loads for an extensive period of time. As leap distance increased, the rates of loading compressive force and patellofemoral pressure increased and the corresponding time to peak values decreased. The rate of force application is important because high rates of loading are known to contribute to tissue damage (Nordin & Frankel, 1989).

The effect of distance on axial (Simpson and Kanter, 1997) and shear (Simpson and Pettit, 1997) forces upon landing from a simplified dance leap also have been investigated. Joint reaction forces and muscle axial forces of the knee and ankle, quadriceps shear force, and ankle shear force increased at longer leap distances. Rates of loading the shear force at the ankle and the axial forces at the knee and ankle increased at longer leap distances. However, the effect of leap distance on the rate of shear loading at the knee was not consistent among the subjects. Muscle axial forces demonstrated a greater influence on the magnitude and rate of applying compressive forces at both joints, than did joint axial reaction forces. Maximum quadriceps shear force was greater than maximum knee joint reaction force for all participants. At longer distances, quadriceps shear force increased; however, the influence of increased quadriceps shear force on knee shear force was inconsistent since knee shear force increased for only half of the participants. Values for gastrocnemius and triceps surae shear force and knee shear force were inconsistent among the sample. Greater leap distances did not result in greater peak values for gastrocnemius and triceps surae shear force and knee shear force for all participants.

The authors failed to mention in any of the articles whether the dancers were asked to maintain knee flexion in the sagittal plane upon landing or if they were allowed to externally rotate their leg as they may be asked to do in a dance class. If the dancers were landing with their leg externally rotated, perspective one error resulting from the use of two-dimensional analysis would have influenced the kinematic data used to derive various muscle and joint force magnitudes.

Although these studies provide a good foundation for comparison with other aerial movements in dance, the leap studied by Simpson and her colleagues (1996, 1997, 1997) cannot be generalized to all dance leaps. Rarely does a choreographer require a dancer to perform one movement in isolation, especially an airborne traveling movement, like a leap. Usually there are steps that lead into traveling aerial movement allowing the dancer to gain horizontal momentum, some of which is converted to vertical momentum to launch the body off the ground. Likewise, steps follow traveling aerial movement as the body continues to move after landing.

Additionally, it is not possible to generalize the findings of the studies by Simpson and colleagues (1996, 1997, 1997) to all dancers. The amount of dance training for the participants in these studies was not specified in any of the articles and inconsistencies existed in the brief descriptions provided about the length of time the participants had been dancing. In the earliest article, examining patellofemoral forces during dance landings, the dancers had a minimum of one year of training at the

University of Georgia (Simpson et al., 1996). The participants of the other two articles were identified as six skilled modern dancers (Simpson & Kanter, 1997; Simpson & Pettit, 1997). It was not made clear how much dance training, if any, the participants had prior to their training at the University of Georgia. It is possible that some of the subjects may have begun their dance training at the collegiate level and, therefore, may have had one year of training. It is doubtful that one year of training in any activity qualifies one as "skilled".

The amount of training is important for two reasons. First of all, those dancers with more training may be expected to jump further than those with less training. This longer jump distance, in turn, would influence the forces acting on the knee and ankle due to the increased horizontal force necessary to complete the jump as specified. Secondly, dance training has been shown to change the way forces are attenuated upon landing from jumps (McNitt-Gray et al., 1992). The preferred aesthetic in dance is to land toe-heel, with training this movement becomes second nature to the dancer. McNitt-Gray et al. found that the landing mechanics of professional dancers and dance students differed from the landing mechanics of non-dancers: those with dance training used greater maximum knee flexion and took longer to reach maximum knee flexion and maximum dorsi-flexion than non-dancers. These differences in how the forces were attenuated upon landing would affect the forces acting at the knee and ankle. Individuals with less training may not have been able to use this landing technique to its full advantage.

Joint Moments

A difficult variation of sauté, entrechat six, was used by Ravn et al. (1999) in a study of jump take-off strategy. Entrechat six was filmed as the dancers faced the camera because external rotation of the hips was required to properly perform the jump. The vertical height of the jumps, performed by three male dancers from the Royal Danish Ballet, ranged from 0.27 m to 0.33 m. It was determined that the dancers used a simultaneous strategy to perform this jump and that the knee and ankle were the dominant joints. A jump was considered simultaneous if: 1) the two dominant joints began extension at the same time and 2) the net joint moment of the two dominant joints peaked at the same time. Ravn et al. referred to flexion-extension moments; however, the terminology is incorrect because movements performed in the frontal plane are referred to as abduction-adduction; hence abduction-adduction moments. Correct movement terms are indicated in parentheses for the Ravn et al. findings. Throughout the extension phase of the jump, beginning with the lowest point of the center of gravity and ending at toe off, the knee and ankle joints demonstrated extension (adduction) moments, while the hip joint showed a flexion (abduction) moment for all dancers. Ravn et al. (1999) could not explain the flexion (abduction) moment at the hip and suggested that extension (adduction) of the hip in the frontal plane occurred because of extension at the knee and ankle joints.

Simpson and Kanter (1997), reported that during the first 50-100 ms of landing from a simple dance jump, some subjects demonstrated a dorsi-flexion moment and a knee flexion moment. For the remainder of landing, extensor moments were produced at the knee and ankle of all subjects. Furthermore, the magnitude of peak extensor moments at the knee and ankle joints increased with longer jump distances as the corresponding time to peak decreased.

Explanation of Grand Jeté

In dance, a leap is defined as an aerial movement that takes off from one foot and lands on the other (Hammond, 1974). Leaps may be large or small, traveling or stationary. A frequently performed traveling leap in classical ballet technique is called grand jeté pas de chat by the Russian ballet school. Figure 1 shows the movement as it is described in Labanotation, a system of recording dance movement devised by Rudolf Laban (Miles, 1976). Outside the realm of classical ballet, grand jeté pas de chat may be called a split or stag leap; however, it will be referred to simply as grand jeté for the purposes of this review. This movement may be performed by men or women and is not the sole property of classical ballet. Grand jeté is often performed as choreography within modern dance, jazz dance, and gymnastics floor and beam exercises. While the arm and head positions may differ from classical ballet, the actions of the legs are the same.

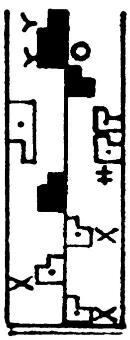

**Figure 1.** Labanotation of grand jeté pas de chat from Gail Grant dictionary of classical ballet in Labanotation (p. 72), by A. Miles, 1976, New York: Dance Notation Bureau. Copyright 1976 by Dance Notation Bureau, Inc.. Reprinted with permission.

As the name implies, grand jeté is a large leap. Preparatory steps, such as a run or glissade (a gliding step) must precede grand jeté (Grant, 1982, Vaganova, 1969) and serve to produce momentum to launch the body into the air (Vaganova, 1969). As the preparatory movement is completed, the leg that will be positioned anteriorly, pushes off the ground and is raised to 90 degrees of hip flexion with the knee flexed. This front leg is extended quickly at the knee as the back leg pushes against the ground to send the dancer into the air. In dance training, the performer is continually reminded to push off the ground with the leg that will be anterior in grand jeté. The timing of this initial push is critical to successful performance of this leap. The dancer is expected to jump high and cover a great deal of distance. Ideally, at peak height of grand jeté the legs are fully extended at the knee anteriorly and posteriorly to form a 180 degree split.

Landing is made on the front leg as the back leg continues moving forward into the next choreographed movement (Grant, 1982). Upon landing from any aerial movement, the landing should be soft and silent. According to Vaganova (1969), the toe should touch the floor first, the heel is lowered, and then the knee bends into demi-plié. Because movement in dance is continuous, demi-plié upon landing is not only the end of the jump, but is also preparation for the following movement (Hammond, 1974).

Biomechanical Analysis of Grand Jeté

Various biomechanical aspects of grand jeté have been explored. Kinematic analysis of take-off and flight phases was done by Ryman (1976) and Murgia (1995), who also measured ground reaction forces of take-off. The effect of body configuration on hang time and the illusion of suspension at the height of the leap was investigated by Midgett et al. (1993) and Rasmussen and Hay (1993). The forces at landing were measured by Becker (1984) as well as Miller et al. (1990). Becker (1984) examined kinetic and kinematic parameters of landing from grand jeté while Miller et al. (1990) used grand jeté to compare the effect of modified ballet shoes on the force and pressure distribution on the foot upon landing.

Ryman (1976) and Murgia (1995) biomechanically examined take-off and flight of grand jeté. With one highly regarded professional ballerina as her subject, Ryman (1976) used one camera for a two-dimensional analysis to compare the ballet definition with the actual performance of six aerial movements, one of which was grand jeté. Additionally, Ryman examined velocity and acceleration of the center of gravity during the push off and time of flight of these movements. Descriptive (kinematic) analysis revealed that grand jeté was performed as it is described in the ballet literature, with the exception that the dancer was unable to defy gravity and hang in the air at the height of the aerial movements. Ryman observed that as body position changed at the peak of each aerial movement, the top of the dancer's head maintained its vertical height. Thus, Ryman reached the same conclusion as two more recent studies (Midgett et al., 1993; Rasmussen & Hay, 1993), the ability to hang in the air was an illusion determined by the configuration of the body throughout the movement. Kinematic analysis revealed that of the six movements studied, grand jeté had the highest vertical velocity at take-off. Furthermore, when ranked with the other five aerial movements, grand jeté had the second highest horizontal velocity at take-off and the second largest vertical displacement as measured from the depth of the preparatory demi-plié to height of the movement. It was not surprising that grand jeté had the longest flight time and the second longest horizontal distance traveled of the movements studied because a projectile's horizontal displacement, peak height, and flight time are due to gravity, angle of projection, initial velocity, and height of take off.

Murgia (1995) used 15 participants with various degrees of dance experience to explore a number of biomechanical variables for three aerial movements commonly performed in dance. The three movements were grand jeté pas de chat, grand jeté performed with the front leg fully extended at take-off, and a jazz leap that required the dancer to change legs in the air and land on the take-off leg. The subjects were allowed a two step preparation for each movement and were instructed to gain as much height and distance as possible. Three-dimensional kinematic and kinetic data were collected and analyzed in this study. No significant differences were found between the aerial movements for many of the variables examined, including magnitude and angle of application of the ground reaction force. Both styles of grand jeté were found to have greater peak angular velocity at the knee than the jazz leap and grand jeté pas de chat demonstrated longer flight time than the other two jumps. The findings of this study were reported as results of statistical analyses. Murgia presented the results of ANOVAs, and when necessary, the results of Scheffé posthoc tests, for each biomechanical variable examined. The age of the subjects ranged from 12 to 34 years and their dance experience ranged from four months to 15 years. Neither the age of the participants nor their level of training was considered in the evaluation of the data. The wide range in ages and skill levels may have contributed to the lack of significant differences for some of the variables.

In biomechanics, extreme skill groups commonly are used for comparison and when comparing low vs. high skills, the levels must be defined. Rarely will one see low vs. intermediate or intermediate vs. high skill comparisons due to the fact that very gross measures are used to try to find subtle differences. Fine measurements are inherently problematic in biomechanics. Additionally, it should be considered that when trying to perform statistical analysis on biomechanical data, the journey (i.e. path of information) is often more revealing than the mean (average) of the path – or any part of the path (V. D. Ulibarri, KIN 830, Fall, 1998).

Midgett et al. (1993) and Rasmussen and Hay (1993) utilized two-dimensional video analysis to investigate the effect of body configuration on hang time in the performance of grand jeté. In an effort to quantify hang time, Midgett et al. (1993) examined the effect of arm position on the relationship between the vertical displacements of specific points on the body and the center of mass. For the purposes of their study, Midgett et al. defined "hang time" as "horizontal movement of the head and trunk during the peak of a leap, with little or no vertical displacement, for a relatively greater period of time than the center of mass" (p. 4). Eleven female advanced-level collegiate dancers performed grand jeté using two different classical ballet arm motions and a modified arm motion. The classical arm motions maintained or raised the arm position during flight and maintained the arm position upon landing, while the modified motion had the dancer lower her arms immediately after reaching the peak height of the leap. The leaps were normalized by calculating the top quarter of the leap, based on the total vertical displacement of the dancer's center of mass, and the relative time each point stayed in this top quarter was determined. As expected, the center of gravity of the body followed a parabolic path from take-off to landing regardless of arm movement during flight. Hang time was found to be longer for the modified motion compared to the standard ballet arm positions. An explanation for a longer hang time with the modified motion lies within the definition of this motion. Ranney (1988) suggested that as the arms were dropped, the head was raised relative to the center of mass. For this study, hang time was defined by head and trunk movement relative to the center of mass.

Rasmussen and Hay (1993) studied hang time and the contribution of all limbs to the illusion of suspension in the performance of several aerial movements, including grand jeté pas de chat. The movements were performed by one female advanced level collegiate dancer. For this investigation, "hang time" was defined as the time the center of gravity of the head, neck, and trunk stayed at a constant elevation within a determined margin of error. Hang time of grand jeté pas de chat was 0.16 seconds, the longest of any of the movements studied. Rasmussen and Hay found that the arms contributed less to the illusion of hanging in the air than the legs and trunk. The higher contribution of the legs and trunk to the illusion of hanging in the air was not surprising, given that the mass of these body segments was greater than the mass of the arms. The researchers suggested that timing of body movements, particularly the legs, was important to insure the illusion of suspension and that the illusion was more effective when hang time occurred during the descent rather than during the ascent.

Kinematics and Kinetics of Landing from Grand Jeté

In an attempt to identify parameters of landing that reveal the most information about impact forces, Becker (1984) investigated kinetic and kinematic factors of the landing technique characteristically used by dancers. He explored the relationship of two descent variables to peak impact force upon landing. These two descent variables were 1) descent to maximum knee flexion and 2) descent to full heel compression. Fifty-six female and nine male dancers volunteered for this study, all of them were considered highly proficient in the performance of aerial movements. The dancers were given a choice between an approach run or a glissade as preparatory steps to the leap. The dancers landed in arabesque supported on the leg further from the camera such that a medial view of the landing leg was visible. Given that the dancers were asked to complete the movement by landing in arabesque, the leap performed was most likely one of several variations of grand jeté; however, a complete description of the leap chosen for study was not provided. Mean peak vertical ground reaction forces upon landing were 5.13 and 4.47 times body weight for females and males, respectively. These values were higher than the peak vertical ground reaction forces of three times body weight reported by Simpson and her colleagues in the performance of a simple dance leap (Simpson et al., 1996; Simpson & Kanter, 1997; Simpson & Pettit, 1997). The main difference between the simple leap studied by Simpson and colleagues and the leap studied by Becker (1984) was the use of preparatory steps which allow the dancer to gain horizontal velocity some of which was converted to vertical velocity upon take-off. Other things being equal, more vertical velocity upon take-off would allow the dancer to attain greater vertical height, possibly increasing the magnitude of the ground reaction force upon landing. Descent to full heel compression coincided with peak vertical force and descent to maximum knee flexion represented completion of landing. However, based on the low positive correlation between the peak force and the two descent variables, neither descent variable was found to be a good predictor of the magnitude of peak landing force.

To determine if pressure across the foot can be more evenly distributed upon landing, one male dancer performed grand jeté with a single step preparation (Miller et al., 1990). Pressure distribution across the foot and vertical force were examined under 13 conditions: barefoot, wearing a standard ballet slipper, and wearing 11 different ballet slippers modified with various materials used for orthotics. Pressure plate analysis was performed for all 13 conditions while force plate analysis was performed for only four conditions: barefoot, in the unmodified ballet slipper, and two of the modified shoes. Force plate data were used to plot the dancer's center of gravity on an outline of his foot. Winter (1990) defines center of gravity as the location of the body's center of mass in the vertical direction and Shimba (1984) and Soutas-Little (1987) define center of pressure as the intersection of the screw axis force system resultant and the horizontal surface of the force plate. Given that force plate data were used in the analysis, the authors may have plotted the path of the center of pressure (kinetic) rather than center of gravity (kinematic) as expressed in the article. Pressure distribution differed under barefoot and ballet slipper conditions with pressure distributed more evenly with the ballet slipper. All 11 of the modified shoes demonstrated pressure distribution across the foot, away from the first and second toes. The modified shoe that most successfully distributed pressure across the foot was also comfortable for the dancer; an indication that ballet shoes could provide protection and not interfere with performance of movement. Peak vertical reaction force under all conditions was determined to be approximately three times body weight. This finding was lower than the findings from Becker (1984), but consistent with more recent studies of dance leaps (Simpson et al., 1996; Simpson & Kanter, 1997; Simpson & Pettit, 1997). Upon examination of the center of gravity outlines, the authors found that the center of gravity was consistently over the first and second metatarsal heads. This may be the only study to date to examine the effect of shoes on external force and pressure distribution in the performance of dance movements.

Problem Statement

Study of aerial movements in dance is essential because they are performed repetitively on a daily basis by both dancers and gymnasts. To the knowledge of this researcher, there has been no three-dimensional analysis of landing from any dance leap reported in the literature, nor has any study investigated the influence of pointe shoes on landing from aerial movements. Because tissue injury can be caused by 1) one maximum load, 2) repetitive loading, and 3) the rate of loading (Nordin & Frankel, 1989), grand jeté is of particular interest. This leap requires the performer to leap high into the air and results in vertical ground reaction forces over three times body weight upon landing (Becker, 1984; Miller et al., 1990). Grande jeté is a common movement, performed numerous times as part of dance training and over the course of a dance career.

The purpose of this case study was to examine the effect of ballet footwear on the three-dimensional sagittal plane kinematics and three-dimensional kinetics of landing from grand jeté. The phrase "sagittal plane analysis" was used when discussing the three-dimensional sagittal plane analysis.

The following variables were measured at landing from grand jeté: (1) angular displacement of the ankle and knee joints, (2) angular velocity of the ankle and knee joints, (3) angular acceleration of the ankle and knee joints, (4) peak vertical ground reaction force and rate of loading, and (5) force-time characteristics of ground reaction force components (FX, FY, FZ). Foot conditions examined were pointe shoes, ballet slippers, and barefoot.

Hypotheses

At landing from grand jeté:

(1) Angular displacement of the knee and ankle joints will differ with foot condition.

(2) Angular velocity of the knee and ankle joints will differ with foot condition.

(3) Angular acceleration of the knee and ankle joints will differ with foot condition.

(4) Peak vertical ground reaction forces will not differ with foot condition.

(5) Peak vertical ground reaction force rate of loading will differ with foot condition.

(6) Force-time characteristics of ground reaction force components (FX, FY, FZ) will differ with foot condition.

# Chapter 3

# Methodology

## Instrumentation

Data were collected in the Biomechanics Research Station of the Department of Kinesiology at Michigan State University. Force data were collected with an AMTI force plate (model OR6-5-2000) and video data were collected with two Panasonic Super VHS video cameras. Timing lights were used to time match the video data from each camera and to coordinate the force data with video data. Round markers with reflective tape were attached to the subject's skin and shoes with non-allergenic tape and were used to define the ankle and knee joints in a coordinate space. A still camera was used to document such details as marker configuration, shoe conditions, calibration set-up for three-dimensional analysis, and data-collection set-up.

Because the floor of the Research Station is of a different material (wood) than the force plate (metal), rosin was spread evenly over the entire surface with which the dancer had contact, including the force plate. Ideally, a section of linoleum flooring or marley would have been used; however, placing these materials over the force plate would have dampened the data recorded from the force plate.

Video data were recorded at 60 Hz, then digitized using the Ariel Performance Analysis System (APAS). The kinematic data was then downloaded from the APAS system for analysis. Forces were recorded at 1000 Hz and downloaded from the APAS system for analysis. Rate of loading was calculated from the force data.

## Subject

One female ballet student who attends advanced level ballet classes at a local ballet school volunteered to participate in this study. The original proposal called for the participation of three to five female professional ballet dancers. No professional dancers were available to participate, therefore the criteria were changed to allow the participation of advanced level ballet students. Only one dancer was available at the time of data collection and the prospects of getting other dancers was not encouraging. Traditionally, researchers in biomechanics have used a low number of subjects due to the time intensive nature of data reduction via digitization. Since it is uncommon for male ballet dancers to wear pointe shoes, no attempt was made to recruit male dancers.

The dancer who participated was 25 years old. She had approximately 15 years of training in ballet and had danced en pointe for approximately eight years.

The dancer wore a leotard, but not tights. The dancer's legs were bare from the greater trochanter to the ankle to prevent any movement of the markers that might have occurred due to movement of the tights over the leg. Movement due to the tights would have compounded any movement of the markers due to soft tissue movement.

The dancer was asked to wear her own ballet slippers and pointe shoes. Both pairs of shoes were prepared as they would have been prepared for rehearsal or performance. Preparation of the ballet slippers included attachment of elastic which helped hold the shoes on the dancer's feet. Preparation of the pointe shoes included attachment of ribbons and elastic which helped hold the shoes on the dancer's feet. Pointe shoes were broken-in, as they would have been for use in rehearsal or performance. Because each dancer has their own preference for the brand and condition of the shoes they wear in rehearsal and performance, the brand and amount of time the shoes had been worn was not controlled, but was noted at data collection. The brand of ballet slippers worn by the dancer was Sansha. The brand and make of pointe shoes was Capezio Aerial that had approximately 20 hours of wear.

Calibration Space

The optimal size of the calibration space was determined by the expected height of the jump, the position of the force plate, and how far the movement was expected to travel anteriorly. The space was large enough to contain the movement, yet small enough that the recorded image was as large as possible.

To determine the area of floor space, a frame was laid on the floor around the force plate such that each corner formed a right angle. Masking tape was placed under each of the corners and the corner point was marked. The sides were measured for accuracy and, to insure that each corner was perpendicular, the diagonals were measured. The space was deemed acceptable when opposite sides were equal to one another in length and the diagonal lengths were equal.

Next, the 16-point calibration frame was erected. A calibration stand was placed outside each corner of the measured space. From the arm extending from the top of each calibration stand, a string of four ping pong balls, each covered with retro-reflective tape, serving as space markers, was suspended. The surveyors' cord was adjusted such that the surveyor's plumb bob point at the end of the cord hovered over the corner marking on the masking tape. The heights of the markers on the first cord were adjusted, using toggles located beneath each marker, so that the markers were approximately equidistant from one another. The heights of the markers on one string matched the heights of the markers on the other cords. The height of each marker from the ground was measured and recorded. The set up of the calibration frame, indicating the height of each marker in centimeters along with the length and width of the calibration space, is shown in Figure 2. Each marker's X, Y, Z coordinates were entered into APAS to define the calibrated space. Movement of the markers attached to the dancer's leg within the calibrated space then could be accurately located.

The cameras were positioned so that the entire frame was visible. One camera recorded grand jeté from the side and the other camera recorded the movement from a corner view (Figure 2). Each camera was focused in the following manner. An individual assisting with data collection stood in the calibration frame and the camera operator focused on the individual's watch. Once the watch was in focus, the operator pulled the field of view out so that all 16 points of the calibration frame were visible.

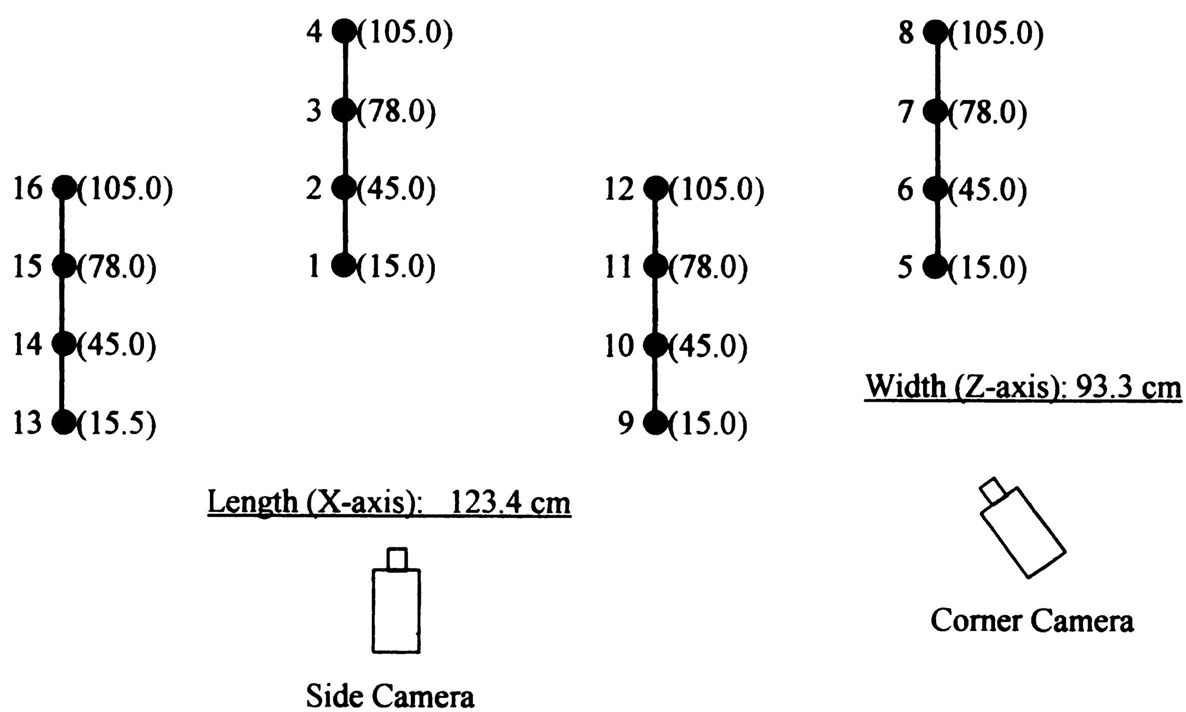


**Figure 2.** Calibration set-up and camera position for data collection.

A fixed point was established by placing a reflective marker on the ground out of the way of the movement. The calibration frame was allowed to settle until no movement was detected. The calibration frame was videotaped simultaneously by both cameras and removed from the area.

A pair of synchronized timing lights was used to coordinate digitization of the two views. One box of timing lights was visible to the side camera; the other, visible to the corner camera. Both boxes of timing lights were placed well out of the way of the dancer and did not affect or hinder her ability to perform the movement.

Subject Preparation

The dancer was responsible for her own warm-up. Once warmed-up, the dancer practiced grand jeté pas de chat so that at landing the entire foot was on the force plate. Practice of the movements allowed the dancer to get a feel for the space and to determine her starting point. The dancer performed grand jeté landing on her right leg, the lateral side of which was visible to both cameras. The sequence of movements was as follows: temps levé en arabesque, tombé, glissade, grand jeté (see Appendix A for a description of these steps). These steps are commonly performed in sequence and were familiar to the dancer. After landing from the grand jeté, the dancer ran, as if exiting the stage. These movements were performed to the first sixteen counts of "Grand Allegro," a selection from "Olga!" Music for Ballet Class by Olga Evreinoff and Lynn Stanford. Since this is a compact disc commonly used by ballet teachers, the music was familiar to the dancer.

Order of foot conditions (barefoot, ballet slipper, and pointe shoe) was randomized to offset the influence of practice and fatigue. Each of the foot conditions was written on a separate card and placed into an opaque bag. Prior to filming, the dancer drew the cards out of the bag and the order the cards were drawn determined the sequence of foot conditions. The order of foot conditions was barefoot, ballet slipper, and pointe shoe. The dancer rested between each trial and the length of the period of rest between trials was determined by the dancer, except when markers fell off and had to be replaced. A trial was recorded and considered good if the entire landing foot were on the force plate, the grand jeté were done in time to the music, all markers stayed attached to the dancer, and the dancer felt the grand jeté was representative of her ability. Ideally, three good trials would have been recorded for each condition. However, due to camera malfunction on the last recorded good trial, only two pointe shoe trials were suitable for analysis. Three good trials were recorded for the barefoot and slipper conditions.

Reflective markers were placed on the right leg as shown in Figure 3. Water soluble, non-allergenic ink was used to place a dot on the skin and shoe of the dancer at each specified site of marker placement. These dots insured accurate replacement of markers, when they fell off during data collection. The anatomical landmarks for the markers were as follows:

1. Greater trochanter
2. Anterior thigh, in area with minimal muscle movement
3. Femoral lateral epicondyle
4. Superior anterior tibia, under the knee (on tibial crest)
5. Inferior anterior tibia, above the ankle (on tibial crest)
6. Lateral malleolus
7. Middle of the top of the rearfoot
8. Fifth metatarsal-phalangeal joint

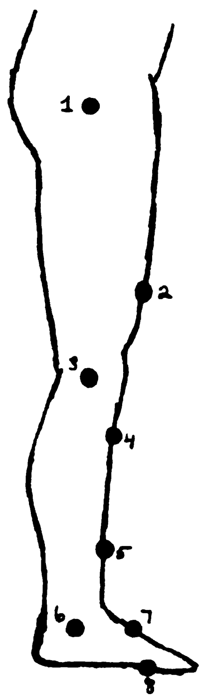


**Figure 3.** Placement of reflective markers.

The points on the leg defined the leg segments in space and from their locations, displacements, velocities, and accelerations of the knee and ankle joints could be determined. The thigh segment was defined by markers one and three; the shank segment, by markers three and six; and the foot segment, by markers six and eight. The knee joint was defined by the thigh and shank segments and the ankle joint was defined by the shank and foot segments.

Pointe shoes and ballet slippers did not seem to pose a problem for marker placement on the foot. Both types of shoes were tight fitting and identifying the bony landmarks of the foot was not difficult. Because ballet shoes are designed to conform to the foot during movement, there should have been little, if any, movement of the markers on the shoe, over the foot. Prior to data collection, the body weight of the dancer was recorded. The dancer weighed 47.61 kg at the time of data collection. The dancer was also filmed standing on the force plate to assure proper placement of markers and to establish a standing file from which relative position was measured. For this standing file, additional markers were placed on the medial condyle and medial malleolus of the right leg. These additional markers were necessary to estimate joint centers of the knee and ankle and would have been required for the calculation of moments about the respective joints.

Identification of Rigid Bodies in Space

Three non-colinear points define a rigid body in three-dimensional space. Points 1, 2, and 3 defined the thigh; 3,4, and 5, the shank; and 6, 7, and 8, the foot. The APAS software defines angular displacement relative to the angle formed between the horizontal and a counter-clockwise rotation to the two-dimensional line representing the segment. The thigh segment was defined as the line between the points 1 and 3; the shank segment, points 3 and 6; and the foot segment, points 6 and 8 (Figure 3).

Knee flexion/extension was determined by the angle between the thigh and shank segments. Knee flexion/extension was calculated by subtracting the complementary angle between the two segments, as determined by APAS, from 180 degrees. Zero degrees represented full knee extension and the angle increased as the knee flexed during landing. Ankle plantar-/dorsi-flexion was determined by the angle between the shank and foot segments. Ankle plantar-/dorsi-flexion was calculated by subtracting the angle between the two segments from 180 degrees. Zero degrees was full plantar-flexion and the angle increased as the ankle dorsi-flexed during landing. Neutral ankle position for the subject was 60 degrees and it is shown on the ankle angular displacement graphs as a darker line.

Data Analysis

The three good trials were recorded for the barefoot and slipper foot conditions. However, only two good trials of the pointe shoe condition were available for analysis due to camera malfunction on the final good trial done by the dancer. Once the trials were digitized, transformed, and smoothed with a cubic spline filter using APAS, change in angular displacement of the knee and ankle joints was plotted against time and was compared and contrasted among foot conditions. The paths of angular velocity and acceleration across time also were compared and contrasted among foot conditions. Special attention was paid to any sudden changes of direction that may have occurred, because sudden changes of direction in displacement, velocity or acceleration may be an indication of an increased risk of injury.

Kinetically, the peak vertical force and force-time characteristics of ground reaction force components (FX, FY, FZ) at landing, as well as the rate at which loading occurred were compared and contrasted among foot conditions. Vertical (FZ) data were not smoothed; however, FX and FY data were smoothed further due to noise in the system. The shape of the graphs were maintained. Difficulties were encountered in calibrating the force plate to record accurate force plate moments. Calculation of the path of the center of pressure and knee and ankle joint flexion/extension moments required force plate moments for calculation and therefore could not be evaluated for this study. Noteworthy kinetic events were coordinated with the corresponding kinematic data by matching the times as recorded by force and video methods, respectively.

## Chapter 4

## Results and Discussion

A trial was considered good if the entire landing foot was on the force plate, the grand jeté was done in time to the music, all markers stayed attached to the dancer, and the dancer felt the grand jeté was representative of her ability. The order of foot conditions was: 1) barefoot, 2) ballet slipper, and 3) pointe shoe. Three good trials were chosen for the barefoot and slipper foot conditions. Due to camera malfunction on the last potentially good trial done by the dancer, only two good trials for the pointe shoe condition were available for analysis. The trials chosen for analysis were Barefoot trials 8, 10, 11 (BF8, BF10, BF11); Slipper trials 6, 7, 8 (SL6, SL7, SL8); and Pointe Shoe trials 1, 4 (PT1, PT4).

For the purposes of this study, landing was defined as contact with the force plate from toe down, the dancer's first contact with the force plate, to toe off, when the dancer lost contact with the force plate. The graphs of landing for kinematic data began with the first frame of video in which the dancer was in contact with the force plate. Knee flexion/extension was determined by the angle between the thigh and shank segments as explained earlier. The thigh segment was defined as the line between the markers at the greater trochanter and lateral epicondyle (points 1 and 3); the shank segment was defined by the line between the markers of the lateral epicondyle and the lateral malleolus (points 3 and 6) (Figure 3). Knee flexion/extension was calculated by subtracting the complementary angle between the two segments, as determined by APAS, from 180 degrees. Therefore, zero degrees was full knee extension and the angle increased as the knee flexed during landing. Ankle plantar-/dorsi-flexion was determined by the angle between the shank and foot segments. The foot segment was defined as the line between the markers of the lateral malleolus and the fifth metatarsal-phalangeal joint (points 6 and 8). Zero degrees was full plantar-flexion and the angle increased as the ankle dorsi-flexed during landing. Neutral ankle position for the subject was 60 degrees, which is shown on the ankle angular displacement graphs as a darker line. Knee flexion and ankle dorsi-flexion were considered positive; knee extension and ankle plantar-flexion, negative.

Kinetic data were recorded during landing from the dancer's first recorded contact with the force plate until the foot left the plate. Relative to the force plate coordinate system, the dancer performed grand jeté in the positive Y direction. Medial/lateral reaction force was dependent upon which leg the dancer used in the landing. In this study, the dancer landed on the foot of her right leg; therefore, medial movements were considered positive; lateral movements, negative.

Kinematics

Kinematic information describes movement. Linear and angular displacements, velocities, and accelerations are used in these descriptions, as well as temporal components. Kinematic information is of interest because sudden changes in direction of displacement, velocity, or acceleration data may indicate an increased risk for injury at the time of the change.

**Flexion/extension angular displacement.** Knee flexion/extension angular displacement for all trials can be seen in Figures 4-6. Ankle dorsi-/plantar-flexion angular displacement for all trials is depicted in Figures 7-9.

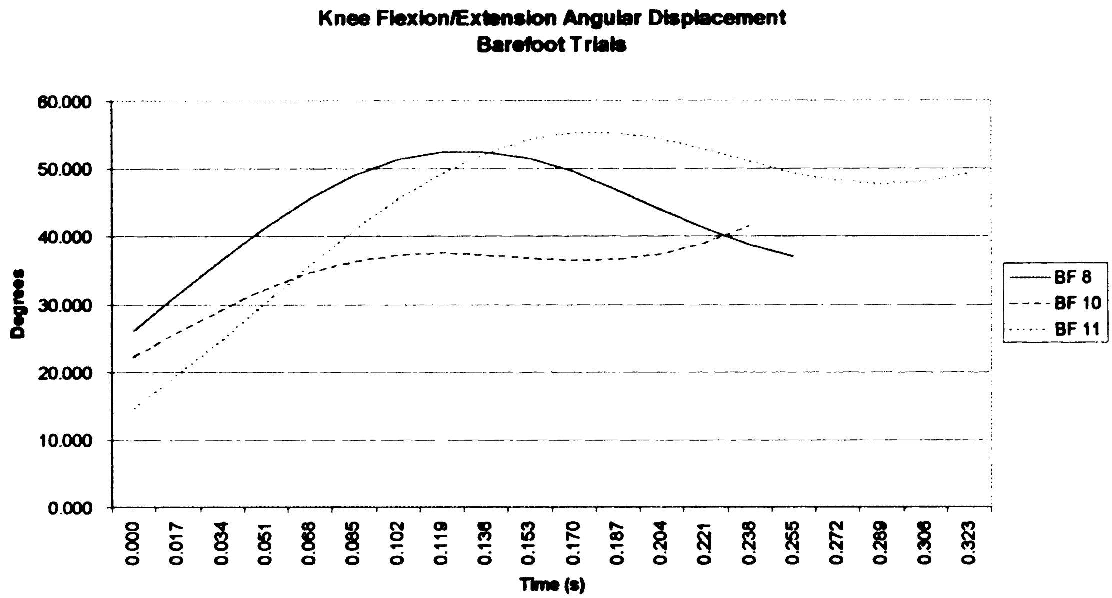


**Figure 4.** Knee flexion/extension angular displacement for the three barefoot trials.

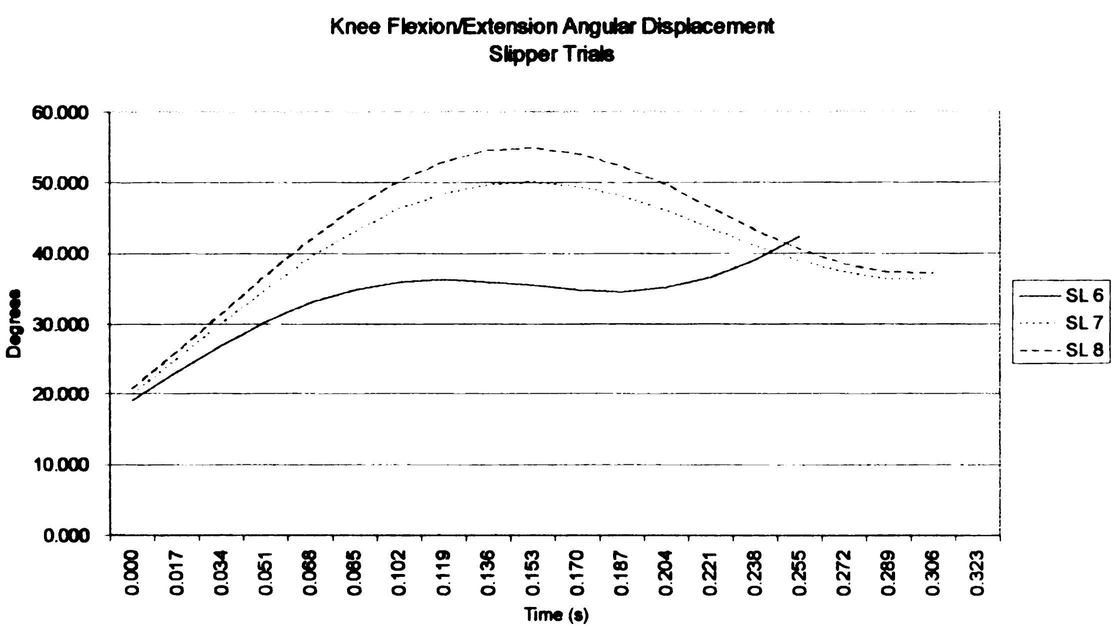


**Figure 5.** Knee flexion/extension angular displacement for the three slipper trials.

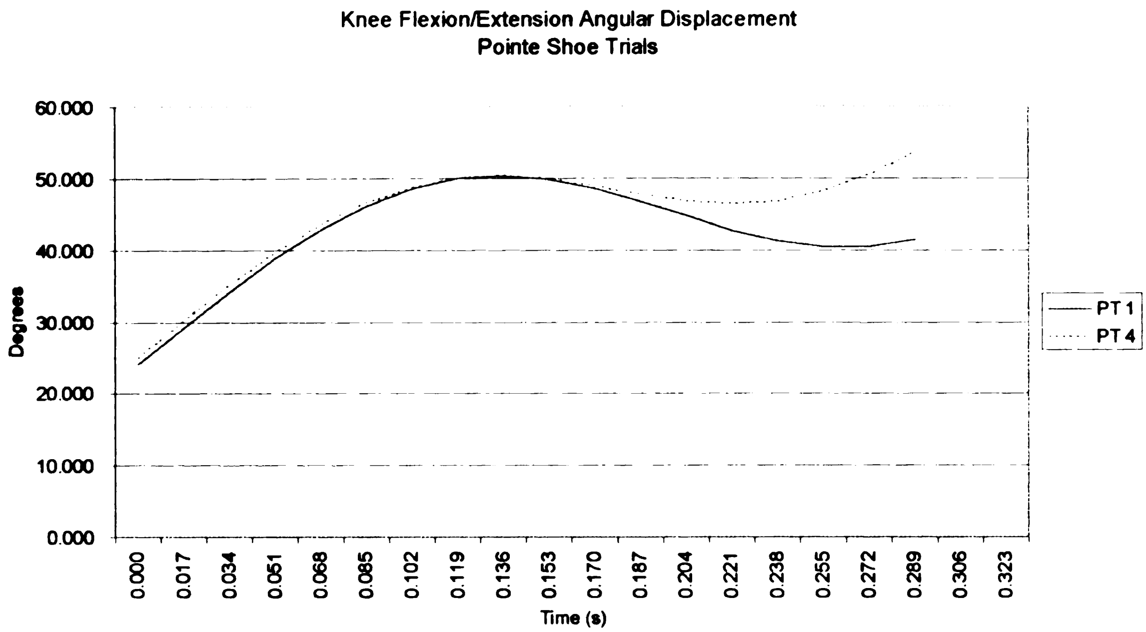


**Figure 6.** Knee flexion/extension angular displacement for the two pointe shoe trials.

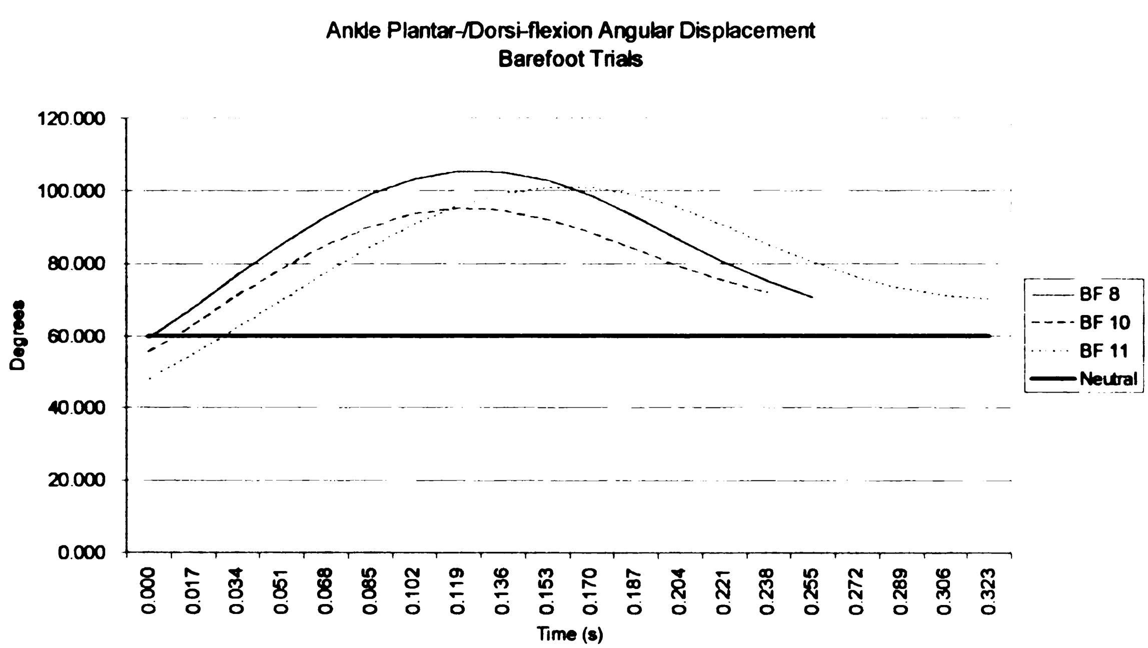


**Figure 7.** Ankle plantar-/dorsi-flexion angular displacement for the three barefoot trials.

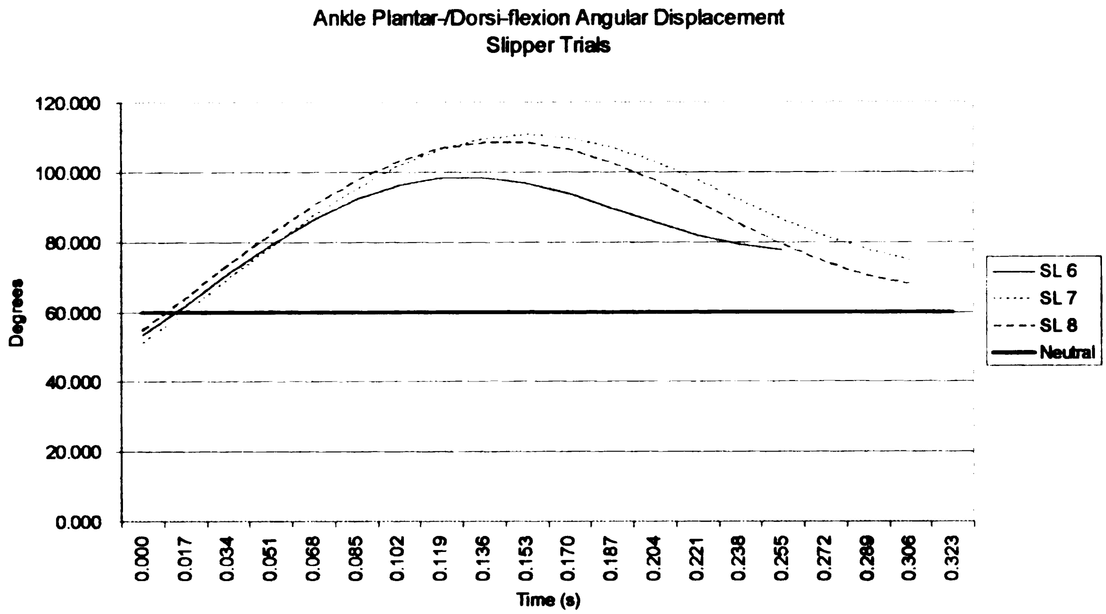


**Figure 8.** Ankle plantar-/dorsi-flexion angular displacement for the three slipper trials.

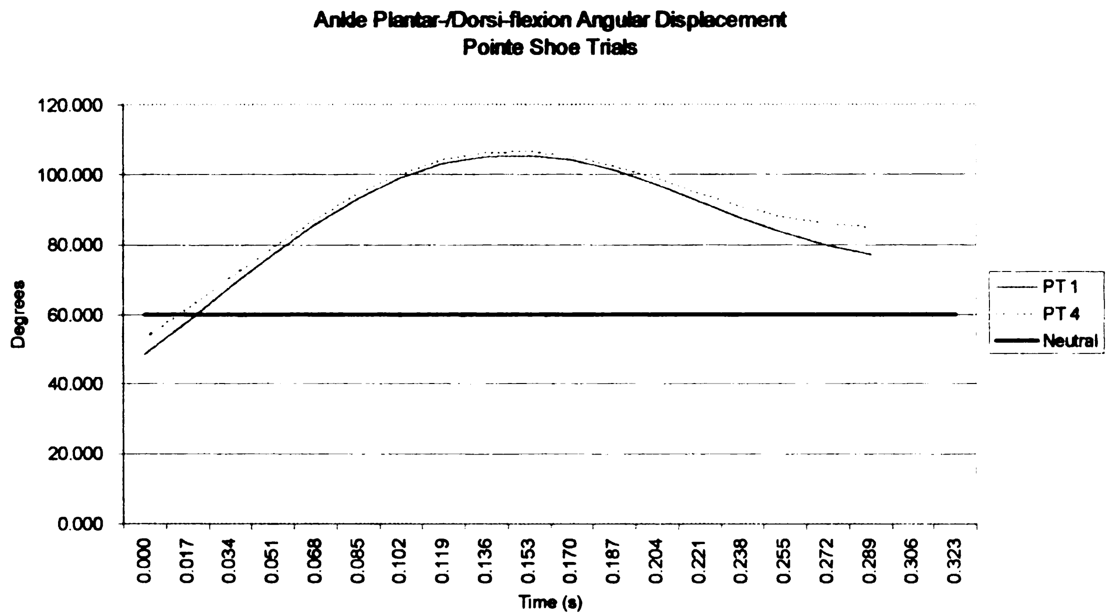


**Figure 9.** Ankle plantar-/dorsi-flexion angular displacement for the two pointe shoe trials.

**Table 1.**

Peak angle of knee flexion and ankle dorsi-flexion with time at peak.

| Trial | Peak knee flexion (deg) | Time at peak flexion (s) | Peak ankle dorsi-flexion (deg) | Time at peak dorsi-flexion (s) |
|---|---|---|---|---|
| BF8 | 52.5 | 0.136 | 105.44 | 0.119 |
| BF10 | 37.44 | 0.119 | 94.94 | 0.119 |
| BF11 | 55.18 | 0.17 | 100.68 | 0.153 |
| SL6 | 35.96 | 0.136 | 98.34 | 0.136 |
| SL7 | 50.01 | 0.153 | 110.52 | 0.153 |
| SL8 | 54.84 | 0.153 | 108.48 | 0.136 |
| PT1 | 50.32 | 0.136 | 106.53 | 0.153 |
| PT4 | 50.31 | 0.136 | 105.58 | 0.153 |

Generally, the pattern and magnitude of knee flexion/extension were similar for all three conditions. Maximum knee flexion ranged from 35.96 to 55.18 degrees of flexion. However, for two trials, BF10 and SL6, the magnitude of maximum knee flexion was lower than any of the other trials (Table 1). When the two lowest values are excluded, the range of values for maximum knee flexion becomes 50.01 to 55.18 degrees. The time to maximum knee flexion after toe down, ranged from 0.119 to 0.170 seconds, with no evidence of any difference between foot conditions.

The apparent outliers in knee displacement, BF10 and SL6, may have occurred because in these trials, compared to the other trials, the dancer brought her leg further underneath herself to a more vertical position as she descended from peak height of the leap. If the dancer brought her leg more underneath herself during descent, she would not have been able to take full advantage of knee flexion to dampen the force at landing because the momentum of her body weight moving forward would not have given her time to reach a greater angle of knee flexion. The relationship between the markers at the greater trochanter and lateral malleolus along the X-axis seemed to confirm this supposition. At contact, during trials BF10 and SL6, there was less difference between the two markers than during the other trials, indicating that the markers were closer to being aligned along the vertical Y-axis.

The pattern and magnitude of ankle dorsi-flexion were similar for all three conditions (Table 1). Of the three foot conditions, the condition that demonstrated, on average, the least amount of dorsi-flexion was the barefoot condition. Average maximum dorsi-flexion for the barefoot condition was 100.35 degrees, while the averages for the slipper and pointe shoe conditions were 105.78 degrees and 106.06 degrees, respectively. While not markedly lower than the other trials, the two lowest magnitudes for maximum dorsi-flexion occurred during trials BF10 and SL6, the trials with the lowest angle of knee flexion. The lower angles of dorsi-flexion seem to support the speculation that the dancer's weight was further forward in relation to her leg and the horizontal momentum of the movement kept her moving forward and did not allow her time to reach a greater angle of dorsi-flexion to dampen the force of landing. Time to maximum dorsi-flexion ranged from 0.119 to 0.153 seconds with no apparent difference between foot conditions.

Throughout landing, knee flexion and dorsi-flexion increased. In each trial, regardless of foot condition, maximum knee flexion and maximum dorsi-flexion were reached within one frame (0.017 s) of each other, however, the order in which these two events occurred differed with foot condition. Peak dorsi-flexion during the barefoot and ballet slipper conditions, occurred before or at the same time as peak knee flexion. During the two pointe shoe trials, however, peak dorsi-flexion occurred one frame after peak knee flexion. The angle of knee flexion at foot contact was higher for the pointe shoe condition than for most of the other trials; the exception being BF8. A higher knee flexion angle at contact would have given the knee joint a head start reaching peak angular displacement compared to the ankle joint. The difference in timing under the pointe shoe condition may also be due to the relatively heavy leather shank of the shoes and/or the elastic and ribbons crossed at the dancer's ankle that held the shoe on her foot during movement. In particular, the shank of the shoe, and also the elastic and ribbons added resistance that the dancer had to overcome during landing.

**Flexion/extension angular velocity.** Angular velocity is the rate at which angular displacement occurs. Knee flexion/extension angular velocity for all eight trials can be seen in Figures 10-12 while ankle dorsi-/plantar-flexion angular velocity for all trials is depicted in Figures 13-15.

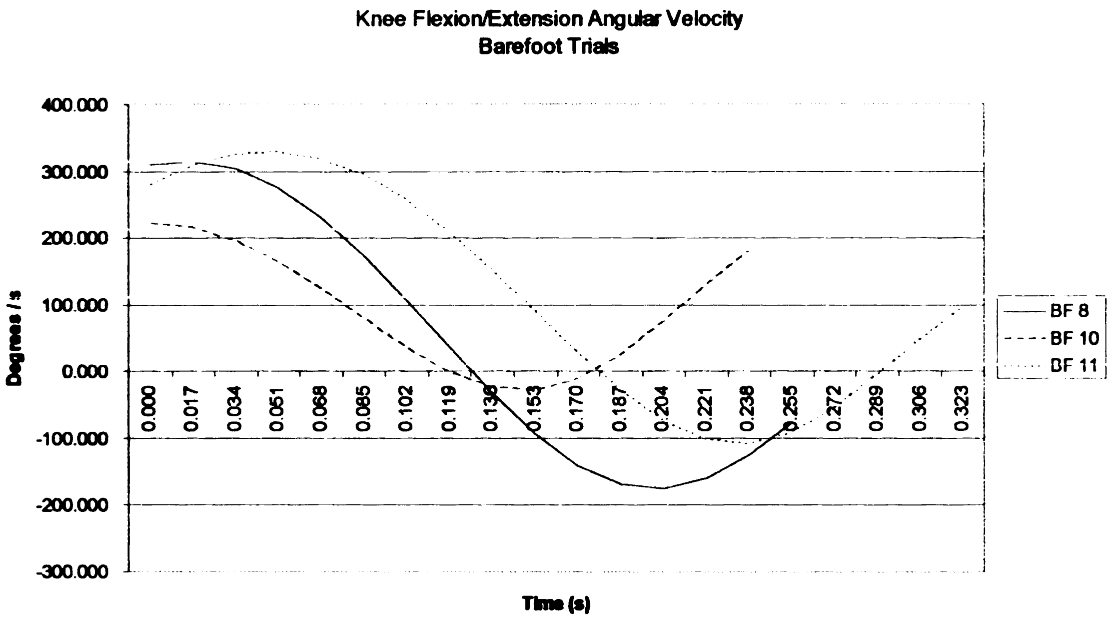


**Figure 10.** Knee flexion/extension angular velocity for the three barefoot trials.

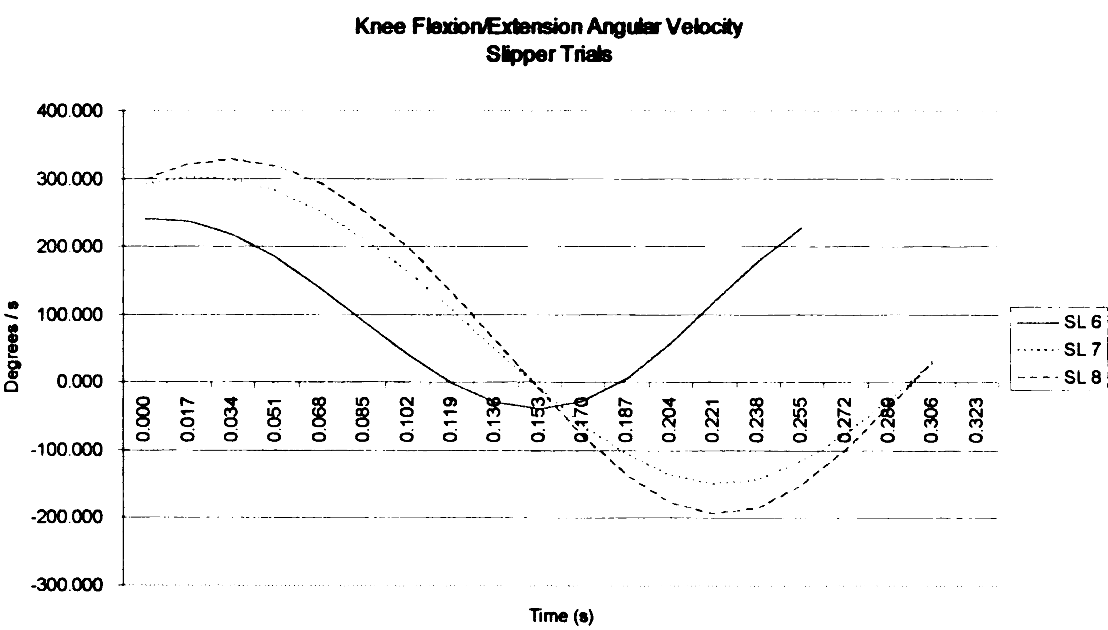


**Figure 11.** Knee flexion/extension angular velocity for the three slipper trials.

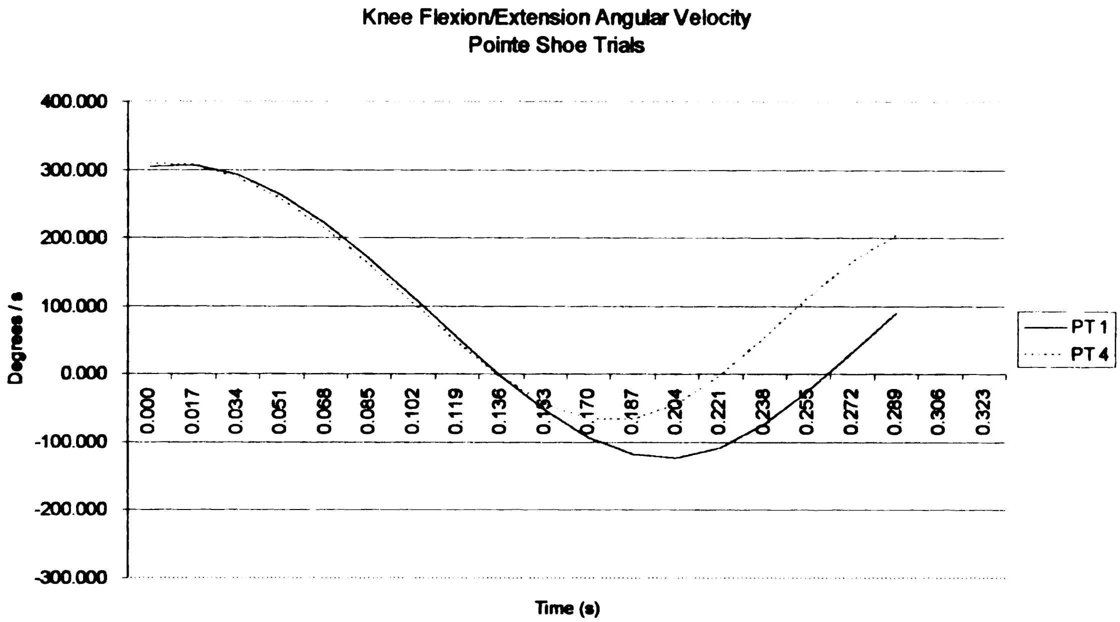


**Figure 12.** Knee flexion/extension angular velocity for the two pointe shoe trials.

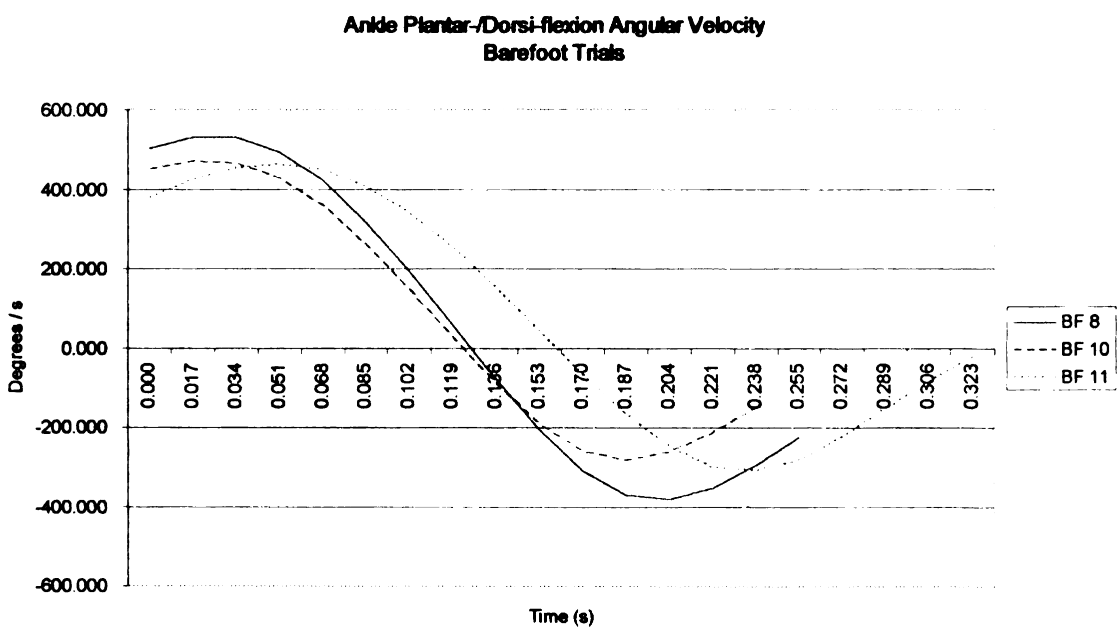


**Figure 13.** Ankle plantar-/dorsi-flexion angular velocity for the three barefoot trials.

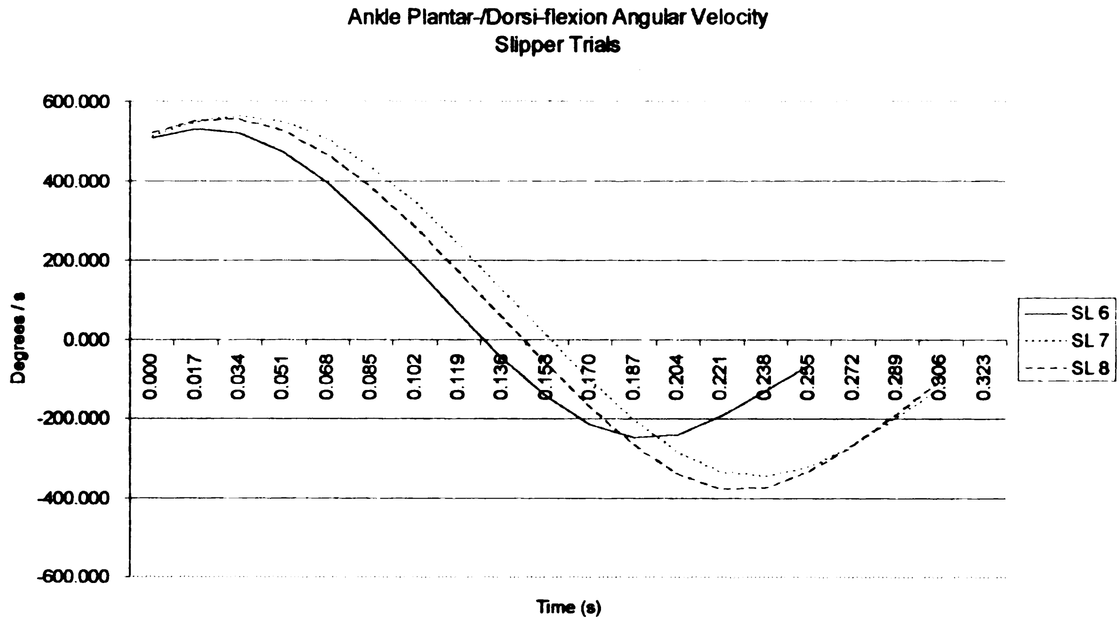


**Figure 14.** Ankle plantar-/dorsi-flexion angular velocity for the three slipper trials.

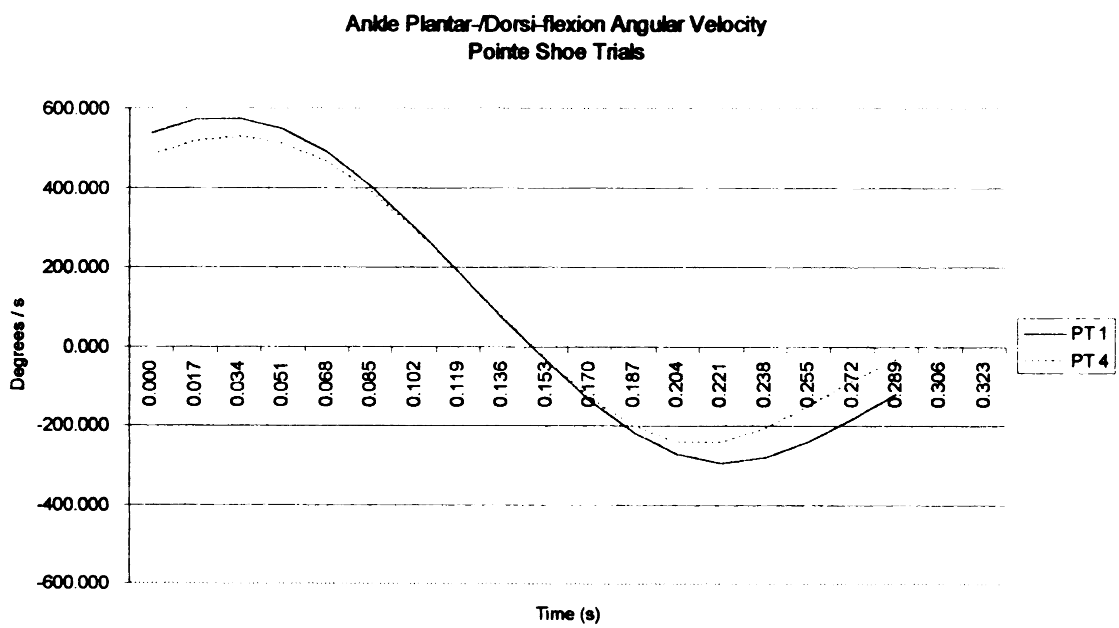


**Figure 15.** Ankle plantar-/dorsi-flexion angular velocity for the two pointe shoe trials.

Maximum angular velocity of the knee occurred at, or within three frames (0.051 s) after, toe down for all trials (Table 2). Peak knee velocity for all trials, ranged from 222.27 to 328.98 deg/s with no apparent difference between shoe conditions. The trials with the highest and lowest magnitudes of peak knee velocity were BF11 and BF10, respectively. The two lowest values for peak knee velocity were recorded for BF10 and SL6, the trials with the least amount of knee flexion displacement. Knee flexion velocity for these two outlying trials was lower than the remaining trials because the knee covered less angular displacement in a similar amount of time. The rate of knee flexion decreased steadily until reaching zero velocity to coincide with maximum knee flexion. Minimum angular velocity of the knee occurred 10 to 12 frames (0.170 to 0.204 s) after peak angular velocity and ranged from -27.99 to -194.82 deg/s. This range included the two highest values for minimum angular velocity, those for BF10 and SL6.

**Table 2**

Maximum and minimum knee and ankle angular velocities with time at occurrence.

| Trial | Knee Max/min (deg/s) | Time from toe down(s) | Ankle Max/min (deg/s) | Time from toe down (s) |
|---|---|---|---|---|
| BF8 | 315.15 / -175.61 | 0.017 / 0.204 | 531.95 / -381.27 | 0.017 / 0.204 |
| BF10 | 222.27 / -27.99 | 0.00 / 0.153 | 471.92 / -283.60 | 0.017 / 0.187 |
| BF11 | 328.98 / -108.52 | 0.051 / 0.238 | 461.31 / -310.56 | 0.051 / 0.238 |
| SL6 | 240.97 / -40.50 | 0.00 / 0.153 | 529.88 / -248.29 | 0.017 / 0.187 |
| SL7 | 301.77 / -150.81 | 0.017 / 0.221 | 561.71 / -347.43 | 0.034 / 0.238 |
| SL8 | 328.09 / -194.82 | 0.034 / 0.221 | 552.94 / -377.08 | 0.034 / 0.221 |
| PT1 | 306.55 / -124.19 | 0.017 / 0.204 | 574.97 / -293.54 | 0.034 / 0.221 |
| PT4 | 308.40 / -66.73 | 0.00 / 0.187 | 528.51 / -243.67 | 0.034 / 0.221 |

For all trials, maximum ankle velocity occurred within 0.051 seconds (three frames) after toe down and ranged from 461.31 to 574.97 deg/s with the barefoot condition showing a lower average of dorsi-flexion velocity compared to the other conditions. The two trials with the lowest magnitude of dorsi-flexion velocity occurred under the barefoot condition. These two trials also had two of the three lowest magnitudes of dorsi-flexion angular displacement. The velocity of ankle dorsi-flexion was lower for those trials with less angular displacement because the ankle did not have to cover as angular displacement in a similar amount of time. After reaching maximum ankle velocity, angular velocity continued to decrease as dorsi-flexion increased. Minimum angular velocities ranged from -243.67 to -381.27 deg/s. As was the case with minimum knee angular velocity, minimum ankle angular velocity occurred 10 to 12 frames (0.170 to 0.204 s) after maximum ankle angular velocity.

Peak knee angular velocity occurred at the same time as peak ankle angular velocity in three of the trials – BF8, BF11, SL8. In the remaining trials, peak knee angular velocity occurred before peak ankle angular velocity. Because two of the trials with simultaneous peak knee velocity and peak ankle velocity were in the barefoot condition, it can be reasoned that the footwear influenced the angular velocity of the knee and ankle joints during landing. Further study may be warranted to examine the effect of footwear on angular velocity of the knee and ankle joints. The ballet slippers and pointe shoes may have provided resistance that hindered the dancer's ability to manipulate as quickly through her metatarsal joints and delayed peak ankle angular velocity of the five non-simultaneous trials.

**Flexion/extension angular acceleration.** Angular acceleration is the rate of change of angular velocity. Knee flexion/extension angular acceleration for all of the trials can be seen in Figures 16-18; ankle dorsi-/plantar-flexion angular acceleration, in Figures 19-21.

The knee angular acceleration pattern demonstrated two peaks. For all trials, the first peak of knee acceleration occurred within four frames (0.119 s) prior to toe down and is not shown on the graphs. The pre-landing peak is not of concern while the individual is in the air but might be of concern as to how it affected the landing and the movement after landing. Further work needs to be done to examine the effect, if any, of this pre-landing peak of knee acceleration. The values for the first peak of knee angular acceleration ranged from 1753.39 to 2994.19 deg/s$^2$ (Table 3). The first peak may indicate the dancer initiated knee flexion in preparation to absorb the impact of landing. The second peak of knee angular acceleration, ranging in value from 3204.33 to 4050.51 deg/s$^2$, occurred as the dancer continued to move forward after maximum knee flexion. The second peak is shown on the graphs for all trials with the exception of the graph for BF8, in which the second peak occurred one frame after toe off. The second peak of knee acceleration was higher than the first peak for all trials because the dancer was preparing for toe off which required an increase in knee flexion as the leg came forward. The pattern of knee angular acceleration and magnitudes of the two peaks in knee angular acceleration were similar for all three foot conditions.

Knee angular deceleration showed one peak. Peak angular deceleration of the knee occurred between 0.085 and 0.153 seconds after toe down and ranged in magnitude from -2749.37 to -4369.43 deg/s$^2$. There were no apparent differences between foot conditions in peak angular deceleration of the knee.

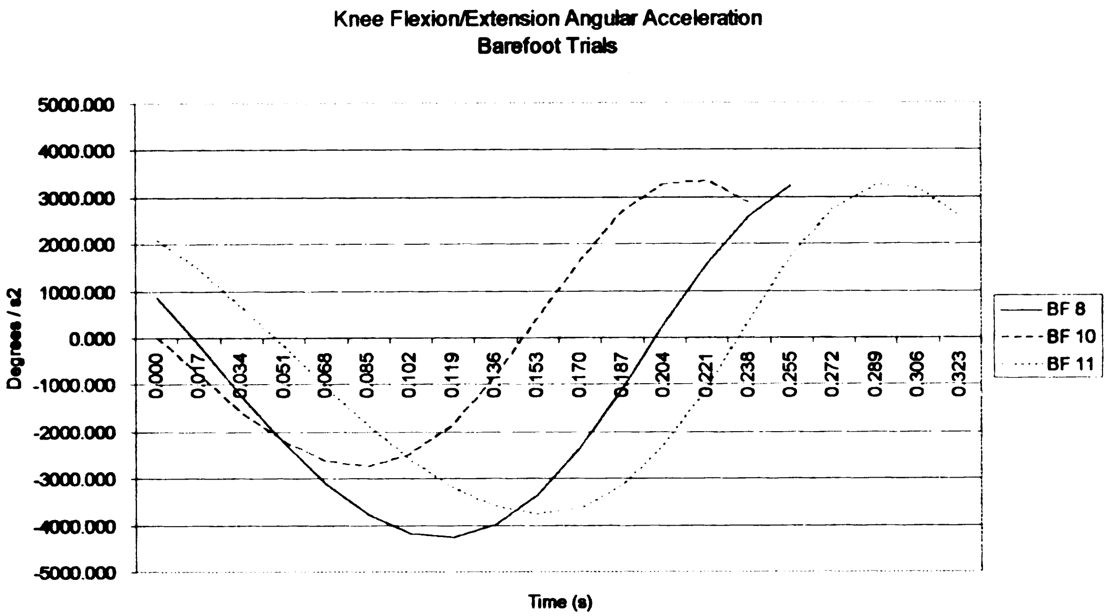


**Figure 16.** Knee flexion/extension angular acceleration for the three barefoot trials.

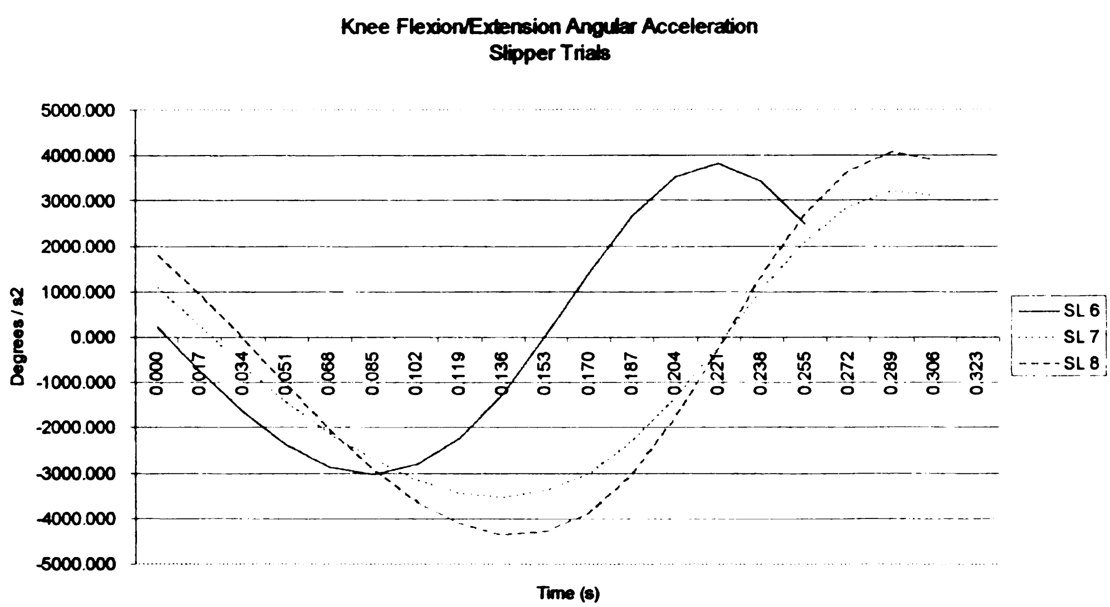


**Figure 17.** Knee flexion/extension angular acceleration for the three slipper trials.

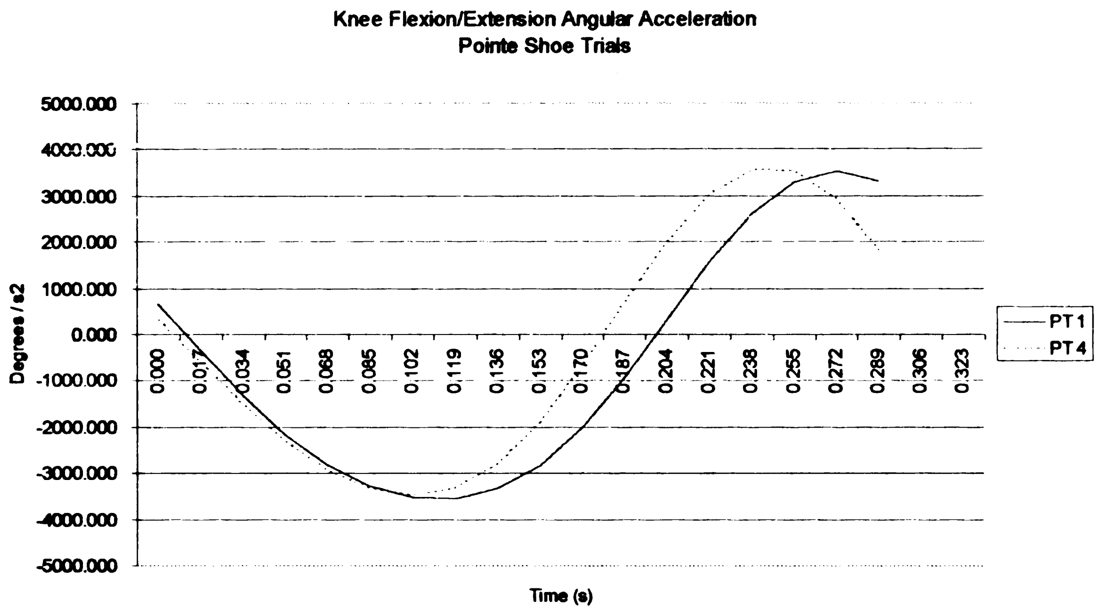


**Figure 18.** Knee flexion/extension angular acceleration for the two pointe shoe trials.

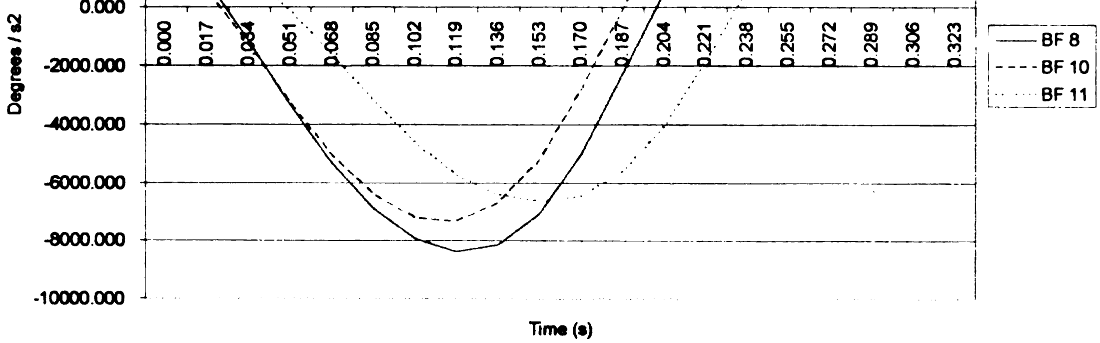


**Figure 19.** Ankle plantar-/dorsi-flexion angular acceleration for the three barefoot trials.

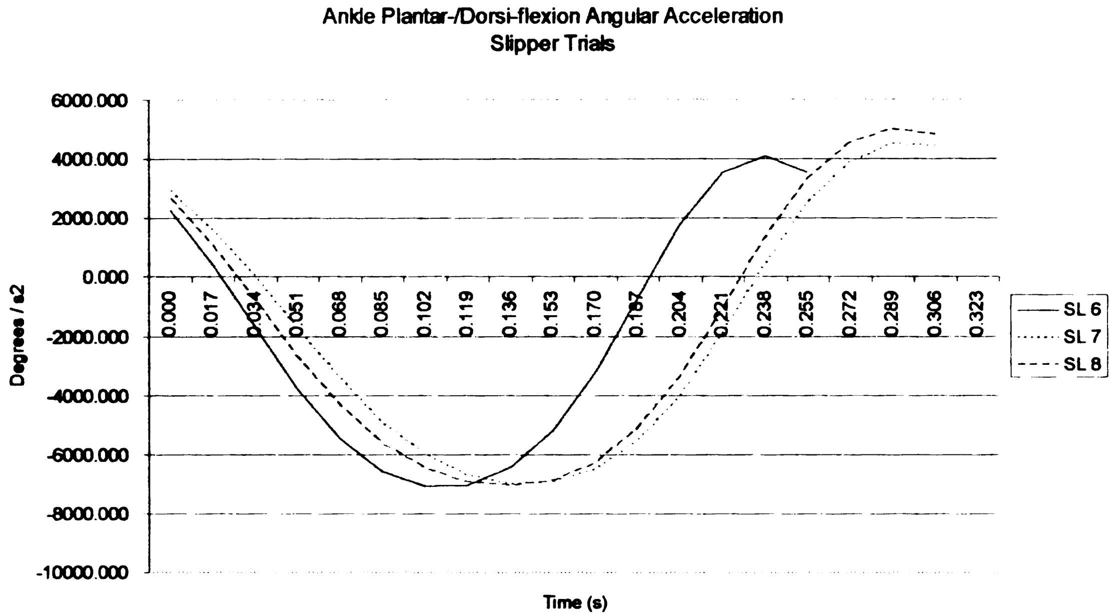


**Figure 20.** Ankle plantar-/dorsi-flexion angular acceleration for the three slipper trials.

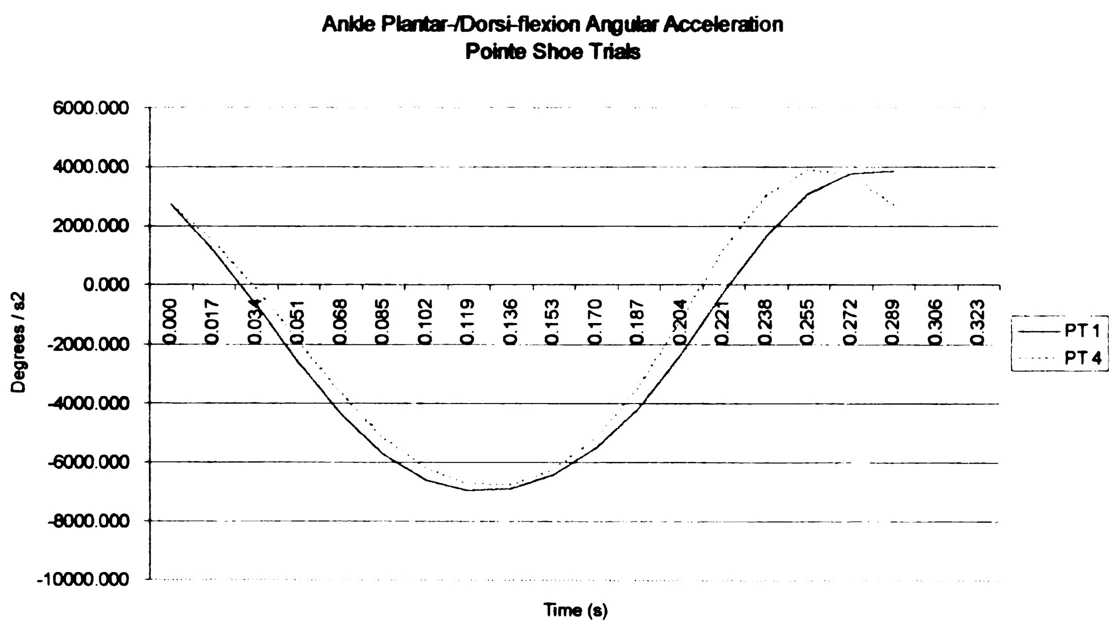


**Figure 21.** Ankle plantar-/dorsi-flexion angular acceleration for the pointe shoe trials.

**Table 3**

Maximum and minimum knee and ankle angular accelerations with time at occurrence.

| Trial | Knee ($deg/s^2$) | | Time from toe down (s) | Ankle ($deg/s^2$) | | Time from toe down (s) |
|---|---|---|---|---|---|---|
| BF8 | Max | 1st 2994.19<br>2nd 3519.66 | -0.068<br>0.272 | Max | 1st 5423.56<br>2nd 4373.54 | -0.068<br>0.255 |
| | Min | -4257.78 | 0.119 | Min | -8394.87 | 0.119 |
| BF10 | Max | 1st 1753.39<br>2nd 3330.39 | -0.068<br>0.221 | Max | 1st 4048.22<br>2nd 3799.76 | -0.051<br>0.238 |
| | Min | -2749.37 | 0.085 | Min | -7350.04 | 0.119 |
| BF11 | Max | 1st 2888.88<br>2nd 3245.62 | -0.051<br>0.289 | Max | 1st 3640.92<br>2nd 4422.90 | -0.034<br>0.289 |
| | Min | -3777.8 | 0.153 | Min | -6694.56 | 0.153 |
| SL6 | Max | 1st 2406.06<br>2nd 3801.48 | -0.068<br>0.221 | Max | 1st 4883.66<br>2nd 4086.88 | -0.051<br>0.238 |
| | Min | -3030.81 | 0.085 | Min | -7101.07 | 0.102 |
| SL7 | Max | 1st 2830.06<br>2nd 3204.33 | -0.068<br>0.289 | Max | 1st 4977.81<br>2nd 4484.65 | -0.068<br>0.289 |
| | Min | -3536.84 | 0.136 | Min | -6989.69 | 0.136 |
| SL8 | Max | 1st 2926.57<br>2nd 4050.51 | -0.051<br>0.289 | Max | 1st 4822.65<br>2nd 4997.22 | -0.051<br>0.289 |
| | Min | -4369.43 | 0.136 | Min | -7063.61 | 0.136 |
| PT1 | Max | 1st 2534.22<br>2nd 3520.15 | -0.068<br>0.272 | Max | 1st 5026.11<br>2nd 3857.48 | -0.051<br>0.289 |
| | Min | -3559.07 | 0.119 | Min | -6961.93 | 0.119 |
| PT4 | Max | 1st 2692.90<br>2nd 3561.76 | -0.068<br>0.238 | Max | 1st 4293.00<br>2nd 3874.28 | -0.051<br>0.255 |
| | Min | -3488.97 | 0.102 | Min | -6761.59 | 0.136 |

As with maximum knee angular acceleration, there were two peaks of ankle angular acceleration. The first peak, ranging in magnitude from 3640.92 to 5423.56 deg/$s^2$, occurred within 0.051 seconds prior to toe down for all trials and is not shown on the graphs. As with the first peak of knee acceleration, the first peak of ankle acceleration may indicate the dancer initiating dorsi-flexion as preparation for absorbing the impact of landing. The second peak in ankle acceleration occurred as the dancer moved forward after completion of landing and ranged from 3799.76 to 4997.22 deg/$s^2$. The second peak of ankle acceleration was comparable to the first peak for all trials. The magnitude of the second peak of ankle acceleration was similar among the foot conditions.

Maximum angular deceleration of the ankle occurred between 0.102 and 0.153 seconds after toe down and ranged in magnitude from -6694.56 to -8394.87 deg/$s^2$. There were no apparent differences among the three conditions in peak angular deceleration.

As indicated by the results for angular acceleration, the knee and ankle joints acted in a coordinated manner throughout landing. Peak knee angular acceleration occurred within 0.017 seconds of peak ankle acceleration for all trials. Peak knee and ankle accelerations occurred simultaneously for three trials: BF11, SL7, SL8. Likewise, minimum knee angular acceleration occurred within 0.017 seconds of minimum ankle acceleration for all trials. Minimum knee and ankle angular accelerations coincided for five trials, BF8, BF11, SL7, SL8, and PT1, and minimum ankle acceleration occurred one frame(0.017 s) after minimum knee acceleration for the remaining trials.

Kinetics

**Ground Reaction Forces.** Ground reaction forces (GRF) are the forces that act on the body in reaction to the forces exerted by the body on the ground. In this study, GRF acted on the dancer as she landed on her right foot. GRF are vectors of equal magnitude and opposite direction to the force exerted on the ground. The three directional components of GRF are superior/inferior (vertical), anterior/posterior, and medial/lateral, identified by FZ, FY, and FX, respectively, in accordance with the force plate coordinate system. GRF were measured by the force plate as separate components and recorded by APAS.

**Vertical ground reaction force (FZ).** Vertical ground reaction force for all trials can be seen in Figures 22-24.

With the exception of BF 10 and the two pointe shoe trials, two distinct spikes were evident on the charts for vertical GRF. The second spike was higher and represented peak GRF. Becker (1984) associated the first spike with full metatarsal head contact and peak GRF was associated with full heel compression. This association between the two spikes of vertical GRF and foot kinematics could not be confirmed in the present study. The patterns of vertical force for the two pointe shoe trials did not show a distinct first peak. The lack of a distinct first peak for the pointe shoe trials may have been due to the heavy leather shank of the pointe shoes which may have prevented the dancer from articulating through the forefoot.

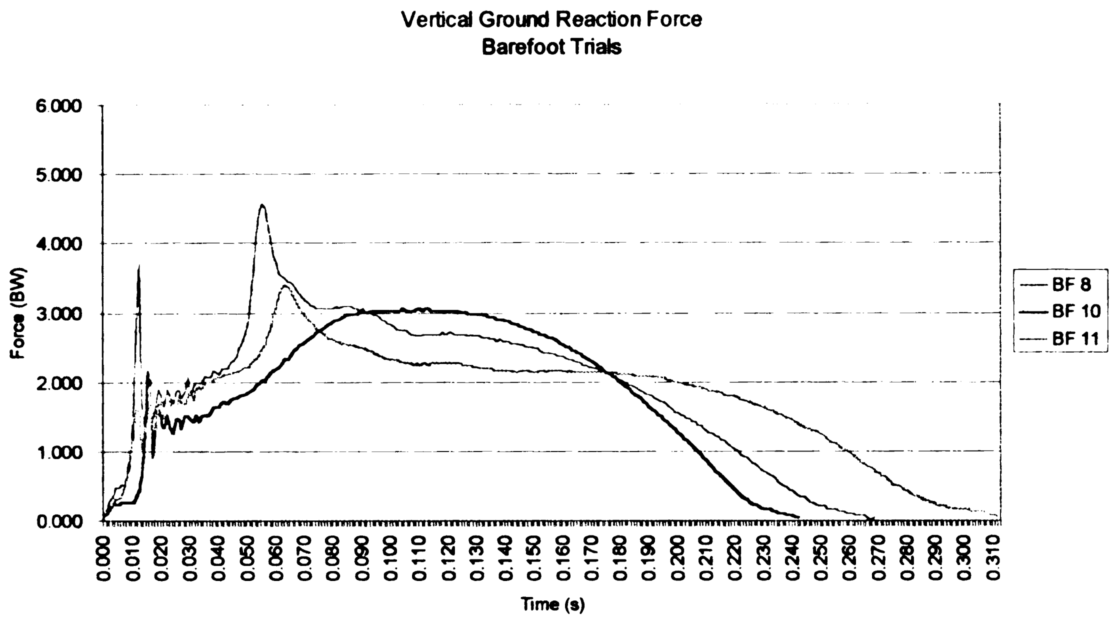


**Figure 22.** Vertical ground reaction force for the three barefoot trials.

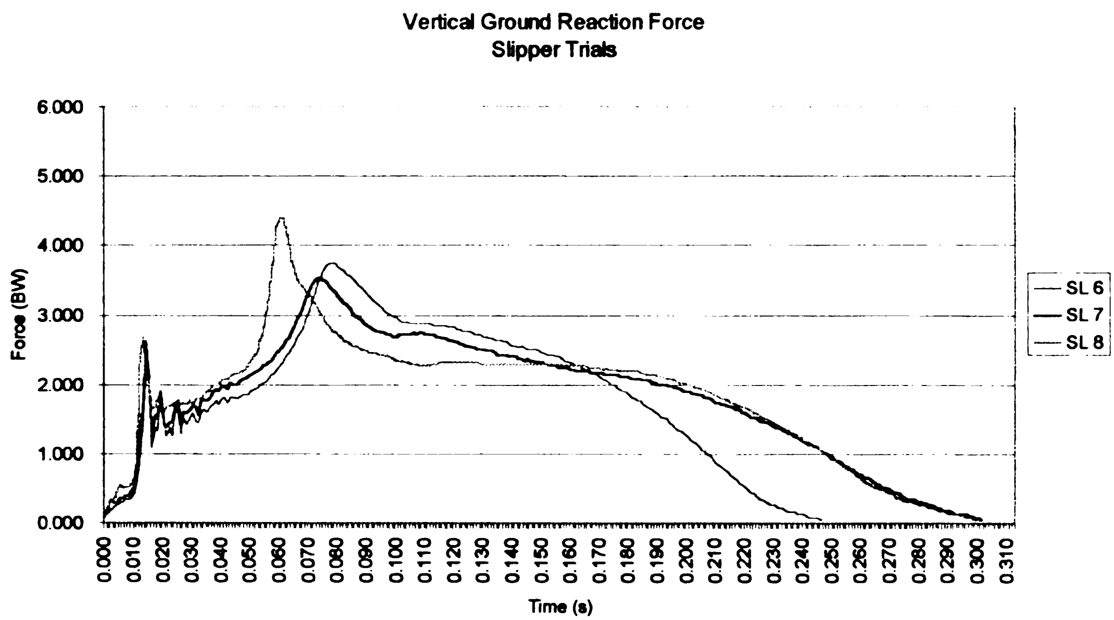


**Figure 23.** Vertical ground reaction force for the three slipper trials.

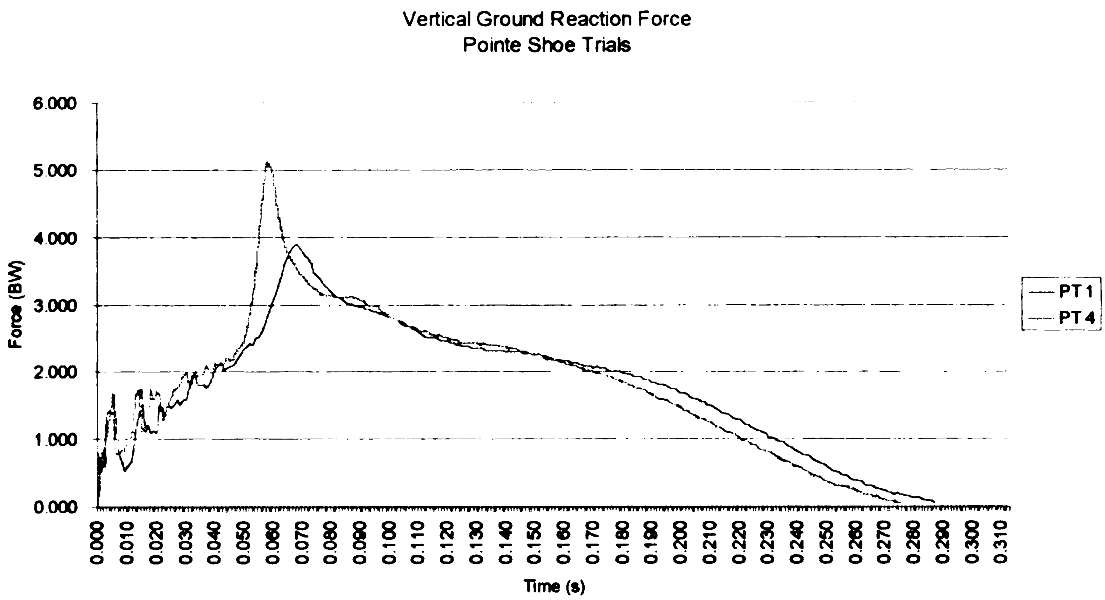


**Figure 24.** Vertical ground reaction force for the two pointe shoe trials.

The pattern of vertical force for BF10 showed a distinct first spike, similar to the other barefoot trials and all of the slipper trials; however, there was not a distinct second spike. After the first spike for BF10, the magnitude of vertical force increased curvilinearly rather than a sharp spike and rapid decline. The different pattern of vertical force for BF10 was due to the dancer not reaching full heel compression in this trial as she did in the other trials. Because she did not reach full heel compression, the dancer bore more vertical force for a longer length of time on her forefoot, than she did in any of the other trials. Landing on the forefoot without full heel compression could increase the dancer's risk of injury, because the forefoot is comprised of bones that are smaller and lighter, compared to the bones in the rearfoot which are better designed to withstand the stress of peak vertical GRF.

The first spikes in GRF for the barefoot and slipper trials were similar in magnitude, ranging from 1.95 to 3.72 BW (Table 4). For those trials with two distinct spikes in vertical GRF, the first spike occurred between 0.043 and 0.059 seconds prior to peak vertical GRF. The time interval between the initial spike and peak GRF was similar among foot conditions.

**Table 4**

Peaks of ground reaction forces with time at peaks.

| Trial | Vertical (BW) | Time (s) | Braking/ Acceleration (BW) | Time (s) | Medial/ lateral (BW) | Time (s) |
|---|---|---|---|---|---|---|
| BF8 | 1st: 3.72<br>2nd: 4.56 | 0.013<br>0.056 | B: 2.70<br>A: 0.78 | 0.015<br>0.196 | L: 1.15<br>M: 0.61 | 0.074<br>0.056 |
| BF10 | 1st: 2.03<br>2nd: 3.06 | 0.016<br>0.105 | B: 0.99<br>A: 1.36 | 0.019<br>0.173 | L: 0.39<br>M: 0.59 | 0.025<br>0.072 |
| BF11 | 1st: 1.95<br>2nd: 3.38 | 0.017<br>0.065 | B: 1.44<br>A: 0.83 | 0.014<br>0.198 | L: 0.52<br>M: 0.51 | 0.028<br>0.062 |
| SL6 | 1st: 2.24<br>2nd: 3.74 | 0.015<br>0.078 | B: 1.46<br>A: 1.04 | 0.017<br>0.178 | L: 0.28<br>M: 0.75 | 0.024<br>0.072 |
| SL7 | 1st: 2.61<br>2nd: 3.53 | 0.015<br>0.074 | B: 1.78<br>A: 0.83 | 0.017<br>0.199 | L: 0.36<br>M: 0.59 | 0.024<br>0.072 |
| SL8 | 1st: 2.69<br>2nd: 4.40 | 0.014<br>0.061 | B: 2.15<br>A: 0.88 | 0.016<br>0.207 | L: 0.60<br>M: 0.56 | 0.030<br>0.062 |
| PT1 | 1st: n/a<br>2nd: 3.90 | -0.069 | B: 1.70<br>A: 0.65 | 0.014<br>0.207 | L: 1.00<br>M: 0.64 | 0.025<br>0.029 |
| PT4 | 1st: n/a<br>2nd: 5.12 | -0.059 | B: 2.28<br>A: 0.91 | 0.014<br>0.018 | L: 0.60<br>M: 1.27 | 0.024<br>0.058 |

For all trials, peak GRF ranged from 3.06 to 5.12 BW. In comparison, the magnitude of peak GRF for running at speeds of 4.5 and 6.0 m/s has been reported to be approximately 2.70 BW (Cavanagh & Lafortune, 1980; Nilsson & Thorstensson, 1989). There was a trend toward higher GRF when the dancer was wearing pointe shoes. Average peak GRF was 4.51 BW for the pointe shoe trials, 3.67 BW for the barefoot trials, and 3.89 BW for the slipper trials. It is not clear whether the higher average peak GRF in the pointe shoe condition was due to the pointe shoes or the influence of practice effect since the pointe shoe condition was the last condition recorded. The pointe shoes may have contributed to the higher average vertical GRF because the relatively heavy shank did not allow the dancer to attenuate any of the initial force of landing through the forefoot. Upon landing while barefoot and wearing ballet slippers, the dancer was able to articulate clearly through the forefoot and, as such, absorb some of the force of landing. Practice effect may also have contributed to the higher vertical GRF in the pointe shoe condition. As the dancer became more familiar and comfortable in the space, her leaps got higher, based on the height of the marker at her greater trochanter, leading to an increased vertical GRF.

The range of magnitudes of peak vertical GRF for this study was comparable to the findings of Becker (1984) who found mean peak GRF upon landing of 5.13 and 4.47 BW for females and males, respectively. The values for peak GRF for this study and that of Becker were higher than the peak GRF of approximately three times body weight reported by other investigators (Miller, Paulos, Parker & Fishell, 1990; Simpson & Kanter, 1997). The higher values of GRF for this investigation and that of Becker (1984) may be explained by the use of preparatory steps. The dancer in the current study performed a series of preparatory movements leading to grand jeté. The entire sequence of movements was as follows: temps levé en arabesque, tombé, glissade, grand jeté. Preparatory steps allowed the dancer to gain horizontal velocity, some of which was converted to vertical velocity upon take-off. More vertical velocity upon take-off would allow the dancer to jump higher, possibly increasing the magnitude of vertical GRF upon landing. The subjects who participated in the study done by Simpson and Kanter (1997) were not given any preparatory steps, while the participant in the study by Miller et al.

(1990) was given a one step preparation.

**Braking/acceleration ground reaction force (FY).** Interpretation of FY GRF is dependent upon the relationship between the coordinate system of the force plate and the direction the subject is moving, as well as the direction of the force applied to the force plate. If the person is moving along the Y axis, when their foot hits the plate, the ground reaction force acts as a braking force. When the person pushes against the plate to propel themself forward, the ground reaction force acts as an acceleration force. Since the dancer performed grand jeté moving in the positive Y direction, braking GRF force is positive, while acceleration GRF force is negative. On the FY graphs, crossover is shown as the point where the X axis is crossed. If the areas under the braking and acceleration curves are equal, the person is moving across the force plate with uniform velocity. Figure 25 shows braking/accelerating GRF for a representative trial, PT4. Peak values for braking and acceleration GRF for all trials are shown in Table 4.

Peak braking GRF ranged from 0.99 to 2.70 BW. Peak braking force of landing from grand jeté was two to six times higher than the peak braking GRF of 0.45 BW for running at 4.5 m/s (Cavanagh & Lafortune, 1980). The magnitudes of peak braking GRF reported for grand jeté in this study were higher than those reported for a dance leap by Simpson and Kanter (1997). Those investigators reported maximum braking GRF magnitudes ranging from 0.21 to 0.98 BW. As with vertical GRF, the preparatory steps performed by the dancer in the current study may have contributed to higher magnitudes of peak braking GRF upon landing. The horizontal velocity attained by the dancer as a result of the preparatory steps would result in higher braking forces at landing compared to a leap performed from a standing position as in the study by Simpson and Kanter.

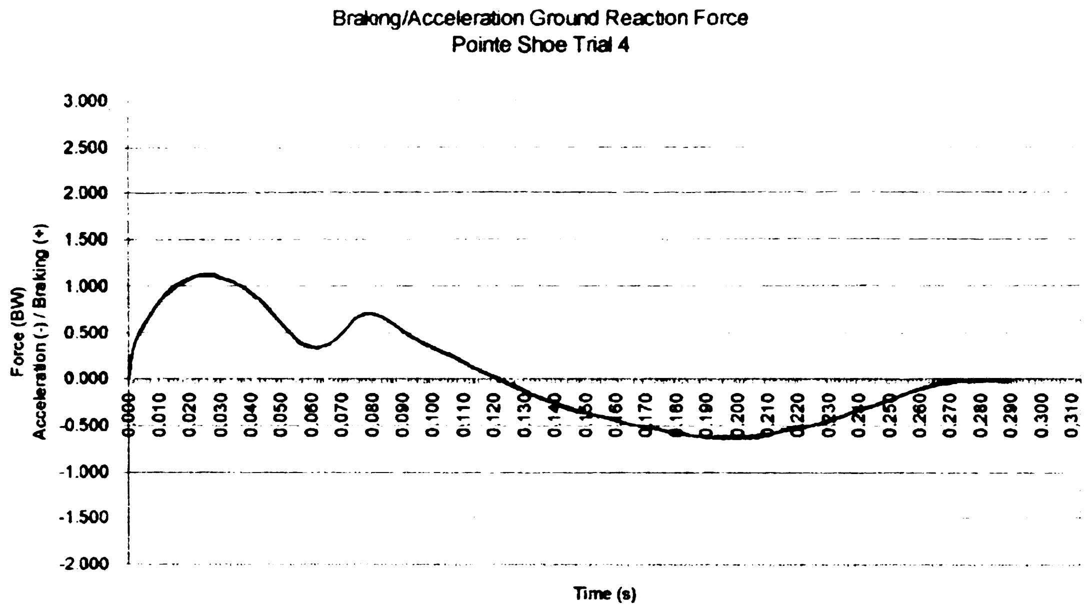


**Figure 25.** Braking/acceleration GRF for trial PT4.

The two lowest values for peak braking GRF, 0.99 and 1.44 BW, occurred in the barefoot condition. It should be noted that the barefoot condition also recorded the greatest magnitude of peak braking GRF. The wide range in magnitudes of peak braking GRF in the barefoot condition may have been the result of the dancer's lack of familiarity with performing grand jeté barefoot. Dancers who normally wear shoes while dancing may be uncomfortable dancing without footwear.

Peak acceleration GRF ranged in magnitude from 0.83 to 1.36 BW. In comparison, the magnitude of peak acceleration GRF for running at speeds of 4.5 and 6.0 m/s has been reported to be approximately 0.50 BW (Cavanagh & Lafortune, 1980; Nilsson & Thorstensson, 1989). In gait analysis, the size of the area under the curve on the FY graph indicates the velocity at which the person carries the force over the foot. Depending on which area is greater, the person is decelerating (seen as positive in this study), accelerating (seen as negative) or, if the areas are equal, moving at a constant velocity during foot contact. Upon completion of grand jeté, the dancer ran as if exiting the stage. Had she been asked to perform a series of grand jetés, the magnitude of acceleration GRF would probably be expected to increase.

Average peak braking GRF was somewhat higher for the pointe shoe condition than for the other conditions. The average peak magnitude of braking GRF for barefoot, slipper, and pointe shoe conditions was 1.71, 1.80, and 1.99 BW, respectively. As previously stated, the dancer leaped higher on the grand jetés performed for the pointe shoe condition, based on the height of the marker at her greater trochanter. A more vertical leap would have lead to higher magnitudes for braking GRF because the dancer would have to control of the effect of increased gravitational acceleration upon landing. Average peak acceleration GRF was somewhat lower for the pointe shoe condition. The average peak acceleration GRF was 0.99, 0.91, and 0.78 BW for the barefoot, slipper, and pointe shoe conditions, respectively. Peak acceleration GRF may have been less for the pointe shoe condition because the dancer had to overcome the resistance of the relatively heavy shank of the pointe shoe as well as the resistance added by the ribbons and elastic that were attached to the shoe.

Peak braking GRF occurred before peak acceleration GRF for all trials. With the exception of PT4, peak acceleration GRF occurred at the end of landing. For all trials, crossover from braking to acceleration GRF occurred between 0.063 and 0.127 seconds after contact. The two trials with the earliest time at crossover to acceleration GRF were BF10 and SL6, whose crossovers occurred at 0.063 and 0.069 seconds, respectively. These trials were the two trials with the lowest magnitudes of knee flexion and ankle dorsi-flexion compared to the other trials. Earlier crossover time compared to the other trials supports the previous discussion that the dancer brought her leg underneath herself more during descent from the leap's peak height. With her leg more vertically oriented beneath her, the dancer's weight was further forward in relation to her leg at contact than it was for the six remaining trials. The horizontal momentum of the movement continued to carry her weight forward as she landed and she spent less time braking.

**Medial/lateral ground reaction force (FX).** Medial/lateral force for a representative trial, PT4, is shown in Figures 26. On the graph for medial/lateral GRF, lateral GRF is graphed as positive, while the medial GRF is negative. Peak values for lateral and medial GRF for all trials are shown in Table 4.

The magnitude of peak medial GRF ranged from 0.51 to 1.27 BW. The magnitude of peak lateral GRF ranged from 0.28 to 1.15 BW. Consistent with the literature for running and walking, the magnitudes of FX are relatively small compared with FZ and FY. Peak to peak amplitude of medial/lateral GRF for individual trials ranged from 0.95 to 1.87 BW, approximately three to five times higher than the peak to peak amplitude reported for running with a forefoot strike (Cavanagh & Lafortune, 1980; Nilsson & Thorstensson, 1989). The average peak to peak amplitude for the pointe shoe condition was greater than for the other two foot conditions. Average peak to peak amplitude for the pointe shoe condition was 1.76 BW, compared to 1.26 and 1.05 BW for the barefoot and slipper conditions, respectively. Since medial/lateral force is an indicator of stability, the greater average peak to peak amplitude for the pointe shoe condition may be evidence of the influence of the shank of the pointe shoe on landing. The shank of a pointe shoe can be as thick as 1/4 inch and the dancer has to stabilize herself over this shank since the shank is smaller than the dancer's foot.

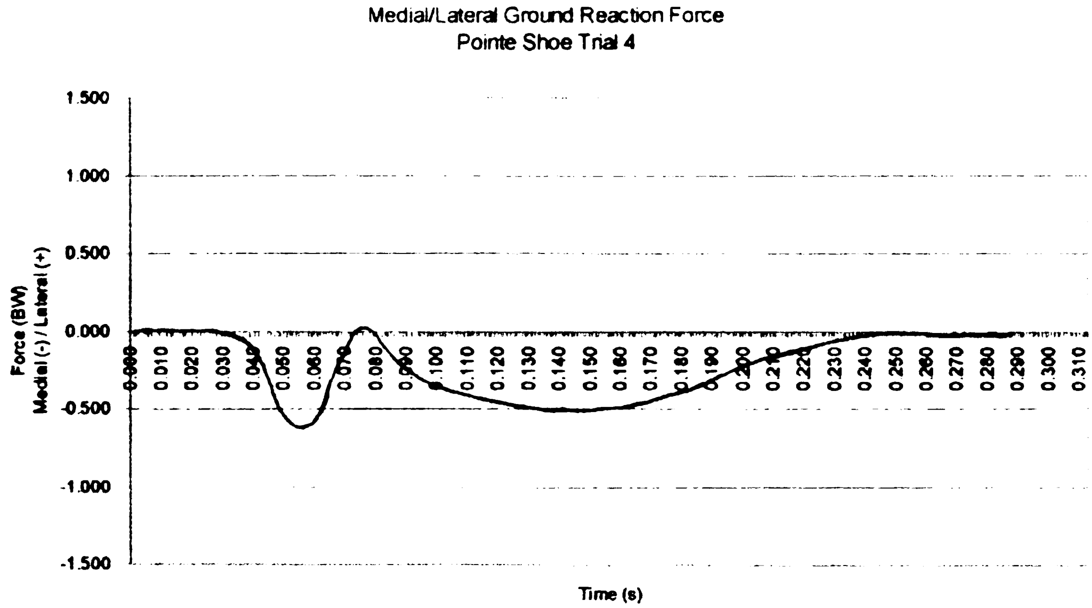


**Figure 26.** Medial/lateral GRF for trial PT4.

Similar patterns of medial/lateral GRF was seen in the graphs for all three conditions. At toe down, a lateral GRF occurred. The force vacillated medially and laterally with a general increase in the medial direction as the dancer stabilized herself over her foot. After peak medial GRF, indicated by a distinct spike for most trials, the force increased for a short period in the lateral direction before dipping medially, and then increasing slightly to hover about zero as the dancer continued to move after the completion of landing. In seven of the eight trials, peak lateral GRF occurred before peak medial GRF. Furthermore, peak medial force coincided temporally with peak vertical force for six of the eight trials. Although not confirmed by the present study, Becker (1984) associated full heel compression with peak vertical GRF. Had peak vertical force coincided with full heel compression, more force would have been applied to the medial side of the dancer's heel compared to the lateral side, for those trials in which peak vertical force coincided with peak medial force.

**Rate of Loading Vertical Ground Reaction Force.** Rate of loading GRF is the speed at which force is applied and is of importance because higher rates of loading are known to cause tissue damage. Tissues are known to be stronger and stiffer under faster loading than under slower loading (Nordin & Frankel, 1989). Rate of loading peak vertical GRF was calculated by dividing the peak vertical GRF by the time to peak vertical GRF. Loading rates for peak vertical GRF are shown in Table 5.

**Table 5.**

Loading rate of peak vertical GRF.

| Trial | Vertical (BW/s) |
|---|---|
| BF8 | 81.4 |
| BF10 | 29.1 |
| BF11 | 52.0 |
| SL6 | 47.9 |
| SL7 | 47.7 |
| SL8 | 72.1 |
| PT1 | 56.5 |
| PT4 | 86.7 |

Rate of loading peak vertical GRF ranged from 29.1 to 86.7 BW/s. These values were equivalent to 1385 to 4128 kg/s, for the dancer in this study. Rate of loading was lowest for trial BF10 because peak vertical GRF was lowest and occurred later for this trial than for any other trial. As previously discussed, the pattern of vertical GRF for

BF10 differed from the other trials since vertical GRF increased curvilinearly, possibly because the dancer did not reach full heel compression during landing. Landing without full heel compression may have increased the dancer's risk of injury because the loading rate of peak vertical GRF was borne by the smaller, lighter bones of the forefoot rather than the larger, heavier bones of the rearfoot, which are better designed to withstand the stress of loading. When the lowest value for loading rate is excluded, the range for all trials becomes 47.7 - 86.7 BW/s.

The range of loading rate of vertical GRF for the pointe shoe trials was 56.5-86.7 BW/s, while the ranges for the barefoot and slipper trials were 47.7-72.1 and 29.1-81.4 BW/s, respectively. Loading rate tended to be higher for the pointe shoe condition, compared to the other two conditions, as the pointe shoe trials had two of the four highest loading rates. The higher loading rates for the pointe shoe condition may be due to the resistance of the relatively heavy shank of the pointe shoe. The shank may have prevented the dancer from articulating through her forefoot which would have delayed time to peak vertical GRF and allowed her to attenuate the initial force of landing. In general, there was little difference in the rate of loading between the barefoot and slipper conditions.

# Chapter 5

## Summary and Conclusion

The purpose of this case study was to examine the effect of ballet footwear on landing from grand jeté using three-dimensional sagittal plane kinematics and three-dimensional kinetics. For the purposes of this study, landing was defined by the time the dancer was in contact with the force plate, from toe down to toe off. One advanced level ballet student performed grand jeté under three foot conditions: barefoot, wearing pointe shoes, and wearing ballet slippers. Three-dimensional high-speed videographic and force plate data were used to investigate the following: (1) angular displacement of the ankle and knee joints, (2) angular velocity of the ankle and knee joints, (3) angular acceleration of the ankle and knee joints, (4) peak vertical ground reaction force and rate of loading, and (5) force-time characteristics of ground reaction force components (FX, FY, FZ).

### Findings

1. Hypothesis 1 stated: Angular displacement of the knee and ankle joints will differ with foot condition. This researcher found the pattern and magnitude of angular displacement of the knee were similar for all foot conditions. The pattern of ankle dorsi-flexion was also similar for all foot conditions; however, the average magnitude of peak dorsi-flexion was lowest for the barefoot condition.
2. Hypothesis 2 stated: Angular velocity of the knee and ankle joints will differ with foot condition. This researcher found the pattern and magnitude of angular velocity of the knee and ankle joints were similar for all foot conditions.
3. Hypothesis 3 stated: Angular acceleration of the knee and ankle joints will differ with foot condition. This researcher found the pattern and magnitude of angular

acceleration of the knee and ankle joints were similar for all foot conditions.

4. Hypothesis 4 stated: Peak vertical GRF will not differ with foot condition. This researcher found the average peak of vertical GRF was higher for the pointe shoe condition compared to the other two foot conditions.

5. Hypothesis 5 stated: Peak vertical GRF rate of loading will differ with foot condition. This researcher found the loading rate of peak vertical GRF tended to be higher for the pointe shoe condition compared to the other two foot conditions.

6. Hypothesis 6 stated: Force-time characteristics of GRF components will differ with foot condition (FX, FY, FZ). This researcher found the force-time pattern of vertical (FZ) GRF was different for the pointe shoe condition. Two distinct peaks were evident for most of the barefoot and all of the ballet slipper trials; however, there was no distinct first peak in the force-time pattern of vertical GRF for the pointe shoe trials. This researcher found the force-time pattern of braking/acceleration (FY) GRF was similar for the three foot conditions. The force-time pattern of medial/lateral (FX) GRF was similar for the three foot conditions.

Conclusion

There were similarities among foot conditions for the following variables: angular displacement of the knee, velocity and acceleration of the knee and ankle joints, force-time patterns of braking/acceleration and medial/lateral GRF. Several findings suggest dance footwear influences landing from ariel movement. The effect of footwear was evident in the difference in force-time pattern of vertical GRF for the pointe shoe condition. The difference in this pattern indicates that the design of pointe shoes as well as the attachment of ribbons and elastic may affect landing from ariel movement. The influence may also be evident in the increased magnitude of all three components of GRF even though it is not clear whether the increase in magnitude can be fully attributed to the pointe shoes.

The results of this study have implications for teaching dancers and gymnasts how to land more safely from aerial movements. The importance of utilizing the entire foot to attenuate the force of landing was demonstrated by the higher vertical GRF and higher rate of loading GRF under the pointe shoe condition. When the dancer was not able to use her entire foot during landing, vertical GRF and loading rate increased. Because aerial movements are integral to dance and gymnastics, the high GRF and high rates of loading that result will take a physical toll on the performer. Learning to land with correct technique early in training may serve to lengthen the performer's career.

The results of this study have implications for teaching ballet students how to dance wearing pointe shoes. While it is important that ballet students learn to dance en pointe, ballet teachers need to recognize the effect of pointe shoes on common movements such as jumping. Ballet teachers need to be aware that while learning to dance in pointe shoes, students will be exposed to higher forces and rates of loading than when barefoot or wearing ballet slippers because as the student adapts to doing the movement in pointe shoes, the student will be less likely to use good landing technique. The intensity and frequency of performing aerial movements while wearing pointe shoes should be increased gradually to lessen the likelihood of injury by allowing the student's body to adapt to the increased stress.

As a result of the findings in this study, several suggestions for future research have emerged:

1) Further study needs to be done on the resistance provided by ballet slippers and pointe shoes that hinders a dancer's ability to manipulate through the metatarsal joints and delays peak ankle dorsi-flexion angular velocity. Additionally, the resistance contributed by the ribbons and elastic which hold the shoes on the dancer's feet should be examined.

2) Further study should be done to examine the effect, if any, on the pre-landing acceleration peak. While this peak is not of concern while the individual is in the air and in an unloaded condition, it might be of concern because of its affect on landing and the movement after landing.

3) Further study needs to be done to examine the effect of the pointe shoes' heavy shank on the magnitude of vertical GRF upon landing. While barefoot and wearing ballet slippers, the dancer was able to articulate clearly through the forefoot and absorb some of the force of landing. However, the heavy shank of the pointe shoe may have contributed to the higher average vertical GRF because it did not allow the dancer to attenuate any of the initial force of landing through the forefoot.

4) Further study should be done to examine the effect of the thickness of the shank of the pointe shoe as well as the size of the shank in relation to the size of the dancer's foot. The shank of a pointe shoe can be as thick as 1/4 inch and the dancer has to stabilize herself over this shank because the shank is smaller than the dancer's foot. The average peak to peak amplitude of medial/lateral GRF was greatest for the pointe shoe condition and may be evidence of the influence of the shank of the pointe shoe on landing.

5) Further study needs to be done to examine how the rate of loading vertical GRF is influenced by the idiosyncracies of the pointe shoe. Maximum rate of loading took place almost immediately upon landing in the pointe shoe condition which may indicate that the hardness of the box area of the pointe shoe prevented the dancer from attenuating any of the initial force of landing. The timing of maximum loading rate for the pointe shoe condition could potentially be injurious to the dancer because the loading rate would affect the phalanges, a part of the foot not designed for high rates of impact.

6) Further study of landing from aerial movements in dance should also include kinematic analysis of the hip, knee, and ankle joints in the frontal and transverse planes as well as examination of the moments at the hip, knee, and ankle joints during landing.

APPENDICES

## Appendix A

## Glossary of Terms

Arabesque: a position of the body in which the weight is supported on one leg and the other leg is extended behind the body (Grant, 1982).

Demi-plié: bend of one or both knees. In ballet technique, turn-out of the legs should be maintained, the knee should be over the toes, and the entire foot should remain on the floor. All aerial movements begin and end with demi-plié (Grant).

Demi-pointe: indicates the dancer is on the balls of the feet, as opposed to en pointe, in which the dancer is on the toes (Grant).

Elevé: a rise onto pointe or demi-pointe without a preceding demi-plié. This movement may be done in all five positions of the feet (Hammond, 1974).

En pointe: indicates the dancer is on the tips of the toes (Grant, 1982).

Entrechat six: a beating jump that begins and ends in fifth position. In the air, the legs cross and uncross three times before landing with the opposite foot in front (Grant).

Glissade: a gliding step used as a transition between other steps. There are several variations of glissade, all of which begin and end in demi-plié (Grant).

Grand jeté: a large leap in which the legs are thrown to 90 degrees and are split in the air. Grand jeté may be performed forward, sideways, or backwards and is always preceded by a preparatory movement such as glissade (Grant).

Grand jeté pas de chat: a variation of grand jeté in which the leading leg is thrown through a bent knee position to full extension anteriorly at the same time as the back leg opens posteriorly to form a split in the air (Grant).

Positions of the feet : see Figure 27.

Relevé: a rise to demi-pointe or pointe preceded by a preparatory demi-plié. This movement may be done in all five positions of the feet (Hammond, 1974).

Sauté: a jump which takes-off of both feet and ends in the same foot position (Hammond).

Temp levé arabesque: a hop beginning and ending in arabesque (Grant, 1982).

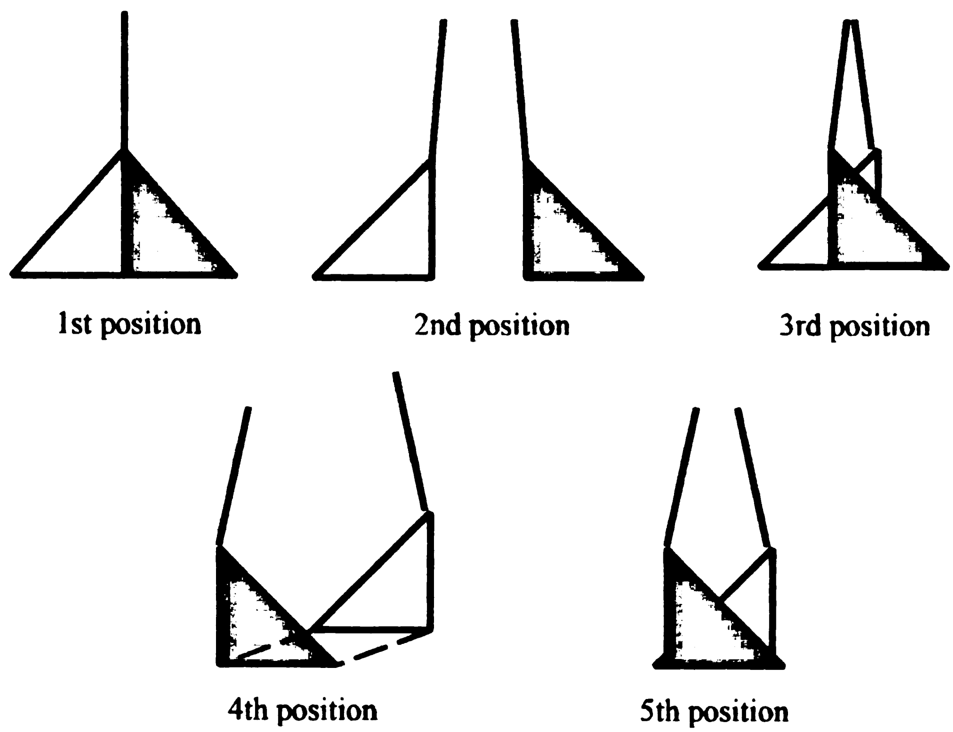


**Figure 27.** Five positions of the feet in ballet.

## Appendix B

### Detailed Description of the Pointe Shoe

There are at least 18 pointe shoe manufacturers worldwide and each has a different method for constructing pointe shoes (Barringer & Schlesinger, 1998). Because feet have different shapes, strengths, and degrees of flexibility, each manufacturer has developed a variety of styles. While some pointe shoe manufacturers use automated machinery to make their shoes, most companies employ many "makers" who construct the shoes by hand. Needless to say, handcrafting pointe shoes results in a great deal of variability among shoes, even between shoes in the same pair.

The most important parts of the pointe shoe are the box and the shank which support the foot while en pointe (Figure 28). The box of the pointe shoe, which extends over the toes and supports the forefoot, is typically constructed of paper mâche or many layers of fabric and glue. The box has a flattened tip on which the dancer balances while en pointe. The box tapers slightly on either side of the foot, not only to emulate the foot's shape, but also to create an aesthetically pleasing line of extension from the leg to the foot (Barringer & Schlesinger, 1998). The tapering of the pointe shoe box forces the great toe into abduction and the lateral toes into adduction, forcing body weight to be borne on the first and second toes (Sammarco, 1982). Some investigators have attributed the usually high prevalence of hallux valgus, or bunions, found in ballet dancers to the combination of the shape of the box and the force distribution en pointe (Sammarco, 1982; Tuckman et al., 1991; Weiker, 1988).

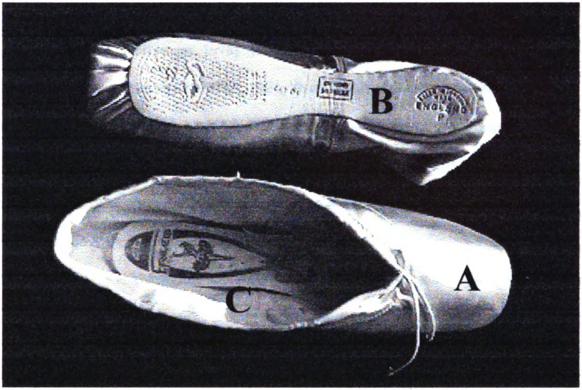


**Figure 28.** The pointe shoe with main components identified: (A) the box, (B) the outer shank, (C) the inner shank. Ribbons and elastic are not attached as they most likely would be for rehearsal and performance. (Photograph by Miguel Narvaez.)

The shank is comprised of the inner and outer soles. The inner sole is made of heavy cardboard or a combination of leather and fiber to support the foot while bearing weight in full plantar-flexion. Additional support is attached beneath the inner sole. This additional support may be one of any number of materials, including wood or steel. Regardless of the material used, it must be pliable enough to follow the line of the foot in plantar-flexion, yet strong enough to support the dancer while performing intricate movements en pointe. The outer sole, on the bottom of the shoe, is leather which provides some traction as the dancer moves. To accommodate the changes in the foot that occur with plantar- and dorsi-flexions, the outer sole does not come to the outer edge of the heel as on a regular street shoe (Barringer & Schlesinger, 1998).

Except for the outer sole, the entire shoe is covered with a cotton lining and pink satin (Barringer & Schlesinger, 1998). It has been erroneously reported in the literature that the satin provides traction (Milan, 1994; Novella, 1987). In fact, satin is a slick fabric that some dancers remove from the tip of the shoe to prevent slipping and falling (Barringer & Schlesinger, 1998). The shoes are held onto the foot with ribbons sewn on by the dancer. The ribbons are crossed at the front of the ankle, wrapped around the ankle just above the line of the medial and lateral malleoli, and tied into a knot on the medial side of the ankle slightly above the medial malleoli. The dancer also may sew a band of elastic to the back of the shoe to keep the heel of the shoe secured to the foot during movement. It is of note that right and left shoes are not designated and that the dancer may choose to alternate her shoes, or assign right and left.

Cunningham, DiStefano, Kirjanov, Levine and Schon (1998) examined the mechanical properties of five different brands of shoes. Static and fatigue materials testings were performed using a servohydraulic device under axial and vertical conditions. Axial conditions simulated the forces applied to the tip on the shoe while en pointe and vertical conditions simulated forces applied to the plantar aspect of the box that would occur in activities such as take-offs and landings in running and jumping. All shoes were found to be stronger and stiffer under static axial conditions, compared to static vertical conditions. Predominant failure under static conditions in all shoes was buckling of the pointe shoe box in on itself, similar to that which occurs with wear and tear in the dance setting. When fatigue testing was conducted in the axial condition, one brand of pointe shoes demonstrated a fatigue range approximately 10 times greater than that of the other four brands. The brand was an innovative shoe whose box and shank were formed from an elastomeric, or rubber-like, material layered with shock-absorbing foam. The elastomeric material is used in these shoes because it is more durable and requires less time to break in than conventional pointe shoe materials (Minden, 2000). While the results of the fatigue testing indicated this brand was more durable, these results should not be interpreted to mean that these are the best pointe shoes for every dancer. The brand and style of pointe shoe a dancer chooses to wear is an individual decision made by taking a number of factors into account including fit, comfort, and appearance (Barringer & Schlesinger, 1998).

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