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Fatigue-related jump landing knee injuries in dancers

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FATIGUE-RELATED JUMP LANDING KNEE INJURIES IN DANCERS

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APPROVAL OF THESIS

We, the faculty supervising the work of Megan Holton, affirm that the thesis, *Fatigue- Related Jump Landing Knee Injuries in Dancers*, meets the high academic standards for original scholarship and creative work established by the School of Kinesiology and the College of Health Professions. This work also conforms to the editorial standards of our discipline and the Graduate College of Marshall University. With our signatures, we approve the manuscript for publication.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Non-contact knee injuries are prevalent in dancers and have great financial and social costs. These injuries may be prevented with training that modifies jump landing movement patterns and improves lower body strength and cardiorespiratory fitness. Identifying the movement-based risk factors that are most strongly related to injury mechanisms allows healthcare providers to create effective training interventions. The purpose of this study was to determine the relationship between multivariate risk factors and injurious knee forces as a dancer lands from a jump. Twenty female dance students with at least eight years of experience were recruited. These dancers were injury-free and actively rehearsing, volunteered to participate, and signed informed consent. Participants took part in two testing sessions. On day one participants completed a dance history questionnaire, had their height and weight measured, tested their knee flexion/extension muscular endurance using an isokinetic dynamometer, and their cardiorespiratory fitness using a sub-maximal, graded step test. On a second day, participants completed switch leap jump landings before and after performing a Dance Aerobic Fitness Test at an increasing tempo. Three-dimensional lower extremity kinematics of their landings were measured using a retro-reflective motion analysis system. Landing forces were measured using two force plates. Joint angles during the leap and at landing, and knee joint anterior shear force and external valgus moment at landing were calculated from the biomechanical data. Stepwise multiple regressions showed that when landing while fatigued, increased knee anterior shear force was predicted by a combination of greater knee valgus angle at landing and greater knee flexion angle at landing. Increased external knee valgus moment was predicted by a combination of decreased knee valgus angle at landing and decreased knee flexion angle at landing. These results indicate that a more extended landing position is possible when a dancer is fatigued, and this position can generate a greater knee valgus

moment, which stresses the MCL. These results also indicate that a knee flexed and valgus landing position in combination with lower fitness levels may generate high knee anterior shear force, which stresses the ACL. A statistically significant interaction term was identified for the regression analyses, indicating that fitness level may function as a moderator of the relationships between knee angles at landing and knee joint anterior shear force, as well as knee angles at landing and external knee valgus moment. These findings can be used to direct training interventions to improve jump landing movement patterns and help to guide future research for a better understanding of fitness and its impact on fatigued landings.

CHAPTER 1

INTRODUCTION

Although dancers sustain knee ligament injuries at a lower rate than team sport athletes, the effect of fatigue on knee ligament injury incidence and risky jump landing motion patterns is similar in these populations. In team sport athletes and dancers alike, non-contact knee ligament injuries occur more frequently at the end of a practice session and later in a season (Borotikar et al., 2008; Liederbach et al., 2008). This suggests the effect of fatigue on injury incidence is similar for both populations. Around 75% of team sport knee ligament injuries and the vast majority of dance knee ligament injuries are non-contact in nature (Liederbach et al., 2008). The knee injuries occur during activities such as jump landings (Hewett et al., 2006), and may be preventable through training (Myer et al., 2005). The effect of fatigue on jump landing motion patterns is also similar for team sport athletes and dancers. Dancers and athletes land with altered motion patterns that are associated with a greater risk of knee ligament injury when fatigued (Liederbach et al., 2014). Interventions for dancers to prevent non-contact knee ligament injuries occurring during jump landings can be developed once cause-and-effect relationships between motion patterns and direct injury mechanisms have been determined.

Knee ligament injury occurs when excessive tensile stress is applied to the ligament resulting in a longitudinal strain. A non-contact knee ligament injury occurs when the person themselves generates a great force or moment at the knee joint caused by gravity, ground reaction forces, and muscular forces that all apply excessive stress to the ligament. During a jump landing, great knee joint forces and moments arise from high ground reaction forces (GRF) due to the impact, and eccentric muscle contractions controlling the motion of the landing (Devita & Skelly, 1992). The most commonly injured knee ligaments are the anterior cruciate ligament (ACL) and the medial collateral ligament (MCL) (LaPrade et al., 2007). Due to its posterior-lateral to anterior-medial alignment, the primary role of the ACL is to resist anterior translation of the tibia, and a secondary role of the ACL is as a restraint to knee valgus. The primary role of the MCL is to prevent any medial opening of the knee joint (DeGrace et al., 2013). The ACL is strained most when the knee is loaded by an anterior shear force as the primary causal factor and an external valgus moment as the secondary causal factor (Berns et al., 1992). The MCL is strained most when the knee is loaded by an external valgus moment as the primary causal factor (Chen et al., 2008; DeGrace et al., 2013). To prevent excessive ACL and MCL stress, we need to know which jump landing motion patterns cause great knee joint forces and moments.

Three theories have been proposed as the motion pattern cause of great knee joint forces and moments during jump landings in dancers, quadriceps dominance, trunk dominance, ligament dominance, and leg dominance (Orishimo et al., 2014). Quadriceps dominance theory proposes a small knee flexion angle at initial contact coupled with great activation of the quadriceps to maintain knee stiffness (Orishimo et al., 2014). The patella tendon-tibial shaft angle increases at small knee flexion angles, which increases the anterior shear component of the quadriceps muscle force causing anterior translation of the tibia on the femur (Nunley et al., 2003). The anterior tibial translation is resisted directly by the ACL. This suggests a smaller knee flexion angle at initial contact is a motion pattern that is an ACL injury risk factor. The trunk dominance theory is characterized by excessive trunk movement over the landing leg, resulting in increased hip adduction and knee valgus (Orishimo et al., 2014). The ligament dominance theory is characterized by increased knee valgus and external rotation (Hewett et al., 2005; Orishimo et al., 2014). A greater knee valgus angle increases the external valgus moment of the

GRF by causing the knee joint to be more medial of the GRF and have a longer moment arm. Any external knee valgus moment causes medial opening of the knee joint, which is resisted directly by the MCL, and secondarily by the ACL. This suggests a larger knee valgus angle at initial contact is a motion pattern caused by great external knee joint valgus moment, and an MCL and ACL injury risk factor. The empirical relationship between these risky jump landing kinematics and great knee joint forces and moments remains undetermined for dancers.

While fatigued, changes in knee kinematics while fatigued have also been examined, where dancers were found to have smaller knee flexion angles and greater knee valgus angles during fatigued landings, with no change for team sport athletes, with no sex differences among dancers (Liederbach et al., 2014; Orishimo et al., 2014). The effects of these kinematic changes on knee joint forces and moments were not examined. Knee joint anterior shear force has not been calculated for dancers' jump landings. External knee valgus moments have been calculated for dancers' jump landings, and this moment tends to increase with fatigue similarly among dancers and team sport athletes (Liederbach et al., 2014). Associations among knee flexion angles, knee valgus angles, knee joint anterior shear force, and external knee valgus moment have not been determined. This is a significant gap in the literature where we do not know which dancers' jump landing motion patterns cause the great knee joint forces and moments that lead to knee ligament injuries.

The amount of knee joint force or moment that applies an excessive stress to a ligament decreases when a person is in a centrally fatigued state. This lower threshold may be due to a decreased capacity to generate muscle force to absorb the GRF, and altered motion patterns that cause a greater proportion of the joint forces to load the ligaments (Asmussen, 1979; Hiemstra et al., 2001). These changes may explain why non-contact knee ligament injuries occur more frequently as dancers' fatigue. Dancers who are stronger (Koutedakis et al., 2005) and have greater cardiorespiratory fitness (Twitchett et al., 2010) have lower injury incidence. This is probably because stronger dancers can maintain their capacity to generate muscle force while fatigued, and fitter dancers can maintain their muscle recruitment patterns, and therefore their motion patterns. Determining the relationship between jump landing motion patterns and great knee joint forces and moments when fatigue is particularly important because interventions to modify fatigued motion patterns will be most impactful. Understanding any moderating effect of local fatigue on the relationship between motion patterns and knee loading will help practitioners decide whether time and effort are best spent on general strength and fitness training programs, or on specific landing re-training programs.

Purpose

The primary purpose of this thesis was to determine the relationship between fatigued landing motion patterns and injurious knee joint loading. The secondary purpose of this thesis was to investigate the moderating effect of fitness on the relationship between locally fatigued landing motion patterns and injurious knee joint loading. To achieve the objectives of this thesis, four research hypotheses were tested

Hypotheses

- NULL1: Knee joint angles at initial contact of a post-fatigued jump landing will not be associated with knee joint anterior shear force.
- H1: A smaller knee flexion angle and a greater knee valgus angle at initial contact of a post-fatigued jump landing will be associated with a greater knee joint anterior shear force.
- NULL2: Knee joint angles at initial contact of a post-fatigued jump landing will not be associated with external knee valgus moment.

- H2: A smaller knee flexion angle and a greater knee valgus angle at initial contact of a post fatigued jump landing will be associated with a greater external knee valgus moment.
- NULL3: Fitness level will have no effect on any relationship between knee joint angle at initial contact of a post-fatigued jump landing and knee joint anterior shear force.
- H3: The relationship between a smaller knee flexion angle and a greater knee valgus angle at initial contact of a post fatigued jump landing and knee joint anterior shear force will be weaker in dancers with greater fitness levels.
- NULL4: Fitness level will have no effect on any relationship between knee joint angle at initial contact of a post-fatigued jump landing and external knee valgus moment.
- H4: The relationship between a smaller knee flexion angle and a greater knee valgus angle at initial contact of a post fatigued jump landing and external knee valgus moment will be weaker in dancers with greater fitness levels.

Delimitations

The delimitations of this study were:

- Subjects were healthy (no current injuries) intermediate-level dancers from local dance schools with at least five years of dance experience.
- An open-ended questionnaire was used to ask about dance and injury history.
- An isokinetic dynamometer was used to measure strength endurance.
- A progressive step test was used to measure cardiorespiratory fitness.
- Subjects completed a dance-specific jump and landing of moderate difficulty before and after a standardized, fatiguing dance routine.
- A force plate was used to measure ground reaction forces of landing.

- Reflective markers and infrared cameras were used to measure subjects' movements during the jump and landing.
- Vicon Nexus software was used to measure three-dimensional landmark coordinates.
- Motion Soft software was used to calculate joint kinematics and kinetics.

Assumptions

The assumptions of this study include:

- Subjects answered the study questionnaire honestly.
- Subjects gave full effort during the strength endurance, cardiorespiratory fitness, and fatiguing dance routine.
- Subjects completed the jump and landing in the same way in the lab as they would during a rehearsal or performance.

Key Terms & Operational Definitions

ACL: Anterior Cruciate Ligament, a ligament in the human knee that resists anterior translation of the tibia.

MCL: Medial Collateral Ligament, a ligament in the human knee that resists medial opening of the knee during knee valgus.

Kinematics: Measurements of movements of the human body, such as joint angles.

Kinetics: Measurements of the causes of movements of the human body, such as joint forces.

Inverse Dynamics: A procedure where Newton's laws of motion are used to calculate resultant forces and moments at the joints from externally applied forces, and accelerations of limb segments, and anatomical data.

Knee Flexion: The primary bending movement of the human knee where the long axes of the tibia and femur become closer to one another in the sagittal plane. Defined mathematically as the rotation of the local reference frame of the lower leg segment with respect to the local reference frame of the thigh segment around a medial-lateral y-axis.

Knee Valgus: Undesired movement of the human knee where the long axis of the tibia deviates away from the midline of the body in the frontal plane. Defined mathematically as the rotation of the local reference frame of the lower leg segment with respect to the local reference frame of the thigh segment around an anterior-posterior x-axis.

Knee Joint Anterior Shear Force: The anteriorly directed component of the resultant knee joint force at the proximal end of the lower leg segment. The resultant knee joint force is calculated by inverse dynamics and transferred to the local reference frame of the lower leg.

External Knee Valgus Moment: The component of the resultant knee joint moment at the proximal end of the lower leg segment that acts around an anterior-posterior axis. The resultant knee joint moment is calculated by inverse dynamics and transferred to the local reference frame of the lower leg.

Switch Leap: A dance or gymnastic leap that requires one leg to split while the other leg takes off, then while in the air the front leg will switch backward to form a split in the air before landing.

Plié: A dance movement where the knees are flexed while the back is held straight.

Spring Leap: A dance leap where both feet take off together, a 360-degree spin is completed, and then both feet land together in the same spot.

First Position: Shoulders flexed to 90 degrees, elbows extended to 25 degrees, wrist flexed to 10 degrees, with hands slightly apart.

Second Position: Shoulders abducted to 80 degrees, elbows extended to 25 degrees, wrist in neutral flexion.

Performance: A presentation of a choreographed dance routine.

Rehearsal: A session of dance exercise or practice in preparation for a public performance.

CHAPTER 2

LITERATURE REVIEW

This thesis had two purposes, the primary purpose was to determine the relationship between fatigued landing motion patterns and injurious knee joint loading. The secondary purpose of this thesis was to investigate the moderating effect of fitness on the relationship between locally fatigued landing motion patterns and injurious knee joint loading. This population, while facing similar impacts of fatigue as team sport athletes, has specific muscular and cardiorespiratory fitness demands, as well as additional skill-related constraints such as body esthetics while landing. Injuries in dancers are not typically acute, they tend to be overuse injuries. There is the potential, therefore, to make a significant impact in reducing injury rates in dancers by understanding the demands of their skills.

Fatigue

The dancing population, while facing similar impacts of fatigue as team sport athletes, has specific muscular and cardiorespiratory fitness demands. Advanced level dancers will spend multiple hours a day during rehearsal, classes, and performances perfecting skills and practicing in a fatigued state. These rehearsals consist of high-intensity intermittent exercise with insufficient rest periods (Wyon et al., 2002).

Fatigue is a loss of central nervous system control or muscle force output, and this is associated with an increased injury risk as decreased neuromuscular control disrupts the ability to perform athletic tasks safely. Fatigue is a state that occurs after an exhaustive practice, rehearsal, or performance. Inevitably a fatigued state happens in every athlete: what occurs in the body due to fatigue is a problem that every athlete, coach, and healthcare provider must understand. Multiple studies have been done measuring fatigue in all different types of athletes and performers to interpret the resulting impact of fatigue, such as altered kinematics, altered muscle recruitment patterns, and altered biomechanics. Measuring and understanding the impact of fatigue on the body and muscle recruitment is important for injury prevention in all athletes. Two types of fatigue occur in the body: central fatigue and peripheral fatigue. “Central fatigue is defined as a failure to maintain the required force for power output that is associated with specific alterations in the central nervous system. Peripheral fatigue influences function of the contractile processes in a muscle.” (Linderbach et al. 2013). Studies have also shown that there are two main influences of local fatigue: muscular strength and cardiorespiratory fitness. These two factors as well as the altered landing patterns, the decrease in muscular output, and the changes in body kinematics all contribute to the increased exposure to injury.

Muscle strength is not a factor often focused on in dance due to the strict aesthetics that college and professional dancers are required to have. However, strength can be injury preventative. Dancers, and ballet dancers, in particular, must meet a specific visual aesthetic look that requires them to be muscular but not so muscular that the muscles become large and unappealing. Modern dancers do not face these strict aesthetic requirements because modern dance is typically considered more athletic than ballet dance. Regardless of the type of dance, dancers typically shy away from strength-building outside of dance rehearsals. Muscle strength, however, is essential because, as Herman et al. (2008) stated, strength training may be of value because by increasing muscular strength there may be a corresponding increase in the threshold for fatigue. In the study done by Koutedakis et al. (2007), strength training alone could not alter kinematics in female athletes, but when done in dancers, supplementary exercise training showed to significantly increase different aspects of dance performance. Muscle strength is an essential variable in fatigue prevention because stronger, better-conditioned muscles will take longer to fatigue. Typically, ballet dancers have a predominance of slow-twitch muscle fibers, which are ideal as dancers with more fast-twitch muscle fibers, typically modern dancers, will have a more muscular look (Koutedakis et al., 2005). The muscle fiber type is an important distinction to make when determining muscle strength and the impact on local fatigue. Slow-twitch fibers are aerobic which take longer to fatigue due to their increased endurance. Fast-twitch muscle fibers are anaerobic, so they will have greater power but decreased endurance. Dancers also face other implications such as a lower daily caloric intake which can consequently cause the muscle to fatigue faster, which in combination with a high exercise demand can result in increased susceptibility to injury (Rodrigues-Krause et al., 2015). Muscle fibers will also, after an extended period of high-intensity exercise, as well as repetitive tasks, begin to break down which can cause damage to the muscle fibers. Damage to the muscle fibers was shown in both male and female team sports athletes to be in part responsible for a decline in performance. Dancers spend multiple hours performing high-intensity, repetitive exercises to train, so this can lead to injuries to the muscle fibers. Increased muscle strength can decrease the potential damage that can occur to muscle fibers which can minimize the corresponding impact on performance, lessening the chance for an injury exposure.

Not only is strength an impacting factor on potential injury occurrence, but cardiorespiratory levels and aerobic fitness are also significant risk factors. One important classification that needs to be made is the differences in the types of fatigue. There are two types of fatigue identified in the current literature. Central fatigue is defined as a failure to maintain the required force output associated with the central nervous system. The processes within the central nervous system that reduce the neural drive to the muscle also can cause a decrease in force or power to a muscle, which is an example of central fatigue. Central fatigue typically applies to single-joint exercises but can also include whole-body exercises involving large muscle mass. (Taylor et al., 2016). Peripheral fatigue influences the function of the contractile processes in a muscle (Linderbach, 2013; Wild, 2017; Wyon, 2002). Any fatigue that occurs through processes at or distal to the neuromuscular drive junction is classified as peripheral fatigue (Taylor et al., 2016). Both of these classifications of fatigue are experienced during a dance rehearsal or performance. The different fatigue types are important in understanding the fatigue experienced and the increased risk of injury with the different types of fatigue. Central fatigue has an inhibitory influence on the muscular system which contributes to the decrease in muscle activation (Linderbach, 2013; Wyon, 2003; Lin, 2016). The fatigue-related desensitized muscle spindles and afferent pathways have shown an increase in the risk of injuries and falls. These changes also indicate a greater displacement of the planes of motion when landing (Lin, 2016; Linderbach, 2014). Both central and peripheral mechanisms are compromised when fatigued, and during complex, dynamic movements they are equally utilized to maintain coordination.

Injury Incidence

The common injuries dancers will present with are lower-body injuries, typically to the ankle, knee, and hip joints. The lack of joint compensation as well as the repetitive, long bouts of choreography contribute to the high injury rates that occur in dancers. Participation in dance rehearsals and performances results in dancers having a of 76% risk of injury per year; when compared to typical adolescent athletes of non-contact sports this was a higher risk of injury (Ekegren, 2013; van Seters, 2017; Wild, 2017). On average, 82%-94% of dancers will experience an injury in the course of their dance career, with re-injuries occurring in 43% of dancers (Caine et al., 2015; Shah et al., 2012). The studies found that the incidence of injuries was higher in modern dancers at 82%, where ballet dancers ranged from 75%-85%, which is greater than the 81% incidence of injuries found in football (Shah et al, 2012). While ankle injuries were the most common, knee injuries were more likely to have a higher number of days lost due to the injury and the cost of the injury was higher than that of ankle injuries. These injury incidences and exposures were consistent among the different dance types, different countries, and multiple systematic reviews and meta-analyses.

Dancers sustain knee injuries at a rate of between 1.38 and 1.87 per 1000 hours of dance (Ekegren et al., 2014). Of these injuries, dancers have a knee ligament injury incidence of 0.009 injuries per 1000 exposures with few sex differences (Orishimo et al., 2014). In contrast, team sport athletes sustain knee injuries at a rate of 3.5 injuries per 1000 hours of sport (Lindenfeld et al., 1994). Of these injuries, team sport athletes have a knee ligament injury incidence of 0.07 to 0.31 injuries per 1000 exposures (Orishimo et al., 2014), with female athletes up to eight times more likely to sustain a knee injury than males (Arendt & Dick, 1995). This is notable because it suggests that the differences in injury incidence may be due purely to biomechanic differences rather than sex differences (Orishimo et al., 2014).

Many dancers will not report their injuries or will decline to take time off due to the injury, but the research shows that on average about 433 days are lost due to injury. The time lost was found to be higher in females and higher with joint-related injuries (Ekegren et al., 2014; Lee, 2017). The average number of days lost due to knee injuries was 36.85 days. This was on average more than ten days longer than an ankle injury. Knee injuries will often result in more severe injuries that typically require some kind of surgical intervention, medical imaging, and multiple referrals to medical specialists. These injuries can quickly become costly: one study found that on average an ACL arthroscope repair can cost $10,144.91 if there is more significant knee damage and an ACL repair plus collateral ligament repair can cost upwards of $15,338.88 with insurance (Herzog, 2017). In addition to the medical costs, there is the cost of rehabilitation and the cost of time lost for the dancer which is typically a minimum of three months and then time to begin a slow return to participation.

Jump Landing Mechanics & Fatigue

Dancers have movement constraints such as body and landing aesthetics because of the requirements of choreography. These aesthetics can impact muscle recruitment when landing and increase the risk of injury when landing fatigued. Fatigue has shown to have an adverse effect on landing mechanics, contributing to increased loads on the knee and hip in both dancers and athletes. Due to the specific landing mechanics required with a dancer's landing, the muscle recruitment pattern changes and leads to an increased risk of injury due to the inability of the body to adequately compensate for the landing.

In dance, a specific landing is required to maintain the required aesthetics when performing. The landing mechanics required of a dancer are in an extended position often with the ankle in a plantarflexed position and toes extended, while the trunk remains uptight and rigid. When a dancer is fatigued, they are unable to maintain these strict requirements. One study showed that dancers exhibited a reduction in ankle plantar flexion, an increase in hip adduction, and a decrease in an external hip rotation (Wild et al., 2017). In addition to these changes, it is important to note that dance landings are typically done taking off and landing on one leg, requiring that leg to absorb the forces while the trunk must remain upright and rigid. The repetitiveness of these take-off and landing requirements has resulted in different outcomes for dancers when comparing them to team sports athletes. One study compared team athletes of both sexes to elite modern and ballet dancers of both sexes on the effects of fatigue during a single-leg drop landing. Once the participant was fatigued, this study did show that there was an increase in peak knee valgus, a decrease in hip adduction, decreased external rotation, and finally an increase in hip internal rotation with an externally rotated landing position (Linderbach et al., 2014). These results support the findings in the previous study, that dancers, no matter the type of dance measured, demonstrated similar altered mechanics. Another study measuring the changes that occur when dancers are fatigued found that post-fatigue measurements showed altered motor adjustments in proximal joints and there was a decrease in the postural and muscular control in the dancers (Lin et al., 2016). In addition, this study showed that when fatigued, the muscles recruited to perform the tasks were decreased and not the same as pre-fatigue. The changes in muscular output while tired can lead to altered neuromuscular control and increase the potential for injury exposure.

Dancers perform many of the same jumps, tasks, and choreography multiple times in one dance, let alone during one entire performance, so a change in muscle recruitment can lead to an increased risk for injury when performing the same jump multiple times. The primary muscles activated during jump landings are the quadriceps and hamstrings. One study measured the changes in these muscle activations in a pre- and post-fatigue setting. The results of their single leg drop test showed that the quadriceps to hamstring co-activation ratio was higher when fatigued. They also discovered that the quadriceps muscle activity was increased post-fatigue with a decrease in hamstring activation. The authors of this study relate the decline in hamstring activation to the required landing of dancers, They state that the upright and rigid trunk with the extension of the knee and hip reduce the hamstring's ability to contract when in a fatigued state (McEldowney et al., 2013). The decrease in hamstring activation and increase in co-activation can result in increased joint stiffness and potential impacts of the neuromuscular system to accommodate landing forces. Increased joint stiffness can increase the risk of injury to the knee and hip joint due to the decreased ability to absorb the landing forces. This change in landing kinematics can lead to an increased risk of injury due to the reduced muscular output and neuromuscular control.

The changes in landing mechanics also occur in the time to force absorption. Due to the strict aesthetics that are required of dancers when they land, even when landing in a non-fatigued state, the lower extremities are not able to slow down the force absorption because dancers must land with the hip, knee, and ankle in an extended position. This specific landing prevents the ability to distribute and slow down the forces when landing, which a traditional athlete can do. When fatigued, the dancers must maintain the extended position when landing as well as be able to absorb the same forces when landing in a non-fatigued state. The decreased ability to absorb the forces when fatigued can lead to the dancer being unable to make the motor adjustments and change their landing mechanics in an attempt to control the forces occurring (Lin 2016, Linderbach 2014). Multiple studies measured different factors of the landing mechanics that could be used as predictors of fatigue-related landing injuries. These studies found that when the dancers were fatigued limited dorsiflexion of the ankle, decreased knee valgus angles along with altered movement control were all factors found in dancers who were at greater risk for fatigue-related injuries (Seters 2017, Lee 2017, Prieske 2017). All of these factors are essential components of the landing mechanics and the potential for injuries related to landing in a fatigued or non-fatigued state.

Knee Ligament Injury Mechanisms

An estimate of the stress on a knee ligament can be made if the loading at the knee joint is determined. High ground reaction forces (GRF) at landing have been cited as an injury risk factor (Chappell et al, 2002; Decker et al, 2003). Using inverse dynamics, a known GRF can be used to estimate forces at joints, so a large GRF will translate to a large knee joint resultant force or moment.

The peak knee joint anterior shear force causes the greatest stress on the anterior cruciate ligament (ACL). A large GRF with a small knee flexion angle is the combination of factors that stress the ACL the most (Nunley et al., 2003), so decreasing GRF and increasing knee flexion angle may help to reduce the risk of ACL injury. Yu et al. (2005) found that peak GRF, peak knee joint anterior shear force, and peak knee extension torque during landing occurred at about the same time. Peak GRFs may be used to predict ACL loading. A combination of greater quadriceps and lower hamstring activation also increases the chances of greater knee joint anterior shear force. Lephart et al. (2002) found that female athletes have smaller knee flexion angles during landing, which means they have a more abrupt absorption of impact forces. This puts a great load on their quadriceps muscles to control knee flexion during landing. Chappell et al. (2002) found that a great knee joint anterior shear force in women may be attributed to a small knee flexion angle, increased quadriceps muscle force, decreased hamstring muscle force, or a combination of these factors.

Medial collateral ligament (MCL) injuries are the most frequently injured of the knee ligaments. More severe MCL injuries are associated with injuries to other structures of the knee, such as the medial meniscus and the ACL (Fetto et al., 1978). The peak external knee valgus moment causes the greatest stress on the MCL as it resists valgus laxity (Chen et al., 2008; DeGrace et al., 2013). Due to the straightforward role of the MCL, the major injury risk factor is the knee valgus angle with a high GRF.

Fitness

Dancers require contributions from multiple energy systems and require their bodies to function both aerobically and anaerobically based on the dance activity and level. To cope with the demands of dance rehearsal and performance a dancer must be both aerobically and anaerobically fit. Dance has been classified as a high-intensity, intermittent form of exercise (Wyon et al., 2003). The primary influence in cardiorespiratory adaptations is due to a change in exercise intensity and in exercise to rest ratio. The exercise to rest ratio is where a dancer's cardiorespiratory fitness is important. Many times during performances, a dancer will have to go on and off stage after minutes of long sections of advanced choreography with little time to rest. While in rehearsals dancers will have similar stresses, during the center-floor exercises, moving and performing elaborate choreography across the floor then rest before repeating the exercise multiple times. This results in a higher VO_2, lactate, and heart rate response, which is predominantly energized by the anaerobic-alactic pathway (Rodrigues-Krause et al., 2015). While some studies have shown that a dancer's VO_2 max is in the range of non-endurance athletes, other studies have also shown that dancers perform at 90% of their max heart rate and up to 73% of their VO_2 max. Dancers with a lower aerobic fitness level have an increased risk of injury. Twitchett et al. (2010) showed that there was a positive correlation between the number of injuries sustained and the heart rate observed during a dance-specific fatigue protocol. This study showed that dancers with a lower level of aerobic fitness suffered more injuries than those with higher levels of aerobic fitness, which include lactate production, resting, and max heart rate. Fatigue will occur faster in dancers with a lower level of aerobic fitness due to their decreased ability to recover from the high-intensity bouts of exercise (Twittchett et al., 2010). Due to these findings, other studies have researched the cardiorespiratory considerations for dancers. These studies have found that the cardiorespiratory and metabolic effects of a dance rehearsal or performance depend largely on the dance style, the dance role, the intensity, and duration of the choreography. One review found that supplementary cardiorespiratory fitness enhances aerobic capacity, strength, and flexibility, which all will lead to a reduction in dance-related injuries. In addition to these findings, Koutedakis et al. (2007) found that when they added an exercise protocol involving both strength and cardiorespiratory fitness, the dancers had a significant increase in their VO_2 max. When a dancer has decreased aerobic fitness, it causes a quicker fatigue response. The fatigue in turn alters the dancers landing kinematics as well as their muscle recruitment patterns, which is when the dancers are at increased risk for injury.

The demands of a dance rehearsal require a dancer to be both aerobically and anaerobically fit (Rodrigues-Krause et al. 2015). The cardiorespiratory adaptions are primarily due to the change in exercise intensity and in the exercise to rest ratio (Wyon et al. 2005). Dancers with a lower aerobic fitness level are at increased risk for injuries; however, including a cardiorespiratory training program helps to decrease dance injury risk (Twittchett et al., 2010). These programs found that dancers with lower aerobic fitness levels will have increased lactate production causing increased difficulty in recovering between bouts of intense physical movements. The research found that female dancers, in particular, show a positive relationship between aerobic performance and metabolic demand and the number of injuries sustained (Twittchett et al., 2010; Bronner, 2014). These dancers had a decreased ability to adapt to demands and reduced ability to recover before repeating the test. Adding a supplementary cardiorespiratory training program increased aerobic capacity among other things, which lead to a decrease in dance-related injury risks (Koutedakis et al., 2007). These studies used a variety of methods to test and increase cardiorespiratory endurance; they found that dancers will push themselves harder using a dance fitness protocol when compared to using a treadmill to measure VO_2 max. The difference in VO_2 max measures was a 46.4 ml-kg-min on a maximal treadmill test compared to a 51 ml-kg-min on the dance fitness test. The measures of fatigue they found were decreased muscular output as well as inability to maintain the set pace. The difference observed on the treadmill test to the dance fitness test is significant and should be noted as an important distinction. Dancers will perform at 90% of their max heart rate and up to 73% of their VO_2 max. If a dancer has low cardiorespiratory fitness, they will be unable to maintain the energy to perform choreography. Jumps and technique that is designed for both for aesthetic purposes but also for the safety of the dancer will be decreased or lost. The decreased cardiorespiratory fitness can increase the risk of injury and the inability of the dancer's body to maintain the control needed to land.

Studies have gone on to determine a link between physical fitness and injury occurrence. These studies (Twitchett et al., 2010; Linderbach, 2013; Bronner, 2014) found a positive correlation between decreased fitness levels and increased injury rate. These studies found that dancers with a higher resting heart rate have a decreased ability to recover when fatigued. These dancers also had a higher history of injuries which all can result in the dancer being at increased risk of injury occurring. The higher resting heart rate was a consistent factor in all these studies. In addition to identifying higher heart rates, researchers found that low levels of the thigh or quadriceps strength were associated with greater severity of injury (Twitchett et al., 2010; Linderbach, 2013). The decreased fitness level and reduced strength levels contribute to both increased risk of injury and the severity of the injury that could occur. These two factors will be the focus of this research along with landing kinematics and body position. The decrease in cardiorespiratory fitness and strength levels can be positively attributed to increased injury rate and injury severity, which are two things critical to the health and performance of a dancer.

Muscular strength and muscular endurance are significant factors in fatigue-related injuries. Muscular strength can be injury preventative. Typically, dancers do not participate in muscular strengthening outside of dance requirements due to limitations they face with visual aesthetics among other reasons (Koutedakis et al., 2007). Muscular endurance however can lead to minimal bulk strength increases but can lead to a decrease in injury risk. Studies using a strength training protocol found that following the strength training, multiple aspects of dance performance such as increased flexibility, increased strength, reduced fatigue, and loss of strength were all improved (Herman, 2008; Koutedakis et al., 2007; Matthews, 2017). These studies support the need for muscular strength and endurance as an injury preventative method.

Muscular strength, muscular endurance, and cardiorespiratory fitness have all been identified in current research as the common factors in fatigue and preventing fatigue from occurring. When fatigue occurs, it can alter landing patterns, muscular recruitment patterns, and biomechanical kinematics which can increase the risk of injury occurring. On average 433 days are lost in a professional dance company due to injuries and with that comes the increasing cost of medical treatment, time lost, and substitutes for the lost dancer. A dancer often rehearses, practices, and performs for multiple hours in a fatigued state. Dancing in the fatigued state, demanding the body to maintain the same energy output as a non-fatigued state, can lead to decreases in a dancer’s performance. Dancers will perform for minutes at a time with intense choreography and little rest between bouts, causing the body to compensate. The research has shown that these compensations include increased angles of joints, decreased movements, and decreased muscular contractions. This research aims to measure the factors of fatigue, and better understand if one of these factors can help to decrease the impacts that fatigue has on a dancer. This research hopes to identify which factor needs to be better incorporated into a dancer's regimen and how these factors can help to limit or prevent fatigue-related changes that occur.

CHAPTER 3

METHODS

Design

The purpose of this study was to determine the relationship between locally fatigued landing motion patterns and injurious knee joint loading. To determine this relationship, an observational study with a cross-sectional, multiple regression design was employed. The population was experienced, female dancers, the intervention was a fatiguing protocol, and the activity for testing was a switch leap. The independent/predictor variables were those identified in the literature as injury risk factors and were the pre-post local fatigue change in landing knee flexion angle at initial contact and the pre-post local fatigue change in landing knee valgus angle at initial contact. The dependent/outcome variables were those identified as the direct cause of excessive ligament stress and were the post-fatigue landing knee anterior shear force at initial contact and the post-fatigue landing knee external valgus moment at initial contact. The secondary purpose of this study was to determine the moderating effect of fitness on the relationship between locally fatigued landing knee kinematics and injurious knee joint loading. The dichotomous categorical variable of high or low fitness level, defined as strength endurance plus VO_{2max}, was the moderator variable used to determine this interaction.

Participants

Twenty-three female dancers from local dance schools were recruited for this study by email advertisement and direct contact through their dance school instructor. Two dancers were excluded due to their inability to perform the skill consistently enough and one was excluded for inability to use data due to missing markers on the Vicon database. The age of the subjects ranged from 18 to 25 years old, and they had an average standing height of 1.65 meters and an average bodyweight of 55 kg. The subjects had an average of 12.5 years of dance experience. Subjects were included if they were currently practicing for at least two hours per week, had no current injury, and had no injury requiring surgery within the past year. Subjects were excluded if they were pregnant, had less than five years of dance experience, were not currently practicing regularly, were currently injured, or had an injury requiring surgery within the past year. Informed, written consent, as approved by the Marshall University Institutional Review Board (IRB#1348790-1), was obtained from each subject before data collection.

Activity for Testing

The dance-specific activity used for testing was the switch leap. This is a relatively advanced skill that is commonly performed in choreographed routines and as an entrance criterion to the Marshall University Dance Team. To complete the switch leap, the dancer skips forward with three leadoff steps, jumps by raising their lead right leg and pushing off with their rear left leg, flexes their lead right leg to 90 degrees of hip flexion, and extends their rear left leg to hip extension to perform a split in mid-air, switches legs so their left leg becomes the lead and their right leg becomes the rear, and then lands on their left leg as a single-leg landing. The take-off leg and the landing leg are the same (Figure 1). While jumping with their legs, the dancer also moves their arms to 90 degrees of shoulder abduction. The switch leap skill can also be completed with opposite legs by leading with the left leg, taking off from the right leg, and landing on the right leg. Both the right and left sides were utilized in this research.

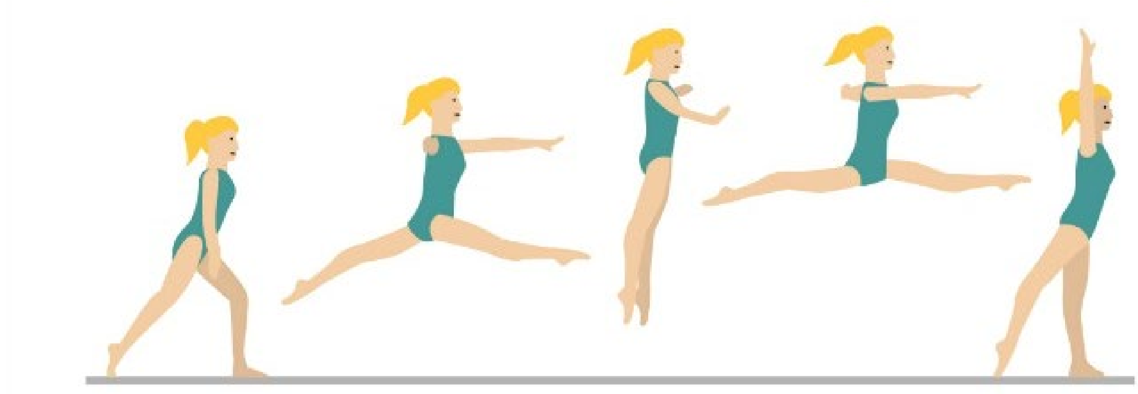

Figure 1. Switch Leap
A jump raising the lead right leg and pushing off with the rear left leg, a split in mid-air with right hip flexion and left hip extension, a switch to left hip flexion and right hip extension, and a single-leg landing on the lead left leg. (GymnasicsHQ, 2017)

Protocol

Each participant was tested on two separate days with a minimum of two days between testing sessions (Figure 2). The first testing session took place at the Exercise Physiology Lab at Marshall University where the participant's demographics were recorded, the participant completed a strength test and then completed a cardiorespiratory fitness test. At the start of this first testing session, the participant listened while the details of the study were explained verbally, and then they read and signed an informed consent form. The participant's anthropometric data were collected, which consisted of height and weight. Then the participant answered questions about their previous dance experience, previous injury occurrences, and the time per week they currently spent dancing.

The participant's quadriceps and hamstrings muscular strength endurance were assessed using a concentric/concentric knee extension/flexion test on a Cybex isokinetic dynamometer.

Each participant was familiarized with the knee extension/flexion movement and the sensation of using the isokinetic dynamometer. Then a warm-up that consisted of four repetitions at 45 degrees/second at sub-maximal effort with their dominant leg was completed (Engelen-van, M. et al 2017). After a one-minute rest period, the subject completed three maximal effort repetitions of extension/flexion at 45 degrees/second with their dominant leg. After another one-minute rest period, the subject completed fifteen maximal effort repetitions of extension/flexion at 225 degrees/second with their dominant leg. The test was then repeated on their non-dominant side following a three-minute rest. The 45 degrees/second speed was selected because this relatively slow speed elicits great force output, and was used as a test of strength. The 225 degrees/second speed was selected because this relatively fast speed was closer to the knee angular velocities observed during jumping tasks while still within safe operating parameters for the isokinetic dynamometer, and was used as a test of strength endurance.

The subject's cardiorespiratory fitness was assessed as they completed a predicted VO_2 test (Shepard et al) using a progressive step protocol at an individualized step rate. Each fitness test began with the subject stepping up onto and down off of a six-inch step for four minutes. The subject was instructed to maintain the pace of one step per metronome beat at their prescribed cadence (up, up, down, down). After one minute their heart rate was recorded and the step height was increased. The subject continued the test for one minute per step height with increasing heights of six, eight, ten, and then twelve inches until they completed two minutes at the twelve-inch height, or if they were unable to maintain their cadence. Upon completion of the predictive cardiorespiratory fitness test, the subject was dismissed for the day and instructed to limit activity to normal levels until returning for the second session of testing.

The second testing session took place at least two days later at the Biomechanics Lab at Marshall University. All subjects were instructed to wear their dance shoes, spandex shorts, and a tank top for this session. The subject was reminded of the details of the study and that their participation was voluntary. They were then asked to perform the dance-specific switch leap that they would be completing for the test to check performance consistency among subjects. They were also shown the dance fatigue protocol and given time to practice sections of it if needed. Once the subject felt comfortable with the procedure they were fitted with reflective markers stuck to the skin over anatomical bony landmarks and asked to walk around and do a short dance warm-up to practice moving with the markers and prepare for physical activity. Once the subjects felt sufficiently warm, they completed two practice leap landings where they were instructed to do three skips followed by a switch leap and to land precisely on force plates in the lab floor. This familiarized the subject with performing the leap landing in the lab setting.

The subject completed six switch leaps, taking off and landing on both right and left legs three times each. These were the pre-fatigue leaps. After a minute of rest, the subject began the Dance Aerobic Fitness Test (DAFT) as a fatiguing protocol (Wyon et al., 2003) (Table 1). The goal of using this protocol was to create local fatigue, specifically in the knee extensors. The DAFT consists of five stages with an increasing tempo for each stage. In stage one they perform steps, lunges, pliés, and turns for four minutes at 68 beats/minute. In stage two they perform steps, lunges, spring hops, pliés with an arm motion, and turns for four minutes at 78 beats/minute. In stage three they perform steps, lunges, spring hops, hop pliés with an arm motion, and turns for four minutes at 78 beats/minute. In stage four they perform steps, lunges, spring hops, and hop turn with arm motion for four minutes at 94 beats/minute. In stage five they perform steps, lunges, spring hops, and hop turn with arm motion for four minutes at 108 beats/minute. The subject progressed through the stages of the DAFT until they completed stage five or they were unable to maintain time with the metronome, indicating they were fatigued.

Stage	Tempo (b.min^{-1})	Movement
1	68	5 steps, lunge, and recover. 4 sets of 2 pliés with 90° turn between each set. Repeat for 4 minutes.
2	78	5 steps, lunge, and recover. 3 spring hops in a circle. 4 sets of 2 pliés with 90° turn between each set, arms moving between first and second position. Repeat for 4 minutes.
3	78	5 steps, lunge, and recover. 3 spring hops in a circle include arm movements. 4 sets of hop plié with 90° turn between each set, arms moving between first and second position. Repeat for 4 minutes.
4	94	5 steps, lunge, and recover. 3 spring hops in a circle include arm movements. 4 sets of a hop, hop with 90° turn between each set, arms moving between first and second position. Repeat for 4 minutes.
5	108	5 springs, lunge, and recover. 3 spring hops in a circle include arm movements. 4 sets of a hop, hop with 90° turn between each set, arms moving between first and second position. Repeat for 4 minutes.

Table 1. DAFT Protocol
The Five-stage Dance Aerobic Fitness Test protocol. (Wyon et al., 2003)

Immediately on finishing the fatiguing protocol, the subject completed six more switch leaps, taking off and landing on both right and left legs three times each. These were the post-fatigue leaps, and once they were concluded, the subject cooled down and was dismissed.

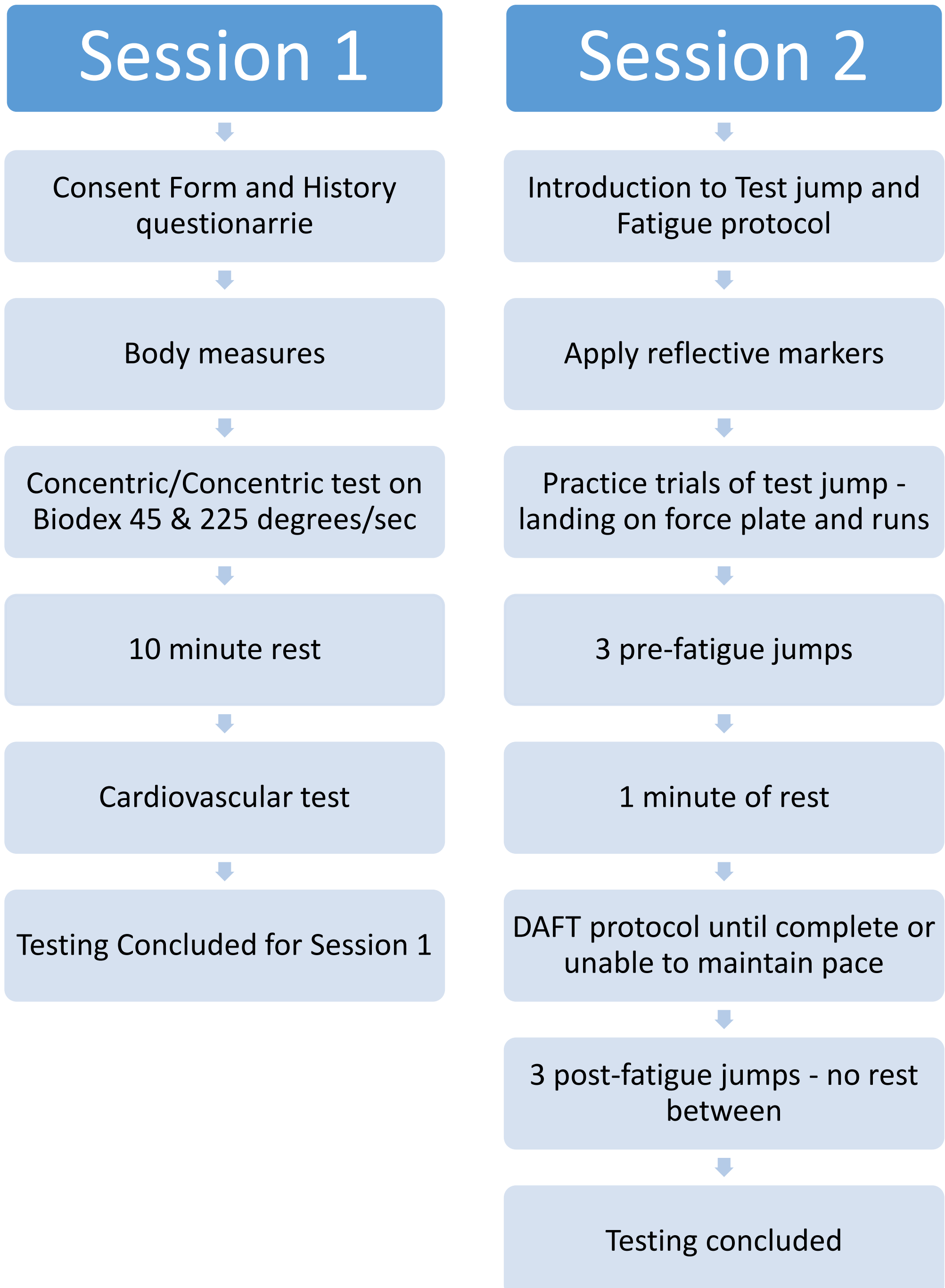

Figure 2. Protocol
Tasks completed by participants on each testing day.

Instrumentation

To collect data, multiple instruments were used. A Seca 220 wall-mounted measuring rod (Seca, Chino, CA) was used to measure the subjects' standing height in meters and a Seca Alpha 770 digital weight scale (Seca, Chino, CA) was used to measure the subjects' body weight in kilograms.

A questionnaire was developed by the researcher to obtain information about dance history, current dance activity levels, and injury history. The questions were open-ended for qualitative purposes.

A Cybex NORM isokinetic dynamometer with HUMAC software (CSMi, Stoughton, MA) was used to assess strength and strength endurance. The test-retest reliability of this equipment has been determined as r = 0.995 (Moffroid et al., 1969) with no significant differences identified among sessions or between males and females (Mawdsley & Knapik, 1982).

Predicted VO_2 max was predicted using a submaximal STEP test, which has been validated (Hayes et al., 2019). A Zacurate Pro Series 500D Deluxe Fingertip Pulse Oximeter (BeyondMed, Stafford, TX) was used to measure heart rate during the step test.

Ground reaction forces were measured with two AMTI OR6 force platforms (Advanced Medical Technology, Inc. Watertown MA). These were embedded flush into the floor of the biomechanics lab. Their analog electric signals were amplified and conditioned with two Gen5 signal conditioners (Advanced Medical Technology, Inc. Watertown MA) with digital output.

Three-dimensional trajectories of reflective markers were recorded with 10 Vicon Vantage infrared cameras (Vicon, Oxford, UK). Trajectories were reconstructed with Vicon Nexus clinical and biomechanics software version 2.8 (Vicon, Oxford, UK). A modified Helen-

Hayes marker set was used, which has high test-retest reliability with CMC's > 0.8 (Collins et al., 2009) and high validity with differences in joint angles of < 3 degrees for segment length differences of 5% (Mentiplay & Clark, 2018; Schwartz & Dixon, 2018).

Joint angles and joint resultant forces and moments were calculated with the MotionSoft 3-D motion data reduction program package version 2016 (MotionSoft Inc, Durham, NC).

Data Collection

For the first testing session, the researcher measured the subject's anthropometric data of height and weight with a wall-mounted measuring rod and a digital weight scale. Then the researcher asked the subject open-ended questions about their previous dance experience, previous injury occurrences, and the time per week they currently spent dancing using a survey that had been approved by the IRB.

The researcher next assessed the subject's quadriceps and hamstrings muscular strength endurance with a Cybex isokinetic dynamometer. The subject's dominant leg was identified by the researcher asking them which leg they preferred for a one-legged hop. The researcher fitted the lower leg attachment to the dynamometer and aligned the medial-lateral knee joint axis of the subject's dominant side knee to the axis of rotation of the dynamometer. The researcher encouraged the subject to provide maximal effort during sets of concentric/concentric knee extension/flexion for three repetitions at 45 degrees/second and fifteen repetitions at 225 degrees/second. They then repeated the procedure for the subject's non-dominant side for four total sets. Torque, angular position, and angular velocity of the dynamometer were sampled over each set at 100 Hz by the Humac software.

The subject's cardiorespiratory fitness was then assessed with a progressive, predictive VO_2 step test. The subject's age, height, and weight were entered into an Excel spreadsheet, and their predicted maximal heart rate was calculated. The subject's current activity level was used to determine their fitness category and appropriate test cadence in a number of steps per minute, which was programmed into a metronome to pace the test. The subject completed sixteen minutes of stepping, with increasing step heights every minute at the pace of one step per beat (up, up, down, down) at their prescribed cadence. The researcher measured and recorded the subject's heart rate at the end of every minute of stepping using a pulse oximeter.

For the second testing session, a Vicon Nexus system with ten infrared Vicon Vantage video cameras was calibrated for a 3.0-meter long × 1.5 meters wide × 2.2 meter high volume. The calibration also established the global reference frame as X-axis = forwards-backward, Y-axis = left-right, Z-axis = up-down, with the origin at the back right corner of the force plates. Passive reflective markers were fixed to the skin of the subject using double-sided adhesive tape, and following a modified Helen-Hayes marker set. Markers were placed bilaterally at the acromion process of the shoulder, anterior superior iliac spine, posterior superior iliac spine, greater trochanter of the femur, medial and lateral femoral condyle of the femur, tibial tuberosity, medial and lateral malleoli, calcaneus, and heads of the first and fifth metatarsals. The infrared video cameras were used to record the real-time 3-D trajectories of the reflective markers, and their positions were sampled by the Vicon Nexus system at a rate of 120 Hz. Electric signals from two AMTI OR6 force plates were sampled by the Vicon Nexus system at a rate of 1200 Hz and converted to Ground Reaction Forces (GRF), ground reaction moments, and center of pressure. The video graphic and force plate data were time-synchronized. All six pre-fatigue and all six post-fatigue leap landings were recorded by the Vicon Nexus software.

Data Processing

All demographic data were entered into a database for analysis. Body Mass Index (BMI) was calculated as weight in kg divided by height in meters squared. This variable was entered into the analysis database and used for the VO_2 max prediction equation.

The torques measured by the dynamometer for the sets of 15 repetitions at 225 degrees/second were used to calculate a measure of strength endurance for each subject. The first two repetitions of the set were identified as the time period from time = 0 to the time at the second local minimum of angular position. The maximum extension torque within that time period was recorded. The last two repetitions of the set were identified as the time period from the time at the penultimate local minimum of angular position to the time at the last local minimum of angular position. The maximum extension torque within that time period was also recorded. Strength endurance was calculated as the percentage change between the maximum extension torque of the first two repetitions and the maximum extension torque of the last two repetitions. This process was repeated for both left and right legs. The strength endurance measure for each subject's dominant leg was entered into the analysis database.

The VO_2 max of each subject was predicted from the results of the predictive step test using a regression equation based on their sex, BMI, and step test average heart rate (Hayes et al., 2019):

$$VO_2 \text{ max} = 63.54 + ([\text{Sex} \times 1.72] - [0.73 \times \text{BMI}] - [0.15 \times \text{HR}]). \qquad \text{(Eqn 1)}$$

The predicted VO_2 max was entered into the analysis database. Subjects were sorted by VO_2 max score and then strength endurance and categorized as high fitness level (top 50%) or low fitness level (bottom 50%) based on their sorted ranking.

The real-time 3-D coordinates of the bony landmark reflective markers were filtered through a Butterworth low-pass digital filter at an estimated optimal cutoff frequency of 7.14 Hz

(Yu et al., 1999). The 3-D coordinates of the toe, ankle, knee and hip joint centers were then estimated from the coordinates of the bony landmark reflective markers. The toe joint center was defined as the midpoint between the markers on the head of the first metatarsal and the head of the fifth metatarsal. The ankle joint center was defined as the midpoint between the markers on the medial and lateral malleoli. The knee joint center was defined as the midpoint between the markers on the medial and lateral femoral condyles. The hip joint centers were defined using the markers on the right and left anterior and posterior superior iliac spines and anatomical data (Bell et al., 1990). Foot, lower leg, and thigh segment masses, moments of inertia, and centers of mass position were calculated from the joint center coordinates and anatomical data (De Leva, 1996). Centers of mass accelerations were calculated as the second derivative of centers of mass position with respect to time.

The 3-D coordinates of the toe joint centers, the ankle joint centers, and the calcanei were used to define the foot reference frames as: x-axis = calcaneus→toe, y-axis = (calcaneus→ankle × x-axis), and z-axis = (x-axis × y-axis). The 3-D coordinates of the ankle joint centers, the knee joint centers, and the medial and lateral malleoli were used to define the lower leg reference frames as: y-axis = lateral malleolus→medial malleolus, z-axis = ankle→knee, and x-axis = (y-axis × z-axis). The 3-D coordinates of the knee joint centers, the hip joint centers, and the medial and lateral femoral condyles were used to define the thigh reference frames as: y-axis = lateral femoral condyle→medial femoral condyle, z-axis = knee→hip, and x-axis = (y-axis × z-axis). The segment angles were defined as Euler angles of the segment reference frame relative to the global reference frame rotated in an order of X, Y, Z. Segment angular accelerations were calculated as the second derivative of angle with respect to time. The knee joint angles were defined as Euler angles of the lower leg reference frame relative to the thigh reference frame rotated in an order of: (y) flexion/extension, (z) internal/external rotation, and (x) valgus/varus.

Joint resultant forces and moments were calculated using an inverse dynamic procedure (Greenwood, 1988). Ankle resultant force and moment were calculated from GRF data, foot mass, foot moment of inertia, foot center of mass position and acceleration, foot angular acceleration, and ankle joint center position using Newton's second and third laws of motion. Knee resultant force and moment were calculated from the ankle joint center position, ankle resultant force and moment, lower leg mass, lower leg moment of inertia, lower leg center of mass position and acceleration, lower leg angular acceleration, and knee joint center position using Newton's second and third laws of motion. Knee joint forces were normalized to standing height. Knee joint moments were normalized to body weight x standing height. All signal processing and data reduction were performed using MotionSoft 3-D.

Knee joint flexion and valgus angles were recorded at the instant of initial contact. The change in knee flexion and valgus angles between the first good pre-fatigue and the first good post-fatigue leaps were entered into the analysis database. Yu, Lin, and Garrett (2005) identified that peak GRF, peak knee anterior shear force, and peak knee moment occur at approximately the same time - during landing at initial contact. Knee anterior shear force was defined as the positive component of knee resultant force acting along the lower leg x-axis, recorded at the instant of initial contact, and entered into the analysis database. Knee external valgus moment was defined as the negative component of knee resultant moment acting around the knee x-axis, recorded at the instant of initial contact, and entered into the analysis database.

Statistical Analyses

Based on preliminary data, pre-post fatigue change in landing knee flexion angle at initial contact and pre-post fatigue change in landing knee valgus angle at initial contact have large effect sizes on knee loading. Cohen's $f^2 = 0.486$ for knee flexion angle and 0.550 for knee valgus angle. With these effect sizes, a type II error rate of $\beta = 0.2$ (80% power), and a type I error of $\alpha = 0.05$, a sample size of at least 25 subjects was required for statistical significance for the multiple regression analyses.

Two multiple regression analyses were conducted to determine the relationship between fatigued landing knee kinematics and injurious knee joint loading. For the first multiple regression, the predictor variables were the pre-post fatigue change in landing knee flexion angle at initial contact and the pre-post fatigue change in landing knee valgus angle at initial contact (Table 2), and the outcome variable was the post-fatigue landing knee anterior shear force at initial contact. For the second multiple regression, the predictor variables were the pre-post fatigue change in landing knee flexion angle at initial contact and the pre-post fatigue change in landing knee valgus angle at initial contact, and the outcome variable was the post-fatigue landing knee external valgus moment at initial contact. To determine the moderating effect of fitness on the relationship between fatigued landing knee kinematics and knee joint loading, fitness level was included in the multiple regression as a dummy variable to investigate its interaction with pre-post fatigue change in landing knee flexion angle at initial contact and pre-post fatigue change in landing knee valgus angle at initial contact. All statistical analyses were conducted using SPSS version 22 with a Type I error rate set a priori at $\alpha = 0.05$.

CHAPTER 4

RESULTS

Demographics and Descriptive Statistics

Descriptive statistics of means, standard deviations, skewness, and kurtosis were calculated for all study variables. No outlier participants were identified (Table 2). Bivariate correlations among study variables were computed to assess independence among study variables. Statistically significant associations were identified among knee flexion angle at initial contact, knee valgus angle at initial contact, knee joint anterior shear force, and external knee valgus moment.

	All Participants Mean ± Std Dev	High Fitness Group Mean ± Std Dev	Low Fitness Group Mean ± Std Dev
Age (years)	18.9 ± 3.7	17.9 ± 4.1	20.8 ± 1.9
Height (m)	1.63 ± 0.06	1.62 ± 0.07	1.63 ± 0.05
Weight (kg)	67.9 ± 17.0	63.9 ± 16.0	75.9 ± 17.9
Body Mass Index (kg/m^2)	25.8 ± 7.1	24.3 ± 6.2	28.7 ± 8.4
Injury Score (number of injuries*severity)	14.6 ± 29.4	16.6 ± 35.2	10.6 ± 14.6
Years Dancing (years)	14.3 ± 3.3	13.2 ± 3.5	16.4 ± 1.3
Hours Per Week Danced (hours)	6.8 ± 2.4	7.1 ± 2.9	6.3 ± 1.1
Predicted VO_2 Max (mL/kg/min)	35.90 ± 4.73	39.90 ± 2.13	31.90 ± 2.69
Pre-Fatigue Knee Flexion Angle at Initial Contact (°)	13.60 ± 7.28	12.98 ± 7.79	14.71 ± 6.96
Post-Fatigue Knee Flexion Angle at Initial Contact (°)	21.13 ± 9.54	16.41 ± 10.49	30.31 ± 8.32
Pre-Post Fatigue change in Knee Flexion Angle at Initial Contact (°)	12.50 ± 11.95	3.80 ± 8.50	21.20 ± 7.81
Pre-Fatigue Knee Valgus Angle at Initial Contact (°)	-0.59 ± 3.83	-1.42 ± 4.08	0.90 ± 3.70
Post-Fatigue Knee Valgus Angle at Initial Contact (°)	0.49 ± 2.27	1.27 ± 2.37	-0.93 ± 2.28
Pre-Post Fatigue change in Knee Valgus Angle at Initial Contact (°)	0.25 ± 6.21	3.20 ± 5.92	-2.70 ± 4.47
Post-Fatigue Knee Joint Anterior Shear Force at Initial Contact (BW)	0.53 ± 0.41	0.29 ± 0.41	0.76 ± 0.24
Post-Fatigue External Knee Valgus Moment at Initial Contact (BW.BH)	-0.12 ± 0.24	-0.31 ± 0.17	0.07 ± 0.13

Table 2. Descriptive Statistics for Study Variables.
Mean and standard deviations of biomechanical variables were measured for this study. For standardized units, kg/m^2 is kilograms per square meter, mL/kg/min is the amount of oxygen utilized per kilogram of body weight per minute of exercise, BW is a force measured in bodyweights, BW.BH is a moment measured in bodyweight-heights.

Hypothesis Tests

To test H_1, a multiple linear regression with stepwise entry was calculated to predict knee joint anterior shear force based on knee flexion angle at initial contact and knee valgus angle at initial contact. A statistically significant regression equation was found ($F_{2,17} = 14.308$, $p < 0.01$) that accounted for 58% of the variance in knee joint anterior shear force. Both knee flexion angle at initial contact ($\beta_{ASFlex} = 0.206$, $t = 4.416$, $p < 0.01$) and knee valgus angle at initial contact ($\beta_{ASValg} = 0.886$, $t = 5.002$, $p < 0.01$) were statistically significant predictors of knee joint anterior shear force (Figure 3). Knee joint anterior shear force increased by 1 BW for each 0.2° of knee flexion angle at initial contact and each 0.9° of knee valgus angle at initial contact.

$$\text{Anterior Shear Force} = ([0.206 \times \text{Knee Flexion}] + [0.886 \times \text{Knee Valgus}]) \quad \text{(Eqn 2)}$$

To test H_2, a multiple linear regression with stepwise entry was calculated to predict external knee valgus moment based on knee flexion angle at initial contact and knee valgus angle at initial contact. A statistically significant regression equation was found ($F_{2,17} = 22.929$, $p < 0.01$) that accounted for 70% of the variance in external knee valgus moment. Both knee flexion angle at initial contact ($\beta_{EVFlex} = -0.857$, $t = -5.678$, $p < 0.01$) and knee valgus angle at initial contact ($\beta_{EVValg} = -0.005$, $t = -1.945$, $p = 0.048$) were statistically significant predictors of external knee valgus moment (Figure 4). External knee valgus moment increased by 1 BW.BH for each decrease of 0.9° of knee flexion angle at initial contact and each decrease of 0.005° of knee valgus angle at initial contact.

$$\text{Valgus Moment} = ([-0.857 \times \text{Knee Flexion}] + [-0.005 \times \text{Knee Valgus}]) \quad \text{(Eqn 3)}$$

To test H_3, a multiple linear regression with stepwise entry was calculated to predict knee joint anterior shear force based on knee flexion angle at initial contact, knee valgus angle at initial contact, and fitness level. A statistically significant regression equation was found ($F_{2,17} =$

9.116, $p < 0.01$) that accounted for 56% of the variance in knee joint anterior shear force. A statistically significant interaction term ($\beta_{ASFit} = 0.001$, $p = 0.05$) was identified for this regression equation, indicating that fitness level functions as a moderator of the relationship between knee flexion angle at initial contact and knee valgus angle at initial contact and knee joint anterior shear force. The relationship was stronger for high-fitness dancers (0.729) than for low-fitness dancers (0.366) (Figures 5 and 6).

To test H_4, a multiple linear regression with stepwise entry was calculated to predict external knee valgus moment based on knee flexion angle at initial contact, knee valgus angle at initial contact, and fitness level. A statistically significant regression equation was found ($F_{2,17} = 16.402$, $p < 0.01$) that accounted for 70% of the variance in external knee valgus moment. A statistically significant interaction term ($\beta_{EVFit} = -0.001$, $p = 0.05$) was identified for this regression equation, indicating that fitness level functions as a moderator of the relationship between knee flexion angle at initial contact and knee valgus angle at initial contact external knee valgus moment. The relationship was stronger for high-fitness dancers (0.491) than for low-fitness dancers (0.359) (Figures 7 and 8).

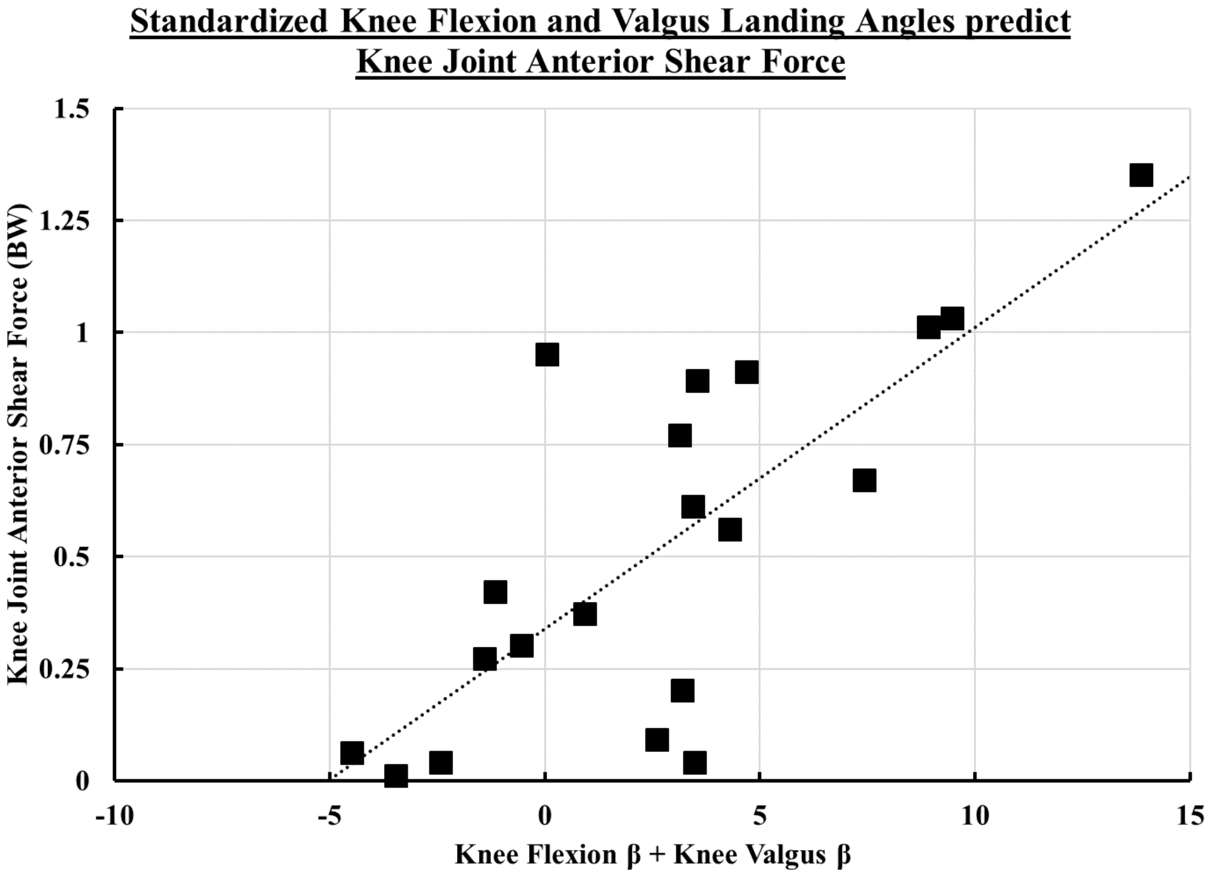

Figure 3. Relationship between a Linear Combination of Knee Flexion Angle at Initial Contact and Knee Valgus Angle at Initial Contact and Knee Joint Anterior Shear Force. A scatter plot with a line of best fit to demonstrate the relationship between knee angles at landing in degrees and knee joint anterior shear force in bodyweights.

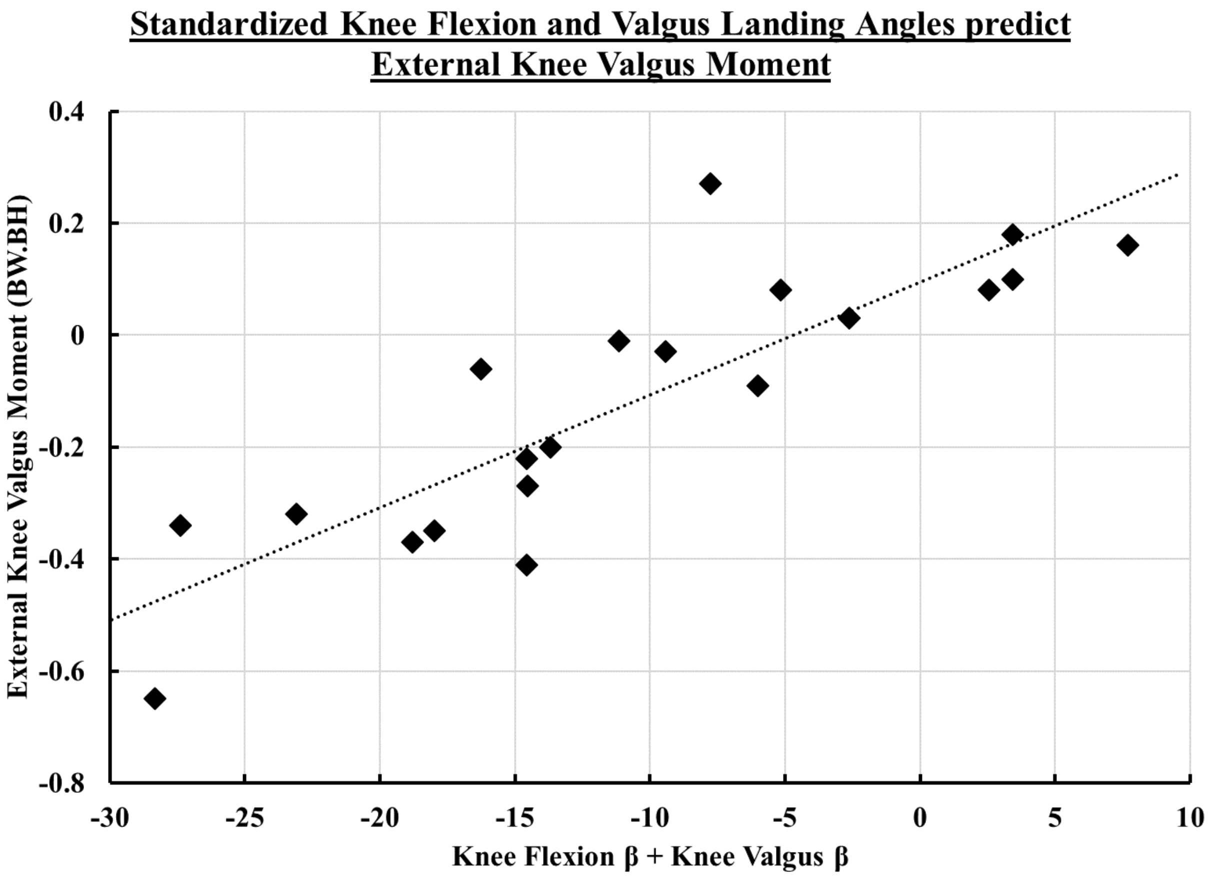

Figure 4. Relationship between a Linear Combination of Knee Flexion Angle at Initial Contact and Knee Valgus Angle at Initial Contact and External Knee Valgus Moment. A scatter plot with a line of best fit to demonstrate the relationship between knee angles at landing in degrees and external knee valgus moment in bodyweight-heights.

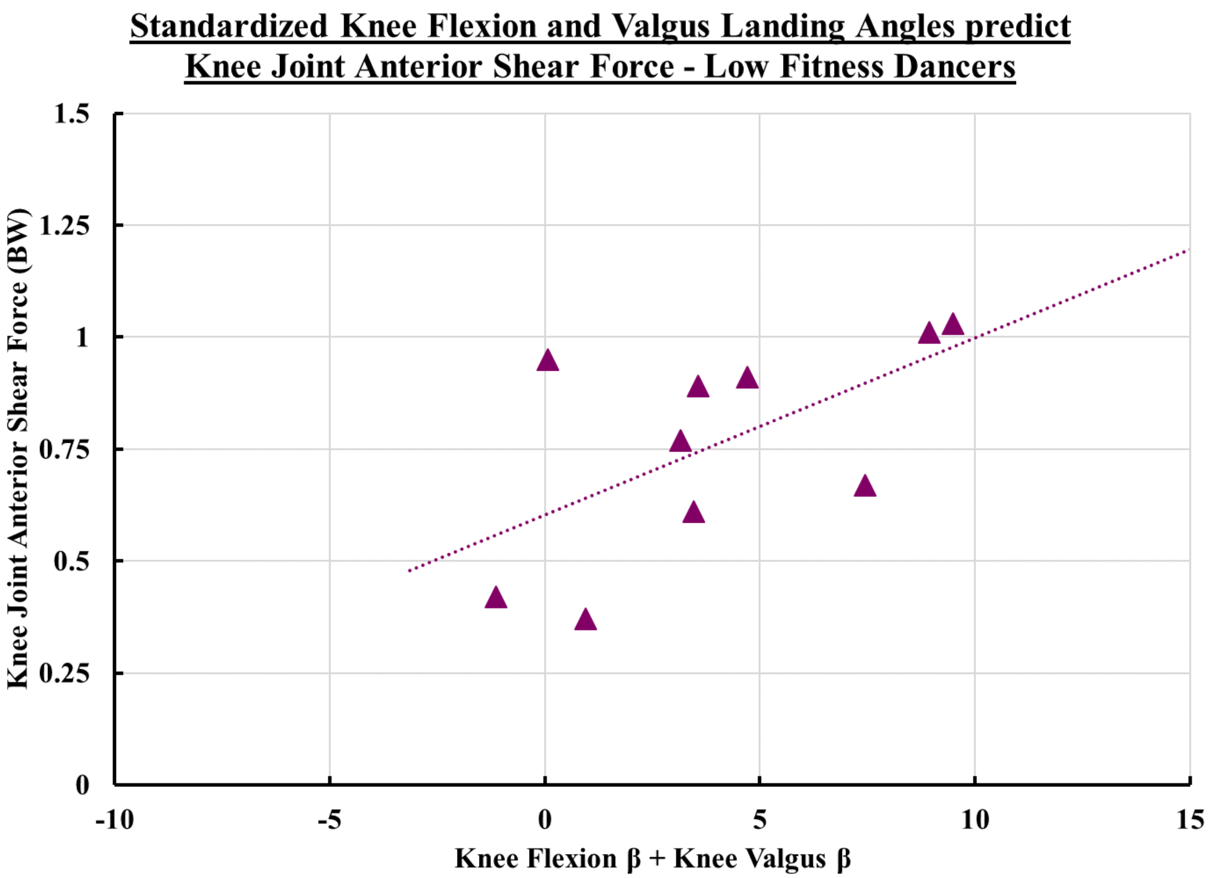

Figure 5. Relationship between a Linear Combination of Knee Flexion Angle at Initial Contact and Knee Valgus Angle at Initial Contact and Knee Joint Anterior Shear Force for Low-Fitness Dancers.

A scatter plot with a line of best fit to demonstrate the relationship between knee angles at landing in degrees and knee joint anterior shear force in bodyweights for dancers with the lowest 50% of VO_2 max scores.

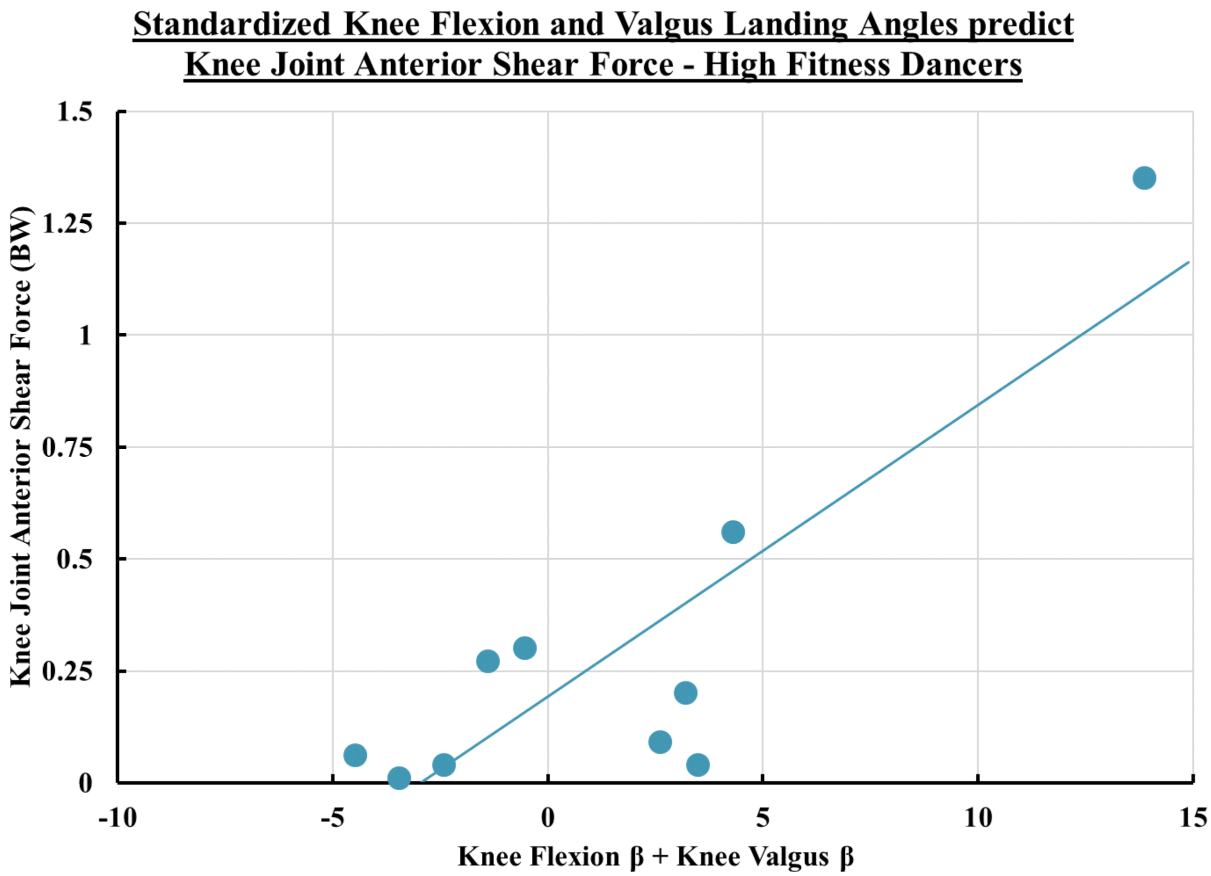

Figure 6. Relationship between a Linear Combination of Knee Flexion Angle at Initial Contact and Knee Valgus Angle at Initial Contact and Knee Joint Anterior Shear Force for High-Fitness Dancers.

A scatter plot with a line of best fit to demonstrate the relationship between knee angles at landing in degrees and knee joint anterior shear force in bodyweights for dancers with the highest 50% of VO_2 max scores.

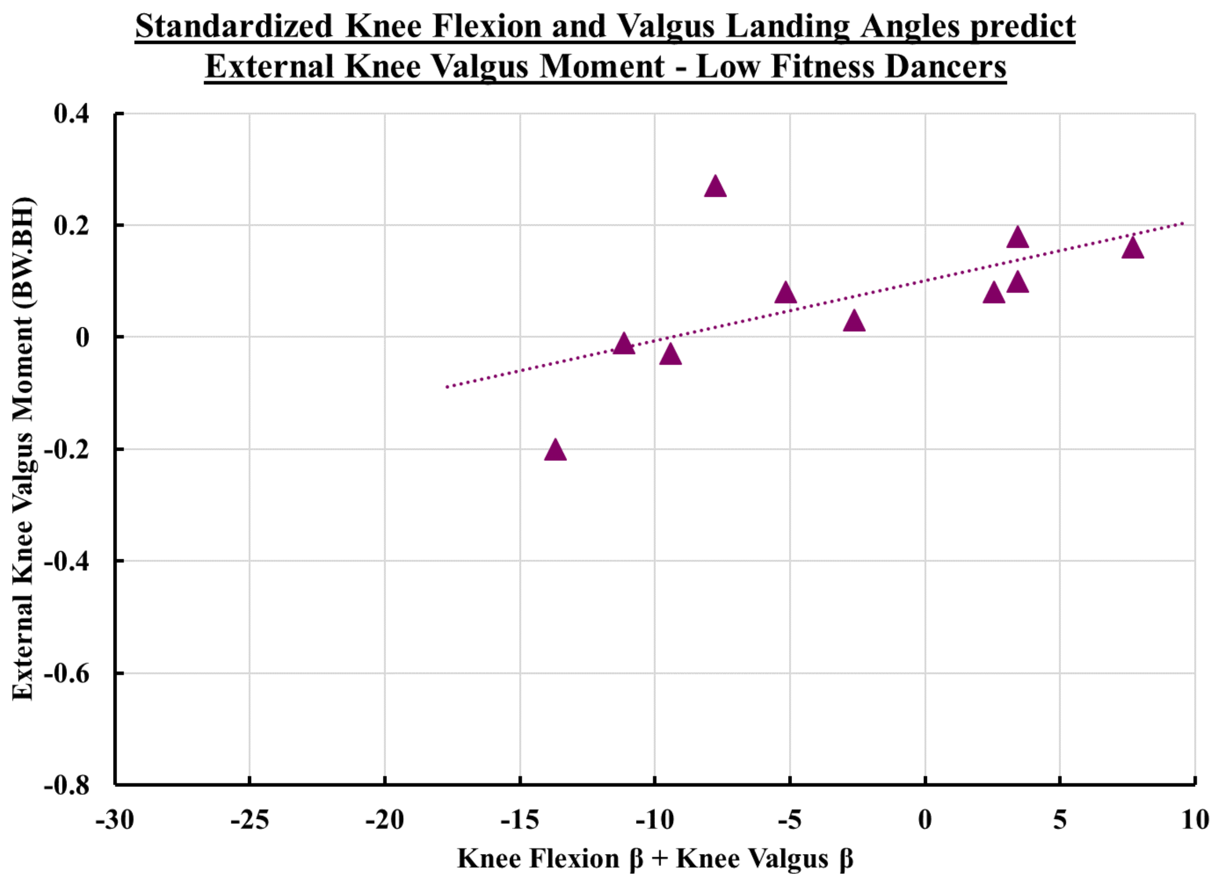

Figure 7. Relationship between a Linear Combination of Knee Flexion Angle at Initial Contact and Knee Valgus Angle at Initial Contact and External Knee Valgus Moment for Low-Fitness Dancers.

A scatter plot with a line of best fit to demonstrate the relationship between knee angles at landing in degrees and external knee valgus moment in bodyweight-heights for dancers with the lowest 50% of VO_2 max scores.

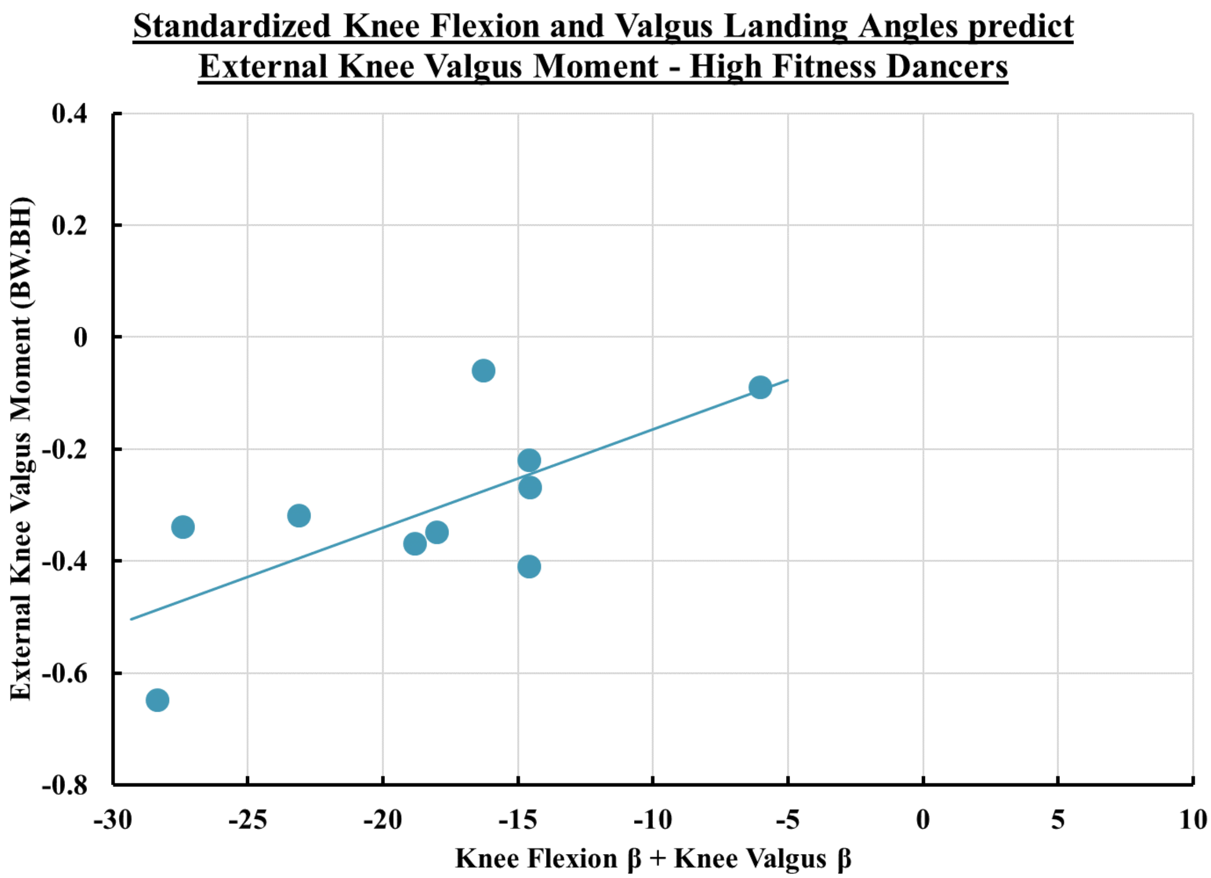

Figure 8. Relationship between a Linear Combination of Knee Flexion Angle at Initial Contact and Knee Valgus Angle at Initial Contact and External Knee Valgus Moment for High-Fitness Dancers.

A scatter plot with a line of best fit to demonstrate the relationship between knee angles at landing in degrees and external knee valgus moment in bodyweight-heights for dancers with the highest 50% of VO_2 max scores.

CHAPTER 5

DISCUSSION

The primary purpose of this thesis was to determine the relationship between fatigued landing motion patterns and injurious knee joint loading. The secondary purpose of this thesis was to investigate the moderating effect of fitness on the relationship between fatigued landing motion patterns and injurious knee joint loading. During the course of this research no participant was injured, so the results should be interpreted as a description of landing technique with implications for injury.

The first research hypothesis developed to address the purposes of this thesis was that a smaller knee flexion angle and a greater knee valgus angle at initial contact of a fatigued jump landing would be associated with a greater knee anterior shear force. The first hypothesis was partially supported by our results, which showed that both knee flexion angle at initial contact and knee valgus angle at initial contact were predictors of the anterior shear force experienced at the knee joint at initial contact when fatigued. For this relationship with knee joint anterior shear force, the regression coefficients for knee flexion and knee valgus were both positive. Knee joint anterior shear force increased as knee flexion and knee valgus increased. This hypothesis was partially supported because our results show greater anterior shear force was associated with an increase in knee flexion, as opposed to smaller knee flexion. This style of bent-knee landing was probably an attempt to use joint motion to absorb landing forces. The requirement for dancers is to land in a straighter knee position, so the fatigued bent-knee landing reflects poor landing aesthetics. The jump required for this research was considered an advanced skill, so participants who may have not been as familiar with this skill may have not been able to achieve the correct height to fully complete this jump, or precisely control their landing on the force plate, causing them to alter their mechanics. Bent-knee landings associated with greater anterior shear force could be a concern for an ACL overload injury. During the study, one participant had an anterior shear force 30% higher than the rest of the participants, which could be a concern for an acute injury. This high amount of anterior shear force demonstrates the high amount of stress being placed on this participant's ACL which, if the participant's landing is not controlled, can lead to an inability of the ligaments to resist these motions and forces, a high risk for an acute injury. While this participant's anterior shear forces were higher than the rest, no injury occurred in this study. These findings suggest greater knee joint angles at initial contact are associated with greater stress on the ACL.

The second research hypothesis was that a smaller knee flexion angle and a greater knee valgus angle at initial contact of a fatigued jump landing would be associated with a greater external knee valgus moment. This hypothesis was partially supported by our results because both knee flexion angle at initial contact and knee valgus angle at initial contact were predictors of external knee valgus moment at initial contact when fatigued. For this relationship with external knee valgus moment, the regression coefficients for knee flexion and knee valgus were both negative. Decreased knee flexion and knee valgus at initial fatigued contact were associated with increased external knee valgus moment. This hypothesis was partially supported because we expected that a greater external knee valgus moment would be associated with a greater knee valgus angle, as opposed to the outcome we found which was that a smaller knee valgus angle was shown to be associated with the greater external knee valgus moment. The association between a more varus knee position and external knee valgus moment may represent the dancer controlling the landing to move back to a more neutral knee position. These findings suggest a stiffer landing is associated with greater stress on the MCL, which may be a concern for an MCL overload injury.

The third research hypothesis, which was developed to understand how fitness affects the relationship between landing biomechanics and knee joint loading, was that the relationship between knee joint anterior shear force and a combination of knee flexion angle and knee valgus angle at initial contact of a fatigued jump landing would be weaker in dancers with greater fitness levels. This hypothesis was not supported by our results. There were significant interaction terms for knee flexion and knee valgus in the regression model with anterior shear force. These interaction terms demonstrate that fitness moderates the relationship between landing biomechanics and knee joint loading. This relationship was stronger in fitter dancers than less fit dancers. Less fit dancers landed with greater knee flexion and knee valgus angles at initial contact. Knee joint anterior shear forces in fatigued landings were greater for less fit dancers, while the dancers that were considered high fitness had decreased knee flexion and knee valgus angles at initial contact. This suggests that the higher fitness dancers had greater control of their knee joint in a fatigued state and were better able to adhere to the required landing aesthetics, while able to absorb the landing forces to prevent an overload injury of the ACL. This also suggests that the higher fitness dancers demonstrate the neuromuscular control when fatigued to maintain knee joint movements and decrease the stress on their ACL which can help to decrease the potential for an overload injury of the ACL. These findings indicate that less fit dancers have greater stress on their ACL at landing and that additional factors other than landing position alone determine the amount of ACL stress. These additional factors that include previous injury, Lee et al. (2017) found that dancers with a previous injury were more likely to demonstrate altered movement patterns. The results of this research show that fitness is a moderator of knee angle and knee forces when landing. Increasing fitness levels might be able to help dancers better control their landings when in a fatigued state, but this needs to be investigated.

The fourth research hypothesis was that the relationship between external knee valgus moment and a combination of knee flexion angle and knee valgus angle at initial contact of a fatigued jump landing would be weaker in dancers with greater fitness levels. This hypothesis was not supported by our results. There were significant interaction terms for knee flexion and knee valgus in the regression model with external knee valgus moment. These interaction terms demonstrate that fitness moderates the relationship between landing biomechanics and knee joint loading. This relationship was stronger in fitter dancers than less fit dancers. Less fit dancers landed with greater knee flexion and in a more varus position with a valgus moment at initial contact. High fitness dancers landed in a more valgus position with a varus moment. These two associations show neuromuscular control of the knee moving back into alignment. The different landing positions for the higher fitness in a valgus position and the lower fitness in a varus position may suggest that the fitness level of a dancer may influence the control of landing and the knee in a fatigued state. Greater valgus moments are a concern for MCL overload injuries due to the opening of the joint to that medial side, placing the stress directly to that MCL. Over time, the overload of the MCL stress can cause the ligament to no longer control that knee joint opening and injure that tissue. During the course of this research, there was a subject that had a varus moment 50% higher than anyone else, which could be a concern for an acute lateral collateral ligament (LCL) injury. While no participants were injured in the course of this study, the participant's outcomes show an increased risk for that LCL injury. The increase in their varus moment causing the knee to open laterally places the increased landing stress on the LCL. In the event of a landing that is fatigued and uncontrolled the increased landing stress can cause that ligament to be unable to control the knee joint. External knee valgus moments in fatigued landings were greater for less fit dancers. This study's findings indicate that less fit dancers have greater stress on their MCL at landing and that factors not related to knee position at landing are important in determining the amount of MCL stress.

The results of the current investigation show that the initial landing position influences the amount of knee anterior and shear force at the knee joint. Previous research shows that decreased landing flexion places abrupt anterior and external valgus forces on the knees, and with the decrease, in knee flexion, the joint has a decreased ability to absorb the forces (Yin et al., 2005). In the results of this research, increased knee joint flexion was shown to increase the stress on the ACL, perhaps due to eccentric loading of the quadriceps. These muscles are able to absorb the ground reaction forces if the landing is slow and controlled. Increased landing knee flexion causes an increased amount of force placed on soft tissue structures of the knee, forces that over time will cause damage to ligaments. Another study found that fatigue has contributing factors that impair dynamic control (Ortiz et al., 2010). This research found that fatigue can place the knee in unstable situations which can cause greater valgus and varus moments. Increased knee flexion can cause an increase in knee valgus as the joint gains greater freedom to move in three dimensions. Increased knee valgus causes knee external valgus moment which places stress on the MCL.

This research found that increased knee flexion angle led to increased knee anterior forces and other knee forces which is different from previous research. The possible explanation for this is that fatigue does not seem to be a factor in the knee landing angles. There is an increase in greater shear force and greater knee angle in both fatigued and non-fatigued states. This could also be related to the position or the training of the participants in this study. When the participants got fatigued, they may have been unable to land in the more aesthetic positions required or be unable to maintain those positions. The second hypothesis also was in opposition with previous research that found those who landed with decreased knee joint flexion saw an increase in valgus forces at the knee. In this study when the dancers landed with increased landing knee flexion there was an increase in knee valgus moment and when they landed with increased flexion there was an increase in knee anterior shear force. The increased knee valgus can be explained by the increased knee flexion found at landing. The participants already land in the increased flexed position, which allows the knee joint to have greater movement and be in a less stable position, making it easier for the knee to move into that greater valgus angle. The valgus forces were increased with the greater valgus angles, which can lead to the increased stressors. Stiffer landings tend to occur when fatigued. This study focused on the change in the angles from pre-to post fatigued, where previous research just looked at the angles at landing. While the outcomes from this study may differ from previous research, these outcomes do show that knee joint angles affect the knee forces which can lead to greater stress placed on the ligaments.

The third and fourth hypotheses show that less fit dancers have greater stress placed on their MCL and ACL with a fatigued landing. Fitness plays a role in these landing stresses, but alternative theories may be that the less fit dancers have less time in dance class training, decreasing the time spent on dance technique and practicing proper dance landing. Dancers are taught specific aesthetics, specifically to land in an extended position, so the less fit dancers may have decreased time in class practicing the aesthetics. Less fit dancers may also present with decreased musculature in their quadriceps and hamstring, decreasing the ability to control the landing when fatigued. When the muscles are fatigued there is a greater risk for shear force which is one explanation for the difference seen in the high to low fitness participants is the effort involved, which can impact the amount of shear force. The lower fitness participants may not have been as relatively fatigued as the high fitness participants. The lower fitness participants may not have put forth as much effort in the fatigue protocol to maintain the proper form and to maintain the proper landing as compared to the high fitness participants, so the higher fitness participants were more likely to achieve true fatigue which can lead to decreased motor control of the joint. This difference in effort from the participants would help to explain the shear force increase as well as the knee flexion increase due to the fatigue protocol. The high fitness participants tried harder and went further in the protocol than the lower fitness participants, so their fatigued landing would have exhibited greater changes in the knee landing angles, demonstrating the increase in shear and anterior forces at the knee. The fitness protocol is designed to achieve equal levels of fatigue, but the effort put forth by the participants can be affected by their overall fitness levels and motivation.

The jump landing pattern found in this study was that dancers will land in a more extended motion and when fatigued there will be an increase in knee joint flexion and valgus. Previous research (Linderbach et al., 2013) shows that injuries most often occur late in the season, stating fatigue is the likely factor. These outcomes support that when fatigued, the dancer landing patterns change, and that change in pattern increases the joint angles, which in turn increases the joint forces and moments. These results are consistent with our results: dancers tend to land in an extended position initially, and when fatigued will increase their knee flexion.

These thesis results also show that increased fitness levels have a positive impact on knee joint angle at landing and knee joint forces. Increased fitness levels help to increase the time to fatigue, which can also increase the amount of knee joint flexion that can cause stress on the knee soft tissues. Fitter dancers will have increased muscular strength and increase neuromuscular control over their knee joints and knee soft tissues. Dancers with increased muscular strength and cardiovascular fitness will take longer to fatigue due to increased endurance. Increased muscular strength will absorb forces longer and be able to withstand multiple repetitions of single-leg landing. The fitter dancers will have better control over their knee joint at landing, controlling their knee flexion angle. The measure of fitness can also be a measure of dance activity. Fitter or higher fitness participants are typically those who are dancing more or spending more time in class where less fit participants may spend less time in class, spending less time on their landing technique. Less fit participants were also those who had less experience dancing and a decreased quality of movements. The difference in the time in training and lower quality movements can also explain the decreased control of the knee joint at landing. The lower fitness participants will demonstrate decreased joint and neuromuscular control along with a less aesthetic landing. These results support previous research that increased fitness level has a positive impact on decreasing the time to fatigue. Knee loading has a major contribution to stress to the knee joint, and other contributions to knee joint stress include decreased muscle, poor landing mechanics, and poor neuromuscular control. The results of this study support the increase for fitness training and increasing fitness levels, supporting the research done by Koutedakis et al. (2007) that when adding an additional fitness program, dancers have an overall increase in fitness, decreasing the landing changes that were observed when fatigued, and increasing that time to fatigue.

Greater knee valgus and knee flexion at initial landing increases the amount of anterior shear force at the knee joint. In this study population, we found that the greater knee angle was associated with greater forces at the knee joint. This may explain why dancers will have fewer knee injuries than their team sports counterparts. Dancers are taught from a young age to land with little knee flexion and taught control of the knee joint when landing. That control of the knee joint upon contact helps to decrease the amount of forces that could potentially be applied to the soft tissues. If the forces are not absorbed in the knee joint musculature, the forces can be absorbed by the ankle and the hip. Previous studies have shown that increasing muscular strength in dancers can increase the time to fatigue but that strength training alone does not alter landing kinematics, but that supplemental exercise training did increase aspects of dancer's performances (Herman et al., 2008; Koutedakis et al., 2007). Team sports counterparts do not have the same jump landing training and landing aesthetics as those in this study. Team sport athletes allow greater joint motion when landing, increasing the stress placed on the knee joint ligaments. Dancers, due to the strict landing requirements, allow for less joint motion at the knee when landing. However, when dancers are fatigued or are lacking supplemental training, they can start to increase their knee joint motion, like their team sports counterparts, as demonstrated in the post fatigue jump mechanics.

Increasing fitness levels overall, such as increasing cardiorespiratory fitness as well as overall muscular strength, may help to increase the time to fatigue, allowing the dancers to decrease the amount of stress placed on these soft tissue structures. Dancers who have greater fitness levels may be able to have better control over their landing form, which can allow for decreased forces placed on ligaments. Increased fitness levels can also help to increase the number of forces absorbed in the muscles decreasing the amount of force absorbed by the ligaments.

This thesis was not without limitations. This study was performed in a small town, where access to dancers was limited. Dancers that volunteered for this study ranged from college dancers participating in college dance classes to high school dancers who were rehearsing multiple days a week in multiple styles of dance. These results can be applied to intermediate to pre-professional dancers. This study was done during the end of the summer, but the lab where some of the data were collected could be warmer at times, potentially increasing that fatigued feeling. Dancers were given a minimum of 48 hours between testing and were told to only participate in light activity prior to the fatigue testing protocol. Dancers were also encouraged verbally to use as much muscular strength they had for the muscular endurance portion of the testing, but due to unfamiliarity with Cybex muscular endurance testing, dancers may have not given full strength or had enough reps to have a significant decrease in power. The cardiovascular test was a submaximal step test that was easier for dancers than a typical cardiovascular workout. The participants heart rate was also recorded at the time of fatigue of the dance fatigue protocol to ensure dancers were reaching consistent levels of fatigue and increased cardiovascular stress. Dancers were asked to perform this test in a laboratory, where they were required to land on a force plate. This can be a challenge for dancers to be able to control their landings to a specific spot.

Suggestions for future research are to implement a longer duration study. Observing dancer's fitness levels after implementing only strength, only cardiovascular fitness, and a combination of both fitness programs for a set duration of time to see which factor of fitness helps to increase a dancer's time to fatigue. Future studies could also look at younger dancers who are just learning the skill, to see if implementing a fitness program before learning the jump could help them learn better landing mechanics before developing compensation patterns. The results of this study do not specify if general strength or fitness programs will help to prevent the change in motion patterns, but that overall general fitness is an important factor. The fitness level outcome can help practitioners encourage general fitness programs and even outside fitness training. Another future direction studies could take would be to follow dancers through a fitness protocol, for example, if researchers take low fitness dancers and implement an overall fitness training protocol and see how the low fitness dancer's landing mechanics might change following a change in fitness levels. Future studies could also recruit dancers from one dance school; this would allow them to study the landing mechanics of dancers who were taught by same instructor. It would also be ideal if dancers in future studies all had the same fitness level and dance experience.

Dancers with increased knee joint valgus and knee joint flexion when landing following the fatigue protocol experienced an increase the anterior shear force. Decreased knee joint flexion and knee valgus increase the knee valgus moment. These forces place stress on the ACL and MCL. Increased fitness levels can have a positive impact on knee kinematics and kinetics. The outcomes of this study support that the dancers with greater respiratory fitness and muscular strength can take longer to fatigue and have a lower injury incidence due to better neuromuscular control of their knee joint at landing. This study shows that fitness is a moderator of knee joint motion, and that increasing a dancer's fitness may help to decrease the risk of knee joint injury to the supporting soft tissues.

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IRB1 #00002205
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November 26, 2018

Steven Leigh, PhD
Marshall University, School of Kinesiology

RE: IRBNet ID# 1348790-1
At: Marshall University Institutional Review Board #1 (Medical)

Dear Dr. Leigh:

Protocol Title:	[1348790-1] Fatigue-related jump landing knee injuries in dancers	
Expiration Date:	November 26, 2019	
Site Location:	MU	
Submission Type:	New Project	APPROVED
Review Type:	Expedited Review	

In accordance with 45CFR46.110(a)(4)(6)(7), the above study and informed consent were granted Expedited approval today by the Marshall University Institutional Review Board #1 (Medical) Chair for the period of 12 months. The approval will expire November 26, 2019. A continuing review request for this study must be submitted no later than 30 days prior to the expiration date.

If you have any questions, please contact the Marshall University Institutional Review Board #1 (Medical) Coordinator Trula Stanley at (304) 696-7320 or stanley@marshall.edu. Please include your study title and reference number in all correspondence with this office.

CHILD'S ASSENT FOR BEING IN A RESEARCH STUDY

Jumping, Landing, and Knee Injuries in Dancers

Steven Leigh, PhD, AMInstP, Principal Investigator
Megan Holton, ATC, Co-Investigator

Why are you here?

We are asking you to take part in a research study because we are trying to learn more about the risks of knee injuries in dancers. We are inviting you to be in this study because you dance regularly.

Why are they doing this study?

This study is being done to see how strength, fitness, and time spent dancing affect jump landing knee forces. We are doing this because not much is known about what causes dancers to injure themselves. We want to find out how dancers can train to land safely.

What will happen to you?

Before the study begins, we will explain what we want you to do and you may ask us any questions. You will then read and sign this assent form if you are willing to be in this study. After signing this form, you will do three tests on two different days:

Day One: Strength and Fitness Tests

- You will do a strength test and a fitness test, which will take you about one hour.
- You will do these tests in Marshall University's Exercise Physiology Lab.
- You will be asked questions about the time you spend dancing each week
- You will be asked if you have had any injuries.
- You will warm-up and stretch as you normally would before dancing.
- We will measure your height and weight.
- You will start with the strength test.
- You will sit in a special chair that is like an exercise machine.
- We will put your knee in a safe position to use the machine.
- You will strap your leg into the machine tightly.
- You will practice using the machine to bend and straighten your leg.
- You will bend and straighten your leg 6 times slowly, and then rest for 2 minutes.
- You will bend and straighten your leg 15 times quickly, and then rest for 10 minutes.
- You will do the fitness test after you have rested from the strength test.

- We will record your heart beat using a clip we put on the end of your finger.
- You will step up and down onto a low step to a beeping noise for 4 minutes.
- We will measure your heart beat again using a clip we put on the end of your finger.
- You will step up and down onto a medium step to a beeping noise for 4 minutes.
- We will measure your heart beat again using a clip we put on the end of your finger.
- You will step up and down onto a tall step to a beeping noise for 4 minutes.
- We will measure your heart beat again using a clip we put on the end of your finger.
- You will cool-down and stretch, and the test will be over for the day.

You will rest for at least 1 day before doing the jump landing test. This is for you to recover from the fitness and strength tests, so they will not affect the way you move when you dance.

Day Two: Jump Landing Test

- You will do a jump landing test, and it will take you about one hour to complete.
- You will do these tests in Marshall University's Biomechanics Lab.
- You will warm-up and stretch as you normally would before dancing.
- We will put shiny stickers on your feet, knees, hips, and back.
- Special video cameras around the room and special scales in the floor will record your jumps and landings.
- You should jump and land like you do in a dance practice.
- You will run and jump three times from your left leg and onto your right leg.
- You will run and jump three times from your right leg and onto your left leg.
- You will do some dance moves to a beeping noise. Every four minutes the beat will get faster. You will stop when you can't move as fast as the beep.
- You will run and jump three times from your left leg and onto your right leg.
- You will run and jump three times from your right leg and onto your left leg.
- You will cool-down and stretch, and the test will be over.

Will the study hurt?

There is a chance you could get hurt because of this study. You should talk with us about this if you have questions about injuries.

Your muscles may feel sore after the fitness and strength tests, similar to after exercising. You may pull a muscle, sprain a joint, or break a bone when you jump and land. There may also be other side effects that we cannot predict. You should tell us about any medicine or vitamins you take, and any injuries or surgeries you have had in the past. No funds have been set aside to give you money for any injury that happens while doing this study.

Will the study help you?

We hope the information learned from this research study will help dancers in the future. The good things that come from doing this study may be: understanding how your strength, fitness, or movements may put you at risk for an injury. Help us learn how to design exercises and instructions to help dancers land safely.

What if you have any questions?

You can ask any questions that you have about the study. If you have a question later that you didn't think of now, you can call me **Megan Holton at (304) 696-5034** or **Steven Leigh, PhD at (304) 696-5405** or ask me next time.

Do your parents know about this?

This study was explained to your parents and they said that you could be in it if you want. You can talk this over with them before you decide.

Do you have to be in the study?

You do not have to be in the study. No one will be upset if you don't want to do this. If you don't want to be in this study, you just have to tell them. You can say yes now and change your mind later. It's up to you.

Putting a checkmark by the word YES and writing your name after that means that that you agree to be in the study, and know what will happen to you. If you decide to quit the study all you have to do is tell the person in charge.

____

You have talked to your parents and the researcher about the study. You have had all of your questions answered. You understand that you can withdraw from this study at any time and no one will be angry or upset with you. Indicate your choice below:

(Check One)

____**YES**, you want to be in the study. ____**NO**, you do not want to be in the study.

______________________	______________________	__________
Name of Child *(Print)*	Signature of Child	Date
Name of Witness *(Print)*	Signature of Witness	Date
Name of Researcher *(Print)*	Signature of Researcher	Date

PARENTAL CONSENT/PERMISSION

FATIGUE-RELATED JUMP LANDING KNEE INJURIES IN DANCERS

Steven Leigh, PhD, AMInstP, Principal Investigator
Megan Holton, ATC, Co-Investigator

Introduction

Your child is invited (with your permission) to be in a research study. Research studies are designed to gain scientific knowledge that may help other people in the future. Your child may or may not receive any benefit from being part of the study. There may also be risks associated with being part of research studies. If there are any risks involved in this study then they will be described in this consent. Your participation is voluntary. Please take your time to make your decision, and ask the research staff to explain any words or information that you do not understand.

Why Is This Study Being Done?

The purpose of this research is to understand how dancers' history, leg strength, and fitness affect their knee forces as they land from a jump to provide advice about training programs and movement patterns that could reduce their injury risk.

How Many People Will Take Part In The Study?

About 30 children will take part in this study. A total of 45 people are the most that would be able to enter the study.

What Is Involved In This Research Study?

First, we will explain the study in detail to you and your child. You should ask the researchers if you have any questions. After completing the informed consent and assent, your child will participate in the following tasks:

Day One: Strength and Fitness Tests

- Your child will perform a strength test and a fitness test, and it will take about one hour to complete both.
- These tests will take place in Marshall University's Exercise Physiology Lab.
- Your child will be asked a series of questions about the time they spend dancing each week and if they have had any injuries.
- Your child will warm-up and stretch as you normally would before dancing.
- We will measure your child's standing height and body weight.
- They will start with the strength test.

- Your child will sit in a Cybex dynamometer, which is like a leg extension or leg curl exercise machine at a gym.
- We will position your child's knee in line with a force cell.
- Your child will strap their leg into the Cybex dynamometer tightly, using a Velcro strap.
- Your child will practice using the Cybex to bend and straighten their leg against a resistance until they feel comfortable to use it for a test of their leg strength.
- Your child will do six repetitions of knee bending and straightening at a slow speed, and then rest for two minutes.
- Your child will do 15 repetitions of knee bending and straightening at a fast speed, and then rest for 10 minutes.
- Your child will do a fitness test after they have rested from the strength test.
- We will measure your child's resting heart rate using a clip we put on the end of their finger.
- Your child will step up and down onto a 4-inch step to the beat of a metronome for 4 minutes.
- We will measure your child's heart rate again using a clip we put on the end of their finger.
- Your child will step up and down onto an 8-inch step to the beat of a metronome for 4 minutes.
- We will measure your child's heart rate again using a clip we put on the end of their finger.
- Your child will step up and down onto a 12-inch step to the beat of a metronome for 4 minutes.
- We will measure your child's heart rate again using a clip we put on the end of their finger.
- Your child will cool-down and stretch, and the test will be over for the day.

Your child will rest for at least 24 hours before doing the jump landing test. This is for them to recover from the fitness and strength tests, so they will not affect the way they move when they dance.

Day Two: Jump Landing Test

- Your child will perform a jump landing test, and it will take about one hour to complete.
- This test will take place in Marshall University's Biomechanics Lab.
- Your child will warm-up and stretch as they normally would before dancing.
- We will stick reflective markers onto your child's feet, knees, hips, and back.
- Special video cameras all around the room will be used to record your child's jumps and landings. These cameras record the positions of the reflective markers only.
- Your child's landings will also be recorded by two force plates placed in the floor of the lab.
- Your child should use a strong effort to jump and land like they would do in a dance practice.
- Your child will jump three times taking off from their left leg and landing on their right leg by running and then leaping towards the force plates. Your child's right foot should land on the force plates each time.

- Your child will jump three times taking off from their right leg and landing on their left leg by running and then leaping towards the force plates. Your child's left foot should land on the force plates each time.
- Your child will complete a dance exercise routine to the beat of a metronome that consists of plies, lunges, hops, and turns. Every four minutes the beat will get faster. Your child will stop when they can no longer keep to the beat, or after 16 minutes.
- Your child will jump three times taking off from their left leg and landing on their right leg by running and then leaping towards the force plates. Your child's right foot should land on the force plates each time.
- Your child will jump three times taking off from their right leg and landing on their left leg by running and then leaping towards the force plates. Your child's left foot should land on the force plates each time.
- Your child will cool-down and stretch, and the test will be over.

How Long Will Your Child Be In The Study?

Your child will be in the study for about two hours on two different days.

You or your child can decide to stop participation at any time. If you decide to stop your child's participation in the study we encourage you to talk to the study investigator or study staff as soon as possible.

The study investigator may stop your child from taking part in this study at any time if he/she believes it is in your child's best interest; if your child does not follow the study rules; or if the study is stopped.

What Are The Risks Of The Study?

There may be these risks: Musculoskeletal or bone injuries and soreness.
Your child's muscles may feel sore after the fitness and strength tests, similar to after exercising. Muscle strain and ligament or tendon sprain may occur, because the jump landing is a dynamic movement that requires high effort. No funds have been set aside to compensate for any injury for participating in this study.

There may also be other side effects that we cannot predict. You should tell the researchers if any of these risks bother or worry you.

Are There Benefits To Taking Part In The Study?

If you agree to allow your child to take part in this study, there may or may not be direct benefit to them. We hope the information learned from this study will benefit other people in the future. The benefits of participating in this study may be: an understanding of movement or strength or fitness factors that may be putting you at risk for an injury. Advice about training programs and movement patterns that could reduce your injury risk.

What About Confidentiality?

We will do our best to make sure that your child's personal information is kept confidential. However, we cannot guarantee absolute confidentiality. Federal law says we must keep your child's study records private. Nevertheless, under unforeseen and rare circumstances, we may be required by law to allow certain agencies to view your child's records. Those agencies would include the Marshall University IRB, Office of Research Integrity (ORI) and the federal Office of Human Research Protection (OHRP). This is to make sure that we are protecting your child's rights and safety. If we publish the information we learn from this study, your child will not be identified by name or in any other way.

What Are The Costs Of Taking Part In This Study?

There are no costs to you for allowing your child to take part in this study. All the study costs, including any study tests, supplies and procedures related directly to the study, will be paid for by the study.

Will You Be Paid For Participation?

You will receive no payment or other compensation for your child's participation in this study. No funds have been set aside to compensate for any injury sustained while participating in this study.

What Are Your Rights As A Research Study Participant?

Taking part in this study is voluntary. You may choose not to allow your child to take part or you may withdraw them from the study at any time. Refusing to participate or leaving the study will not result in any penalty or loss of benefits to which you or your child are entitled. If you decide to stop your child's participation in the study we encourage you to talk to the investigators or study staff first.

Whom Do You Call If You Have Questions Or Problems?

For questions about the study or in the event of a research-related injury, contact the study investigators, **Steven Leigh, PhD at (304) 696-5405** or **Megan Holton at (304) 696-5034**. You should also call the investigators if you have a concern or complaint about the research.

For questions about your rights as a research participant, contact the Marshall University IRB#1 Chairman **Dr. Henry Driscoll or ORI at (304) 696-7320**. You may also call this number if:

- You have concerns or complaints about the research.
- The research staff cannot be reached.
- You want to talk to someone other than the research staff.

You will be given a signed and dated copy of this consent form.

SIGNATURES

You grant permission for your child ___________________________________ to take part in this study. You have had a chance to ask questions about this study and have had those questions answered. By signing this consent form you are stating that you are not giving up any legal rights to which you or your child are entitled.

____
Parent Name (Printed)

____ _________________
Parent Signature Date

____
Person Obtaining Consent (Printed)

____ _________________
Person Obtaining Consent Signature Date

DANCE HISTORY QUESTIONNAIRE

How many years have you been dancing?

What styles of dance have you studied?

Do you prefer one style of dance?

How many hours a week do you spend in practice?

How many hours a week do you spend in rehearsal?

How often do you compete in dance competitions?

Have you ever missed multiple practices due to an injury?
If so, how much time did you miss?

Have you ever had surgery due to an injury?
If so, which joint was injured?

RESUME

MEGAN HOLTON, ATC

14389 Bassett, Livonia MI
734-516-2321
megan.holton10@gmail.com

Education

Marshall University **Aug 2017-Present**

- Masters of Exercise Science Expected Completion May 2019
- Graduate Assistant Athletic Trainer
- Teaching Assistant
- Athletic Training Students Preceptor

Eastern Michigan University **Graduation 2017**

- Bachelor of Science in Athletic Training
- Dean's List 2015, 2016

Athletic Training Experience

Athletic Training Student, Eastern Michigan University

Dean College- Palladino School of Dance Jan 2017-April 2017

- Uncertified Internship
- Assisted in prevention, evaluation and rehabilitation of dance and theater majors
- Maintained accurate records of treatments
- Provided coverage for multiple dance performances

Skyline High school Aug 2016-Dec 2016

Stevenson High School Jan 2016-May 2016

- Assisted in daily duties of prevention, evaluation and rehabilitation of athletic injuries
- Maintained accurate records of treatments and injuries
- Oversaw multiple varsity sports teams games and practices
- Baseline concussion testing and hydration assessment

Mercy Elite Sports Performance and Physical Therapy Jan 2016-May 2016

- Assisted in rehabilitation of injuries of athletes and patients
- Coordinated with Athletic Trainers and Physical Therapists to crease fitness classes and plans for sports performance of athletes and teams
- Helped to plan and implement exercises to reduce player injuries
- Assisted in modifying exercises for patients in physical therapy

St. Mary Mercy Hospital Jan 2016-May 2016

- Assisted with inpatient rehabilitation, occupational therapy and speech and language pathology
- Observed in general medical office
- Observed orthopedic surgery

Eastern Michigan Crew Team Sept 2015-Dec 2015

Eastern Michigan Softball Team Jan 2015-May 2015

- Assisted in pre-participation physical evaluations
- Assisted with game and practice coverage
- Provided coverage for preseason and off season camps
- Assisted in prevention, evaluation and rehabilitation of athletic injuries
- Assisted in writing end of season reports

Related Employment Experience

Mercy Elite Physical Therapy Aide

- Assisted physical therapists with patients and required paperwork
- Performed daily cleaning duties and office work
- Additional day to day tasks

Eastern Michigan University Sports Camps

- First Aid and first responder for football, soccer and various sports camps
- Filed paperwork and filled out injury reports as needed
- Assisted in hydration and nutrition of athletes

Memberships/Certifications

- CPR and First Aid 3/2016-present
- National Athletic Trainers' association member 2014-present
- Great Lakes Athletic Trainers' Association 2014-present
- Michigan Student Athletic Trainers; Association 2014-present
- Sigma Sigma Sigma Sorority 2013-present

References Available Upon Request