A BIOMECHANICAL COMPARISION OF SUCCESSFUL AND UNSUCCESSFUL TRIPLE-TURN *PIROUETTE EN DEHORS* TRIALS IN BALLET

A DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
IN THE GRADUATE SCHOOL OF THE
TEXAS WOMAN'S UNIVERSITY

SCHOOL OF HEALTH PROMOTION AND KINESIOLOGY

COLLEGE OF HEALTH SCIENCES

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DECEMBER 2018

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To the Dean of the Graduate School:

I am submitting herewith a dissertation written by Jemin Kim entitled "A Biomechanical Comparison of Successful and Unsuccessful Triple-Turn *Pirouette en dehors* Trials in Ballet." I have examined this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy with a major in Kinesiology.

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DEDICATION

I am dedicating this dissertation to the memory of my late former professor Cha-Young, Suh.

ACKNOWLEDGEMENTS

I am greatly thankful to my advisor, Dr. Young-Hoo Kwon, whose knowledge in biomechanics, mathematics, and programing has broadened my skills towards being a true biomechanist. His understanding, generous advising, service, and support helped me accomplish my doctoral degree.

I would like to thank Dr. Margaret Wilson for supporting my research, advising, and assistance in editing my dissertation.

I would like to thank Dr. David Nichols for teaching and assisting me in statistics.

I would like to thank Dr. Kevin Becker for the sharing of ideas, advising, and for editing my dissertation.

I would like to thank my family members, especially, my parents (father, Kyung-Bok Kim and mother, Eui-Sook Moon Kim). My family has stood by my side providing physical, financial, and most importantly emotional care as I have worked towards my degree. Finally, my most sincere thanks go to God.

ABSTRACT

JEMIN KIM

A BIOMECHANICAL COMPARISION OF SUCCESSFUL AND UNSUCESSFUL TRIPLE-TURN *PIROUETTE EN DEHORS* TRIALS IN BALLET

Pirouette en dehors is a turn in which the dancer's body rotates and completes at least one full revolution with one foot on the floor. It is considered difficult to learn and perform in classical ballet. The purpose of this study was to identify biomechanical kinetic differences between the successful- and unsuccessful-trials groups in triple turn *pirouette en dehors* motion. It was hypothesized that the successful trials group would have larger longitudinal whole body angular momentum (AM), pivoting moment (PM) and ground reaction force moment (GRFM) than the unsuccessful trials group. Forty skilled collegiate or professional classic ballet dancers (11 males and 29 females) were recruited for this study. The participants were divided into two groups based on their successful and unsuccessful trials. Selected variables were computed through a seven-camera (Qualisys-three-dimensional) motion capture system (250 Hz) and two force-plates (Kistler-2500Hz), with 48 reflective markers. The data was imported into the Kwon3D (5.0) motion analysis software for subsequent data processing. Three MANOVA (SPSS 25.0) were used to compare the dependent variables between successful trials group and unsuccessful trials group conditions (each MANOVA was set $p < .025$). The first MANOVA was completed to compare all primary variables. The

second MANOVA was performed to compare explanatory variables. The peak longitudinal AM, AM generation rate, and peak combined PM, gesture foot PM at TPM (time of peak PM) and gesture foot horizontal GRF at TPM were significantly different between the successful- and unsuccessful-trials groups. The successful trials group was characterized by larger whole body longitudinal AM, AM generation rate and peak PM, meaning this group demonstrated superiority in the generation of angular motion. The unsuccessful trials group had an inefficient double-to-single stance phase for the kinetic variables caused unsuccessful triple turn *pirouette en dehors* motion. While peak PM is lower for the unsuccessful trials group, a loss of whole body AM and AM rate creates a failed motion. Kinetics plays a major role in the performance of the triple-turn *pirouette en dehors*. Further investigation to compare kinematic variables for successful- and unsuccessful- trials group is warranted.

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CHAPTER I

INTRODUCTION

Pirouette, meaning ‘turn’, is a sophisticated maneuver that can commonly be observed in many different dance genres and sports such as gymnastics and figure skating. The dancer spins about the vertical axis and completes at least one full revolution with one foot in contact with the floor (Kim et al., 2014; Figure 1). *Pirouette* is an important part of dance choreography because it is included in all solo variations and group dance (Suh, 1992). *Pirouette* is considered difficult to learn and constantly perform because of the multiple skills required for success: force exertion, balance, body posture, flexibility, timing, and control of body sway during the motion. Dancers often struggle to perform *pirouettes* successfully for this reason.

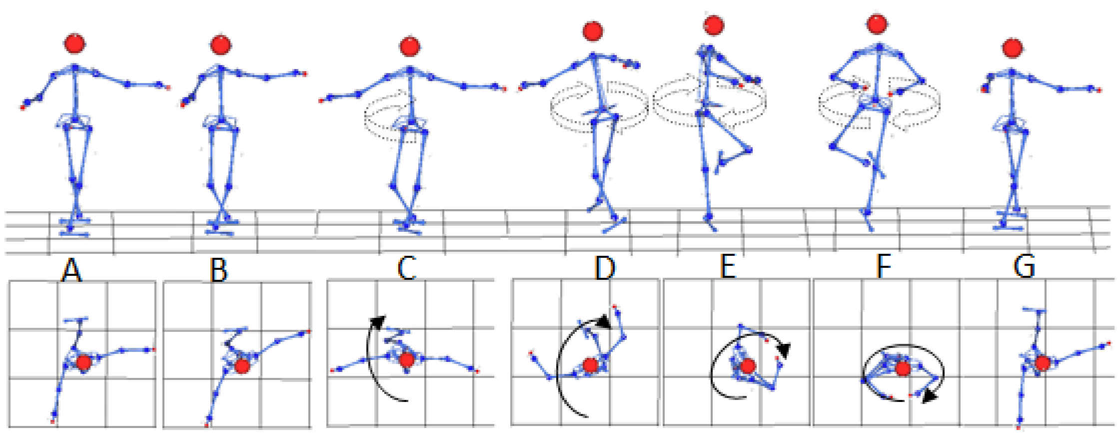

Figure 1. *Pirouette en dehors* (outward turn).

In spite of its importance in ballet, there has not been much biomechanical research on the *pirouette*. Previous research on ballet maneuvers has presented basic mechanical concepts such as kinematics (Wilson & Kwon, 2008) during *plié* (Barnes, Krasnow, Tupling, & Thomas, 2000), *passé relevé* (Fagundes, Chen, & Laguna, 2013), turnout (Grossman, Krasnow, & Welsh, 2005), dance *grand jeté* jump (Kalichová, 2011), postural control (Kiefer et al., 2011), balance (Krasnow, Wilmerding, Stecyk, Wyon, & Koutedakis, 2012; Pederson, Erleben, & Sporring, 2006), jump landing (Walter, Docherty, & Schrader, 2011) and *pirouette* (Laws, 1984; Lin, Lee, Liao, Wu, & Su, 2011; McMillan, 1972). Early *pirouette* research highlighted several key mechanical concepts that have positive effects on the turning motion such as generation of turn (Biringen, 2010; Imura, & Yeadon, 2010; Laws, 1979; Sugano & Laws, 2002), generation of angular momentum (Kim et al., 2014), and kinematic characteristics (Kuno-Mizumura & Yoshida, 2015; Lin, Su, Wu, & Lin, 2013). Research and pedagogy commonly focuses on body segments movement patterns (arm and foot placement) and balance has been recognized as an important factor for the success of a *pirouette* motion (Grieg, 1994; Pederson et al., 2006). Furthermore, the ability to generate sufficient angular momentum received attention as a pre-requisite of high rate of revolutions in *pirouette* (Kim et al., 2014). Despite these findings, there still is a lack of information in regards to how successful *pirouette* motions are performed as compared to unsuccessful trials.

Two key aspects of a successful *pirouette* are: (1) development of sufficient AM about the longitudinal axis of dancer's body during the transition from double- to single-stance and (2) maintenance of a good dynamic balance in this process. At the beginning of the *pirouette* motion (typically using the 4th position of the feet for a preparation) the dancer needs to generate a quick body rotation while precisely directing the whole body toward the support foot, which is a difficult task (Biringen, 2010; Kim et al., 2014). Without precise control of dynamic balance, a dancer's center of mass (COM) may move in a wrong direction while shifting weight onto the supporting leg (Wilson, 2009). Failure to keep the body COM over the narrow base of support formed by the support foot results in a loss of balance during the single stance phase as the rotation continues.

Insufficient AM results in a premature termination of the rotation or hopping for additional AM generation regardless of how well the dancer can maintain dynamic balance. For this reason, generation of sufficient AM is a pre-requisite of good dynamic balance control and successful completion of prescribed turns in *pirouette en dehors* (Kim et al., 2014). AM is mainly generated during the double-stance phase (preparation) through various foot-ground interaction mechanisms utilizing the ground reaction forces (GRF) and ground reaction moments (GRM) acting on the feet. The pivoting moment (PM) produced by the horizontal GRFs about the vertical axis (Laws, 1979) passing through the combined center of pressure (COP) is the main source of longitudinal AM. During the single- to double-stance transition, the combined COP moves toward the support foot and, as a result, the proportions of the PMs generated by the support and gesture foot vary as the transition progresses. While the GRF moment (GRFM) produced by the combined GRF about the body COM may not be that important in longitudinal AM generation, it can potentially play an important role in controlling dynamic balance during the transition. In spite of their importance in AM generation and dynamic balance control, the foot-ground interaction mechanisms (i.e, PM and GRFM) are not well understood yet.

Purpose of the Study

Triple-turn *pirouette* is considered a difficult maneuver for ballet dancers in general and for female dancers (male dancers have greater mass and strength) in particular. Three revolutions provide sufficient challenge to the dancer's ability to generate sufficient AM; control of dynamic balance can be fully evaluated in triple-turn *pirouettes,* as slowing forces such as friction can lead to a potential loss of balance. Therefore the purposes of this study were: (1) to investigate how ballet dancers utilize various foot-ground interaction mechanisms in generating longitudinal AM and controlling dynamic balance during the double- to single-stance transition phase in triple-turn *pirouette en dehors*, and (2) to highlight the biomechanical differences between successful and unsuccessful trials of triple-turn *pirouette en dehors,* using three-dimensional motion analysis. Ensemble-average patterns of key foot-ground interaction parameters were derived and select peak values of these parameters were extracted to assess the differences between successful and unsuccessful triple-turn *pirouette* trials.

Research Hypotheses

It was hypothesized that a successful triple turn would be:

1. The peak longitudinal AM would be larger in successful trials.
2. The longitudinal AM generation rate and time would be larger in successful trials.
3. The peak combined PM and the PMs of individual feet at the time of peak combined PM would be larger in successful trials.
4. The horizontal GRFs at the time of peak combined PM would be larger in successful trials.

5. The peak horizontal GRFMs would be larger in successful trials.
6. The GRFs at the time of peak GRFM would be larger in successful trials.

Significance of the Study

Biomechanical research in dance is lacking and furthering its knowledge will push the field to educate dancers on successful methods of turning. Understanding the biomechanical principles can enhance and clarify methods of ballet training. Previous research has benefitted dancers and teachers of dance in identifying key components of movements (AM generation, feet stance, etc.) and this study will contribute to the understanding and teaching of *pirouette en dehors*. *Pirouette en dehors* is a challenging movement to learn and perform in ballet training because of force exertion, balance, body posture, flexibility, timing, and control of body sway. However, there are no established biomechanical parameters that differentiate between successful multiple-turn *pirouette* and unsuccessful turns. Factors affecting the outcome of a *pirouette* need to be understood for dance instructors to help dancers become successful at performing the turning motion. Therefore, this study investigates biomechanical differences in kinetic patterns to indicate factors for a successful and unsuccessful trial of triple-turn *pirouette en dehors*.

Assumptions

1. Random experimental errors are eliminated during the data processing process and there are no systematic skin motion artifacts in marker coordinates.

2. The body segments are rigid and there is no shift in mass within the segments during the motion.

Delimitations

1. The *pirouette en dehors* trials were performed in the clockwise direction (rightward) regardless of dancers' preferred (dominant) legs.

2. The participants of the study were limited to college students majoring in ballet and professional ballet dancers. The minimum training was 5 years.

3. *Pirouette* trials that did not have any elements of hopping, wobbling, or falling motions but had clear head spotting were considered successful.

4. To standardize the trials, each trial was performed to the same music, Waltz with a time signature of 3/4 and 128 beats/min.

5. The force-plates were covered with Marley dance floor, a heavy-duty slip-resistant floor covering used in dance studios and theatre stages, to imitate a typical performance environment.

6. Participants were not permitted to use rosin (chalk powder) on their shoes or on the Marley dance floor.

Limitation

The footwear was not standardized. Participants used their own ballet canvas training shoes.

Definition of Terms

Angular Momentum (AM): The quantity of angular motion. It is the product of moment of inertia, and angular velocity.

Center of Mass (COM): The balance point of an object. The COM of the dancer's body is determined by the body posture and mass distribution within the body.

Center of Pressure (COP): The point of action of the GRF acting on a foot. The combined COP is the point of action of the combined GRF.

Ground Reaction Force (GRF): The reaction force supplied by the ground. This is the equal and opposite reaction (Newton's 3rd Law of Motion) to the force the dancer exerts to the ground (floor). The combined GRF is the sum of the GRFs acting on individual feet.

Ground Reaction Force Moment (GRFM): The moment produced by the combined GRF about the COM of dancer's body.

Ground Reaction Force Moment Arm (GRFMA): The MA of the combined GRF that causes a GRFM.

Kinematics: An area of biomechanics concerning description of the motion without regard to the forces causing the motion.

Kinetics: An area of biomechanics which concerns explanation of motion focusing on the cause of motion.

Local Reference Frame: The reference frames attached to a segment, and expressed relative to the global reference frame.

Moment (Moment of Force): Rotary force that causes angular motion.

Moment Arm (MA): The shortest (perpendicular) distance from the center of rotation to the line of action of the force. Moment is force magnitude times MA.

Pivoting Moment (PM): The moment produced by a GRF about the vertical axis that passes through the combined COP. The combined PM is the sum of the PMs generated by individual feet. PM is the main source of the longitudinal AM.

Pivoting Moment Arm (PMA): The MA of a horizontal GRF that causes a PM.

CHAPTER II

LITERATURE REVIEW

A search of the literature was conducted using the electronic databases Google-Scholar, PubMed, ScienceDirect, SPORTDiscus, and EBSCOhost. The keywords used were 'dance kinematic motion,' 'dance kinetics,' 'difference successful and unsuccessful *pirouette* motion,' 'dance biomechanics,' 'definition of dance motion,' 'ballet position,' 'angular momentum,' 'inverse dynamics,' 'torque,' 'axis of rotation,' ' precession,' 'foot stance,' 'balance and timing with dance motion,' 'center of mass,' 'moment arm,' 'center of pressure,' 'flexibility relative to dance motion,' '*arabesque* turn,' '*fouette* turn,' '*en dedans* turn,' '*plié*,' '*battement tendu*,' '*relevé* motion,' '*retiré passé*,' '*pirouette*,' 'ground reaction force,' and 'global reference frame.' The inclusion criteria were that the sources had to be written in English and had to be from peer reviewed journals or books. A total of three hundred and one papers and books were found. The articles selected for this investigation were those that contained any of the biomechanical terms associated with the research hypotheses. Finally, a total of fifty-four papers and books were used.

This chapter presents the mechanical influences of the following in terms of the *pirouette* motion: foot stance, balance or timing (body segment synchronization), COM, COP, flexibility and AM. Variations of the *pirouette* motion to which the same mechanical analyses can be applied are also discussed.

Description of *Pirouette* Motion

Pirouette is a movement in which a dancer rotates clockwise or counter-clockwise and completes at least one full revolution (Kim et al., 2014; Figure 1). This sophisticated motion includes the five formal foot and arm positions of ballet (Figure 2).

All ballet foot positions are set on double foot stance with a specific distance between the feet (Figure 2). The first and second positions have common foot placement. For the third, fourth, and fifth foot positions, the feet are placed based on dominance. A common sequence of foot motions involves the use of the fifth foot position, followed by the fourth foot position, the *pirouette*, and a finish in the fourth foot position (Suh, 2003).

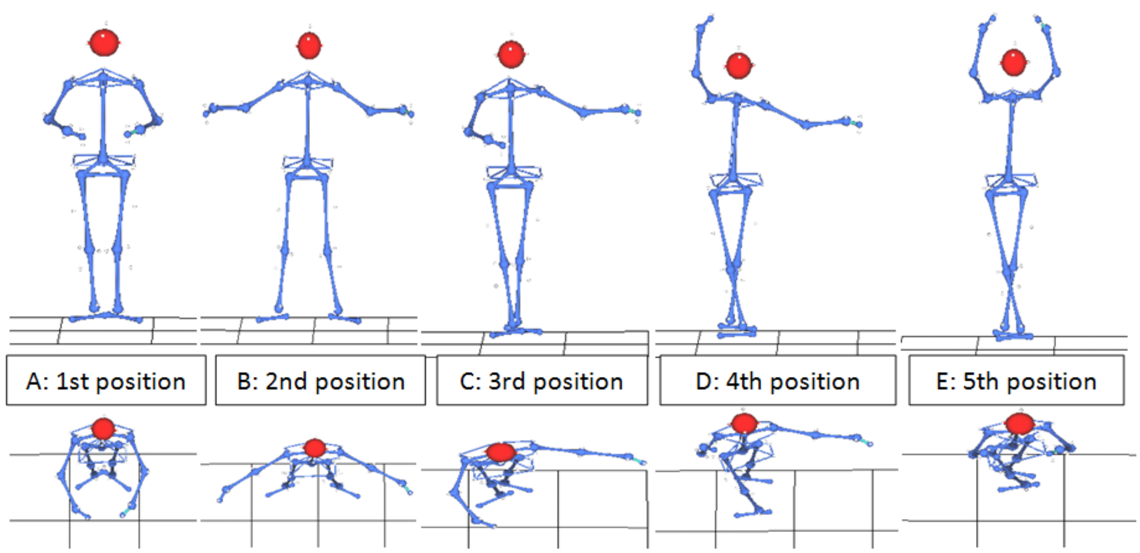

Figure 2. Ballet foot and arm positions (At the start of the *pirouette*, the dancer can work through 1st to 5th foot and arm positions).

For the 5th foot position, the legs are externally rotated from the hip and secondary rotation (abduction) at the ankle and pressed together with the heel of the right foot against the toe of the left and vice versa. If the dancer is right dominant, the right foot is placed in front of the left. For left side dominant dancers, the foot position is reversed (Figure 2E). After the preparation of the 5th foot position, the next motion is typically the 4th foot position (Figure 2D: right dominance dancer).

The next movement is the ‘gesture foot off,’ which transitions the dancer from double- to-single stance. During the single stance, one leg becomes the gesture leg while the other leg is the support leg. During the *retiré* phase, the gesture leg rests on the knee of the straight support leg. The landing foot positions are planned by the choreographer and based on desired ballet effects.

Each foot position is matched with a specific arm position. The first, second, and fifth foot positions are accompanied by named arm positions: *en avant* (Figure 2A), *a la second* (Figure 2B) and *en haut* (Figure 2E). Many types of ballet use variations of arm and leg positions such as the *pirouette retiré passé, arabesque* (one leg extended posterior), *attitude* turns (same as *arabesque* but bending the gesture leg), and *tour en l'air* (turn in air).

Mechanics of the *Pirouette* Motion

In order to execute a particular motion perfectly within the performance the most important thing in classical ballet dance is control (Kalichová, 2011; Kwon, 2001). Biomechanic studies of dance focus on the functional aspects of human movements (kinematic and kinetic). Kinematics is the study of the description of motion, and involves parameters of motion such as position, speed (velocity) and acceleration of the movement; height and distance through which the body moves; and angular motion

(Wilson, 2009). Kinematics also describes the movement of segments and the associated joint motions, allowing for an analysis of the dance motion (Wilson & Kwon, 2008). The range of motion of the joints provides the basis for understanding the contribution of each joint towards the dancer's movement (Koutedakis, Owolabi, & Apostolos, 2008). Kinetics is the study of the action of forces and torques on a body. It focuses on the cause of motion, both linear and angular (Wilson & Kwon, 2008).

The important contributing factors for successful *pirouette* motions are stance, balance, timing (double-to-single stance), and AM distributions (Kim et al., 2014). The considerations are: force generation, timing of sequential actions and balance over the supporting foot around the longitudinal axis (Kim et al., 2014; Laws, 1979). When performing a turning motion, dancers cannot easily identify the cause of their imbalanced motion, ineffective timing, and injury (Lobo-da-Costa, Nora, Vieira, Bosch, & Rosenbaum, 2012). Thus a detailed kinematic and kinetic analysis is vital to the development of more successful *pirouettes*. The selection of the appropriate skills, such as the magnitude of torque of the whole body and each of its segments, can be guided by evidence regarding the most effective, efficient, and safe way to perform the turn motion, biomechanically.

Foot Stance (Torque generation)

While a force is a push or a pull, torque can be thought of as a twist (Serway & Jewett, 2003). Turning the handle of a wrench connected to a nut or bolt produces a torque that loosens or tightens (Kane & Levinson, 1985). For the *pirouette* motion, torque (rotation force) is created when the dancer pushes sideways in opposite directions with the feet (Laws, 1984). The force exerted by the feet on the floor results in an opposite force acting on the feet that creates a force-couple, allowing the dancer to start turning (Vilma, Marcella, Marisa, Maria, & Alberto, 2011).

The torque to initiate a turn can be exerted against the floor by both feet with a certain distance between them (as seen in ballet 2nd or 4th foot positions), where the distance between the feet is no greater than the length of the dancer's foot (McMillan, 1972; Laws, 1979; Vilma et al., 2011). During the turn from the fifth foot position, a narrow stance width requires more force to produce the same torque than a wider stance. The larger force which is required makes the turn more difficult for fifth foot positions (Laws, 1979), which have limited distance between the feet (Figure 2D & 2E: 5th foot position is small distance between feet compared to 4th foot position).

According to Sugano and Laws (2002), approximately 60% of the dancer's weight was observed to be over the front foot during preparation, thus necessitating a more extended knee during the fourth foot position for successful turns. The knee extension increased the distance between the feet, resulting in a commensurate displacement of the center of gravity towards the front foot. Even though the wider position was favored, it required more practice since the dancers had to redistribute the weight over the front leg as they turn (McMillan, 1972). On the other hand, when the narrow foot stance width was chosen, the dancers were not able to increase peak torque. Therefore, foot stance width is an important factor in successful turning for the *pirouette* motion (Sugano & Laws, 2002). In the results of an investigation when the dancer's foot stance width was normalized by height, 22.7~22.8% of stance width was an ideal width during the fourth foot position, for the single-, double-, and triple- revolutions (Kim et al., 2014).

Balance and Timing (Body Segment Synchronization)

Body posture (position or formation), coupled with balance, also has an important role in successful motion. Imbalance results from the COM of the dancer not being directly above the base of support. All dancers instinctively maintain balance and equilibrium with dance motion. Professional dancers are said to perform impressive movements on stage by maintaining constant stability and holding a specific position in balance (Guillou, Dupui, & Golomer, 2007; Krasnow et al., 2012; Schmit, Regis, & Riley, 2005). During a successful movement on the single supporting leg, the gesture leg performs the action and the supporting leg bears the entire weight. In most of the foot positions, the supporting leg is in a stable joint configuration. However, when the ankle and foot are in a *demi-pointe* position in a small three points (middle phalange, 1st lateral metatarsal bone and 5th lateral metatarsal bone point) forefoot area (Lin et al., 2011), a dancer exerts more effort to maintain stability than for the entire foot position, making it harder to determine specific balance requirements (Kiefer et al., 2011; Pederson et al., 2006; Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998).

Center of Mass and Center of Pressure

Weight shift, technically termed *center of mass shift*, is also an important factor in dance motion because it is related to timing strategies. For example in a *pirouette* motion, the change in angle of the lower extremity joints (feet, ankles, knees, and hips) is based on weight shift (Krasnow et al., 2012; Lobo da Costa et al., 2012). The ideal dance movements or positions demonstrate a projectile motion pattern of around the center of mass, while the longitudinal axis remains at the center of the supporting leg. During weight shift, the upper extremity remains straight, along the line of gravity in the sagittal and frontal planes, over the feet, which are on the floor (Laws, 2011). It is required that the dancers keep their upper extremity (trunk and shoulders) along the longitudinal axis by a counter movement, when the hip joints are extended, during the body-lifting phase (Mouchnino, Aurenty, Massion, & Pedotti, 1992; Pederson et al., 2006).

COM strategies that have been researched typically involve the maintenance of COM within the base of support. The general strategy for dynamic motion with rotation controls the equilibrium of the body as a projection of COM relative to planes (Pederson et al., 2006).

Ballet dancers must control the whole body movement such as hip rotation during the turn motion produced by a counter movement in the pelvis segment (Grieg, 1994). Dancers and athletes can change their upper body position while keeping their abdominal muscles contracted and it will change the location of COM. According to Pederson's research, the abdominal muscles are extremely important for the aesthetic motion of dance movements. Hence, a controlled motion of the trunk and pelvis is used to limit rotation in the sagittal plane and improve the visual aspect of the motions. The change in sagittal plane angle and the COP from the GRF are mostly seen during the weight shift (Pederson et al., 2006).

Biomechanics looks at balance, as biomechanists have compared the COM with respect to the COP (Ruhe, Fejer, & Walker, 2011). One study suggests that controlling the COP by shifting foot pressure in the opposite direction from the desired COM movement direction can also help to maintain balance. In fact, it might be a more efficient strategy, requiring less time to execute (Laws, 1979).

The COP is another important factor in maintaining balance during dance turn motions. The COP is the term given to the point (area) of application of the GRF (Rodgers & Cavanagh, 1984). The GRF vector represents the magnitudes and directions of all forces acting on a body by the ground (Hall, 2007). During the *pirouette*, the COP acts through both legs before the gesture foot off; after gesture foot off to before gesture foot contact (during the rotational phase of the turn), it acts only through the supporting leg. The COP moves onto a small contact area, from the double stance phase to the single stance phase. During the gesture foot off movement, the body rises up as the supporting leg position changes from a flat foot to an on-toe or *demi-pointe* position.

The COP strategy also has far less amplitude of COP oscillation. To position the body over the support leg involves a lift of the non-support (gesture) leg, followed by a lifting of the support leg onto the toes only. The gesture leg is raised by maintaining the COP through the center of the support leg. Then the weight is shifted onto the ball of the foot by using COP strategies for both the ankle of the support leg as well as the MPT toe joints. When the support surface is smaller, the whole body movement limits the COM of the support leg to the hip joint, so to maintain the balance (Pederson et al., 2006).

Flexibility

Normally, dancers train to enhance the flexibility in the lower extremity of the body, such as the pelvis joints (important during turnout; external- and lateral rotations) and the thigh muscle (Wilmerding & Krasnow, 2011). Flexibility has various advantages such as good posture, good balance, and improved range of motion of the joints (Hubley, Kozey, & Stanish, 1984; Raab, Agre, Mcadam, & Smith, 1988; Wilson, Elliott, & Wood, 1992). Moreover, flexibility as enhanced through exercise acts as a preventive measure, in case of musculoskeletal injuries (Doucette & Goble, 1992). Stretching performed with exercise increases muscle, ligament, and tendon flexibility through two major effects on the body. First, the effect of stretching includes an improvement in the elastic functions of the muscles, ligaments, and tendons, which in turn improves joint ranges of motion (Raab et al., 1988). Second, exercise helps to maintain a good body posture such as *arabesque*. Therefore, flexibility training is important to a dancer since it affects joint range of motion and also maintains muscular strength (Koutedakis et al., 2008).

Angular Momentum

AM, the quantity of all rotating or turning motions, is defined as the product of angular velocity and the moment of inertia (Hall, 2007; Laws, 1979; Laws 1984). When the axes of rotation do not go through an object's COM, a 3 × 3 matrix termed an inertia tensor, replaces the moment of inertia of planar motion (Rodgers & Cavanagh, 1984). Angular velocity is the rate of change of angular position and the line of segment of orientation (vector quantities; Hall, 2007). The moment of inertia (**I**) of rotating bodies shows resistance to angular acceleration based on the axis of rotation and the distance of the radius of gyration from that axis (Rodgers & Cavanagh, 1984). For a body of constant mass, inertia increases if the mass moves further from the axis of rotation. Thus, mathematically, the AM (**L**) can be expressed as $\mathbf{L} = \mathbf{I} * \boldsymbol{\omega}$ (**I** = moment of inertia * **ω** =

angular velocities; Hall, 2007; Laws, 1984). The total AM of a body can change only if there is external torque acting on the body. As the mass configuration within a system cannot change (Serway & Jewett, 2003; Bennett, Russell, Sheth, & Abel, 2010), once the initial torque has been exerted on the dancer, and the performer has risen onto the supporting foot AM is effectively conserved, decreasing gradually only because of the friction with the floor (Laws, 1979; Vilma et al., 2011).

The selection of the style of motion relies on the magnitude of AM of each segment of the body. If the AM is not large the effect of rotation can be ignored, and the process of restoring balance can be analyzed as if the dancer were not rotating but just shifting the center of mass above the supporting point or area. If the AM is large, then the motion and its analysis are more complicated (Kane & Levinson, 1985). The turning dancer would have to be treated like a spinning top with the possibility of precession of the axis of rotation (such as seen in the wobbling of the axis of a top). Spinning is affected by the AM, and must be compared to the torque produced due to gravity, acting in a direction which might destabilize the body's balance (Kane & Levinson, 1985).

Sufficient whole body AM and the contribution from the body segments is an important factor for the successful *pirouette* motion (Kim et al., 2014). The difference in the rate of turn depends on the distribution of body mass position relative to the rotation axis, and the phenomenon may be seen through other turn motions such as *arabesque* turns and turn *al a seconde*, which are always slower than *pirouettes* in the *retiré passé* position (Laws, 2002). The total AM for the *pirouette* is about 30% less than for the *arabesque* turn (Laws, 1979). During the *arabesque* turn motion (gesture leg extended behind the body with turn; Wong, 2011), the trailing leg is far from the axis of rotation of the body. Therefore the *arabesque* turn creates a greater distribution of mass from the COM and axis of rotation, requiring greater AM and inertia. One interesting aspect is that the rate of turn of the *pirouette* is greater (more than double revolutions) than that of the *arabesque* turn. The *arabesque turn* is therefore slower than the *pirouette* turn. The moment of inertia is an important factor for the turning motion in dance. Although large AM is required for the rate of turn, the angular velocity is small, because of the large moment of inertia in the *arabesque* turn (Laws, 1979).

While in *pirouette* posture, if the ballet dancer holds the body upright along the longitudinal axis, forces act on the off-center body segments to produce a rotation. Such forces help to create the motion in the sagittal, frontal, and transverse planes, when the dancer moves from double- to single-stance. When the rotation is mainly about the longitudinal axis, off center forces are reduced, and thus the total rotation force of all the segments for the total turn duration is reduced, since the segments cannot provide consecutive pulling and pushing forces from friction. After the gesture foot off, the dancer's gesture (*retiré passé*) leg moves away from the start position. This is because the whole body mass supports the gesture leg far from the longitudinal axis of rotation needed during turns, which can possibly generate a significant amount of AM (Laws, 2011).

Components of *Pirouette* Motion

The *pirouette* comprises multiple ballet motions, including the *plié, battement tendu,* and *relevé* with *retiré passé*:

Plié

The *plié* is a basic and an important motion in all dance techniques (Figure 3), and can be divided into two types of motion: *grand plié* and *demi plié*. '*Grand-plié*' *and* '*Demi-plié*' mean 'big bending' and 'small bending', respectively (Barnes et al., 2000; Wong, 2011). A *plié* motion looks simple but is quite difficult to perform because it needs high flexibility and muscle strength, as well as balance and an increased range of motion of the lower extremity joints (Volchenkov & Bläsing, 2013). Higher flexibility is required for a larger duration of balance, while strength is required for higher force of motion. Biomechanics researchers and dance experts have been studying the *plié* motion to understand visualization of the movement and its function and the potential risks to the lower extremity joints such as the hips, the knees, and the ankles (Wilson & Kwon, 2008). The *plié* motion is an important motion during warm up, and is used to strengthen the lower extremity muscles (Wilson, 2009).

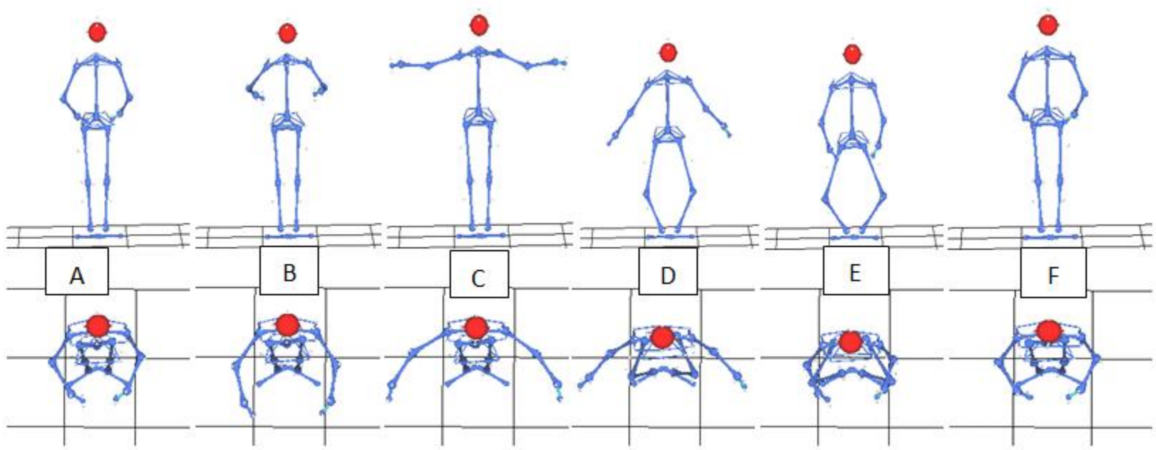

Figure 3. Ballet *demi-plié* position.

Battement Tendu

The *battement tendu* is another one of the main fundamental steps of classical ballet (Figure 4). In French, *battement tendu* means to stretch the lower extremities. The sequence of *battement tendu* is an extension of the leg to the front, side, or back, either one at a time or as a single movement (Wong, 2011). Among different types of *battement tendu* the representative technique is when one leg is extended until it touches the ground with only the toe, in any direction (Khoo-Summers & Bloom, 2015).

The *battement tendu* is a dancer's first experience with standing on one leg, with the foot brushing the ground. The working leg may touch the floor in *tendu* back (called *arabesque par terre*), or be elevated (at least forty-five degree or above), and this step eventually leads to learning *pirouettes* motion such as foot positions. As a start, the working leg (from any of the foot positions) lifts from the ground. Both knees must be kept straight without gesture leg *retiré passé* position. When the foot reaches the position *pointe tendu*, it then returns to either the 1st or the 5th position (Wong, 2011).

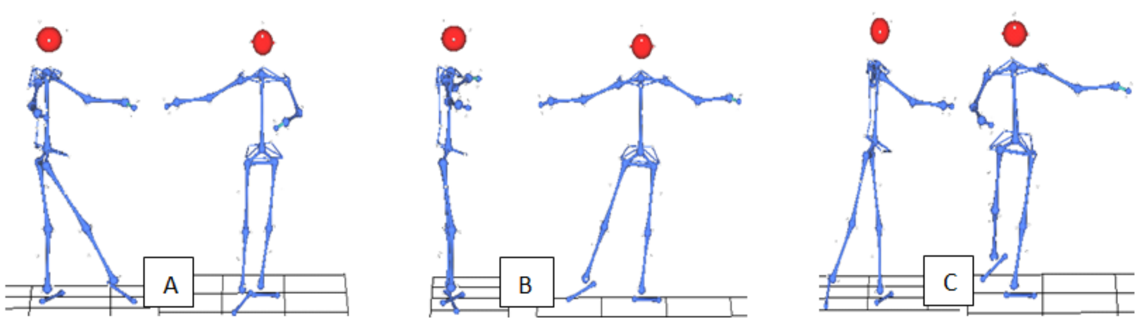

Figure 4. Ballet 1st foot position with *tendu*; A: *tendu devant* (front), B: *tendu a la seconde* (side), and C: *derriere* (back) positions.

Relevé with *Retiré passé*

Relevé, means, "lifted." The position involves rising from any foot position (1st, 2nd, 3rd, 4th, and 5th foot positions; Figure 2), to balance on either one or both toes, which are raised to at least *demi-pointe*. In *demi-pointe* the heels are off the floor, while in full *pointe* (commonly used only by female dancers) the dancer (Wilson & Kwon, 2008; Wong, 2011) is actually balancing on just the toes, supported by *pointe* shoes. The *relevé* motion may also be used with ballet motions such as *en attitude*, *en arabesque*, *devant*, *derrière*, *en tournant*, *passé en avant*, and *passé en aarrière*. For the *pirouette en dehors* motion, the *retiré passé* and *relevé* involves a small contact area between the supporting foot and ground (Fagundes et al., 2013). The *retiré passé* that immediately follows the *relevé* involves lifting the gesture foot to touch the support leg knee joint.

The Turn Motions of the Ballet Dance

En dedans Turn

En dedans means a circular motion in the inward direction (Golomer, Toussaint, Bouillette, & Keller, 2009). At gesture foot off, the gesture leg moves from the ground to a *retiré* position, and the support leg remains in contact with the ground with a straight knee (Wong, 2011). For the *En dedans* motion (Figure 5), the support leg's knee joint is bent, and then extends as a start of the turn motion. The support leg can exert the torque, which generates AM (Golomer et al., 2009). A skilled dancer uses the turn-out motion (which involves a quick lateral rotation movement of the leg) to rise to *retiré* with a *pointe* foot. Dancers may benefit from understanding biomechanical terms related to the *pirouette en dedans* motion relative to the initial motion of the trailing arm and gesture leg working quickly as the supporting leg straightens (Laws, 1979).

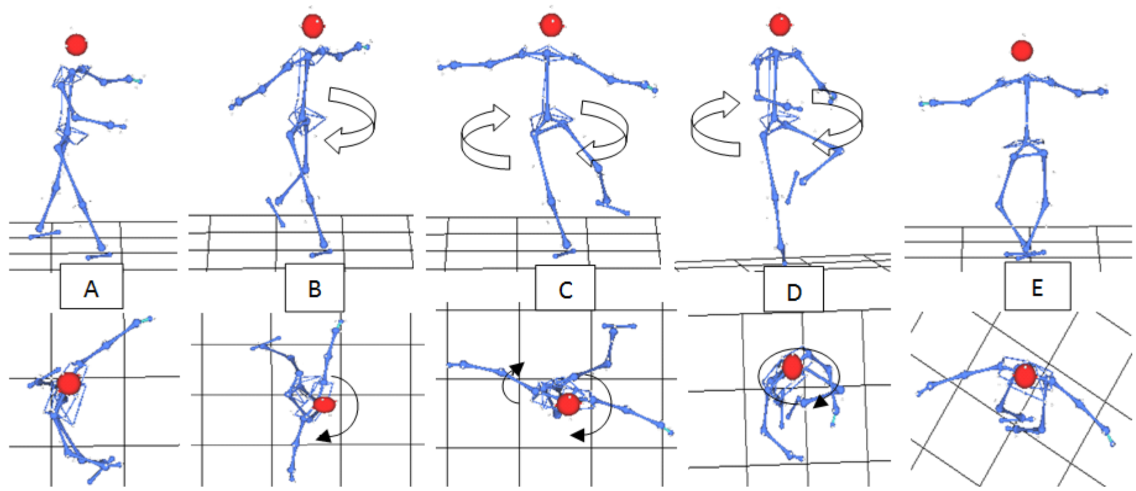

Figure 5. *En dedans* Turn; A: preparation, B: counter-motion start, C: Take-off motion, D: turn with *retiré* position, and E: landing with *plié*.

Fouette Turn

The *fouette* turn, which involves multiple revolutions, is one of most difficult movements in ballet and is performed by both female and male dancers. This turn motion includes consecutive revolutions. In classical ballet, the *fouette* motion is different between female and male dancers, with respect to gesture leg knee (females bend then straighten; males maintain an extended knee during the turns) movements (Imura & Yeadon, 2010). Most skilled male and female ballet dancers can perform at least 30 consecutive revolutions (Laws, 1998).

Arabesque Turn

An *arabesque* is one of the most beautiful and familiar movements in classical ballet. It has both an *en dedans* (inward) turn (Figure 6), as well as, an *en dehors* (outward) turn. It involves a body position in which a dancer stands on the support leg with the gesture leg extended behind the body and both knees either extended or flexed (Wong, 2011), which followed by a turnout spiral. All dancers work hard to adjust this movement, which is technically and physically challenging.

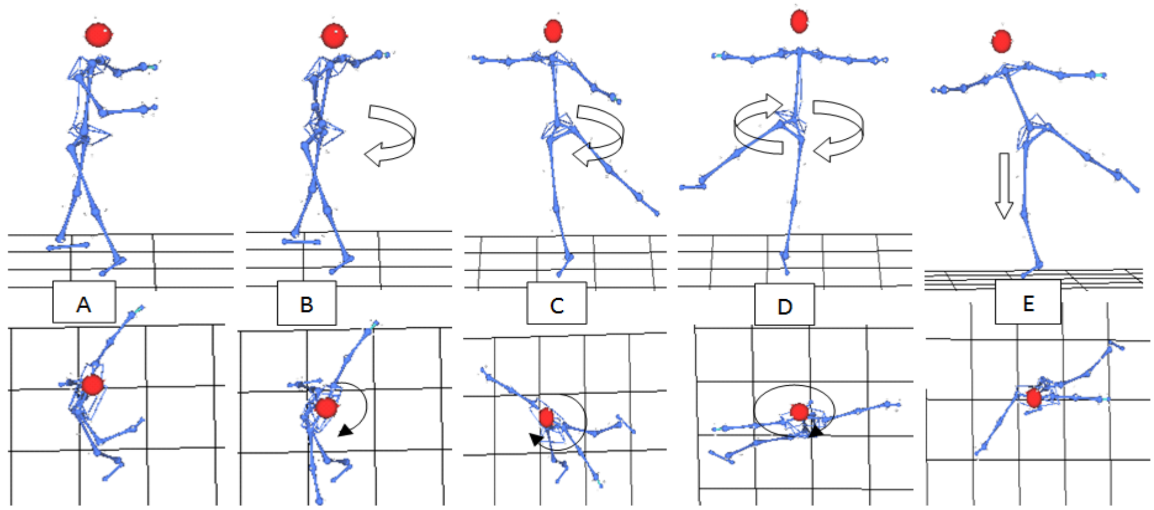

Figure 6. *Arabesque en dedans* turn; A: preparation, B: counter-motion start, C: Take-off motion, D: turn with *arabesque* position, and E: landing with *plié*.

CHAPTER III

METHODS

This chapter is divided into five sections: participants, trial conditions, experimental setup, data processing and analysis, and statistical analysis.

Participants

Forty skilled collegiate or professional classic ballet dancers were recruited for this study (Table 1). Skilled dancers (collegiate or professional) trained in classic ballet were recruited. All participants were recruited from university dance departments in Seoul, Korea. Participants who were able to perform at least one successful trial of double-turn *pirouette en dehors* were recruited for this study. All participants were right leg dominant.

Table 1

Participant Characteristics (*M* ± *SD*)

	Age (year)	Mass (kg)	Height (cm)	Experience (year)
Successful (*n = 20*)	22.1 ± 1.3	58.4 ± 9.8	172.8 ± 8.4	8.6 ± 3.7
Unsuccessful (*n = 20*)	22.0 ± 2.3	50.3 ± 3.4	164.8 ± 3.5	9.1 ± 4.4

The participants were free of major injuries at the time of data collection that might hinder the performance. The Institutional Review Board (IRB) of Texas Woman's University approved the human participant research protocol and informed consents were obtained from the participants prior to data collection. The purpose, procedures and potential risks of the study were explained to the participants before the consent form was signed.

Trial Condition

Each participant was asked to perform seven trials of triple-turn *pirouette en dehors* (Figure 1). If three or more trials were successful, the participant was placed in the successful group. If less than three trials were successful, the participant was placed in the unsuccessful group. Three successful trials were selected and used for analysis in successful-group participants and three unsuccessful trials were used in unsuccessful-group participants. If all seven trials were successful or unsuccessful, then three trials were randomly assigned to the proper condition.

The preparatory motion was preset to fifth foot position at the start (Figure 3E), followed by *relevé* (Figure 1D), *retiré passé* (Figure 1F), *plié* with fourth foot position (Figure 1C), turn and ending with fourth foot position (Figure 1G). All trials were restricted to *en avant* arm position (arms in front of the trunk at the height of the xyphoid process) and gesture leg foot on the supporting leg knee joint during the turning motion (Figure 1F). Failure to stick to the prescribed arm and gesture leg position, premature termination of the turn, hopping or wobbling motions, and loss of balance made the trial classified as unsuccessful. If the participant's support leg was off the force plate or if there was an absence of clear head spotting, the trial was also considered unsuccessful. To standardize the trials, all trials were performed to the same music: Douglas Shultz, *Learning on Tradition*, Volume 1, track number 34, *Pirouette* Waltz; 3/4, 128 beats/min.

Dancers were asked to warm up for at least 10 min prior to data collection and were encouraged to keep moving between trials.

Experimental Setup

All testing procedures took place at the Motion Analysis Laboratory, Korea National Sport University, Seoul, Korea. A 250-Hz 7-camera Qualisys real-time motion capture system (Oqus 300; Qualisys, Gothenburg, Sweden) was used for kinematic data analysis by capturing the three-dimensional motion trajectories of the retro-reflective markers (10 mm diameter) placed on dancer's body. The 'TWU Dancer' marker set with 48 markers was used: 4 head markers, 5 trunk markers, 5 pelvis markers, 16 arm markers, and 18 leg markers (Table 2). A static T-pose trial was collected and used to locate joint centers and the medial knee and ankle markers were removed afterwards in the motion trials (Kim et al., 2014). All participants were asked to wear a dark-colored leotard, black swimming cap, and training ballet canvas shoes.

Two force plates (Kistler 9286AA; Kistler Instruments AG, Winterthur, Swiss) were used to collect the GRF data at a sampling frequency of 2,500 Hz. The plates were covered with Marley dance floor, a heavy-duty slip-resistant elastic floor covering used in dance studios and theatre stages. Dancers placed one foot on each plate in the starting position. After the turns, the gesture-leg foot was expected to return to the same plate.

Data Processing and Analysis

The captured marker coordinate and force plate data were imported to Kwon3D Motion Analysis Suite (Visol, Seoul, Korea; version XP 5.0) for subsequent data reduction and processing. To remove random experimental errors involved in the marker coordinates, a 4th -order zero phase lag Butterworth low-pass filter was used with a 6-Hz cut off frequency. The inertial data (mass, moment of inertia, and COM location)

Table 2

Forty Eight-point 'TWU Dancer' Marker set and Body Model

Section	Markers/computer points	
Head	Primary Markers (4)	Forehead, vertex, and right and left head markers
	Computed (1)	Head center is the mid-point of the right and left head markers.
Trunk	Primary Markers (5)	Acromions, supra-sternal notch, C7 (7th cervical vertebra), and T12 (12th thoracic vertebra)
	Computed (1)	Mid-shoulder is the mid-point of the shoulder joint centers. (Shoulder joints were computed from the upper arm markers.)
Arms	Primary Markers (8×2)	Anterior and posterior shoulders, medial and lateral epicondyles, radial and ulnar styloid processes, and medial (2nd) and lateral (5th) metacarpals (distal head)
	Computed (4×2)	Shoulder joint is the mid-point of the anterior and posterior shoulder markers. Elbow joint is the mid-point of the epicondyle markers. Wrist joint is the mid-point of the styloid markers. Hand center is the mid-point of the metacarpal markers.
Pelvis	Primary Markers (5)	Anterior superior iliac spines (ASIS; right and left), posterior superior iliac spines (PSIS; right and left), and sacrum
	Computed (5)	Mid-ASIS is the mid-point of the ASIS markers and L4/5 was computed using the ‘MacKinnon Method’ (Mackinnon & Winter, 1993) while the hip joints were computed using the ‘Tylkowski-Andriacchii Hybrid Method’ (Bell, Pedersen, & Brand, 1990). Mid-hip is the mid-point of the hip joint centers.
Legs	Primary Markers (9×2)	Greater trochanter, lateral thighs, medial and lateral epicondyles, lateral shank, medial and lateral malleoli, toe (distal end of the second metatarsal) and heel (calcaneus). The greater trochanter, medial epicondyle and medial malleolus markers were removed in the dynamic motion trials.
	Computed (2×2)	Knee joint (mid-point of the epicondyle markers) and ankle joints (mid-point of the malleolus markers)

were estimated from De Leva's male and female body segment parameter (BSP) set (De Leva, 1996).

The dancer's body was modeled as a system of 15 segments (head, trunk, pelvis, upper arms, forearms, hands, thighs, shanks, and feet) linked through 13 joints (L4/L5, hips, shoulders, elbows, wrists, knees, and ankles). The location of the L4/L5 joint was determined by using the method outlined by MacKinnon and Winter (1993). The hip joint centers were located by using the Tylkowski-Andriacchi hybrid method (Bell, Pedersen, & Brand, 1990). The shoulder, elbow, and wrist joints were defined as the mid-points of the proximal humerus markers (anterior and posterior shoulder markers), epicondyle markers (medial and lateral epicondyle markers), and wrist markers (medial and lateral wrist markers), respectively. Similarly, the knee and ankle joints were modeled as the mid-points of the femoral epicondyle markers (medial and lateral) and malleolus markers (medial and lateral), respectively. A T-pose static trial was collected before the medial markers in the legs were removed for the motion trials.

The segmental reference frames fixed to the segments were defined for angular kinematics. In each frame, an anatomical plane was established using the primary axis and the temporary second axis. The third axis was computed from these two axes and the true second axis was computed from the first and third axes (Kim et al., 2014; Table 3).

The attitudes (orientations) and angular velocities of the segments were computed from the attitude matrices of the local reference frames (Kim et al., 2014):

Table 3

Local Reference Frames for the Segments

Segment	First Axis	Temporary Second Axis	Anatomical Plane
Head	Left head → right head (+X axis)	Left head → anterior head (+Y axis)	Transverse plane
Trunk	Center: PSIS → SJC (+Z axis)	C7 → SS (+Y axis)	Sagittal plane
Upper arm	SJC → EJC (–Z axis)	Left elbow → EJC (+X axis for the right upper arm and –X axis for the left upper arm)	Frontal plane
Fore arm	EJC → WJC (–Z axis)	Left wrist → WJC (+X axis for the right fore arm and –X axis for the left forearm)	Frontal plane
Hand	Hand center → WJC (Z axis)	5^{th} metacarpal → 2^{nd} metacarpal (+X axis for the right hand and –X axis for the left hand)	Frontal plane
Pelvis	LASIS → RASIS (+X axis)	Sacrum → mid-ASIS (Y axis)	Transverse plane
Thigh	KJC → HJC (+Z axis)	HJC → lateral thigh marker (+X axis for the right thigh and –X axis for the left thigh)	Frontal plane
Shank	AJC → KJC (+Z axis)	KJC → lateral shank marker (+X axis for the right shank and –X axis for the left shank)	Frontal plane
Foot	Toe → heel (+Z axis)	Heel → AJC (+Y axis)	Sagittal plane

Note. *Abbreviations*: A-P SIS (anterior-posterior superior iliac spines), SJC (shoulder joint center), C7 (cervical-7), SS (supra sternum), EJC (elbow joint center), WJC (wrist joint center), KJC (knee joint center), HJC (hip joint center), and AJC (ankle joint center).

$$\mathbf{T}_i = \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix} \quad (1)$$

where i is the local frame of interest and $\mathbf{T}_i$ is the attitude matrix of frame i. Angular velocities of the segments were computed from the relative orientation angles of the segments and their first time derivatives:

$$\boldsymbol{\omega}_i = \boldsymbol{\omega}_j + \mathbf{T}_i' \begin{bmatrix} C_2C_3 & S_3 & 0 \\ -C_2S_3 & C_3 & 0 \\ S_2 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} \quad (2)$$

where $\boldsymbol{\omega}_i$ is the angular velocity of the local frame i, $\boldsymbol{\omega}_j$ is the angular velocity of its linked proximal frame (frame j), and C_k and S_k are abbreviations of cos θ_k and sin θ_k, respectively. θ_1, θ_2, and θ_3 are three relative orientation angles of frame i to frame j. The AMs of the segments about the whole-body COM were computed from the positions, velocities, angular velocities, and inertial parameters of the segments (Kwon, 2008):

$$\mathbf{L}_i = \boldsymbol{m}_i\tilde{\mathbf{r}}_i\mathbf{v}_i + (\mathbf{T}_i'\mathbf{I}_i\mathbf{T}_i)\boldsymbol{\omega}_i \quad (3)$$

$$\tilde{\mathbf{r}}_i = \begin{bmatrix} 0 & -z_i & y_i \\ z_i & 0 & -x_i \\ -y_i & x_i & 0 \end{bmatrix} \quad (4)$$

$$\mathbf{I}_i = \begin{bmatrix} I_1 & 0 & 0 \\ 0 & I_2 & 0 \\ 0 & 0 & I_3 \end{bmatrix} \quad (5)$$

where **L** is the AM, **r** is the relative position of the segmental COM to the whole-body COM. $\tilde{\mathbf{r}}$ is the skew-symmetric form of **r** for the cross product operation, and **v** is the relative velocity of the segmental COM to the whole body COM. **I** is the inertia tensor described in the segmental reference frame, with I_1, I_2, and I_3 being the principal moments of inertia.

The foot-ground interaction moments were computed from the position of COM and COP, and the GRFs acting on dancer's feet (Figure 7A):

$$\mathbf{M} = \mathbf{R} \times \mathbf{F} + \sum_i (\boldsymbol{\rho}_i \times \mathbf{F}_i) + \sum_i \boldsymbol{\tau}_i \qquad (6)$$

where **M** is the total moment of force generated by the GRFs about the whole body COM, **R** is the relative position of the combined COP to the COM, **F** is the combined GRF, $\boldsymbol{\rho}_i$ is the relative position of the COP of a foot to the combined COP, $\mathbf{F}_i$ is the GRF acting on a foot, and $\boldsymbol{\tau}_i$ is the GRM acting on a foot.

The first term in Equation 6 is the GRF moment produced by the combined GRF about the body COM. The GRF moment has all three components about the axes of the laboratory reference frame: lateral axis (x-axis), stance axis (y-axis), and vertical (z-axis) (Figure 7). The second term in Equation 6 is the PM produced by individual GRFs about the combined COP. The PM is vertical as the combined COP is the balance point of the vertical GRFs so the horizontal moment components become zero (Note here that this particular moment was labeled 'pivoting moment,' instead of 'coupling moment,' as the horizontal GRFs of individual feet have neither the same magnitudes nor the opposite directions). The third term in Equation 6 is the foot contact moment (FCM) which is also vertical. The PM and FCM are the primary causes of the longitudinal AM.

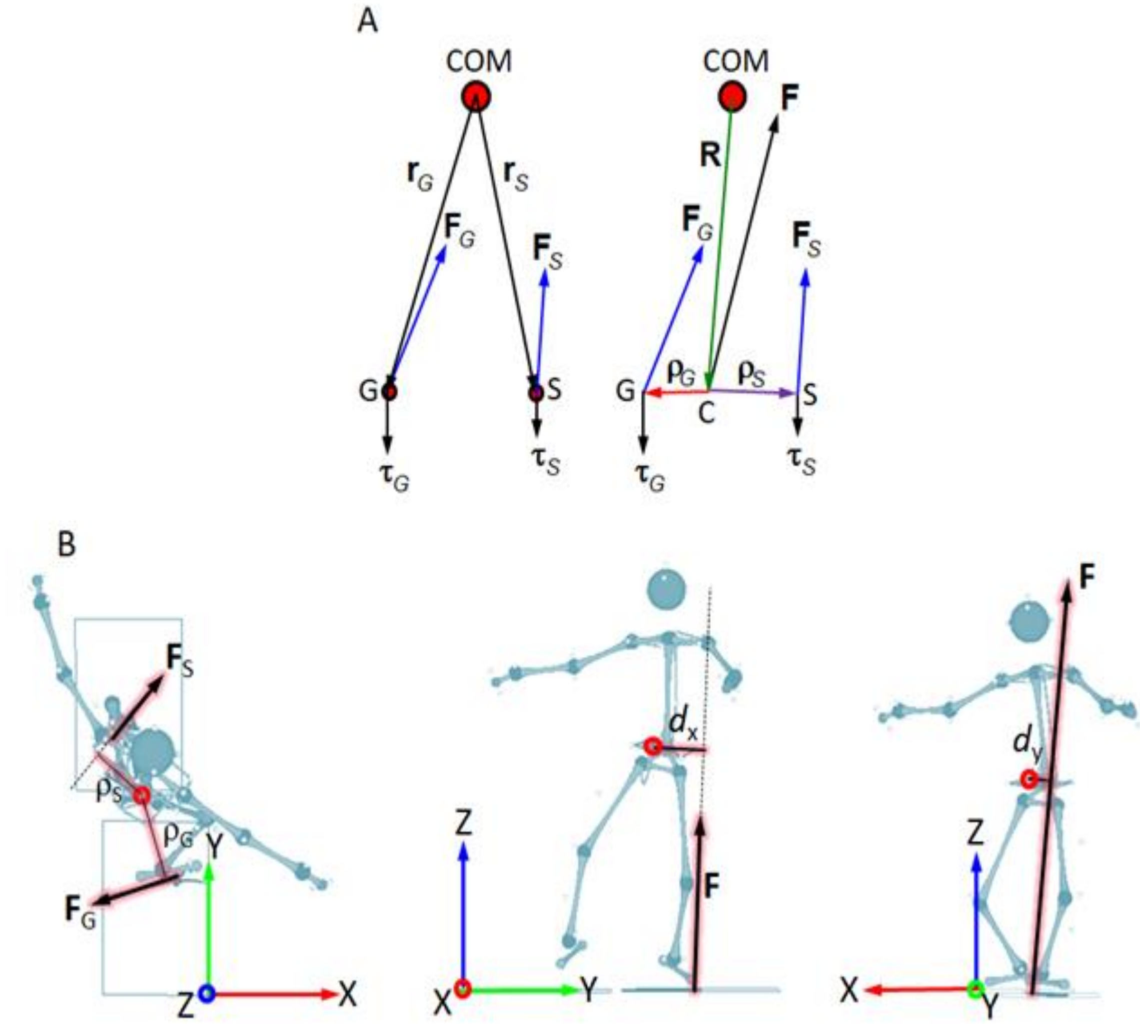

Figure 7. Moments generated through the dancer-floor interaction: ground reaction forces (A) and their moment arms (B).

With force magnitudes and moment arms, Equation 6 can be rewritten to

$$\mathbf{M} = \begin{bmatrix} d_x F_{yz} \\ d_y F_{xz} \\ d_z F_{xy} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \sum_i \rho_i F_{xyi} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \tau_i \end{bmatrix} \tag{7}$$

where $\left[d_x, d_y, d_z\right]$ are the MAs formed by the combined GRF about the coordinate axes passing through the body COM, $\left[F_{yz}, F_{xz}, F_{xy}\right]$ are the projections of the combined GRF to the *yz*-, *xz*-, and *xy*-plane, respectively, ρ_i is the pivoting MA of the GRF acting on a foot, F_{xyi} is the projection of the GRF acting on a foot to the *xy*-plane, and τ_i is the vertical FCM acting on a foot (Figure 7B). A counterclockwise moment yielded a positive MA.

To facilitate data analysis, five meaningful *pirouette en dehors* events were identified: Start (start position), BAMG (beginning of AM generation), LCP (lowest COM position) near *a la seconde* position, TO (toe-off), and TD (touch-down) (Figure 8). Four additional time points were also identified when the longitudinal

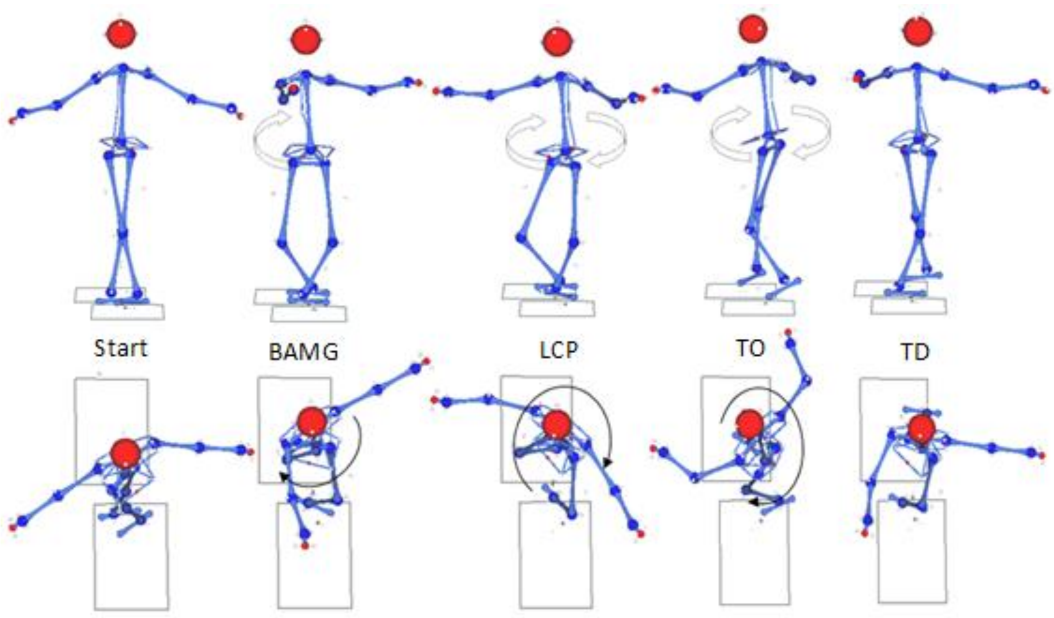

Figure 8. Triple-turn *pirouette* events used in the analysis.

AM and foot-ground interaction moments reached their peak values: TAM (time of peak longitudinal AM), TPM (time of peak combined PM), TGMX (time of peak GRFM about the global *x*-axis [lateral axis]), and TGMY (time of peak GRFM about the global *y*-axis [stance axis]). Ensemble average patterns of the foot-ground interaction moments, forces, and MAs were derived and the time axis was normalized to the BAMG-TAM time in the ensemble averages.

For data analysis, peak longitudinal AM, AM generation time (BAMG to TAM), and AM generation rate (peak AM divided by generation time) were computed from the longitudinal AM data. From the PM data, peak combined PM (at TPM), PMs of individual feet at TPM, PMAs of individual feet at TPM, and horizontal GRFs of individual feet at TPM were extracted as well. From the GRFM data, peak horizontal GRFMs, GRFMA at TGMX and TGMY, and individual GRFs projected to the vertical planes at TGMX and TGMY were also extracted. MA parameters were normalized to participant's body height (BH). GRF parameters were normalized to the body weight (BW). Moment and AM parameters were normalized to [BW*BH] of the participant.

Statistical Analysis

The dependent variables used in the statistical analysis were the longitudinal AM parameters (peak AM, generation time, and generation rate), the PM parameters (peak combined PM, individual foot PMs at TPM, and individual horizontal GRFs at TPM), and the GRF moment parameters (peak *x*- and *y*-axis GRFMs and combined GRFs projected to the *xz*- and *yz*-plane at TGMX and TGMY, respectively). The average values of three repeated trials were used in the statistical analyses.

The variables were divided into two groups: primary (peak AM and peak moments) and explanatory (AM geration rate and time, and forces and MAs at the time of peak moments) and two multivariate analyses of variance (MANOVA) were conducted to compare these dependent variables between the participant groups (successful vs. unsuccessful). The first MANOVA involved all primary dependent variables. The second MANOVA, however, included only those explanatory variables associated with the primary variables that revealed significant group effects in the first MANOVA. Follow-up univariate analysis was performed if the factor effect was significant in each MANOVA. The level of significance (α) of each MANOVA was set to 0.025 (Bonferroni adjustment) to control the experiment-wise Type-I error to 0.05. SPSS (Statistical Package for Social Sciences version 25.0 software) was used for all statistical tests.

CHAPTER IV

RESULTS

Figures 9-12 show the ensemble average patterns of the longitudinal AM parameters (Figure 9), the GRF components (Figure 10), the PM parameters (Figure 11), and the GRFM parameters (Figure 12) during the AM generation phase (BAMG-TAM). Table 4 presents the results of the statistical analyses.

The first MANOVA with the primary variables revealed a significant factor effect (Wilk's $\lambda = 0.531$, $F_{1, 38} = 4.858$. $p < .001$) between the successful and unsuccessful groups (Table 4). Follow-up univariate analysis showed significant differences in peak longitudinal AM ($p < .001$), peak PM ($p = .018$), trail-foot PM at TPM ($p = .008$), and peak *y*-axis (stance-axis) GRFM ($p = .005$). The successful group generated larger means when compared to the unsuccessful group. The support-foot PM parameters and the x-axis (lateral-axis) GRFM parameters were excluded in the second MANOVA.

The second MANOVA with the explanatory variables showed a significant factor effect (Wilk's $\lambda = 0.644$, $F_{1, 38} = 3.036$. $p = .018$) between the successful and unsuccessful groups (Table 4). Follow-up univariate analysis showed significant differences in AM generation rate ($p = .006$), gesture-foot F_{xy} at TPM ($p = .021$), and combined F_{xz} at TGMY ($p = .046$). The successful group exhibited larger means in these parameters than the unsuccessful group.

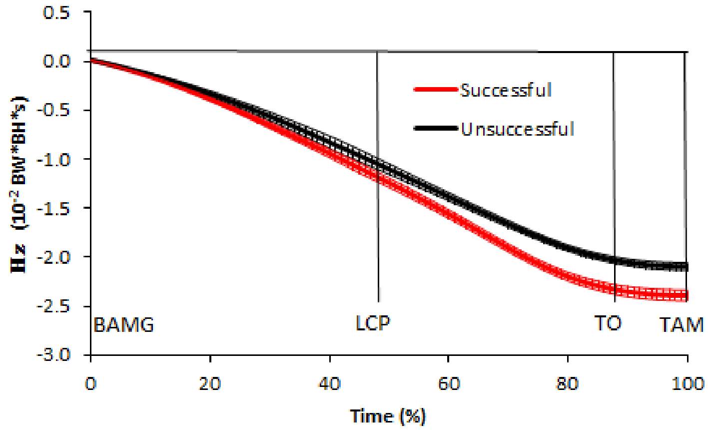

Figure 9. Ensemble-average patterns of the peak longitudinal AM (H_z) of the whole body ($M \pm SE$).

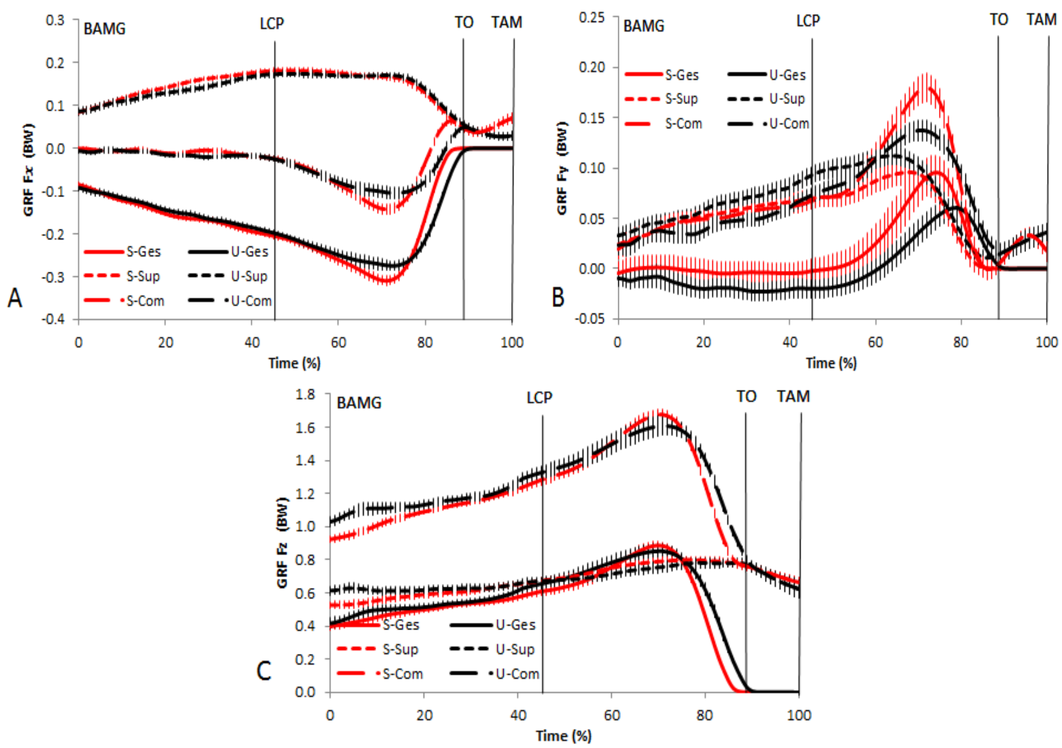

Figure 10. Ensemble-average patterns of the GRF components F_x (A), F_y (B) and F_z (C). ($M \pm SE$).

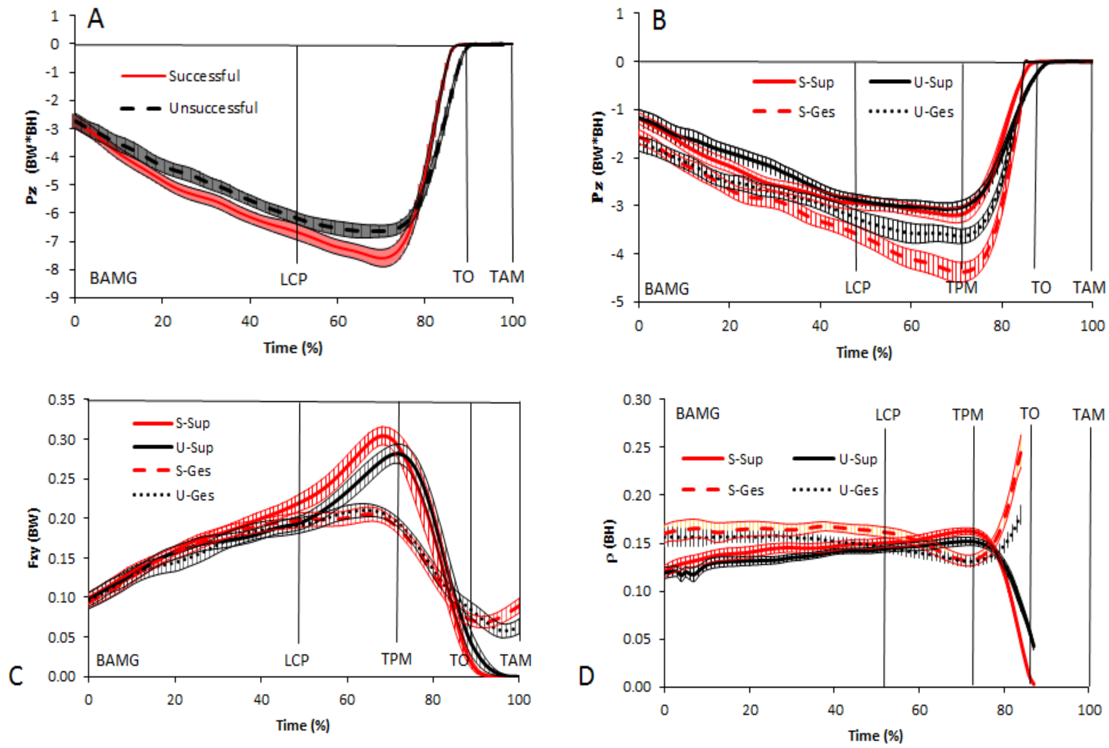

Figure 11. Ensemble-average patterns of the PM parameters: peak combined PM (P_z) (A), support- and gesture-foot PM (P_z) (B), support - and gesture-foot horizontal GRFs (F_{xy}) (C) and PMA (ρ) (D) ($M \pm SE$).

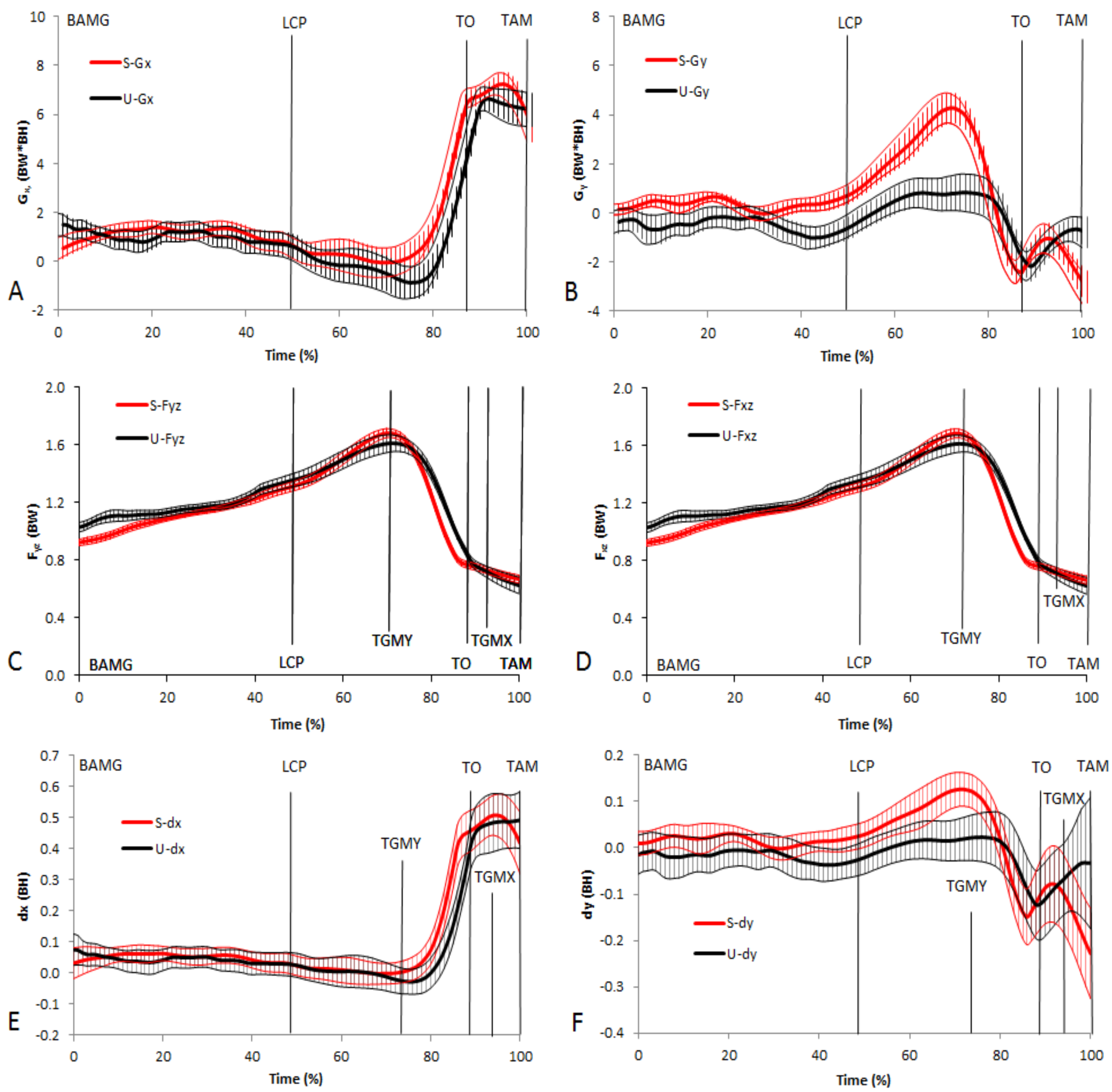

Figure 12. Ensemble-average patterns of the GRFM parameters: G_x (A), G_y (B), F_{yz} (C), F_{xz} (D), GRFMA (d_x) (E) and GRFMA (d_y) (F) ($M \pm SE$).

Table 4

Summary of Statistical Analysis Results

Variable Group / Variable	Successful (n = 20)	Unsuccessful (n = 20)
Primary Variables		
Peak H_z (10^{-2} BW*BH*s)	2.43 ± 0.25*	2.12 ± 0.18
Peak Combined P_z (10^{-2} BW*BH)	8.13 ± 1.26*	7.30 ± 0.84
Support-Foot P_z at TPM (10^{-2} BW*BH)	3.40 ± 0.75	3.27 ± 0.53
Gesture-Foot P_z at TPM (10^{-2} BW*BH)	4.67 ± 0.83*	4.00 ± 0.71
Peak G_x (10^{-2} BW*BH)	8.59 ± 1.34	8.13 ± 2.18
Peak G_y (10^{-2} BW*BH)	5.39 ± 2.20*	3.33 ± 2.14
Explanatory Variables		
AM Generation Time (s)	0.52 ± 0.06	0.52 ± 0.07
AM Generation Rate (10^{-2} BW*BH)	4.70 ± 0.68*	4.13 ± 0.55
Gesture-Foot F_{xy} at TPM (BW)	0.33 ± 0.04*	0.30 ± 0.04
Gesture-Foot ρ at TPM (BH)	0.034 ± 0.015	0.027 ± 0.019
Combined F_{xz} at TGMY (BW)	1.64 ± 0.17*	1.49 ± 0.28
Gesture-Foot d_y at TGMY (BH)	5.49 ± 2.28	4.24 ± 3.03

Note. Symbols: H_z – longitudinal AM, P_z – pivoting moment, [F_{xy}, F_{xz}, F_{yz}] – projections of the GRF to the *xy*-, *xz*-, and *yz*-plane, respectively, [G_x, G_y] – GRF moment about the *x*- and *y*-axis, respectively, ρ – pivoting moment arm, and d_x – GRF moment arm about the *y*-axis.

Abbreviations: BW – body weight, BH – body height, TPM – time of the peak P_z, and TGMY – time of the peak G_y.

*Significantly different from the unsuccessful group ($p < .05$)

CHAPTER V

DISCUSSION

This study highlighted the biomechanical differences between the successful and unsuccessful groups during triple-turn *pirouette en dehors* in three groups of variables: longitudinal AM (peak AM, generation time, and generation rate), PM (peak combined PM, individual foot PMs at TPM, and individual horizontal GRFs and MAs at TPM), and GRF moment (peak *x*- and *y*-axis GRFMs and combined GRFs projected to the *xz*- and *yz*-plane at TGMX and TGMY).

Vertical Angular Momentum

Generation of AM during the double-stance phase is one of the most important aspects of *pirouette*-family movements in ballet as the generated AM allows the body to continue rotating during the non-AM generation phase (i.e., single-stance phase; Imura, & Iino, 2018; Kim et al., 2014; Laws, 1979). In this study, peak AM and AM generation rate were significantly different between the groups (successful > unsuccessful) while the generation time was not (Table 4). As shown in Figure 8, the longitudinal AM of the dancer increases gradually throughout the double-stance phase (BAMG-TO) and early single-stance phase (TO-TAM). The inter-group difference gradually increases as the AM generation continues, with the successful group yielding significantly larger peak

AM and AM generation rate. The longitudinal AM reached its peak value slightly after TO due to the friction between the support foot and floor and motions of the body parts.

The whole body AM is the sum of those of the individual body parts and motions of the body parts contribute to the whole body AM differently. For example, Kim et al. (2014) reported that the contribution of the trailing arm was the largest among the body parts in a group of skilled ballet dancers. Relative body motions among the body parts also cause transfer of the AM from one body part to another. Nevertheless, the peak whole body longitudinal AM is a good indicator of the overall level of dancer-floor interaction. As the longitudinal angular velocity of the body decreases during the single-stance phase due to the friction between the shoe and floor, an insufficient AM terminates the turn prematurely. This is often manifested in the form of hopping. Development of sufficiently large longitudinal AM during the double-stance phase before TO is thus crucial for successful multi-turn *pirouette*.

Ground Reaction Force

The vertical GRF patterns (Figure 10C) reveals that during the AM generation phase (BAMG-TAM) ballet dancers experience active loading (vertical GRF > body weight) initially, followed by unweighing (vertical GRF < weight). The vertical GRF reaches its peak value near TPM/TGMY where the PM about the Z-axis and the GRFM about the Y-axis become largest. The peak vertical GRF at this point creates favorable mechanical conditions for the PM and GRFMY: (1) increased vertical loading increases the maximum static friction (friction coefficient * vertical force) between the feet and floor; (2) the vertical push and increased maximum static friction allows harder horizontal push along the lateral direction (X-axis) in both feet and in the gesture foot in particular (Figures 10A-B); (3) increased lateral push increases the coupling effect generated by the feet about the vertical axis (Figure 11C); (4) increased lateral push lengthens the MA of the GRFMY (Figure 12F).

The gesture foot generated larger F_z than the support foot at TPM (and TGMY) (Figure 10C). This means the combined COP was located closer to the gesture foot at this point. The position of the combined COP is determined by the relative magnitudes of the F_z acting on the individual feet and, as a result, the PMA of the gesture foot must be slightly shorter than that of the support foot at TPM, as shown in Figure 11D. The successful group was characterized by larger F_z values in the gesture foot at TPM (or TGMY). The gesture foot left the ground at TO and thus its vertical force became 0 (N/N).

In general, the successful group showed larger lateral pushes in the X-direction than the unsuccessful, and the gesture foot than the support foot (Figure 10A). It is evident in the F_z pattern that the successful group generated larger force in the gesture foot than the unsuccessful. The successful group was characterized by a more unbalanced lateral push, with the gesture foot (negative in Figure 10A) pushing harder than the support foot (positive). This larger net F_z generated a larger GRFMY in the successful group than in the unsuccessful (Table 4; Figure 12B & D) while increasing the GRFMA about the Y-axis in the successful group (Figure 12F).

The F_y patterns also show that the successful group generated harder push with the gesture foot near TPM where the vertical force reached its maximum value (Figure

10B). As a result, the net F_y was also larger in the successful group at this point. This means the gesture foot accelerated the body COM toward the support foot faster in the successful group than the unsuccessful.

Pivoting Moment

The PM (Figure 11) is generated about the vertical axis by the coupling action of the feet against the floor and is the main source of the longitudinal AM. During the double-stance phase, the feet push the floor horizontally in different directions, causing an effect similar to a force couple (Laws, 1979; Figure 9A). The successful group generated significantly larger peak PM than the unsuccessful (Table 4; Figure 11). The PM reached its peak value at midway between LCP and TO. This point corresponds to the steepest slope of the AM-time curve (Figure 9). LCP is where the COM of the body assumes the lowest position vertically and lowering of the body allows the feet to interact with the floor more rigorously.

It was evident that the difference in peak PM (at TPM) between the groups primarily came from the gesture-foot PM (Table 4; Figure 11B). PMs generated by the individual feet are a function of the magnitudes of the horizontal GRFs (F_{xy}) and the lengths of the MAs formed by the horizontal GRF vectors with respect to the combined COP (i.e., the perpendicular distance from the combined COP to the line of action of the horizontal GRF; Equation 6). Although no statistical analysis was performed on the contributions from the individual feet, the gesture foot generated a substantially larger horizontal GRF than the support foot (Table 4; Figure 11C), and this yielded a larger PM in the gesture foot than in the support foot at TPM. The PMAs of the support foot, however, were slightly longer than those of the gesture foot (Figure 11D). Overall, the support foot provided about 56.5% of the peak PM and it was evident that this discrepancy was derived primarily from that in the magnitude of the horizontal GRF (Figures 11B-D).

Between the groups, the successful group was characterized by significantly larger gesture-foot horizontal GRF and PM at TPM (Table 4, Figure 11). Both groups generated similar support-foot PM (Figure 11B) and, in turn, similar support-foot horizontal GRFs (Figures 11B-C). The support-foot horizontal GRF and gesture-foot PMA were quite similar between the groups (Figure 11D). The successful group was characterized by a substantially larger gesture-foot horizontal GRF and slightly longer support-foot PMA at TPM than the unsuccessful (Figure 11C-D). The peak gesture-foot PM occurred at TPM when the PMA of the gesture foot became shortest (Figure 11B & D).

Longitudinal AM and PM are directly related to each other as the time-integral of the PM should explain most of the longitudinal AM. The successful group developed the AM more rapidly than the unsuccessful by generating larger PM consistently throughout the entire double-stance phase (Figure 9 & 11A).

GRF Moment (GRFM)

Two key aspects of a multi-turn *pirouette* are: (1) generation of sufficient longitudinal AM and (2) maintenance of dynamic balance during the double- to single-stance transition. The GRFMs are closely related to the dynamic balance during the transition, as these are the moments that rotate the body about the horizontal axes. Two GRFMs were considered in this study: GRFMX and GRFMY.

At the beginning of the AM generation phase, the feet were aligned along the Y axis in the 4th position. The dancer had to move the COM mainly in the +Y direction toward the support foot during the double- to single-stance transition. The GRFMY is the moment generated by the GRF about the Y-axis and is closely related to the lateral dynamic balance. The GRFMY reached its peak value near TPM (Figure 12B). The successful group generated significantly larger peak GRFMY than the unsuccessful (Table 4). It was evident that the difference in GRFMY between the groups was primarily derived from the difference in the GRFMA (Figure 12F). The successful group was characterized by clearly defined peak GRFMY and its MA, while the unsuccessful group tended to exhibit variability in terms of timing of the peak GRFMY (Figures 12B & F). Larger F_x near TPM in the successful group (Figure 10A) causes more inclination of the GRF vector in the XZ-plane, which lengthens the MA for the GRFMY.

Although combined F_{yz} reached its peak value near TPM (Figure 12C), the GRFMAX was close to zero at this point (Figure 12E). The GRFM about the X-axis actually reached its peak value near the end of the AM generation phase (Figure 12A). This is because when the gesture foot leaves the ground at TO, the GRF acts on the support foot only and the COP moves to the support foot. The moment GRFMAX thus becomes longest after TO (Figure 12E). The GRFMX at TGMX showed no significant difference between the groups (Table 4).

In summary, the successful group was characterized by more active horizontal foot-floor interaction in the 'gesture foot' during the push phase (LCP-TO) near TPM (or TGMY). In terms of the moments generated through the foot-floor interaction, larger horizontal peak GRFs offer several benefits: (1) larger resultant horizontal force (F_{xy}) increases the PM which is the source of the longitudinal AM, and (2) larger horizontal force increases the inclination of the GRF vector in the XZ-plane and lengthens the MA for the GRFMY. The successful group exhibited apparent superiority in generating PMs about the vertical axis. It could be speculated that the GRFMY may play a crucial role in controlling the lateral dynamic stability and the gesture foot plays a crucial role in this. Further study on how dancers control the dynamic postural balance using the GRF-induced horizontal moments is warranted.

Practical Implication

The findings of this study highlighted that the successful group used the gesture foot more actively during the double- to single-stance transition phase than the unsuccessful in the triple-turn *pirouette en dehors* (Figure 10). The primary push occurs midway between the lowest COM position and gesture-foot toeoff. A right leg-dominant ballet dancer generates an upward, forward (i.e., toward the support foot), and leftward gesture-foot GRF by pushing the floor downwards, backwards, and rightwards. The successful group pushed the ground harder than the unsuccessful in all three directions at this point. This harder push is directly translated to a larger gesture-foot PM and a larger GRF moment about the stance axis.

The dancer's body COM must move along the stance axis primarily during the single- to double-stance transition phase, so a minimal COM motion along the lateral axis is expected in the perspective of the lateral balance. The successful group, however, generated a larger net negative (leftward) GRF along the lateral axis at the time of the primary push. This net lateral force accelerates the body COM leftwards, while the GRF moment produced by the combined GRF about the stance axis (GRFMY) angularly accelerates the body in the clockwise direction in dancer's perspective. This suggests that the successful ballet dancers use a more dynamic balance strategy involving the lateral foot-floor interaction during the single- to double-stance transition phase. It is therefore important for the ballet dancers to understand the role of the gesture foot in generating moments and controlling balance and to learn how to use the gesture leg for successful execution of the multi-turn *pirouette en dehors*.

Limitations of the Study

One limitation of this study is that there are different ballet training methods (Royal, Cecchetti, American, and Vaganova) and the participants used in this study were mainly trained in the Vaganova method. Foot stance and preparatory motion for the *pirouette* can be different across different methods. The floor-foot interaction pattern may also change from one method to another. Therefore, the findings of this study may not be generalized to other training methods and further studies involving various ballet training methods is necessary.

Participants were required to perform triple-turn *pirouettes* on force plates covered with Marley dance floor and the gesture foot was required leave the rear plate and return to the same plate after the turns for a successful trial. While sufficient practices were allowed for familiarization to the experimental setting, the environment could have affected performance of the dancers. Moreover, the preparatory position and motion were restricted to the 5^{th} foot position and *relevé* (single leg support), respectively, in this study. Another common preparatory motion is *tendu*/ *rond de jambe* in which extended gesture leg circlest around the body while the toe touching the floor. Naturally the *tendu* position does not include the same single leg support during the preparatory motion. It was possible that the preparatory motion used and dancers' familiarity to the prescribed preparatory motion could have affected dynamic balance during the execution of the triple-turn *pirouette*.

Conclusion

The purposes of this study were to investigate how skilled ballet dancers generate various moments and longitudinal AM during the AM generation phase of triple-turn *pirouette en dehors* and to identify biomechanical differences between the successful and unsuccessful groups. Three groups of biomechanical parameters were used in the analysis: longitudinal angular momentum, pivoting moment about the vertical axis, and GRF moments about the horizontal axes. From the analysis it was concluded that:

1. The successful group generated a larger normalized longitudinal AM and generation rate during the double-stance phase.
2. The successful group generated a larger peak PM which occurred at mid-way between LCP and TO. The larger PM mainly came from a larger gesture-foot PM

which in turn came from a larger gesture-foot horizontal GRF (F_{xy}). The source of the larger gesture-foot horizontal GRF was identified as lateral force component (F_x).

3. The successful group also revealed a larger peak GRF moment about the forward/backward axis (Y-axis) that occurred mid-way between LCP and TO. The larger Y-axis GRF moment mainly came from the larger lateral GRF (F_x). It was speculated that this particular moment plays a crucial role in controlling the dynamic balance during the double- to single-stance transition.

In this study, dancers were classified into two groups (successful and unsuccessful) based on their ability to perform triple-turn *pirouette en dehors* consistently and, as a result, a between-subject approach was used. Also, this study focused more on the foot-floor interaction and AM generation aspects of the multi-turn *pirouette* maneuver. Another important aspect of the *pirouette* family maneuvers is maintenance of dynamic balance during the double- to single-stance transition phase and further in-depth studies on how the dancers control the dynamic balance (precession of the body axis, body posture and angles, excursion of the COM, counter-movements and relative motions among body parts, balance between linear and angular motions, etc.) are warranted. One possible approach is a within-subject design comparing successful and unsuccessful trials of the same dancer group. It is speculated that the comparison of successful and unsuccessful trials of the same skilled dancer could highlight the differences in dynamic balance control more than those in AM generation.

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APPEMDIX

INFORMED CONSENT FORM

TEXAS WOMAN'S UNIVERSITY
CONSENT TO PARTICIPATE IN RESEARCH

Title: A biomechanical comparison of successful and unsuccessful triple-turn pirouette trials in ballet.

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Advisor: Young-Hoo Kwon, Ph.D. .... ykwon@twu.edu (940) 898-2598

Explanation and Purpose of the Research

Triple-turn *pirouette* is considered a difficult maneuver for ballet dancers in general and for female dancers in particular. It requires a sufficient number of revolutions (three) which will be enough for monitoring issues in dynamic balancing during the single support phase. Advanced and professional dancers use a variety of strategies to control the body movement and balance which include: directions and posture of whole body movements (take-off motion) during the turn, also it has been found appropriate angular momentum (rotation force) in the whole body relative to the ideal center of mass excursion during turn motion.
The purpose of this study is to investigate the biomechanical differences between successful and unsuccessful trials of triple-turn *pirouette en dehors* using three- dimensional motion analysis and ground reaction force data. Select kinematic (study of motion: stance width, center of mass excursion in all three directions, body segment angles at 180º and 270º turn positions) and kinetic (study of force: vertical ground reaction force, maximum pivoting torques, maximum longitudinal angular momentum, angular momentum generation rate, time to maximum vertical grand reaction force, and time to maximum torque) variables will be computed. Using motion analysis and force plate data, the efficacy of these strategies relative to the required of turns can be analyzed.

Research Procedures

All testing procedures will take place at the Motion Analysis Laboratory, PilsesoungKwan (Room 303), at the Korea National Sports University, Seoul, Korea. You will be asked to wear an un-reflected black leotard and tights and bring classical canvas shoes. If you do not have appropriate clothing for testing, suitable clothing will be provided. You will have a preliminary meeting where the procedures are explained and time is provided for questions.
If you meet the inclusion criteria (five years or more of training, 18-35 years of age, ability to consistently perform triple-turn *pirouette en dehors*, no skin sensitivity or lower body injury), you will be asked to read and sign the Informed Consent Form. If you do not meet the inclusion criteria, or choose not to participate, you will be thanked and sent home. The approximate time commitment for successful completion of the study is two hours, including time to review the project and explain the consent form.

Participant Initials ______

For the purposes of motion capture, a total of 48 small reflective markers (diameter < 10 mm) will be placed on specific body landmarks using double-sided tape using the following pattern: 5 markers on the pelvis, 9 markers on each leg, 5 markers on the trunk, 8 markers on each arm, and 4 markers on the head (See diagram below).

You will be asked to perform *pirouette en dehors* on the force plate in the Biomechanics Lab. The force plate will be covered with Marley which is a traditional floor covering used in dance studios and stages. You will be asked to perform 7 trials of triple revolution *pirouette en dehors*. Instructions will be given before each turn, and you will complete the turns to recorded music. Motion capture and force plate data will be collected during each turn.

Potential Risks

Coercion: Your participation in this research study is strictly voluntary, and you are free to withdraw at any time. If you are a student at Sejong University or ballet company dancers, your student-status and academic grades/standing or company status will not be affected in any way. Participation in this study is voluntary and their student-status and academic grades/standing will not be affected in any way.

Loss of Anonymity: You will be assigned a personal identification number. It is possible that more than one participant will be present at the same time or that testing may take place such that the participant is exposed to the general public because of this each participant will be informed prior to the study and that the loss of anonymity is present. Participation in this study is voluntary, and the participant may withdrawal at any time at their discretion.

Loss of Confidentiality: Confidentiality will be protected to the extent that is allowed by law. You will be assigned a unique study ID code. Only the research team will know which data is associated with each research participant. All data collected as part of the testing is solely for research purposes. All data will be stored electronically. Paper records will be stored in locked cabinets and offices at the Biomechanics Laboratory at Texas Woman's University. All computers on which electronic information is stored are password protected. All data will be destroyed 2 years following publication of the results. Paper records will be shredded and electronic records will be erased. There is a potential risk of loss of confidentiality in all email, downloading and internet transactions.

Risk of Fatigue: You may have a fatigue while performing the *pirouette en dehors.* You will be allowed to resting periods during between trials if you needs. All trials will be made to ensure the safety of each participant during the time of data collection. If you express a desire to stop at any time, you will be allowed to do so without any penalty.

Embarrassment: Only research team members will be present during your testing session. Other participants and outside visitors will not be allowed to view the testing session, except with permission you. You will be wearing typical dress (same as the normal dance class cloths) during the data collection testing. The researchers will try to prevent any embarrassment issue that may occur prior to incident. You should let the researchers know at once if there is a problem of if you are uncomfortable. Each practitioner (Co-investigator) will be instructed to assist you in meeting your needs. Participation is voluntary and you can withdraw at any time. Small markers will be placed on your body during testing.

Muscle Soreness: Muscle soreness will be minimized by having each participant warm-up before the data collection. To minimize the risk of muscle soreness, you will be asked to warm up and stretch before *pirouette* turn testing and encouraged to do so when exercising on your own. If muscle soreness does occur, you will be instructed to perform additional stretching. However, TWU does not provide medical services or financial assistance for injuries that might happen because of participation in the current research study.

Skin irritation: The markers used during testing will be placed on your body using double-sided tape. When the markers are removed, there may be slight pulling of the skin or hair, which may feel similar to the removal of a Band-aid. If you have skin sensitivity to adhesives, please let the research team members know now, as this may exclude you from the study.

Risk of Injury: The potential for injury is no greater than that encountered while turning during dance class or performance. However, every effort will be taken to minimize these risks by providing proper instructions throughout the testing session. You may take rest breaks as needed, and if you feel uncomfortable at any point during the test, please let the research team members know right away. You are free to stop your test at any time. Prior to the data collection, you will be asked whether you have any marker surface problem. This step is necessary to ensure good skin-reflective marker adherence during each trials. Erroneous results can occur if this step is not taken. Care will be taken in skin preparation to minimize this risk. Disposable alcohol prep pads will be used to clean the skin before and after the application of markers.

The researchers will try to prevent any problems associated with this research. You should let the researchers know at once if there is a problem and they will help you. However, TWU does not provide medical services or financial assistance for injuries that might happen because you are taking part in this research.

Participation and Benefits

Your participation in this study is completely voluntary. You are free to withdraw from the study at any time without penalty. If you are a student at Sejong University, your student-status and academic grades/standing will not be affected in any way. The direct benefit to you is that you will gain knowledge of the research process through your participation in this study. There is no monetary award for your participation in this study. If you are interested, you will be provided an opportunity to view your computerized pirouette trials captured for an objective observation of your skills and techniques.

The researchers of this study will benefit from the knowledge that is gained from the analysis of turning.

Questions Regarding this Research Study

You will be given a copy of this signed and dated consent form to keep. If you have any questions about the research study you should ask the researchers; their phone number and email address are at the top of this form. If you have questions about your rights as a participant in this research or the way this study has been conducted, you may contact the Texas Woman's University Office of Research and Sponsored Programs at 1-940-898-3378 or via e-mail at IRB@twu.edu.

_______________________________________ ____________________
Signature of Participant Date

If you would like to receive a copy of the published results of this research study, please provide the following contact information:

____
Full Name

____
Mailing Address

____
City, State and Zip Code

Email address (If you prefer to receive the published results via email.)

Approved by the
Texas Woman's University
Institutional Review Board
Approved: November 2, 2017

Marker setting