COMPARISONS IN PHYSICAL CHARACTERISTIC OF PROFESSIONAL BALLET AND COLLEGIATE DANCERS

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Dancers are a group of athletes with unique physical and performance characteristics. Dance medicine and science is a growing field, as researchers and clinicians see the need for information specific to this population due to high injury rates. Comprehensive information on separate types of dancers, especially collegiate dancers, is unavailable. The purpose of this study was to describe and compare characteristics of professional ballet and collegiate dancers, as well as investigate the relationships among these characteristics. The first portion of the study investigates differences in body composition, lower extremity and trunk muscular strength, dynamic postural stability, and landing kinematics of professional ballet dancers and collegiate dance majors. The second portion of the study determines the ability of strength to predict dynamic postural stability and kinematic variables that are potential risk factors for injury including, knee valgus, ankle inversion, and foot pronation.

Fifty nine dancers participated in the study (30 professional ballet and 29 collegiate). Equal proportions of males and females were in each group. Dancers completed an injury history questionnaire, followed by assessments of body composition, dynamic postural stability, kinematics during a dance jump task, and isokinetic and isometric muscular strength.

Results demonstrate that professional dancers are significantly stronger than collegiate dancers for most muscle groups tested. The study found no significant differences in dynamic postural stability, and minimal differences in kinematics. No differences were found in self-reported injury histories, except that a greater proportion of professional dancers reported injuries to the ankle, and foot and toe regions. Regression analyses revealed that gender and trunk rotation strength predicted dynamic postural stability. Gender and knee flexion strength predicted maximum knee valgus angle. Gender and knee extension strength predicted ankle inversion angle at initial contact and, gender and knee flexion strength predicted maximum inversion angle. No significant predictors of foot pronation angle were found. This study provides a comprehensive assessment of professional ballet and collegiate dancers and provides insight into the relationships among their characteristics and abilities. Further research should investigate relationships in each gender separately, as well as study additional variables that explain the relationship between strength and biomechanics.

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PREFACE

I would like to thank those who have helped me throughout the process of earning my PhD. Firstly, I thank my dissertation committee for their openness to my topic of research. Dance medicine and science was new to them, but they were fully supportive of my passion for working in this area. They were adaptable, insightful, and encouraging as they guided me in becoming a researcher. I would especially like to thank my committee chair, Mita Lovalekar, for her persistence and dedication as I completed all phases of the project. The graduate students at the Neuromuscular Research Laboratory all deserve a special thank you for providing support for both work and morale. I have learned a lot from their different backgrounds and perspectives, and would not have made it through classes, data collection, and data processing without them. I have developed great lasting friendships with my colleagues in the lab, and wish those that are still completing their work the best of luck. You will finish.

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and coaches, and part to my parents, Mark and Patty Williams. I thank my Mom and Dad for spending countless hours editing my papers and reviewing my math homework during primary school. At the time I hated this, but in the end I must have liked it for staying in school for so many more years. Thank you Mom and Dad for loving and supporting me through it all, and yes I am finally done. Lastly, I would like to thank my fiancé, David, for his love and support. He met me during the final stages of my PhD while completing my dissertation, when I am sure I was not at my best, and still wanted to marry me. For that, I am the luckiest.

1.0 INTRODUCTION

Dance is a performing art in that it requires great artistic ability, but is also similar to a sport given the physical requirements.[1] Some movements are very unique to dance while others are similar to athletics. The specific techniques and standard movements, as well as expressive and creative qualities and requirements create a challenging context in which dancers work. For many dancers, dance is their passion and artistic outlet, as well as their vocation. Because of the highly artistic and physically demanding requirements, dancers are a unique type of athlete and are referred to as performing athletes.[1-3] Dancers sustain a high rate of musculoskeletal injuries related to their activity each year, and as such, dance medicine and science have recently emerged in the field of sports medicine with the purpose of keeping dancers healthy and injury free.[4] In the field of dance there are multiple genres, which generally include ballet, modern, and jazz. Dancers often begin training at a young age and progress through training in dance schools until the end of adolescence. If a young dancer is especially talented they may wish to further pursue their career by auditioning for a professional company or collegiate program. Most of the research has included studies on professional dancers and often only include small sample sizes, making it difficult to make comprehensive assessments and compare groups.[1,4-6]

Clinicians, researchers, and dance educators strive to reduce injury incidence and quickly rehabilitate injuries when they do occur. To understand how and why dance injuries occur, one must begin by understanding the physical characteristics of dancers. While there will be variability among different types of dancers based on genre and level of training, when compared to other athletes and the general population, dancers have unique body composition, aerobic capacity, anaerobic capacity, joint range of motion, muscular flexibility, muscular strength, endurance, balance ability and biomechanical movement patterns.[1,7-9] While some of these characteristics are acquired through training, it is likely that some dancers advance in their field due to genetic characteristics.[10,11] In fact it is common practice for elite level dance schools to choose students to enter training with a certain somatotype and physical characteristics including high muscular flexibility and joint range of motion, knee hyperextension, and increased plantar flexion. These characteristics are potentially enhanced to a greater extent with dance training.[10] Recently researchers have shown that dancers can further improve physical ability with supplemental training.[12,13] Focusing on rehabilitation and training to improve physical performance in dancers will hopefully mitigate and prevent the occurrence of injuries which are a significant problem for dancers.

1.1 INJURY EPIDEMIOLOGY IN DANCERS

Dancers sustain a high number of injuries each year.[4] Numerous authors have studied injury frequency in dancers. Injuries are a problem for dancers beginning at a young age, with 43.1% of dancers aged ten to eighteen years becoming injured over a two year period.[14] One year long study of collegiate dancers found the percentage of dancers who self-reported injuries in a year range from 67% to 77% each semester, while chart reviewed data from the onsite clinic revealed only 30% to 37% of dancers sought care each semester.[5] Annual proportions of dancers injured in professional ballet and modern companies have been reported to range from 67% to 95%.[6,15-19] Injury incidence has been reported for professional dancers in various ways. High injury incidence has previously been reported in professional ballet dancers, with the highest values ranging from 3.2 injuries per dancer per season and 4.44 injuries per dancer per 1,000 dancing hours.[19,20] A recent systematic review of injuries in professional ballet dancers found the injury incidence from combined data from multiple studies, which meet inclusion/exclusion criteria for the analyses to be 1.24 injuries per 1,000 dancing hours.[21] In professional modern dancers injury incidence has been reported to be lower, with 0.48 to 0.58 injuries per dancer per 1,000 dance hours.[6,15] The difference between the two studies on professional ballet dancers with very high injury incidence and the two on modern dancers is that the former included all injury reports and visits; the later included only injuries that resulted in the filing of health insurance claims. The injury types and severity of injuries are similar in professional dancers with the most common types of injuries being overuse injuries that do not often involve full cessation of dance activities including class, rehearsal and performance.[6,15,19,20] Traumatic injuries are less common, however they are very costly.[16,18] Similarly, recurrent injuries, minor injuries and overuse injuries still contribute costs to dance companies and to dancers themselves using their private insurance.[6,16,22,23] The most commonly injured locations are similar across studies on many types of and levels of dancers. They include the foot and ankle, lower leg, lower back, hip, and thigh followed by the rest of the spine and upper extremities.[4,5,14,15,19,20,24,25]

1.2 PHYSICAL AND NEUROMUSCULAR CHARACTERISTICS OF DANCERS

Deficits in physical abilities can lead to injury, especially in the context of the dance work environment. One aspect of sports medicine research focuses on physical characteristics considered neuromuscular in nature. These neuromuscular characteristics include muscular strength, postural stability, and biomechanics. They require muscular ability as well as neural control and coordination to execute planned movements and react to unexpected perturbations.[26-28] It is likely that by understanding these characteristics specifically in dancers, we can begin to identify risk factors for injuries, leading to the development of better rehabilitation and injury prevention programs for that population.

1.2.1 Muscular Strength

Muscular strength is one of the components of physical fitness and also required for athletic performance. In dance, muscular strength is required for leaping, jumping, maneuvering, holding the leg off the ground for periods of time, and maintaining balance in various positions.[9] Despite these performance requirements, some studies have found that dancers have lower strength than other athletes and healthy controls.[29-31] Dance training alone may not be enough to develop optimal strength. This may be related to a general idea within the dance culture that strength training will lead to a “bulky” appearance, decreasing the desired artistic aesthetic for dancers. Many dancers are fearful of appearing too large and may avoid strength training.[32] These fears are unfounded and unfortunate, because stronger dancers have been found to have fewer injuries.[25,33-35] Additionally, strength training for dancers has been found to improve their strength and performance without interfering with the artistic and physical requirements.[10,12,33,36] Other studies have found that strength and plyometric training can improve both fitness and aesthetic for dance.[13,37] Currently in the field of dance medicine there is a push to improve the strength of dancers and change the negative bias against strength training in order to improve fitness and reduce the risk of injury.

The research available indicates that dancers may have inadequate strength of their lower extremities and may benefit from strength training to reduce injury rates.[1,12,25,33,34,36,38,39] The studies available on dancers are limited, but studies in other athletic populations have more clearly demonstrated that there is a relationship between lower extremity muscular strength and injury, which have important implications in the field of dance medicine and science. In female athletes, a trend towards those with knee extension and knee flexion strength imbalances experiencing higher injury rates has been identified.[40] Hip abductor and adductor strength imbalance is related to increased risk of adductor muscular strains in professional hockey players.[41] Similarly, sprinters with weakness of their hamstrings compared to their quadriceps were more likely to sustain hamstring injuries.[42] Athletes with weakness and muscular imbalance of the ankle musculature have a higher incidence of ankle sprain.[43] Those with patellofemoral knee pain have weakness of their hip abductors and external rotators compared to those without this common knee pathology.[44] In other athletes, maintaining adequate hamstring strength in relationship to quadriceps strength has been promoted to reduce the risk of anterior cruciate ligament (ACL) injury of the knee [45,46] It has also been proposed that adequate strength of the trunk musculature protects the spine from injury as well as helping with maintaining proper alignment of the body during movement, and keeping alignment over the base of support.[47] The trunk musculature is thought to provide a strong center from which the extremities can move.[48]

These factors related to the trunk musculature have been proposed to have a protective relationship with lower extremity injuries.[49-51]

Sports medicine literature suggests the importance of investigating the strength of multiple muscle groups in the lower extremities and the trunk as risk factors for injuries. However, information available on dancers' strength is incomplete. Most studies on dancer strength measures strength of the thigh musculature; the quadriceps and in some instances also includes hamstrings.[31,33,34,36,52-55] Few studies have investigated strength of the hip and trunk musculature in dancers.[56,57] Surprisingly, literature available on the ankle strength of dancers is very limited even though this is a commonly injured area.[58,59] In relation to injury, deceased strength of the quadriceps measured with an isokinetic dynamometer was correlated with increased number of injuries.[34] This study was limited in that it used a small sample size and only measured one muscle group. Other larger studies investigating the relationship between strength and injury risk have used fairly subjective manual muscle testing procedures and have been completed on young student dancers.[25,35,39] While this provides useful insight, studies investigating the relationship between strength and injury in adult dancers are important for making inferences about a skeletally mature population. A more comprehensive description of dancers' strength is needed since they do experience injuries at multiple locations especially in the lower extremities and spine.[4]

1.2.2 Postural Stability

Dancers require postural stability for dance performance. Generally, balance is the ability to maintain the center of mass over the base of support.[28] When a subject is able to maintain balance with minimal movement, they have better postural stability.[60] In all types of athletics, increased postural stability is considered an indicator of better performance, but especially so in dance. In fact, the ability to quickly establish and maintain postural stability often over a small base of support, is characteristic of and required for ballet and most other genres of dance.[61,62] Studies on professional dancers indicate they have high postural stability performance.[63-67] Studies have compared professional to amateur or student dancers and demonstrate professionals have higher postural stability.[7,68] Within the literature comparing different types of dancers and comparing dancers to other types of athletes, different testing procedures have been used making direct comparisons between groups difficult. However, overall research suggests that dancers have better postural stability than team sport athletes and healthy controls.[7,67,69-72] They have been found to have high postural stability along with gymnasts and marital artists.[65,73] This is not surprising because it is a requirement for many of the tasks and movements in these activities. As dancers train to improve their technique and performance they are likely training the systems responsible for maintaining postural stability more than other athletes.[64,74]

In addition to being an indicator of performance ability, decreased postural stability has an important relationship with injury. Sports medicine research has demonstrated that postural stability assessment is able to discriminate between those with functionally stable and unstable ankles, and those who have previously been injured.[75] Furthermore, dancers who have had an ankle injury in the past year have worse postural stability than those who have not.[76] In other types of athletes, prospective studies have identified that those with worse postural stability are more likely to sustain a lower extremity injury.[77-81] Even though dancers likely have better postural stability than other athletes, it is important to continue research in this area because dancers may require a higher level of postural stability that is specific to their population because of the tasks which they regularly perform.[61,62,64] Examples of tasks that require and challenge postural stability due to a small base of support include balancing on one leg with a flat foot or on the ball of the foot (metatarsal heads) or tip of the toes (for women only). Dancers also need postural stability when performing many types of one legged jumps and turns which required stabilization after landing and while their body is rotating. Higher level of accomplishment in dance is related to better balance ability. Professional dancers have been found to have better balance than amateur dancers.[7,68] It is unknown if differing postural stability in different levels of dancers' affects injury risk. Hutt et al.,[62] found that a dance specific progressive balance training program utilizing eyes closed tasks improved postural stability in dancers.[62] To improve dance technique and performance ability, as well as decrease the risk of injury, dancers may need to utilize greater training challenges to achieve greater postural stability.

Just as training exercises to improve postural stability in dancers may need to be more challenging and specific to dance, the tests used to measure and describe postural stability in dancers may also need to be appropriately selected. Many studies on dancers have included investigation of static balance or simple movement tasks, which may be important factors, but may also be a relatively easy task for dancers to complete. These types of tests may be limited in their ability to determine the significance of postural stability as a risk factor of injury because it may not be specific to tasks when injuries occur. Allen et al.,[23] found that many injuries to dancers occur during movement tasks. Specifically, Liederbach et al.,[82] found that all ACL injuries in dancers occurred while landing from a jump. This is supported by other sports medicine literature that has found many injuries occur during dynamic tasks.[83-86] The investigation of dynamic postural stability will be useful because it more closely represents the dynamic tasks of sport and performance.[87]

1.2.3 Biomechanics

Biomechanics during performance of the activity is another important factor related to sport injury. Studies involving biomechanics investigate the position of and forces acting upon the body during movement. It is thought that certain movements and poor positioning of the body throughout the kinetic chain can lead to injuries because positioning of the trunk over the legs is thought to impact alignment of the lower limbs.[47,51] A significant amount of research has been done on biomechanics in relation to injury at the knee. [83,88-93] Increased knee valgus motion and moments during landing predict ACL injury in female athletes.[88] Other biomechanical factors found to be related to ACL injury include; decreased hip and knee flexion during landing, decreased tibial internal rotation and increased femoral internal rotation during landing, as well as increased knee extension at initial contact.[83,88,89] Similar patterns are also thought to be related to the development of patellofemoral pain.[90,91] Landing strategy has also been found to be related to patellar tendinopathy. Those with history of patellar tendinopathy displayed stiffer landing mechanics at the knee and ankle compared to controls.[92] Similar findings were seen in dancers with patellar tendinopathy who had higher ground reaction forces when landing than those without the pathology.[93] Ankle sprains are a significant problem for dancers, as well as all other athletes. Inversion ankle sprains are the most common type of ankle sprain, occurring with increased ankle inversion motion, often during landing.[94,95] A study investigated the landing patterns of recreational athletes who had a history of ankle sprain and divided them into three groups; mechanically unstable after ankle sprain, functionally unstable after ankle sprain, and coper with ankle sprain. They found that those with mechanical instability display landing patterns at the ankle that are different from the others and may be deleterious to the ankle joint.[96]

Some research has shown that dancers display different movement patterns than other athletes when they are landing and jumping. In fact, at the knee, professional dancers do not display risky movement patterns or have the gender differences observed in other groups of athletes.[2,3,8,82] Furthermore, both collegiate and professional dancers experience fewer ACL injuries than other athletes, which may be because dancers spend a considerable amount of time practicing and rehearsing dance movements in technique class and rehearsals for performances.[69,82,97,98] They are trained to land well; softly and with proper alignment of the knee. Still, dancers experience knee and other lower extremity injuries. ACL injuries occurring during sports often occur during unplanned or reactive movements.[83,84] During reactive movements, there are altered knee joint kinematics and joint loading that may contribute to injury.[99] It is possible that biomechanical risk factors for these injuries are present at additional joints, reinforcing the importance of looking at other joints in the kinetic chain. Kulig et al.,[100] demonstrated the importance of looking at the entire kinetic chain during a dance specific task found that dancers with Achilles tendinopathy had increased hip adduction and increased knee internal rotation during a dance jump.[101] In reviewing the literature on biomechanics of dancers, studies describing biomechanics in professional dancers have used traditional sport research tasks such as drop landings.[2,3,8,102] This is useful in that they included larger sample sizes and allowed researchers to compare dancers to other athletes, but this task may not be specific to dance movements. Some studies have included collegiate dancers performing various dance jump tasks.[93,100,101,103] These studies are important in describing dancers performing specific tasks, but have been limited in that they have used smaller sample sizes. Moving forward, it will be useful to compare different types of dancers performing the same task.

1.3 COMPARISIONS BETWEEN PROFESSIONAL AND COLLEGIATE DANCERS

Much of the literature in the field of dance medicine has been completed on professional dancers.[4] Epidemiological studies on injury frequency, incidence, type, severity and location have included professional ballet and modern dancers.[6,16-20,22,24,104] There have also been several studies on injury epidemiology in young student dancers, however this group should be considered separately from adult dancers.[14,25,105,106] Another group of adult dancers are collegiate level dancers, who are continuing their dance education and training as dance majors at colleges and universities. To the authors knowledge, there have only been two studies that have reported the annual occurrence of injuries and described common injury locations in collegiate dancers.[5,107] Currently, many dance medicine researchers and clinicians make inferences about collegiate dancers based on literature published on professional dancers. It would be beneficial to the collegiate dance cohort, and clinicians working with this group, if there was more information regarding the injuries they sustain.

Similarly, research on physical characteristics, for descriptive purposes or in relation to injury in dancers, has been completed predominately on professional dancers. This includes studies that have investigated muscular strength, postural stability and biomechanics. Sports medicine literature suggests these are important characteristics to study as potential risk factors for injury. The strength literature available on dancers described previously included mostly subjects who were professional dancers.[9,31,33,34,36,55,57] A few studies have included collegiate dancers, but none have directly compared them to professional dancers.[53,54] Chmelar et al.,[52] included both professional and collegiate level dancers, which they reported on together for study results. Further investigation into the strength data tables from their study suggests that there may be differences between the type of dancers (professional and collegiate). In the literature regarding the postural stability of dancers several descriptive studies indicating dancers have high postural stability were completed on professional dancers.[7,63-68] A few more studies have been completed on collegiate level dancers and indicate their postural stability is not as high as professional dancers, but are higher than some types of other athletes and control subjects.[7,70-72] There have been more studies in the dance biomechanical literature that include collegiate level dancers.[93,100,101,103] However, within both postural stability and biomechanical literature multiple testing procedures, which are not always specific to dance tasks, have been used. This makes directly comparing groups difficult. There is limited information on collegiate level dancers. It would be beneficial to further study this group of dancers because their strength, postural stability and biomechanical patterns may be different from professional dancers. This may indicate separate training and rehabilitation needs.

1.4 DEFINITION OF THE PROBLEM

The field of dance medicine is under-researched compared to other sports. Currently, most research has been done on professional ballet dancers. Collegiate level dancers are also important to consider. Some physical characteristics and performance requirements are similar across these different groups of dancers, especially in comparison to other types of athletes and the general population. However, within the field of dance there have been few studies directly comparing different types or levels of dancers. Being able to fully understand each group of dancer is important for the clinicians and instructors who work with them. Furthermore, research describing the physical characteristics of dancers, especially with neuromuscular characteristics that may be risk factors for injury is limited in the muscle groups and tasks studied. Specifically, adequate data to describe the neuromuscular characteristics of muscular strength, dynamic postural stability, and biomechanics during dance jumps are not available. Furthermore, the relationship among these variables is not fully understood. Having a better understanding of all types of dancers and multiple neuromuscular characteristics they display will be useful in understanding their risk for injury and performance abilities.

1.5 PURPOSE

The purpose of this study was to describe and compare body composition, lower extremity muscular strength, trunk muscular strength, dynamic postural stability, lower extremity landing kinematics during a dance jump, and injury histories between professional ballet and collegiate dancers. It also determined the ability of the strength variables to predict dynamic postural stability and kinematic variables that have previously been found to be risk factors for injury.

1.6 SPECIFIC AIMS AND HYPOTHESES

The specific aims of this study were to investigate the differences in physical characteristics and self-reported orthopaedic injury history between professional ballet and collegiate dancers. The relationships among physical characteristics, specifically the ability of the strength variables to predict dynamic postural stability and landing kinematics was also be investigated.

Specific Aim 1: To describe physical characteristics and orthopeadic injury histories of professional ballet and collegiate dancers and determine if differences exist between these groups.

Hypothesis 1a: Professional dancers will have significantly lower percent body fat than collegiate dancers.

Hypothesis 1b: Professional dancers will have significantly higher trunk muscular strength than collegiate dancers.

Hypothesis 1c: Professional dancers will have significantly higher lower extremity muscular strength than collegiate dancers.

Hypothesis 1d: Professional dancers will have significantly better dynamic postural stability than collegiate dancers.

Hypothesis 1e: There will be a significant difference in lower extremity landing kinematics between professional and collegiate dancers at the trunk, pelvis, hip, knee, ankle, rearfoot and forefoot.

Hypothesis 1f: A significantly greater proportion of professional dancers as compared to collegiate dancers will have self-reported history of injury in their total injury history and in the past one year.

Hypothesis 1g: Professional and collegiate dancers will have significantly different proportions of injuries reported at different body regions.

Specific Aim 2: To determine if lower extremity and trunk muscular strength predict dynamic postural stability.

Hypothesis 2a: Lower extremity and trunk muscular strength will significantly predict dynamic postural stability. As muscular strength increases, dynamic postural stability will improve.

Specific Aim 3: To determine if lower extremity muscular strength predicts lower extremity kinematics when landing from a dance jump task. The kinematic variables of interest are knee valgus, ankle inversion and foot pronation.

Hypothesis 3a: Knee valgus at initial contact will be predicted by strength of the lower extremity musculature. As strength decreases, knee valgus angle at initial contact and maximum angle during landing will increase.

Hypothesis 3b: Maximum knee valgus ankle during landing will be predicted by strength of the lower extremity musculature. As strength decreases, maximum knee valgus angle during landing will increase.

Hypothesis 3c: Ankle inversion at initial contact will be predicted by strength of the lower extremity musculature. As strength decreases, inversion at initial contact will increase.

Hypothesis 3d: Maximum ankle inversion will be predicted by strength of the lower extremity musculature. As strength decreases, maximum inversion during landing will increase.

Hypothesis 3e: Foot pronation at initial contact will be predicted by strength of the lower extremity and trunk musculature. As strength decreases, foot pronation angle at initial contact will increase.

Hypothesis 3f: Maximum foot pronation angle will be predicted by strength of the lower extremity and trunk musculature. As strength decreases, maximum foot pronation during landing will increase.

1.7 STUDY SIGNIFICANCE

This study helped to more thoroughly describe the physical characteristics and orthopaedic injury histories of both professional ballet dancers, including lower extremity and trunk muscular strength, dynamic postural stability, and kinematics landing from a dance jump. Data on these characteristics are currently limited. It provided insight into which variables may be associated with injury and need to be investigated further. This can help direct future research by indicating which variables may be important to include in prospective risk factor analysis and intervention studies aimed at different types of dancers. The finding of this study will be helpful for clinicians working with different types of dancers by determining which characteristics may need to be addressed with rehabilitation or supplemental training programs. These types of programs may need to be different for different types of dancers, depending on the variables where significant differences are found. This study makes significant contributions to dance medicine literature because it investigates the relationship among these characteristics; specifically if strength can predict dynamic postural stability and landing kinematics that may increase the risk for knee and ankle injury. This information provides insight into the relationships among variables and help explain if performance in one area predicts performance in another. This information can potentially aid clinicians in developing strengthening programs that could improve dynamic postural stability and landing biomechanics.

2.0 REVIEW OF LITERATURE

It has been well reported that dancers are a unique group of athletes in that they have both high physical performance demands and aesthetic performance requirements.[1] The physical and performance characteristics are specific to the requirements of dancing. Similar to other groups of athletes they experience musculoskeletal injuries from their physical performance. The physical characteristics of dancers and types of musculoskeletal injuries they sustain can be discussed generally to describe this group as a whole, as well as by the genre of dance and level of training of dancers. It is important for clinicians and researchers working with dancers to have a broad understanding of this group and then focus on the specific qualities of a particular sub-group with which they may be working.

2.1 BACKGROUND ON DANCE TRAINING AND PERFORMANCE

2.1.1 Basic Dance Technique Overview

Dancing involves a plethora of different types of movements. Most dancers will train in ballet for basic technique in their careers. Classical ballet has set positions of the feet and legs from which steps and movements are based. These positions are used throughout a dancers training and career. Even dancers in other genres than ballet will be familiar with these positions, as they are used in all types of dance. The basic five positions of dance are displayed in Figure 1.[108]

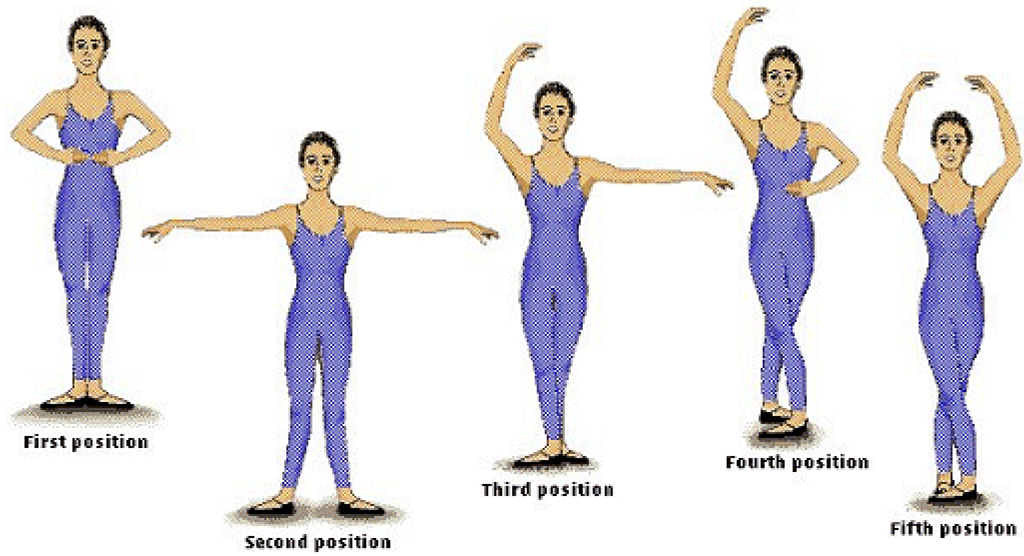


Figure 1: Basic Dance Positions

Generally dance classes will involve warm up movements and progression to dance combination exercises. Dance combinations will include slow dances requiring the dancer sustain elevated positions of the legs for a period of time while balancing on the other, small, medium and large traveling jumps, and turning both in place and traveling across the floor. While there are specific modern dance techniques, the dance class will have a similar flow. Modern dance will include other types of movement than classical ballet which are also fairly standardized within that genre. Different choreographers will build off these basic techniques when developing new dances for performances.

Professional and high level competitive dancers have unique physical and aesthetic demands and requirements and may vary according to the genre of dance being performed. There are numerous genres of dance including classical ballet, various modern dance techniques or styles, contemporary ballet, traditional cultural dance forms, ballroom dancing, musical theater production dancing, and recently hip hop and breakdancing has emerged as a highly competitive dance form.[1,4,15,104,109,110] Dance training often begins early in childhood and will become more rigorous between the ages of 10-12 if the dancer is inclined to begin a progression towards highly competitive and professional dance.

2.1.2 Professional Dance

From the time training intensifies the goal of many dancers is to train at an elite level and attain a job in a professional company. This requires training in competitive schools through the teenage years, after which most dancers are expected to begin work with a professional company. Entry into prestigious dance schools and all professional companies requires rigorous auditions. Dancers are selected based on their technical ability, physical appearance, and artistic performance. Some dancers may work at the pre-professional level for a few years in their late teens to early twenties, after which time they would join a company. This pathway to professional dance is typical for classical ballet and many modern and contemporary companies. Professional dancers will most often focus on one genre of dance and style for their particular company. Their job will entail daily technique classes in their respective genre of dance as well as rehearsal. However, it is becoming more common for dancers to rehearse and perform other types of dance for some performances during the company season. Professional dance companies can have a large amount of variability in size, season length and number of performances. A recent report has combined data from ten professional dance companies (six ballet and four modern) in the United States. In this study, company size ranged from six to ninety dancers, annual company budget was from $750,000 to $15 million or greater, the number of performances per year ranged from 31 to 152, and over an average of 40 contract weeks with a range of 35 to 47 weeks.[24] The number of hours danced per week was not collected in this study, however, six out of the ten companies were members of the American Guild of Musical Arts (AGMA), a labor union for performing artists which regulates member companies.[24] AGMA regulates that dancers may not dance more than 30 hours a week, or 6 hours a day, in rehearsal and performance, or they must be paid overtime. Class time, typically 2 hours per day, is not included in these regulated hours.[111] Allen et al.[20], studied a professional ballet company in England and reported the dancers participated in 31.5 hours of dancing a week during rehearsal periods and 35.5 hours of dancing per week during performance periods of the season.[20] Shah et al.[6], found from a survey of 185 professional modern dancers from various companies that dancers reported they spent 8.3 ± 6.0 hours per week in class and 17.2 ± 12.6 hours a week in rehearsal.[6]

2.1.3 Collegiate Dance

Some dancers will choose to attend college and major in dance. This career path is found more commonly in the United States. Collegiate dancers will have similar dance backgrounds to professional dancers through their teenage years, and also compete in auditions to attain enrollment in a dance program. Their training in college will often include multiple genres of dance. Some programs will allow for a major or concentration in one type of dance. These dancers will work on a normal academic schedule with two semesters. They will complete dance and academic coursework, as well as rehearse and perform on a semester basis. Weigert et al.,[5] reported the average hours danced per week at the collegiate level to be 13.24.[5] Similarly, Martyn-Stevens et al.,[54] reported the weekly hours danced of collegiate dancers to range from 8 to 18 hours.[54] Their coursework includes dance technique of multiple genres, composition of dance, theory and history courses. These dancers are often exposed to some dance science classes which may include information about anatomy and exercise training. Collegiate dancers will also fulfill the liberal arts requirements of their school and graduate with a bachelor's degree. Upon graduation, some dancers will audition for jobs with professional companies. These are usually modern and contemporary companies. It is very rare for a collegiate dancer to go into a professional classical ballet company, as those dancers are expected to join at a younger age. Some graduates will choose to go into teaching dance for younger students or into the organizational and business aspects of the profession.

2.2 INJURY EPIDEMIOLOGY IN DANCERS

2.2.1 Injury Incidence

Dancers performing all types of dance sustain injuries. Percentages of dancers injured annually in professional dance companies range from 67% to 96%.[15-17,19,20,112] Studies on injury rates in collegiate dancers are limited. Weigert et al.[5], report that 30% of collegiate dancers were injured during the first semester and 36.4% of dancers were injured during the second semester based on site clinical data. Self-reported injury rates were higher in this group of collegiate dancers being 67% and 77% for the first and second semester respectively. This study suggests that collegiate dancers do not seek care for all of their injuries and sustain more injuries in the second semester.[5]

That is consistent with literature on professional dancers, which also suggests self-reported injuries and musculoskeletal complaints have higher frequency than injuries resulting in a workers compensation or health insurance claim, and that injury has a cumulative effect over the dance season.[6,16,20,22,23,113]

Even young dancers become injured. In fact, 50% of dancers who begin dance at age eight will sustain at least one injury by the time they are 16 years old, with the most common injuries in the youngest dancers being tendinopathy of the foot and ankle, followed by knee injuries.[106] A cross sectional study on 1,336 young dancers (mean age = 13.3 years, range 8-16 years) training in multiple dancer forms (ballet, modern, jazz), with at least 2 hours of ballet a week found that 42.6% of the dancers were injured as diagnosed through screening and subsequent evaluation by a physician specializing in dance medicine. The average hours of dance a week increased with age from 3.2 hours at 8 years, 8.8 hours at 13 years and 11.3 hours at 16 years.[106] Another study on young dancers at an elite pre-professional ballet boarding school (mean age = 14.7 ± 1.9 years) had similar results. The annual percentage of young dancers injured range from 32% to 51%, with the cumulative percentage over the study being 42%. Injuries were diagnosed by a physical therapist specializing in dance medicine and counted when the dancer came to a formal physical therapy session. The annual injury rates ranged from 0.41 to 0.67 injuries per dancer per year, with a cumulative rate of 0.55 over the five years of the study. This study also investigated injuries per exposure, which included dance classes, rehearsals and performances per week (14 exposures), as well as injuries per hours of dance per week (20 hours). For each dancer there were 1.09 injuries per 1,000 exposures and 0.77 injuries per 1,000 hours of dance.[25]

The incidence of injury increases in professional dancers. The highest injury rates reported have come from a recent prospective study, which tracked the injuries in a professional ballet company among 52 dancers (27 females, 25 males) for one year. This included 46 work weeks of dance with an average of 31.5 hours of dance during rehearsal periods and 35.5 hours during performance periods. Injuries were diagnosed by the company's physical therapist and included "any injury that prevented a dancer from taking full part in all dance-related activities that would normally be required of them for a period equal to or greater than 24 hours after the injury was sustained."[20,114,115] There was an overall incidence of 4.44 injuries per 1,000 hours of dance. There were no differences in the injury incidence between females (4.14) and males (4.76).[20] The incidence in this study is higher than previously reported in professional ballet dancers (3.2 injuries per dancer). [19] Unfortunately, this study did not report if these incidences were per hours of dance or exposures. An eight year study of a comprehensive rehabilitation program and its effects on injury incidence was completed on a professional modern dance company. Compared to other companies discussed, this one was smaller (n=30 dancers each year) with a 41 week season. For the first two years of the study no intervention was applied and the average annual percentage of dancers injured was 87%. Injury incidence was found to be much lower than reported in other studies on professional dancers and was 0.52 injures per dancer per 1,000 hours of dancing. Injuries included in the analyses were those resulting in financial outlay (workers compensation or personal health insurance claim) or time loss from dancing beyond the day of injury.[22] To the authors' knowledge, no studies have reported injury incidence per hours or exposures in collegiate dancers.

The differences in injury incidence among these studies may be due to injury occurrence variation from year to year, training and performance schedules, or physical fitness and health profiles in the dancers in the different companies. Another important factor is the injury definition. Some authors may include injuries that other authors would consider only a complaint rather than injury. Some are injuries that result in any modification of activity and others may only include those that result in cessation of activity. This difference has been discussed as a problem in dance medicine research and a call for a common injury definition has been made.[4] Another factor that could potentially alter the number of injuries reported is the access of the dancers in the company being studied to medical care and/or research team tracking injury. Ojofeitimi et al.[22], discussed that dancers with onsite medical care tend to seek care for more musculoskeletal complaints, with potential subsequent diagnosis more often that those without readily accessible care.[22] All injury rates, however, are very high demonstrating the importance of preventing injuries and providing sound rehabilitation for dancers.

2.2.2 Injury Location and Type

Even with the differences in injury incidence from different studies, the injury type and location remain very similar. Gamboa et al.[25], studied elite pre-professional ballet dancers for five years and found that the most commonly injured areas were the foot/ankle (53.4%), hip (21.6%), knee (16.1%), and low back (9.4%). Each year the majority of injuries were classified as atraumatic overuse injuries ranging from 55% to 88%.[25] Another study on young dancers found that the most common injuries included the knee (29.4 %), tendinitis of the ankle or foot (24.5%) and back injuries (16.7%).[106] These differences could be due to difference in the number of hours danced per week and type of dance training of the dancers in the different studies. In the first study the dancers danced 20 hours per week in predominately classical ballet, and those in the second study participated in fewer hours of dance a week in multiple dance forms.

As dancers' progress to more advanced levels studies on professional dance companies repeatedly report similar body regions with the highest amount of injuries. Studies show that the most injuries occur to the foot, ankle and lower leg, followed by the low back, hip, and knee.[16,19,20,22,112,116] Most recently, a combined project of several professional US dance companies reported dancers in their companies had history of orthopeadic injury in the following locations: 76% ankle, 65% foot/toes, 44% knee, 43% calf/shin, 43% lower back, 40% hip, 35% shoulder, 30% elbow/wrist hand, 24% neck, 22% upper back, 16% thigh, and 12% rib/chest.[24] Far less information is available regarding collegiate dancers, but data indicates injury location is similar in this group as well. Chmelar et al.,[107] reported 21% of injuries at the ankle, 26% at the back, 21% at the knee, 16% at the foot, 5% each at the shin, hip and hamstrings in collegiate dancers.[107] A study that included dancers at a performing arts institution (university and high school) have also reported common injury locations to be ankle 22.2%, spine 17.6%, foot 14.8%, knee 14.5%, hip 14.2%, shin splints 5.4% and other 11.4%.[117]

It has been reported that in professional modern dancers, 49% of injuries occur to joints (non-bone structures) and ligaments, 29% to muscle and tendon, 5% as fractures and bone stress, and 1-2% as contusion, lacerations and skin lesions.[22] More injuries are classified as overuse than traumatic. Overuse injuries have been reported to range from 60% to 79% of all injuries in professional dancers.[20,22,118] Percentage of annual injures reported to be traumatic are 28%, with about 1% of injures being "other" diagnoses including such things as dehydration, hyperthermia and unexplained pain.[22] Similarly, most are considered minor to moderate in severity, compared to severe injuries.[19,20,22] Severity is often classified by the number of days away from dancing. In a study on professional ballet dancers, the number of injuries when the dancer could return to full participation in less than seven days was significantly greater than those with longer duration until returning to dance ($p<0.05$).[20] The injuries resulting in loss of more than 29 days of dancing in a professional modern company was 3% and 2.5% for professional ballet dancers.[20,22] The average numbers of days modified or missed dancing due to injury in collegiate dancers was 7.27 ± 11.61 days for the first semester and 8.73 ± 16.35 days for the second semester, with a median of 3.0 days for each semester.[5]

2.3 RISK FACTORS FOR INJURY IN DANCERS

Injury is a significant problem in the dance profession. Its incidence has a significant impact on cost to the company. In a three year study on a professional ballet company, the dancers sustained a total of 309 injuries, an average of 2.97 injuries per injured dancer. The average medical cost was $1,289 per injury. It is important to note that this average is from workers compensation claims and does not include services provided by on site physicians (3 days per week) or physical therapists (5 days per week), or any self-referral and treatments sought by the dancers. The authors suggest that if those services had been billed at average rates the cost likely would be doubled.[16] This study was published in 1993 so it is reasonable to expect that the present cost per injury per dancer would be greater due to the rising cost of health care in the United States since the publication of that study. To reduce injuries it is necessary to identify and address the risk factors for injury. Some factors associated with injury that have been identified relate to the physical dance environment. Several studies have indicated that the type of floor on which dancers train and perform affects their risk of injury, with more injuries occurring on harder surfaces, inclined surfaces, or surfaces with abnormal friction.[104,119-125] Because environmental issues can be difficult for clinicians to overcome, it is important to identify other risk factors directly related to the dancer that can be controlled for or modified with treatment and prevention interventions. Other injury risk factors relate to exposure to dance and fatigue. These factors are inherent in a dance season but still important to health care providers to be aware of, when, attempting to prevent injuries and counsel dance administrative and artistic staff. Lastly, various physical characteristics have been proposed as risk factors for injury. Some of these are modifiable and others are not. Because most dancers will experience injury, knowledge of all risk factors is important to help prevent injury and re-injury.

2.3.1 History of Injury

History of injury has repeatedly been found to be associated with increased risk of new injury. In a five year study on pre-professional ballet dancers, there was a significant difference in the number of dancers injured and non-injured who had history of low back pain ($p=0.017$). The relative risk and 95% confidence interval of becoming injured for having history of low back pain in student ballet dancers was 1.56 (1.10-2.23).[25] Subsequently, the risk of having a second injury when already injured, is greater than the risk of having a first time injury.[106]

Having multiple injuries encompasses history of injury as a risk factor for subsequent injury. Multiple injuries as an injury risk factor is supported by evidence from a three year study on a professional ballet company. Twenty four of the dancers sustained five or more injuries, which accounted for 52% of all of the injuries in the study. The groups with five or more injuries had an injury incidence of 6.7 injuries per person, compared to other injured dancers with less than 5 injuries who averaged 1.86 injuries per person.[16] In addition to the cost to the dancer in terms of disability, potential time loss from dance and the need for rehabilitation from multiple injuries, the financial cost is very great. During this same study there were nine severe injuries that cost greater than $10,000 to treat, accounting for 37.8% of the total costs. All of these dancers with these major injuries had additional injuries during the study. All together they sustained 26 additional injuries which increased the average cost per dancer by 30%.[16]

Having multiple injuries could include different injuries to multiple body parts, recurrent injury or exacerbation of an existing injury or musculoskeletal complaint. All of these types of injury are related to the risk factor of history of injury. Recurrent injury and exacerbations of existing complaints are a problem for dancers. During one year 40% of injuries were recurrent and 11% were exacerbations in professional female ballet dancers; although they had significantly more first episode injures (49%) the proportions of recurrent and exacerbation injuries is clinically significant. This corresponds to injury incidence (95% CI) of 1.64 (1.29, 2.08) and 0.46(0.29, 0.72) per 1,000 dancing hours respectively. Males experienced significantly more exacerbation injuries 2.76(2.28, 3.34) than first episode and recurrent injuries.[20] This difference in recurrence and exacerbation injuries could be due to differences in the types of dancing/roles performed by males and females during that particular season. The requirements of the dances being learned and performed are entirely up to the dance company artistic staff, administrative staff and choreographer. This is often what defines the artistry and creative nature of dance itself. The medical professional can help mitigate injury by knowledge of the choreography. They can develop training programs based on the demands of a particular dance, educating both the dancers and the instructors or choreographers if there are any particularly risky movements being required. Studies of longer duration can help to better describe the incidence of recurrence and exacerbation of injury and any gender differences that may exist.

2.3.2 Factors Related to Fatigue, Dance Exposure, and Dance Training

The frequency of injury occurrence and recurrence can be partially accounted for by fatigue that develops from dancing. Fatigue is a complex phenomenon with strong relationship with injury risk. Fatigue encompasses "compromised structural and functional integrity including neural, musculoskeletal, mechanical, and psychological components."[126] Traditionally fatigue is described as an acute decrease in exercise performance that includes the decreased ability, and eventual inability, to produce desired force and power output, which coincides with increased effort and perceived effort of performance. [127] Fatigue occurs both peripherally at the muscle and centrally within the nervous system.[128] With peripheral fatigue the muscle's contractile ability is decreased due to impaired physiologic function between the neuron to the muscle or within the muscle itself. This could also be the result of a poor metabolic environment surrounding the muscle.[129] Central fatigue accounts for control the central nervous system has over muscle and exercise performance. Function and performance will decrease with central fatigue because of alterations in the central nervous system and include physiological components.[127,128] Knicker at al. summarize that there are many physiologic and metabolic factors of fatigue including "diminished carbohydrate availability, elevated serotonin, hypoxia, acidosis, hyperkalemia, hyperthermia, dehydration and reactive oxygen species" that will contribute to peripheral and central fatigue symptoms.[128] Because these factors and underlying mechanisms of fatigue can all interact, it is supported that fatigue is best understood as a global phenomenon of decreased exercise performance.[113,126,128]

In dance, fatigue can occur acutely during a discrete episode as in one strenuous dance combination, class, or performance. It likely has more significance as it accumulates over time as in periods of highly strenuous and repetitive rehearsals or performances, and over the dance season as a whole. Sometimes the cumulative effects of fatigue manifest themselves in overtraining syndrome, which is a drop in performance not able to be explained by injury or illness.[113,130] Overtraining is observed in other types of athletes and often occurs when training has been intense, repetitive, and has not allowed for adequate rest. In overtraining literature on dancers and other athletes, the subjects very frequently report fatigue at the time of injury.[130-132] Dance training regimens lend themselves to the development of fatigue and overtraining because they allow little time for rest and recovery.[126] Because the physical components of fatigue are complex, interrelated and often difficult or expensive to measure, fatigue could also be accounted for and explained in time and exposure to dance as the risk factor for injury.

Injury risk increases with total amount of time danced in a season. In a study on dance students attending an advanced dance school, regression analysis on multiple variables including the hours in various types of dance classes, number of performances, hours per week in other types of physical activities and sports, total months of training in the dance program, and anthropometrics (limb circumferences) found that total months in dance training program predicted injury, with an odds ratio (95% CI) of 1.044 (1.014-1.075). In collegiate dancers, both the clinical visits and self-reported injuries increased from first to second semester, by 7% and 10% respectively. This coincides with an increase in the mean number of days missed or modified from 7.27 to 8.73 from first to second semester.[5] Similarly, 67% of injuries reported by dancers occurred in the middle to end of the dance season or semester.[132] In youth dancers, the relative risk for sustaining an injury increases with age. The relative risk of injury is twice as large at age 15 years as it was at 8 years. However, the hours of dance also steadily increased with age, so this increase in injury may be related to exposure.[106] Once dancers reach a professional level, no correlation between age and injury was found.[126]

In addition to total time danced injuries often coincide with increases in training intensity and volume. This observation is seen even in young dancers. In a five year study on pre-professional ballet dancers, monthly increases in injuries coincided with abrupt increases in training intensity. These injuries primarily occurred at the onset of a new season (9 month training cycle), increased rehearsal periods prior to performances (3 months into training), or prior to ballet exams (7 months into cycle).[25] Intensity at these times could have been greater, although the training time of these students should have been fairly consistent (20 hours per week) due to the specific program in which they were enrolled. Increased intensity could be explained by the students transitioning from a period of inactivity and at times they were learning new dance material followed by increased repetition of dances within the allotted time for practice of dances for performance and exams. Even though the work week for a dancer may be kept fairly homogenous for all dancers; some dancers may actually have to dance more than others depending on the roles for which they are rehearsing. In professional dance, the factor that is most predictive of injury is exposure to dance. Female dancers are more likely to develop a stress fracture when they are dancing greater than five hours per day than when they are dancing less than five hours per day.[133] These training factors have been observed in professional dance. One professional ballet company reported that the highest injury rates over a season beginning in August and ending in May, occurred in October (11.3%), January (13.3%) and March (18.8%).[16]

These fluctuations in rates likely coincide with periods of dance activity characterized by high repetition and frequency of rehearsal and/or performance activity. Seventy nine percent of dancers reported that they are engaged in familiar repetitive work when they are injured.[132] This could be during rehearsal or performance periods. Professional companies have reported periods of increased injury frequency in the beginning of the season.[15,16,18] The start of the season can be considered a rehearsal period and is characterized by highly repetitive activity as the dancers learn and practice new choreography. In a five year study of a professional modern dance company an average of 37% of injuries occurred during this rehearsal period and tended to be overuse in nature.[15] Injury rates may pick up again later in the season with fluctuation in rehearsal and performance schedule. Studies on professional dancers also show increased injury rates during performance periods.[16,18,82] In one study specifically looking at the incidence of anterior cruciate ligament (ACL) injuries of the knee in professional ballet and modern dancers, Liederbach et al.,[82] found that most ACL injuries occurred during the middle to end of the performance season, more often during the evening hours of the day after the dancers had been dancing for several hours, and that just over half of the injuries occurred during a performance.[82] In professional modern dancers occurrence of a traumatic injuries, such as ACL injuries, were also more common during performances (54%).[15] During performance traumatic injuries may be more common because the dancers are executing movements at their highest ability. The environment may be less controlled than during class and rehearsal, therefore the possibility for potential unexpected situations to arise, more similar to other sports. Dancers could also be affected by fatigue during performance periods, which is largely influenced by the company schedule and dancer’s individual resting habits.

2.3.3 Metabolic Considerations

Issues related to metabolic health are important to acknowledge when discussing the risk for injury in dancers, especially in women. Javed, et al., acknowledged ballet dancers as a group with increased risk for developing the female athlete triad.[134] From a young age these issues are related to injury. A study comparing injured and uninjured youth dancers found no difference in the age of menarche between the two groups, which was 12.6 ± 1.3 years and 12.6 ± 1.1 years respectively. Injured dancers had more occasions when they went more than three months without a period. This number was 2.8 ± 0.6 occasions in the injured group and 2.7 ± 0.5 occasions in the uninjured group.[14] Though statistically significant ($p<0.05$), the difference in the occasions of 0.1 is not possible to count clinically. It does, however, indicate that missed periods are important to monitor in young dancers. In contrast to this study, a longitudinal study that included professional ballet dancers has found that delayed menarche predicted stress fracture. Subjects with stress fractures were older at the time of menarche (15.2 ± 2.3 years) than those without stress fractures (13.5 ± 1.5 years).[135] The age of onset of menarche in the stress fracture group categorizes them as having "delayed menarche" or first menses at greater than 14 years. [136]

The significance of regular menstruation is further supported in literature on professional dancers. Dancers often have irregular menstrual cycles. Only 11% of professional ballet dancers were eumenorrheic as defined as having menstrual cycles occurring at intervals ≤ 38 days.[111,133] Furthermore, this study found that dancers who had stress fractures had significantly longer duration of amenorrhea compared to those without stress fracture ($p<0.001$). The odds ratio and 95% CI for having amenorrhea greater than six months and developing a stress fracture was

93(5.3, 1644) with a p value of 0.015. Interestingly, number of hours danced was also investigated in this study and also found to be an independent risk factor for developing a stress fracture.[133] Once a dancer becomes amenorrheic for more than 6 months she was very likely to develop a stress fracture. The importance of monitoring training amount has been discussed previously. This study shows that it is very important to monitor both training and menstrual cycle. The importance of this female health issue is also strongly supported by literature on the female athlete triad of amenorrhea, low energy availability and decreased bone mineral density.[135,137]

Menses can be difficult to monitor. The woman may consider it to be a sensitive and/or personal topic. The use of birth control can also confound the ability to track menses. A recent study of multiple dance companies found that 30% of dancers reported irregular menstrual cycles. However, the study did not control for the use of birth control so the true incidence of irregular periods is unknown. Some dancers said their periods were irregular before they started using birth control so they did not know if their menstrual cycles would have been regular at the time of the survey.[24] In addition to the possibility of the use of birth control creating regular periods, prolonged use of oral contraceptives can lead to less frequent or even the cessation of periods. Therefore, it is difficult to track menses in women who are using birth control. From an injury risk factor perspective, researchers and clinicians will need to find another related variable to track as the use of oral contraceptive becomes more common. Often the women seen with the energy deficiency disorder and irregular periods have low percentages of body fat. Additionally, a study of elite professional dance students found that dancers with lower body fat percentages took significantly longer to recover from injury. The correlation coefficient of body fat percentage and number of days missed due to injury was $r = -0.614$ ($p=0.026$).[39] Therefore the measurement of body composition, fat mass and fat free mass, will be used in this study. This will also allow for similar issues to be examined in male subjects who can also suffer from poor body image and body dysmorphia. This is often seen in male body builders who would like to be very lean and increase their amount of lean body mass.[138] Male dancers may have some component of wanting to have a muscular physique but still be worried about not being lean enough. Eating disorders and disordered body image are observed in male as well as female dancers.[139] This could lead to poor body composition and increased injury risk in male dancers as well. Additionally, Southwick et al., found that professional dancers had no difference in the number of stress fractures between genders (n=253, females= 141, males=112).[24]

2.4 PHYSICAL CHARACTERISTICS OF DANCERS

Dancers have a unique profile of physical characteristics. Some of these may be adaptations that develop over time due to the demands of dancing. The case that those processing certain physical qualities and abilities are those that become dancers may also be made.[140] The exact characteristics may be different among different dancers defined by type of dance performed and level of training. However, there are basic generalizations that may be made about dancers that define them as a unique group of athletes in terms of body composition, joint range of motion and flexibility, aerobic and anaerobic fitness, and muscular characteristics.

2.4.1 Body Composition

Dancers typically have low body mass and a smaller physique, which is often favored especially for ballet.[1] Dancers have been found to have low waist to thigh and waist to hip ratios.[141] During adolescence female dance students tend to have average heights but below average weights.[10] Body fat percentages reported for student dancers are 20% for females and 15% for males.[142] Female professional dancers also tend to have low body weight, as well as lean mass despite having a high muscular performance demand..[143] Body fat percentages for ballet dancers have been reported to range from 16%-18% for females and 5%-15% for males.[33,143,144] Data on the body composition of female collegiate modern dancers have been reported to range from 18% to 25.9% body fat percentage.[54,145] While the desire for a thin physique is still present in these groups, the expectation is generally not quite as restrictive as in professional ballet. Unfortunately there is a high prevalence of eating disorders, low energy intake, and image distortion in the dance population as they strive to meet aesthetic expectations of the profession.[135,146-150] In female dancers, these factors are related to reproductive issues of decreased or absent menses and injury.[133,135,136] There is some evidence that suggests dancers, as well as other athletes who have low body fat percentages and bone mineral density have a higher risk of and longer recovery from injury.[39,135,137,139] Body composition may be a useful potential risk factor to study and monitor because it is not gender specific, as in monitoring menstruation, and can be measured in both males and females who are both at risk for injury.[24]

2.4.2 Aerobic and Anaerobic Capacity

Dance classes are typically one to two hours in length with progressive difficultly in the movements performed. Movements are typically performed in combinations of short duration with a rest break in-between when other dancers perform the combination or they learn the next combination. The intensity of the dance exercises varies from a low to moderate level during warm up with 36% to 46% of VO_{2max}.[151] Harder class combinations, solo and partnering and dances in rehearsals and performances reached intensities up to 70%-80% of VO_{2max}, but these activities account for less of dancers' time.[151-153] As such, dance activities may not be intense enough to greatly develop aerobic capacity in dancers, which tend to be lower than other athletes. VO_{2max} for professional ballet dancers has been reported to range from 40.9 to 50.9 ml/kg/min in females and 53.8 to 59.3ml/kg/min in males.[152,154,155] A study on collegiate and professional modern dancers for a modern dance company found these dancers to have slightly higher VO_{2peak} values of 51.27 ml/kg/min in females and 66.19 ml/kg/min in males.[156] Conversely, another study on female collegiate modern dancers found lower values with an average of 42 ml/kg/min.[54] Aerobic fitness may depend on the level of dancer, with more elite dancers having higher capacity.

Similar results have been found for the anaerobic capacities of dancers. Dance certainly has anaerobic power requirements for high jumps. Also, high levels of blood lactate concentration (10 mM) have been measured in dancers performing solo dances. The average blood lactate concentration level during ballet class, however was lower, averaging 3 mM.[151] Anaerobic capacity tests performed on female collegiate modern dancers showed absolute power and relative peak power to be 463.92 Watts and 8.00 Watts/kg respectively.[54] Vertical jump height is also sometimes used as a measure of power. Vertical jump height in females has been reported to range from 33.0 to 39.2 cm, and 50.5 to 55.3 cm in males.[32,54] These physiological factors are important to consider when working with dancers. Twitchett et al.,[39] found that dancers with lower aerobic fitness measured using a dance specific aerobic fitness test monitoring heart rate, suffered more injuries during a fifteen week period than dancers with better aerobic fitness. The correlation between heart rate responses (higher indicating less fitness) with number of injuries was r = 0.590 (p-value = 0.034).[39]

2.4.3 Joint Range of Motion and Muscular Flexibility

In addition to physiological demands and characteristics, dance places demands on the musculoskeletal system. Dance movements require dancers to have high amounts of joint range of motion and muscular flexibility. Studies have reported that hypermobility occurs among 2% to 44% of the dance population and greatly depends on the criteria used to define hypermobility.[11,157,158] Hypermobility is more common in ballet students than professional dancers.[159] When hypermobility criteria include a forward flexion component a much higher percentage of dancers will be categorized as being hypermobile.[11,160] The forward flexion component of the Beighton hypermobility test accounted for 84% of the score in dancers.[159] This can likely be explained by the fact that dancers' training lead them to use and develop increased hip flexion and hamstring flexibility, therefore it is not surprising that such a high percentage of dancers score positive on this particular hypermobility component of the Beighton test.[158,159] Klemp et al.,[159] have suggested that the forward flexion component of the Beighton test does not need to be used for dancers as it is an acquired trait and over inflates the percentage of dancers who are pathologically hypermobile.[158] Similarly, Foley et al.,[161] suggest that unless the joint hypermobility is extreme and/or associated with a connective tissue disorder, it is a physical characteristic required for dancing.[161] Furthermore, Roussel et al.,[157] have found that hypermobility is not predictive of injury in ballet dancers, and suggested that maybe the issue of injury may be related to movement control.[157]

Dance training in all types of dance leads to increased muscular flexibility and joint range of motion.[162,163] Many related characteristics of dancers have been included in risk factor analyses. Characteristics studied that have not been found to be related to injury include trunk posture (cervical, thoracic and lumbar position/ curvature), knee hyperextension, hip internal and external ROM, hip anteversion and retroversion, and ankle dorsiflexion.[25] Regression analyses have found that scoliosis is predictive of back injury in adolescent dancers and is likely an important factor to screen for and monitor in this younger population.[105] Characteristics that are potential risk factors are often related to the ankle and foot posture. Gamboa et al.,[25] found that more dancers who became injured had a pronated right foot in standing posture than those who did not become injured ($p=0.005$) with a relative risk and 95% confidence interval of 1.74 (1.19-2.54). This study also found that dancers who had decreased ankle plantar flexion ROM were at increased risk of being injured 1.1.3 (0.76-1.67). Injured dancers had significantly less right ankle plantar flexion ($p=0.037$), however the authors did not report the cut off value they used to determine the dancers had insufficient plantar flexion.[25] This may be because of the increased plantar flexion required for ballet. If dancers do not naturally have the amount of plantar flexion required for ballet they may become injured.

2.5 NEUROMSCULAR CHARACTERISTICS OF DANCERS

The remaining sections of this review will focus on physical characteristics of dancers that are potentially risk factors for injury that are modifiable with training and rehabilitation programs. These characteristics include muscular strength, postural stability or balance, and biomechanics during movement. These factors are related to muscular ability and coordination with the nervous system and are considered neuromuscular characteristics.

2.5.1 Muscular Strength

Muscular strength is an important neuromuscular physical characteristic to consider when evaluating risk for injury and performance. Muscular strength is required for dancing; however, data show that dancers may have decreased strength, with female professional ballet dancers having the least strength compared to other types of dancers and other athletes.[9,10,31,56] Decreased strength observed in professional ballet dancers may also be present from the time ballet dancers begin their training. Bennell et al.,[56] studied the strength of seventy seven female ballet students aged 8-11.1 years and forty nine female controls aged 8.2 – 11.2 years and found that the dance students had significantly less strength in four out of the five muscle groups tested. Dancers had less strength of their hip flexors, hip external rotators, internal rotators, and hip adductors but not their hip abductors.[56] This strength characteristic may be related to the small body size and lean muscle mass seen in ballet dancers and may also be due to the fact that there is a common fear among dancers of appearing too large if they have increased muscle.[1]

The quadriceps strength of professional dancers has been used in most studies of dancers' strength. Kirkendall et al.,[31] compared the isokinetic quadriceps strength of male and female ballet dancers to several groups of other types of professional and elite athletes. In comparison to other athletes, professional ballet dancers had the lowest relative strength to their body weight. Female comparisons included figure skaters, swimmers, cross-country runners, rowers, basketball players, volleyball players, and alpine skiers. Male comparisons included speed skaters, boxers, biathlon, figure skaters, ice hockey, gymnasts, swimmers, football players, and volleyball players.[31] The authors considered the strength of the male dancers, although lowest in comparisons to other athletes, to be sufficient. They calculated the male ballet dancers' strength to be 98% of the other athlete groups. In contrast, the strength of the female ballet dancers' was only 77% of the other athletes.[31] The study by Kirkendall et al.,[31] also showed that female dancers had lower relative strength to body weight than males. At time of pre-season testing females had 25%, 27% and 27% less strength relative to body weight, and 16%, 18% and 19% lower quadriceps strength relative to lean body mass at the 45, 90 and 180 degrees per second respectively.[31]

Another study investigating isokinetic strength data on female dancers also found the dancers to be weaker compared to female collegiate athletes. This study included both professional and collegiate ballet and modern dancers, and grouped them all together when comparing them to other athletes. The dancers' strength relative to body weight was 21% lower for quadriceps and 17% lower for hamstrings than track athletes.[52] When Chmelar et al.,[52] compared these dancers to collegiate female basketball players they considered both groups to be similar.[52] However, statistical tests and values for the strength of the basketball players were not displayed. Visual inspection of the graphic representation of the groups in Chmelar's paper allows for clinical interpretation that the quadriceps strength of the basketball player is higher than the dancers. In looking up the original work on the basketball players, the units of measure are not clearly stated so it is hard to tell how the data was transformed to compare the study on dancers, warranting further investigation into the differences between dancers and other athletes.[52,164]

Some authors suggest that modern dancers may be more athletic than ballet dancers, as some have also trained in other types of sports.[165] Chmelar et al.,[52] studied the strength of collegiate and professional ballet and modern dancers. In this study the professional ballet dancers had the lowest quadriceps strength values normalized to body weight of any group at all test speeds of the isokinetic dynamometer, except at 180 degree per second where collegiate ballet dancers had the lowest values. Overall, collegiate modern dancers had higher quadriceps strength than collegiate ballet dancers. Similarly, professional modern dancers had higher strength than professional ballet dancers across all test speeds.[52] Interestingly this study found that both groups of professional dancers were weaker than both groups of collegiate dancers.[52] These finding are similar to another study on female collegiate dancers, by Martyn-Stevens et al.,[54] which found that this group of dancers has adequate lower body strength according to ACSM guidelines.[54]

There is evidence that decreased overall strength increases the risk of musculoskeletal injury in dancers. A prospective study on pre-professional ballet dancers found that injured dancers had significantly decreased lower extremity muscular strength than non-injured dancers ($p=0.045$). Strength tests included manual muscles test for the hip motions of flexion, extension, abduction, adduction, internal and external rotation, as well as knee flexion and extension.[25] This study was limited in that it used manual muscle test grading (0-5) rather than a continuous numeric quantification of strength. Another limitation is that all lower extremity muscle groups tested were averaged together for the results, so it does not provide any information to determine if certain muscle groups are more important than others. It does however indicate a relationship that decreased strength is associated with injury. Koutedakis et al.,[34] have found that dancers with less quadriceps and hamstring muscle strength measured with an isokinetic dynamometer reported they had more days off due to lower body injuries then those with higher strength. This relationship was significant for both males (n=20) and females (n=22) with correlation coefficients (p value) of -0.61($p<0.01$) and -0.70 ($p<0.005$) respectively.[34]

When looking at the relationship between strength and injuries, one well researched area in the sports medicine literature is ACL injuries and knee strength of the quadriceps and hamstrings, most specifically the hamstrings to quadriceps strength ratio. It is accepted that the hamstrings should be at least two thirds as strong as the quadriceps.[166] This is a proposed risk factor for ACL injuries to the knee due to the fact that female athletes have decreased hamstring strength compared to their quadriceps compared to males and also sustain more ACL injuries than males.[46,167] Some studies on dancers' strength have investigated the hamstrings to quadriceps strength ratios. Kirkendall et al.,[31] found that even though females had less strength than males when normalized to body weight, when the hamstring muscles were tested each gender had appropriate quadriceps to hamstring strength ratios. They did not compare the hamstring strength or strength ratios of the dancers to other athletes.[31] Chmelar et al.,[52] did compare this ratio to those of basketball players and found that female dancers had higher ratios than female basketball players. More specifically the ratio of hamstring to quadriceps ratio of ballet dancers was highest, compared to modern dancers and basketball players; with the percentage being 85.1%, 75.1% and 71.4% respectively.[52] This study also looked at the hamstrings to quadriceps ratios of all of the dancers by genre (ballet and modern) and level (professional and modern). They did not perform statistical tests, but the data tables show that professional ballet dancers had the highest hamstring to quadriceps strength normalized to body weight of all groups tested using the isokinetic dynamometer. They collected an isometric test as well as isokinetic tests at speeds ranging from 60 to 240 degrees per second.[52] Together, these studies seem to indicate that female ballet dancers achieve an appropriate balance of thigh muscular strength, despite having lower muscular strength overall. This may be one factor explaining a lower incidence of ACL injury in dancers, as well as a lack of a gender discrepancy in ACL injury in professional dancers.[82]

Other literature on the thigh musculature includes the relationship between hamstring and quadriceps strength ratio with hamstring injury and hip adductor and abductor strength ratios with groin injuries in different types of athletes. Decreased hamstring to quadriceps concentric strength ratio tested at 180 degrees per second has also been found to be an important risk factor for hamstring strain injuries in runners. This was the only significant predictor ($p=0.01$) of hamstring injury found with regression analyses which also included hamstring flexibility, hamstrings and quadriceps peak torque, peak torque angle, and the strength ratios concentrically and eccentrically at three different speeds. Runners with hamstring strength less than 60% of quadriceps strength were 17 times more likely to sustain a hamstring injury. The hazard ratio (95% CI) and p value was 17.4 (1.31, 231.4) and 0.03.[42] In hockey players groin strains are very common. Tyler et al.,[41] measured the preseason hip abduction and adduction strength of professional hockey players and followed them to see who sustained a groin strain. Pre-season hip adduction strength of injured hockey players was found to be 18% less than in uninjured players ($p=0.021$). The adduction and abduction ratio was also different between injured and uninjured players and found to be the strongest predictor of injury (p=0.003). The injured players' adduction strength was 78% of their abduction strength, while in uninjured players' adductors was 95% as strong as their abductors. Furthermore players whose preseason adductor strength was less than 80% of their abductors were seventeen times more likely to sustain a groin strain, with a relative risk of 17:1.[41] These studies point out the importance of looking at muscle balance using strength ratios as they are associated with injury in other athletes. They may also be important in dancers who also sustain muscle strains.

One area of great importance to dancers is the foot and ankle, where most injuries occur, but the relationship between ankle strength and ankle and foot injury as not been well studied.[4]. Baumhauer et al.,[43] studied various potential pre-season risk factors for ankle sprains in male and female athletes and made comparisons between those that sustained an ankle sprain and those who did not over a year. Of the strength variables collected the only one found to be different between athletes who became injured and those who did not was the eversion to inversion strength ratio. The injured group had equal eversion to inversion strength with a ratio of 1.0, however the uninjured group had stronger inversion compared to eversion with an eversion to inversion ratio of 0.80 (p value= 0.04). However when the strength of the individual muscles in each group were compared, there were no significant differences. This study has high impact because it is prospective, however, only a 15 out of 145 athletes (10.3%) sustained an ankle sprain. When the authors looked at the data in more detail they found that 67% of the injured group had eversion to inversion strength ratios of greater than 1.0, indicating that many still had strength imbalances.[43] It is likely that strength of the ankle musculature is important as a risk factor for ankle sprain, especially muscle imbalance, and it warrants further investigation.

Ritter and Moore have proposed that there is a relationship between ankle strength, ankle sprains, and the development of tendinitis of the ankle musculature in dancers. Their article proposed that the peroneal tendons were most at risk for developing tendinitis because of their proximity to the lateral ankle ligaments damaged in a lateral ankle sprain. The peroneals muscles are important for ankle joint stability, especially in the common dance position of relevé when the dancer is weight bearing in extreme plantar flexion.[168] Dance requires that the dancers have and use higher flexion range of motion which can potentially be unstable for the talocrural joint and put strain on the anterior talofibular ligament (ATFL) as they are standing and balancing in this position.[169] This, along with other dancing tasks such as jumping and turning, can lead to ankle sprains of the ATFL in dancers.[170] Repeated ankle sprains can lead to ankle instability.[171] While Ritter and Moore suggest the peroneals are most important to be strong for stabilizing the ankle joint due to their proximity to the ATFL, they acknowledge that the other musculatures surrounding the ankle joint would also be active in stabilizing the joint to prevent instability, ankle sprain and tendinitis.[168] Instability has been linked to over-activity of the muscle about the unstable joint, which can lead to overuse and tendinitis.[172] In dancers this would also be true for the invertors, especially the flexor halluis longus and posterior tibialis. These muscles, along with the peroneals, cross over the talocrural joint into the midfoot and forefoot to help stabilize these more distal joints which are prone to injury in dancers.[173,174] Strength of the local musculature at the ankle and its relationship to ankle and foot injury, especially in dancers, warrants further investigation beyond discussion of the anatomical basis and theory of the relationship.

Strength of muscles and muscle groups at locations other than the injured site may also be important in risk factor analysis. Several studies have looked at hip strength in relation to knee injury. In a study using hand held dynamometry to measure strength, hip abduction and external rotation strength was found to be decreased in female athletes with patellofemoral pain on the side of the injury compared to their uninjured limb (p values 0.003 and 0.049 respectively). The injured limbs were also found to have weaker hip flexion, extension, abduction, internal rotation and external rotation than those of uninjured age and sport matched controls (p values 0.033, 0.029, 0.010, 0.049, and 0.033 respectively).[175] A limitation of this study was that it is not prospective, and the injured subjects had been diagnosed with patellofemoral pain at the time of the study, so we do not know what their strength was like prior to them becoming injured. However, since patellofemoral pain is a common pathology, testing hip strength and providing appropriate strengthening exercises can help to improve strength deficits, restore strength balance and hopefully rehabilitate, and prevent recurrence of, the injury. This idea is supported by a study by Fredericson et al.,[176] which found that male and female runners with iliotibial band syndrome had weakness of their hip abductors in their injured leg compared to their non-injured leg as well as healthy controls (all p-values <0.05). This study was a six week intervention study that included hip abduction strengthening to treat iliotibial band syndrome. At the end of the study twenty two of the twenty four injured runners were pain free and had initiated a running program. Both male and female runners had significantly ($p <0.05$) increased their strength by 51.4% and 34.9% respectively. Six month follow revealed that successfully rehabilitated runners remained pain free.[176]

Another prospective study found several hip strength characteristics to be related to the development of patellofemoral pain syndrome in male and female high school runners. This study had similar findings in that runners with hip weakness and imbalance were more likely to develop patellofemoral knee pain. Runners with weak hip adductors in comparison to their abductors had increased odds of developing knee pain, with an odds ratio (95% CI) and p value of 14.14 (0.90-221.06, p=0.05). Having increased hip external rotation strength compared to internal rotation decreased the odds ratio <0.01 (0.01, 0.44, p value = 0.02).[177] The strength of the hip abductors has also been prospectively linked to pain even lower in the kinetic chain. Regression analysis found that total work of concentric abduction tests (TWABC) and average power of concentric abduction tests (APABC) were significant predictors of exertional medial tibial pain, with p values of 0.010 and 0.045 respectively. This study also found that increasing TWABC by 1 joule decreased the risk of developing exertional medial tibial pain by 1% and that if APABC increases by 1 Watt the risk of pain decreased by 4%.[178] The body of literature on muscular strength as a risk factor for injury indicates that those with lower strength values are more likely to become injured. Starting proximally the trunk and core musculature is likely important to consider with strength risk factor analyses, based on the theoretical foundation, although definitive research is still limited. The hip musculature, including the abductors, adductors and rotators, has an important relationship with regional muscular strains. Strength of these muscles is also important in preventing injury lower in the kinetic chain at the knee, lower leg, and potentially lower in the foot and ankle. At the thigh and knee, quadriceps and hamstring strength are both important as risk factors for injury to the hamstring and for ACL injuries at the knee. Strength of the ankle musculature, especially the evertors and invertors, are important to protect the joints of the ankle and foot. These muscles and joints are especially important for dancers due to the high incidence of lower leg, ankle and foot injuries. Research suggests that strength ratios, which are indicative of muscle balance, are important to utilize in risk factor analyses. The current study measured strength of antagonist muscle groups to investigate the strength of individual muscles as well as strength ratios.

2.5.2 Postural Stability

Dancers have high levels of postural stability compared to the general population and, in some cases, other athletes.[65,67,70,71] Balance is the ability to maintain the center of mass over the base of support. Maintaining postural stability is achieved through coordinating corrective movement strategies to keep the body balanced within the base of support with minimal motion.[179-181] This state is considered postural equilibrium and occurs through equalization of the forces acting on and keeping alignment of the body segments.[179] Maintaining postural stability requires proper function of the three sensory systems, which are the somatosensory, vestibular and visual systems. It also requires the integration of this sensory information in the central nervous system and the execution of appropriate motor responses.[26,27,181] Postural stability can be tested with procedures that systematically alter visual and somatosensory conditions. This will challenge all systems and provide insight into how well each system can compensate when the others are compromised. Historically this was done using the Foam and Dome test. This test has six conditions which are: 1) standing on the floor with the eyes open; 2) standing on the floor with the eyes closed; 3) standing on the floor with an altered visual surround (paper covering over the subjects head); 4) standing on foam with eyes open; 5) standing on foam with eyes closed; and 6) standing on foam with the altered visual surround. This test was developed to test balance ability and gain insight into which sensory system may be impaired in elderly and other patients with balance disorders.[182] This test was modified by Crotts et al.,[67] so that the six conditions were performed in unilateral stance instead of bilateral stance to more appropriately challenge healthy adult subjects and collegiate dancers. The dancers had significantly better total balance scores combining all conditions, better scores on the most challenging conditions (5 and 6), and a greater proportion of perfect scores on all of the conditions. This study indicates that dancers are better able to integrate somatosensory and visual information as well as use appropriate motor strategies to maintain postural stability.[67]

Other clinical tests indicate that dancers have superior balance than non-dancers. A study comparing collegiate modern dancers and active non-dancers found that dancers had better balance scores on the Balance Error Scoring System (BESS) and the Star Excursion Balance Test (SEBT), but not the Modified Bass Test of Dynamic Balance (BASS).[72] These tests are both more challenging than the one previously described study by Crotts et al.[67] For the BESS, errors are counted as the subjects balance with their eyes closed for 20 seconds each in 6 conditions (three foot positions on a firm surface and then a foam surface) and keep their hand on their hips. Errors include such things as opening the eyes, lifting hands from the hips, stepping, hoping or moving the stance feet or foot, lifting the toes or heel, moving the hip into greater than 30^0 flexion or abduction, and remaining out of position greater than 5 seconds.[60] Dancers had fewer errors on the BESS than non-dancers, 12.0 ± 6.9 and 25.3 ± 9.1, respectively ($p<0.001$).[72] Dancers also had significantly ($p=0.03$) better SEBT scores than non-dancers. They were able to reach a farther distance with one foot expressed as a percentage of their leg length while maintaining a fixed position with their stance leg ($89.7 \pm 5.8\%$) than non-dancers ($85.6 \pm 5.3\%$). Dancers performed significantly better on both legs. The three directions of the SEBT thought to have highest sensitivity were looked at individually and were the anteromedial (AM), medial (M), and posteromedial (PM) directions. Dancers had better scores than non-dancers in the M and PM directions only. This is likely because the AM is the easiest direction to reach during the SEBT. The dancers in this study did not perform better than non-dancers on the BESS ($p=0.58$, 90.6 ± 5.8 and 91.7 ± 5.6 respectively).[72] This test includes both static and dynamic tasks. The results from this study only report the overall score, not performance on individual tasks where there may have been differences between groups.

Postural stability is more accurately assessed using force plate technology. There are various methods which use force plate data to quantify a person's balance including variation in ground reaction forces and center of pressure and/or mass in the x, y and z directions. When balance tasks are performed on a fixed, firm unmoving base of support static postural stability is achieved.[179] Studies on dancers using force plate technology have been used to describe the balance abilities of dancers. Professional dancers were found to have better balance scores on a force platform system utilizing a force plate which described balance as an overall index of movement as well as in the anteroposterior and mediolateral directions. The professional dancers performed better in all types of scores in bilateral stance and unilateral stance on each foot compared to both amateur dancers and non-dancers ($p<0.017$) in that they displayed less movement.[7]

Force plate technology has also been used to compare dancers to other types of athletes. Gerbino et al.,[71] found collegiate level female dancers have better static balance than collegiate female soccer players, matched for age, height and years of training with some balance variables. During unilateral stance the dancers had significantly lower sway index scores indicating they moved less during the task. The median and interquartile range were $0.2cm^2$ (0.1- 0.4) and $0.4cm^2$ (0.2-0.7) respectively ($p < 0.01$). The subjects in this study also performed unilateral stance on a foam mat. Again, the dancers had significantly lower sway index scores than the soccer players, whose scores were were$1.1cm^2$ (0.5-1.3) and $2.9cm^2$ (0.6-2.4) respectively ($p < 0.05$). Dancers also had shorter center acquisition time (CAT), which were reported as means with standard deviations. The dancers' CAT was 1.3 ± 0.8 seconds during unilateral stance on the stable surface compared to the soccer players whose mean CAT score was 1.9 ± 1.2 seconds. This indicates they were able to achieve quiet stance more quickly ($p < 0.01$). When unilateral stance was performed on a foam mat, the dancers had shorter CAT time (2.5 ± 1.7 seconds) than the soccer players (3.2 ± 2.9 seconds), but it was not found to be significantly different.[71] However, this difference in CAT time is close to 1 second and may be clinically significant.

A study by Schmit et al.,[70] found that dancers did not perform better than other athletes with traditional force plate measures of COP motion variability. This study compared collegiate ballet dancers to collegiate track athletes and found that the dancers performed better with some but not all balance variables collected during bilateral stance for four conditions that altered vision (eyes opened or closed) and surface condition (stable or foam). There were no differences between the groups for postural stability measures of COP variability. This study, however, found differences between the groups for variables that described the dynamic pattern of postural sway using recurrence quantification analysis (RQA) a type of mathematical modeling.[70] Using these methods the variables created described the regularity and complexity of postural sway dynamics. Five variables were used including, percent recurrence, percent determinism, entropy, maxline, and trend. Those with better postural stability are expected to have lower values for percent recurrence, percent determinism, entropy and maxline with higher trend.[183,184] Dancers demonstrated better postural stability during all conditions in four out of the five RQA variables, which was all but percent determinism.[70] Overall these findings indicate that dancers had better balance than the track athlete because their dynamic patterns of postural sway were mathematically less nonlinearly autocorrelated, less stable, less complex and more stationary, all of which indicate better balance.[70,183,184] The RQA variables describe the qualitative nature of the way the subjects maintained balance. These results may mean that dancers use different underlying postural control and motor behaviors to maintain postural stability.[70]

Studies comparing dancers to other groups will be dependent on the level of dancer. The years of experience of these dancers and level of training in collegiate dance can be much more variable than professional dance. Additional research should further investigate the differences among level of dancer. Even though not all force plate measures of postural stability show that dancers have better balance in terms of motion variability, it can still be argued that overall dancers do have superior balance abilities, especially compared with the normal population. Dancers and other athletes may have similar balance abilities and will be dependent upon the balance task and level of athlete or dancer. This is demonstrated in the tasks that they are able to perform during dance in which they do remain stable on one limb. Perhaps this can be best understood in the way they process the motion that is occurring and still maintain balance. Additionally more research is needed to describe dynamic postural stability, as most injuries occur while the dancer or athlete is moving.

2.5.3 Biomechanics

Biomechanics as it applies to the field of sports medicine is broadly defined as the study of human movement. It includes the description and assessment of the kinematics, and kinetics acting within and upon, the body during movement.[185] Biomechanical factors and potential risk factors for injury in athletes, include joint positions and forces that put increased strain on the body's tissues leading to injury. Some biomechanical factors related to injury have been found at the trunk, hip, knee and ankle. [83,88-95,186]

The literature on biomechanical risk factors for injury is similar to that on strength related risk factors in that risk factors have been proposed both locally or regionally, as well as distally.[47,51] Another similarity to the literature on strength and injury risk, is that much of the research has been done at the knee. It is well-recognized that increased loading and valgus collapse of the knee are associated with increased risk of ACL injury in female athletes, who have higher incidence of ACL injury than males.[88,167] Similar landing patterns have also been observed in females with patellofemoral pain.[90] Professional dancers have been found to have a decreased incidence of ACL injuries compared to other athletes, even with performance demands that include jumping.[82] Dancers may perform up to two hundred jumps in a single class, at least half of which are single leg landings.[187] Some larger dance jumps, that are a longer distance, create forces at the knee exceeding twelve times the dancer's body weight.[188] Over a five year period tracking time loss injures in 298 (183 females, 115 males) professional ballet and modern dancers, the overall incidence of ACL injury was 0.009 ACL injuries per 1000 exposures.[82] All but one injury were non-contact in nature, with the contact injury accruing during a planned choreographed partnering maneuver. Liederbach et al., found that 92% of the ACL injures occurred while landing from a single leg jump. ACL injures represented only 0.2% of all injuries in ballet dancers, and 0.4% of injuries in modern dancers.[82] ACL injuries incidence in dancers is lower than other team sports which report that non-contact ACL injuries account for 1% to 8% of total injuries.[189-193] There were no significant differences in the incidence of ACL injuries among the dancer types (ballet vs modern) or gender.[82]

It has been suggested that dancers experience fewer ACL injuries than other athletes because they have different biomechanical characteristics when they jump and land.[2,3,8] Some studies have been completed using a single leg drop landing task, making it possible to directly compare dancers to other athletes.[3] Orishimo et al.,[3] found that dancers had similar vertical ground reaction forces during landing (4.0 NM/kg) when comparing the dancers in their study to athletes in other studies. The dancers used a longer landing phase duration, allowing them to attenuate the landing force over a longer period of time (260 milliseconds vs 130-180 milliseconds).[2,89,194] This could help dissipate impact force at the knee and reduce risk for knee injury. The same study also found that dancers land with patterns associated with decreased risk for ACL injury; increased hip flexion and minimal hip adduction. Additionally they found no gender differences in kinetic or kinematic variables at the hip, knee, or ankle.[2] Similar results were later found by the same research group when they directly compared dancers to other athletes performing the same drop landing protocol. In this second study by Orishimo et al.,[3] they found that male dancers, female dancers and male athletes displayed similar landing patterns at the knee in the frontal plane. However, female athletes were different and landed with significantly greater peak knee valgus ($p = 0.007$). Male and female dancers had similar amounts of trunk side flexion and forward flexion, which were significantly lower than the male and female athlete groups ($p = 0.002$ and 0.032 respectively).[3] Further analyses presented in another paper from this study showed that after all groups were fatigued they displayed similar increased risky biomechanical patterns; increased peak knee valgus, decreased hip external rotation, increased trunk flexion and increased trunk lateral lean. The dancers however, took longer to fatigue than the athletes. They took 40% more exertional bouts until reaching fatigue, defined as a 10% decrease in vertical jump height.[8] The healthy dancers in these studies did not display biomechanical characteristics at the knee that are considered to increase risk for knee injury, therefore it may be important to consider biomechanics in injured subjects.

Injured dancers may display biomechanical patterns associated with injury. Fietzer et al.,[93] described the landing patterns of dancers with patellar tendinopathy. They found that injured dancers landed with increased peak vertical ground reaction force while landing from a dance jump, the *saut de chat*, which is a leap where the dancer takes off from one foot and moves forward through the air with their legs in a split position and lands on the other foot. The injured dancers landed with 36% higher peak vertical ground reaction force ($p < 0.001$) than the uninjured group. There were, however, no differences in landing kinematics at the hip, knee or ankle between the two groups.[93] It may be important to look at other joints, the ankle and foot in particular, where there is a higher incidence of injury.[4,109] Furthermore, it is also likely important to look at biomechanics in a turned out position, with dance specific tasks and to make comparisons between healthy and injured dancers.

A study supporting these ideas was completed by Lee et al.[103] This study compared several biomechanical factors of ballet dancers who had one or more ankle sprains limiting dance training for at least twenty four hours in the past year and uninjured dancers landing from a dance jump called a *sissone fermée*. During this jump the dancer starts from two feet in fifth position and jumps forward, landing on the foot that was in front followed by the other. The kinematics of the hip and knee joints did not differ between the two groups; however there were differences at the ankle and foot. The injured dancers had higher peak ankle eversion during landing than the uninjured dancers ($p = 0.030$).[103] Overall ankle eversion values from a three dimensional (3D) model creating a lower leg and one foot segment is associated with a pronated position of the foot.[195] The kinematic marker set and model used by Lee et al., enabled a more detailed examination of the ankle and foot motion by creating a rearfoot segment and a forefoot segment. The injured dancers displayed statistically less eversion of the rearfoot relative to the tibia than the uninjured group ($p = 0.034$). Some motion of the rearfoot into eversion is desirable during landing to unlock the foot joints and dissipate force through the foot during landing. The average peak eversion of the injured group was 0.6 ± 17.1 degrees, compared to 10.4 ± 13.7 degrees.[103] The injured dancers had a relatively rigid rearfoot during the landing indicated by the difference in means, as well as a varied type of response indicated by the standard deviation values reported. Similar findings have been found in athletes who have ankle instability and land with less ankle dorsiflexion to increase joint stability.[96] The decreased rearfoot eversion seen in the injured dancers was associated with an increase in forefoot to rearfoot abduction. The forefoot abduction of the injured group was 25.0 ± 13.7 degrees and 18.1 ± 11.1 degrees in the uninjured group ($p = 0.064$). This difference was not statistically significant; however the effect size was 0.560 indicating the magnitude of the difference between the two groups was large and likely clinically meaningful.[103,196] The decreased rearfoot motion and increased forefoot motion indicate that injured dancers with history of ankle sprain compensate with motion of the forefoot to dissipate force through the foot to maintain proximal ankle stability. This can eventually lead to increased strain on the distal joints of the ankle and foot. This compensatory mechanism cannot be observed with a traditional two segment model for the ankle and foot, although it does show that overall the subjects move into more eversion or pronation.

Another study has compared kinematics during a different turned out dance jump of dancers with Achilles tendinopathy to those without this pathology. The dance jump task used in this study is called a *saut de chat*. For this study, Kulig, et al.,[100] decided to investigate the takeoff for the jump rather than the landing. This study did find that injured dancers had different movement patterns at the knee. They moved into more hip adduction (13.5 ± 6.1 vs 7.7 ± 4.2, $p = 0.046$) and knee internal rotation (13.2 ± 5.2 vs 6.9 ± 4.9, $p = 0.024$).[100] These movements are indicative of knee valgus, a motion associated with knee injury.[88,197] This demonstrates that injury at one location can affect other joints in the kinetic chain. Others have suggested that ankle and foot pathology and pathomechanics can affect the knee joint.[198] The study by Kulig et al.,[100] did not find that the dancers differed in their ankle kinematics. However, they did not use a model creating a joint for the foot, so it is possible that using a more detailed model that includes joints for the foot would allow for a better description of injured and uninjured dancers, and possibly a better ability to detect differences. The use of multi-segmental foot models as been supported in literature on gait in other populations, and is supported because it better describes the complex motions of the foot and ankle.[199,200] A relationship between distal biomechanics and more proximal injury has also been proposed and observed. Two motions associated with ankle injury are excessive ankle inversion at landing and excessive pronation. The former is related to mechanism for lateral ankle sprains in athletes and dancers.[85,170] The latter is a proposed risk factor for a variety of injury including plantar fasciitis, stress fractures, Achilles tendinitis, patellofemoral pain syndrome and other anterior knee pain, iliotibial band syndrome, and lower leg exertional and stress syndromes.[198]

In addition to distal mechanics contributing to proximal injury, proximal mechanics can contribute to distal injury. Strength of the core musculature can help to stabilize the spine dissipating local loading to the spine.[201] Core muscle strength also has implications for helping maintain the center of mass over the base of support, as well as keeping a stable center from which the lower extremity can move.[48,49] Less information is available describing the biomechanics of the trunk and pelvis in relation to injury. One such study by Verrelst et al.,[186] prospectively investigated trunk and hip kinematics during landing from and subsequent takeoff from a single leg jump landing in female physical education students to predict the development of exertional medial tibial pain (EMTP). They studied eighty six subjects, twenty two of whom developed EMPT, and they found that subjects with increased hip and trunk motion in the transverse plane during both landing and takeoff were more likely to become injured. During landing the hazard of developing EMPT increased by 15% with a one degree increase in transverse plane motion of the thorax, with receiver operator curve (ROC) analyses indicating a cut of value of >12.27 degrees to predict injury. During takeoff the hazard of developing EMPT increased by 9% with a one degree increase in transverse plane motion of the thorax, with ROC analyses indicating a cut off value of > 13.24 degrees to predict injury. Pelvis motion in the transverse plane was also predictive of injury. During takeoff a one degree increase in motion of the pelvis in the transverse plane increased risk of injury by 10%, and ROC analyses identified that > 16.76 degrees of motion predicted EMPT. Significant findings were not found for the pelvis during landing. Additional significant findings were found for hip motion in the transverse plane. The hazard for developing EMPT increases by 13% with each one degree increase in motion during landing, and by 10% during takeoff. These hazards are associated with ROC cut points of > 8.93 degrees of hip motion in the transverse plane during landing and > 6.12 degrees of motion in the transverse plane during takeoff as being predictive of EMPT.[186] The findings from this study are especially useful in dance medicine due to the high incidence of lower leg pathology including exertional pain, stress reactions and stress fractures.[4]

In summary, dancers display safe kinematic patterns at the knee and are able to attenuate forces during landing. Potentially, dancers with Achilles tendinopathy and history of ankle sprains display risky landing patterns at the knee and foot respectively.[100,103] Overall there is limited information regarding injured dancers. Unfortunately, there is also little information available regarding kinematic patterns at the ankle and foot, especially using a multi-segment model in healthy dancers. The ankle and foot are very important to investigate in dancers because they sustain a high amount of injuries to this region.[4,109] Ankle and foot biomechanics may also have implications for injury risk higher in the kinetic chain. Similarly, it is important to investigate trunk kinematics in dancers because of its relationship with lower leg injury. Furthermore kinematic studies on dancers should include dance specific tasks. The proposed study will describe the kinematic landing patters of dancers during a dance jump at the trunk, hip, knee, ankle, and foot (rearfoot and forefoot). This will help to fill some of the gaps in the literature regarding biomechanics during a dance jump.

2.6 METHODOLOGICAL CONSIDERATIONS

2.6.1 Body Composition

Body composition assessment measures the percentages of body fat and fat free mass. Fat mass is the amount of fatty tissue and fat free mass is all of the other body tissues that is not fat, including muscle, bone, organ, and other tissues.[202] Body composition can be measured with many methods including different types of densitometry, imaging, and field techniques. Field techniques are valuable tools that are more accessible and less expensive than laboratory densitometry and imaging techniques. They include estimation of body fat percentage with skinfold fat thickness measurements and bioelectrical impedance. Both of these field techniques use equations to estimate body composition and correlate fairly well with laboratory techniques.[202] Skinfold measurement can be affected by tester proficiency and error.[203]

Bioelectrical impedance can be affected by subject hydration status and the equation used to estimate body fat percentage, therefore, it is best to use laboratory methods when possible.[204] One very good lab based technique is dual-energy X-ray absorption (DXA). Traditionally used for measurement of bone mineral density, DXA uses photon absorptiometry to estimate bone and other soft tissue composition and is thought to be a very precise and reliable method of body composition measurements of body tissues including fat. An advantage of this technique is that it allows the tester to determine bone density and location of adipose tissue in additional to overall body composition percentages. DXA systems, however, are very expensive and not always available. Other imaging techniques include radiography, computed tomography and magnetic resonance imaging. These techniques are also expensive and require specialized equipment, and are not often used in athletic populations.[202]

To establish the validity of body composition measurements, they are often compared to densitometry which is the measurement of a person's density. Density is calculated by dividing the measured mass by the measured volume. Mass is measured on a scale. The most common and widely accepted way of measuring body volume is through hydrostatic weighing. With this method the subject is weighed again underwater. Body volume is calculated using the difference between the land and underwater weight and converting it to volume using the known density of the water that was displaced by the subject in the pool. A final measurement of lung volume is made when the subject expels all of their air and the volume measurement is corrected to provide the subject's body volume. This measured volume and the subject's mass are used to calculate the subject's density. Density equations using the known density of fat and fat free mass are used to calculate body fat percentage.[202,204] Furthermore, there are different equations used to calculate body fat percentages based on different fat free mass tissue density values thought to be more appropriate for different populations who have differences in the density of their lean body mass. The Siri equation is the most commonly used equation, applicable for a wide variety of populations.[203] The Schutte equation can be used for people of African descent who have slightly higher lean body density than Caucasians.[205] The Brozek equation has been found to be best for calculating body fat percentage in an elite athletic population.[206,207]

Density calculation using hydrostatic weighing is very accurate if the mass, underwater weight and lung volume are measured correctly. The underwater measurement and lung volume measurement can sometimes be uncomfortable and difficult for subjects to perform. Another densitometry technique called air plethysmography has developed which addresses these limitations. It uses air displacement as opposed to water displacement and is based on the same principals of measuring mass and volume to estimate density to calculate body composition. It has been found to be reliable and valid compared to hydrostatic weighing as well as DEXA.[208-211] This method uses an airtight unit with two chambers. The volume of air in each chamber is known when it is empty. When the subject sits in the test chamber the volume of air in that chamber will decrease, increasing the volume of air in the back chamber. The corresponding pressure changes in each chamber and differences in each chamber with and without the subject present are used to find the subject's body volume. The volume of air in the lungs is also measured by using a breathing tube, which is much easier than with hydrostatic weighing where the subject has to hold their breath and expel all of their air.[212] A highly accurate scale is used to measure the subject's mass. The same densitometry equations as hydrostatic weighing are then used to determine fat and fat free mass for body composition assessment. Air displacement plethysmography will be used to measure body composition in this study. It is reliable, valid, safe, and non-distressful for the subjects to complete.[204]

2.6.2 Muscular Strength

Muscular strength can be quantified by measuring force output of a limb or body segment against a sensor. Strength can be measured isometrically, when the muscle contracts against a fixed resistance and no skeletal motion occurs. It can be measured istotonically when the muscle contract against a resistance set with a constant load and variable speed. Finally muscular strength can also be measured isokinetically when the muscle contacts maximally against a resistance that moves at a constant speed.[213] There are implications for each method of strength testing. This study will utilize both isometric methods with a hand held dynamometer and isokinetic methods with an isokinetic dynamometer. All tests will be completed in the open kinetic chain which allows the tester to have more control over the testing parameters compared to tests performed in closed kinetic chain. The parameters the tester can control are the position and range of motion of the limb being tested as well as the placement of sensors and stabilizing pads to help control for translational forces.[213] The limb position is held constant for isometric testing and the range of motion is controlled during isokinetic testing. Traditionally isokinetic testing with an isokinetic dynamometer is preferred for muscular strength testing; however, the case can be made for isometric testing using hand held dynamometry.

2.6.2.1 Hand Held Dynamometry

Hand held dynamometry will be used to test the isometric strength of the hip and ankle musculature. The hip and ankle musculature are generally comprised of smaller muscles acting in multiple directions. The muscles being tested are the hip abductors, hip adductors, hip external rotators, hip internal rotators, ankle evertors and ankle inverters. Using the hand held dynamometer (HHD) allows these muscles to be isolated through limb positioning and dynamometer placement. Subjects are positioned in side lying for hip abduction and adduction testing. The tester can ensure the subject's hip alignment is maintained to avoid compensation with other hip musculature. For hip rotation strength testing the subject is lying prone. The tester ensures the subject maintains proper position throughout the test, without compensating with the hip flexors or abductors. The isokinetic dynamometer attachment which is available for ankle inversion and eversion does not allow the slight rotation that naturally occurs at this joint with these motions. This hinders the subject's ability to exert maximal force. Using the HHD allows the tester to position the joint in a neutral position and allow the joint to rotate naturally about its axis. The HHD procedures utilize isometric tests, which is the type of muscular contraction similar to how these muscles function to stabilize the joint.[214]

2.6.2.2 Isokinetic Dynamometry

Isokinetic dynamometry was used to assess the strength of thigh and trunk musculature. During isokinetic testing the angular speed of the limb or body segment being tested is held constant throughout the range of motion of the test, regardless of magnitude and velocity with which the subject moves against the dynamometer.[213] For large muscle groups, which can exert high amounts of force, dynamometry is appropriate so that the subject does not over power the tester.[215] Isokinetic dynamometry allows the subject to move dynamically through a range of motion. Subjects can also be adequately stabilized to isolate the intended movement as the subjects exerts maximally against the dynamometer. The muscle groups chosen (knee and trunk) to be tested with the isokinetic dynamometer are large, strong muscle groups, which can be appropriately aligned in the dynamometer so that the axis of rotation is aligned with the joint where motion will occur and the attachment of the dynamometer will move freely within the same plane of motion being tested naturally occurs. The knee extensors and flexors are also primary lower limb movers, rather than stabilizers, during dance activity; therefore using isokinetic testing is more functional for these muscles.

2.6.3 Dynamic Postural Stability

The measure used to assess postural stability depends on the setting in which testing occurs. They range from highly technologically advanced laboratory methods, to fairly subjective, but clinically friendly tools. Laboratory methods for measurements are preferred when the purpose of the research is to most accurately and precisely describe balance and postural stability. They have higher sensitivity for the detection of movement and small changes and can also help make inference to performance of the underlying sensory motor systems responsible for maintaining balance and postural stability.[60,216] These methods are preferred for the current project because the purpose of the study is to describe the balance ability of different types of dancers, as well as determine the relationship of postural stability with the other variables being measured. Therefore, force plate measures of postural stability will be used.

Postural stability is a specific component of the ability to maintain balance. Balance is the ability to maintain the center of mass over the base of support.[28] Postural stability is the ability to maintain the body in equilibrium by keeping the center of mass within the base of support.[181] Maintaining postural stability requires the integration of sensory information and execution of appropriate motor responses.[26,27] Postural stability is most accurately assessed using force plate technology which quantifies the movement ground reaction forces about the base of support. This provides an objective measurement of the ability to stay as motionless as possible, or steadiness.[217] When steadiness is maintained on a fixed, firm, unmoving base of support, static postural stability is achieved.[179] Dynamic postural stability is the ability to achieve steadiness after performing a movement requiring a change in position of the stance leg or change in location.[217,218]

Postural stability will be quantified using ground reaction forces rather than center of pressure measurements because the former have been found to be more sensitive in discriminating changes in steadiness.[217] Dynamic postural stability measures the ability to stabilize when transitioning from a dynamic, or moving, to static state.[217] Time to stabilization measures have been used to assess dynamic postural stability, with longer times indicating worse dynamic postural stability.[219] However, it has been proposed that time to stabilization calculations can be influenced by individual differences in range of variation of the ground reaction force measurement.[219] A recommendation for correcting this potential error was made by Ross, et al., using a vibration magnitude of curve fit.[219] Furthermore, time to stabilization is reported in each of the three force directions (x, y, and z). Newer dynamic postural stability methods control for original calculation errors and report a score that incorporates movement in all directions.[87,220] The dynamic postural stability index (DPSI) was calculated using the x, y and z ground reaction forces, using the equation by Wikstrom et al.[87] Larger values indicate less postural stability. This equation for calculating DPSI has been found to be reliable with an ICC of 0.96.[87] This equation is beneficial because it incorporates the ground reaction forces in all axes for a total balance score, rather than providing multiple scores for each direction.

The dynamic task used for dynamic postural stability measurement was an anterior single leg jump from a distance of 40% of the subject's height over a hurdle. Sell et al.,[221] have demonstrated this specific task, and calculation of the DPSI score, to be reliable in physically active adults (ICC = 0.86). This task was chosen, as opposed to a dance jump, because there has been little research in dynamic postural stability of dancers to date. As a preliminary study, a task that is reliable, standardized and easily repeated will allow for a basic description of the dynamic postural stability of dancers, as well as allow for comparison to other types of athletes. There is no reason to believe the dancers will not be able to perform the task as they are familiar with jumping from two feet and landing on one foot.[187]

2.6.4 Biomechanics

Kinematic variables were used to describe lower extremity biomechanics of dancers performing a dance specific jump task. Three dimensional motion analyses using an infrared camera system tracking reflective markers was used. Three dimensional motion analyses are preferred compared to two dimensional methods because they more accurately describe joint position.[185] The ankle and foot joints are especially important in dance, and motion at these joints involves complex movements about all three axes. The marker set chosen for this study uses multiple markers about the lower leg, ankle and foot to adequately describe motion of the segments in each plane. A 3D motion capture system using multiple cameras is more appropriate for this type of study because it allows for a larger capture volume than an electromagnetic tracking system. This is necessary for the dancers to perform the dance jump task. Additionally, an electromagnetic tracking system was not appropriate for this study because it involves wires being attached to the subject which would limit their motion. Even though electromagnetic tracking does not have line of sight issues which can occur with 3D motion analysis, the ability to create a larger capture volume and no use of wires outweighs this limitation.[185]

A dance specific task was chosen for this study because previous work has been able to describe dancers in comparison to other athletes performing traditional tasks; drop landings. However, less work has been done to analyze how dancers jump during performance of dance tasks. Moving forward these tasks are important to investigate, as dancers are injured performing movements specific to dance technique. The dance task chosen is a forward *grad jeté*. This task is appropriate to use in the study population because dancers regularly perform this kind of jump. It is similar to the *saut de chat* jump used by Kulig and her colleagues in their studies on dancers.[101] Both are forward moving leaps where the dancer takes off from one foot, moves with the legs in a split position through the air, and lands on the opposite foot. The grad jeté was selected for analysis as it is a well-practiced movement and considered easier for the dancer to perform consistently and requires less room. The difference between the two jumps is the movement of the front leg and height as the dancer moves into the air. The *saut de chat* uses a *developé* (or kick moving from a bent knee to straight knee). With the "brush" approach the dancer keeps the knee straight as is moves forward into the air. The *grad jeté* was easier to perform with a two-step approach, which more appropriately fits on the platform surrounding the force plate in the motion capture space, and consistently land in the center of the force plate. During pilot testing dancers performing the *saut de chat* often felt more comfortable using a three to four step approach for the jump and either over or under shot the force plate depending on the height they achieved during the jump.

To standardize the dance jump task, all dancers took off from a position of 60% of their height away from the force place. This position was chosen during practice testing with a professional and a collegiate dancer. One was a female and one was a male. Both dancers performed multiple jumps landing on the force plate and their take off position was measured. The most frequently chosen take off position for both dancers was approximately 60% of their height. The pilot subjects performed leaps ranging from approximately 45% to 90% of their height. This jump distance is safe because it does not result in maximal axial or shear forces, yet still appropriately challenge the subjects.[188,222] Simpson et al., investigated the axial and shear forces on dancer's lower extremities performing jumps of varying distances (30%, 60%, and 90%) based on dancer's maximum jump distance. Overall, as jump distance increased, so did the axial and shear forces at the ankle and knee.[188,222] A dance jump distance is likely to be safe and representative of a typical movement, improving the applicability to the typical dance setting. A dance jump distance of 60% of dancer height is more reliably standardized than a jump distance based on maximum jump distance because the maximum distance a dancer jumps may be variable. The height of the jumps will not be standardized for this task so that the dancers' natural movement will not be hindered. The jump height will be collected and reported with the results to be used for discussion and explanation of the findings.

3.0 METHODOLOGY

3.1 EXPERIMENTAL DESIGN

This was a cross sectional study of professional ballet and collegiate dancers. Dancers were tested over two test sessions.

3.2 SUBJECT RECRUITMENT

The study was approved by the Institutional Review Board at the University of Pittsburgh prior to data collection. Subjects were recruited from professional dance companies and collegiate dance programs. The Principal Investigator (PI) has developed relationships and contacts with several institutions through clinical and academic work. The PI provided information about the study to Pittsburgh Ballet Theater (PBT), Texture Contemporary Ballet (TCB), Point Park University Dance Department (PPU), and Slippery Rock University Department of Dance (SRU). Informational presentations describing the study were provided to recruit volunteers. Interested subjects contacted the PI and completed a phone screening to determine eligibility. Eligible subjects who wished to participate scheduled a time to complete their testing sessions. On the first day of testing the inclusion and exclusion criteria were re-confirmed and they completed informed consent with the PI. The proportion of genders recruited were 60% female and 40% male. This was reasonable and reflective of the dance population and will help with the generalizability of the study to this community.

3.3 SUBJECT CHARACTERISTICS

3.3.1 Inclusion Criteria

Male and female dancers between the ages of 18 and 45 years were recruited for the study. Dancers had a contract to dance with a professional company or had been enrolled as a dance major at a collegiate institution, in the past twelve months. All dancers were currently dancing in class, rehearsal or performances at least three days a week at the time of the study.

3.3.2 Exclusion Criteria

Subjects were excluded from the study if they had a current musculoskeletal injury that was currently preventing the dancer from full participation in required dance activities (class, rehearsal, performance) and had been diagnosed by a licensed health care professional. Dancers were also excluded if they had any current neurological disorder, concussion, or allergy to adhesives at the time of the study.

3.4 POWER ANALYSIS

The statistical program G Power 3.1.5(Franz Faul, Universitat Kiel, Germany) was used for power analyses based on two independent means (two groups). The power analyses were completed using a *t*-test for between group comparisons, with alpha of 0.05, power set at 0.80, and a large effect size of d = 0.80. The effect size is Cohen's effect size for the expectation that there will be large differences between groups.[196] Means and standard deviations of quadriceps strength (peak torque/body weight) of professional ballet and collegiate dancers were used to calculate effect size, which was found to be d = 0.93.[52] To the author's knowledge, other studies have not provided sufficient example data (means and standard deviations) for effect size calculations for other muscle groups and variables. The author expected that similar differences will be seen for other muscle groups, as well as for the kinematic variables due to increased training of the professional group. Results indicated that 52 total subjects would be needed, with 26 subjects in each group. To account for possible 15% attrition and data loss, an additional 4 subjects were added to each group. Therefore 30 subjects were screened and recruited from professional dance organizations and 30 from collegiate dance institutions, a total of 60 subjects for the study.

Power analysis for regression using an F-test linear multiple regression fixed model R^2 deviation from zero, with alpha 0.05, power set at 0.80, a large effect size $f^2 = 0.35$, and six predictor variables indicated 46 subjects were needed..[196] Grouping all dancers together supported the sample size requirement for the regression analyses. Level/type of dancer and gender were used as two of the predictor variables for each regression. Four other variables were chosen from the strength variables for each regression.

3.5 INSTRUMENTATION

3.5.1 Bod Pod Body Composition

The Bod Pod® Body Composition System (Cosmed, Chicago, IL) was used to measure percent body fat and fat free body mass. The Bod Pod uses air-displacement plethysmography to calculate these percentages by measuring body volume. It is reliable and valid in measuring body composition. [208,209,211,223,224] These procedures have ICC(SEM) values of 0.996 (6.69) for males and 0.995 (6.48) for females.[225]

3.5.2 Hand Held Dynamometry

A handheld dynamometer (Lafayette Instrument Co., Lafayette, IN) was used to assess isometric muscle force for the motions of ankle inversion and eversion, and hip abduction, adduction, internal rotation, and external rotation. For all measures peak force produced was measured by the dynamometer to the nearest 0.1 kilogram. Hand held dynamometry has been found to be reliable in assessing strength of the lower extremity musculature. [215,226-228] The ICCs for the lower extremity musculature range from 0.74 – 0.99 for hip abduction, adduction, flexion, extension, internal and external rotations tested in supine or prone,[215,227,228] 0.85 to 0.96 for hip abduction tested in side lying,[176,228,229] 0.77 for knee extension and 0.85 for knee flexion,[215] and ranges from 0.78-0.94 for ankle and foot dorsiflexion, plantar flexion, inversion, eversion and toe flexion tested in supine, prone and side lying.[215,226] Because a variety of HHD testing methods have been used in previous reliability studies, the reliability of the methods to be used in this study, from unpublished NMRL data, is displayed in Table 1. The same testers from which the intra-tester reliability was calculated collected the strength measurements for this study.

Table 1. Hand Held Dynamometry (HHD) Reliability

HHD Strength Variables	Intra-tester Reliability		Inter-tester Reliability	
	ICC	SEM (kg/body mass)	ICC	SEM (kg/body mass)
Right Hip Abduction	0.91	1.84	0.60	3.95
Left Hip Abduction	0.84	3.06	0.91	2.18
Right Hip Adduction	0.87	2.38	0.76	2.79
Left Hip Adduction	0.95	1.53	0.87	2.18
Right Hip Internal Rotation	0.60	1.87	0.48	2.50
Left Hip Internal Rotation	0.74	2.12	0.77	2.40
Right Hip External Rotation	0.71	2.20	0.77	2.42
Left Hip External Rotation	0.86	1.58	0.82	2.14
Right Ankle Inversion	0.94	3.57	0.25	5.93
Left Ankle Inversion	0.91	3.59	0.34	6.82
Right Ankle Eversion	0.66	5.31	0.25	4.70
Left Ankle Eversion	0.79	4.25	0.20	4.76

3.5.3 Isokinetic Dynamometry

Knee flexion and extension and trunk flexion, extension, and rotation strength was assessed using the Biodex System 3 Multi-joint Testing and Rehabilitation System (Biodex Medical Inc., Shirley, New York) isokinetic dynamometer. The Biodex system has been found to be reliable and valid for measuring muscular strength.[230] The reliability, ICC (SEM), for knee strength testing is 0.93-0.98 (9.3 %BW) for knee flexion and 0.96-0.97 (12.7 %BW) for knee extension.[231] Unpublished data from the Neuromuscular Research Laboratory has found the reliability, ICC (SEM), of the trunk flexion testing to be 0.92 (1.7 %BW) and 0.98 (0.6 %BW) for trunk extension. The reliability of the trunk rotation strength testing is 0.91 (12.4 %BW) for left rotation and 0.89 (13.5 %BW) for right rotation.[232]

3.5.4 Dynamic Postural stability

A Kistler (Kistler 9286A, Amherst, NY) force plate was used to collect ground reaction force data to assess postural stability. The force plate was calibrated according to manufacturer's guidelines. Ground reaction force was collected in the x (mediolateral), y (anteroposterior), and z (vertical) directions, as shown in Figure 2.[233]

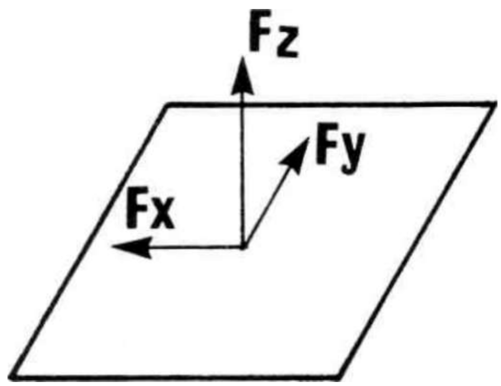


Figure 2: Force Plate Ground Reaction Force Directions

Force plate data was collected at a sampling frequency of 1200 Hz. The signal from the force plate was passed through an amplifier and analog to digital board (DT3010, Digital Translation, Marlboro, MA) that converted the signal from analog to digital. Data was stored on a personal computer.

3.5.5 Biomechanics

Trunk and lower extremity kinematics during a dance jump were assessed using a three dimensional (3D) optical motion capture system. Raw coordinate data for lower extremity kinematics were collected using the Vicon 3D Infrared Optical Capture System (Vicon Nexus, Centennial, CO) with 10 high speed cameras sampling at 200 Hz. Data were transferred to the Nexus software system (Vicon Nexus, Centennial, CO) where it was synchronized and combined to construct a 3D rigid body model to acquire joint position and orientation. The Vicon system has been found to have overall accuracy of 65 ± 5 micrometers and precision of 15 micrometers with optimal combination of camera positioning, calibration, maker size, and lens filter.[234] The NMRL has previously determined the accuracy of the laboratory instrumentation, and found the root mean square errors to be 0.002 meters and 0.254 degrees for position and angular data respectively. A custom model combining the Lower Extremity Plug in Gait Model (PIG) and the Oxford Foot Model (OFM), with the addition of a trunk segment, was used in this study. The Vicon system and PIG have been found to be reliable for determining joint position and orientation of the lower extremity during gait.[235,236] The OFM was used to create segments for the tibia, rearfoot, forefoot and hallux. This model has also previously been found to be reliable and valid for gait analysis.[195,199,237] The motions associated with pronation during gait measured using the OFM have been found to be significantly correlated with a pronated foot type identified via radiographs and a commonly used clinical assessment, the Foot Posture Index.[195,238]

The reliability of the dance jump task being used in this study, with custom model, has not been reported previously. The intratester reliability of the primary investigator using these methods was determined. The ICC and corresponding SEM values were calculated for angles at initial contact for all joints in all three planes. They are displayed by leg in Tables 2 and 3.

Table 2: Reliability of Right Lower Extremity Kinematic Variables at Initial Contact

Variable (direction)	ICC	SEM
Trunk (x) Flexion/Extension	0.87	2.33
Trunk (y) Lateral Flexion	0.64	2.00
Trunk (z) Right/Left Rotation	0.88	3.75
Pelvis (x) Flexion/Extension	0.58	4.65
Pelvis (y) Lateral Flexion	0.86	1.87
Pelvis (z) Right/Left Rotation	0.84	3.49
Hip (x) Flexion/Extension	0.90	4.64
Hip (y) Abduction/Adduction	0.96	1.68
Hip (z) Internal/External Rotation	0.95	3.42
Knee (x) Flexion/Extension	0.70	4.94
Knee (y) Varus/Valgus	0.69	2.09
Knee (z) Internal/External Rotation	0.89	3.06
Ankle(x) Dorsi/Plantar Flexion	0.94	5.70
Ankle (y) Inversion/Eversion	0.94	7.28
Ankle (z) Internal/External Rotation	0.97	2.82
Forefoot (x) Dorsi/Plantar Flexion	0.86	3.15
Forefoot (y) Abduction/Adduction	0.67	2.78
Forefoot (z) Pronation/Supination	0.83	3.64

Table 3: Reliability of Left Lower Extremity Kinematic Variables at Initial Contact

Variable (direction)	**ICC**	**SEM**
Trunk (x) Flexion/Extension	0.91	2.46
Trunk (y) Lateral Flexion	0.46	3.82
Trunk (z) Right/Left Rotation	0.73	7.33
Pelvis (x) Flexion/Extension	0.90	2.12
Pelvis (y) Lateral Flexion	0.91	2.06
Pelvis (z) Right/Left Rotation	0.97	2.45
Hip (x) Flexion/Extension	0.93	2.54
Hip (y) Abduction/Adduction	0.95	2.87
Hip (z) Internal/External Rotation	0.96	3.00
Knee (x) Flexion/Extension	0.98	1.11
Knee (y) Varus/Valgus	0.91	2.43
Knee (z) Internal/External Rotation	0.75	4.53
Ankle(x) Dorsi/Plantar Flexion	0.94	3.04
Ankle (y) Inversion/Eversion	0.88	5.39
Ankle (z) Internal/External Rotation	0.95	3.94
Forefoot (x) Dorsi/Plantar Flexion	0.86	2.65
Forefoot (y) Abduction/Adduction	0.60	2.74
Forefoot (z) Pronation/Supination	0.76	2.87

3.6 INJURY HISTORY

3.6.1 Retrospective Self-Reported Injury History and Supplemental Training Information

Demographic information was collected along with the dancer's injury history. This included the dancer's age, gender, current dance institution, position/year in company/school, number of years with current company/school, previous professional/collegiate experience, total years of professional/collegiate dancing, participation (hours) in dance activities including class, rehearsal and performance, start date of current season/semester, number of weeks of season/semester, number of performances in the current season/semester to date, and number of performances in the past twelve months. A self-reported orthopeadic injury history was collected on the first day of testing. The form was modified from the one used at PBT and PPU. It is a self-reported orthopeadic injury history by anatomic location. These injuries are those that resulted in time loss from or modification of dance activities for at least one day after the injury occurred, and/or required formal treatment from a licensed professional even if dance time loss or activity modification did not occur. Dancers indicated a total injury history, as well as specifying those that occurred in the past year. Supplemental training information was collected on the first day of testing. This was self-reported by the dancers and included information on the type, frequency and duration of supplemental training in the past six months. Types of other training could include strength training, cardiorespiratory training, Pilates, Yoga, Gyrotonics, and other. (**See Appendix A**)

3.7 TESTING PROCEDURES

Each dancer completed two days of testing. One day was completed on site at the dancer's respective institution or at the University of Pittsburgh Neuromuscular Research Lab (NMRL). All dancers completed the second day of testing at the NMRL. On the first day informed consent was obtained, followed by the procedures for the injury history and supplemental training questionnaire, and lower extremity muscular strength testing using the HHD. Subjects completed the procedures of the second test day in the following order; body composition, dynamic postural stability, kinematic assessment during a dance jump, ending with trunk and knee strength testing using the Biodex system. Some subjects requested to complete all testing at the NMRL on the same day. If subjects completed testing in one day, testing was completed in the following order; informed consent, body composition, dynamic postural stability, kinematic assessment, isometric strength, and isokinetic strength.

3.7.1 Informed Consent, Injury History, and Supplemental Training Questionnaire

All subjects provided written informed consent prior to participation in the research study. The PI reviewed the informed consent document with the subjects and allowed them to ask questions regarding the study. Inclusion/exclusion criteria were confirmed prior to data collection. Subjects completed an injury history form and supplemental training questionnaire. They were allowed to ask questions and review the form with the PI, who is a licensed medical professional.

3.7.2 Body Composition

Body composition was assessed using the Bod Pod according to the manufactures' guidelines. The Bod Pod was calibrated according to manufacturers' guidelines prior to testing. The subjects removed excess clothing and jewelry, wore spandex type shorts, and a swim cap. Female subjects wore a sports bra for testing to minimize air being trapped around the body and affecting measurement. The subjects sat in the Bod Pod for a series of measurements each lasting fifty seconds.[178] The first measurement was for total body volume. The subjects were asked to sit as still as possible in the Bod Pod and breathe normally. A second measurement was taken in the same manner. During the third measurement, lung volume was measured using the breathing tube. The tester and computer screen signaled the subject to put the breathing tube in their mouth, pinch their nose shut, and breathe normally through their mouth with the tube. After taking a few breaths with the tube in the mouth the tester and computer signaled the subject to puff three times into the tube to expel the air from their lungs. Additional trials were completed until two consistent air displacement measurements are taken. Consistent measurements were determined mathematically within the Bod Pod software based on the merit of the relationship between the airway and chamber.[208,239] Percentage of fat mass and fat free mass were calculated using measured lung volume and appropriate densitometry equation.

3.7.3 Muscular Strength

Lower extremity muscular strength was assessed using a hand held dynamometer (HHD) and an isokinetic dynamometer.

3.7.3.1 Hand held dynamometry for hip and ankle strength

Hip and ankle strength procedures used standard manual muscle testing positions with the tested limb moving in a direction against gravity.[214,240] All HHD tests were "make test" procedures in which the tester matched the force exerted by the subject but did not overcome the subject's effort. One tester held the HHD against the subjects' lower extremity, while a second tester provided stabilization to ensure appropriate testing position was maintained. Pillows were used to support the limb when appropriate. Subjects were given practice trials for each test at a perceived effort of 50% of their maximal effort until they felt comfortable with the procedure. For each test trial the subject pushed maximally into the HHD for five seconds. Three trials were collected for each muscle tested with a rest period of sixty seconds. Trials were averaged and then normalized to the subjects' body weight.

Strength of hip abduction and adduction were tested with the subject in side lying with the HHD at the distal one third of the lower leg and the second tester stabilizing the pelvis and shoulders.

Figure 3. Hip Abduction Strength

Figure 4. Hip Adduction Strength

Hip internal and external rotations were tested in prone with the HHD placed at the distal one third of the lower leg and the second tester stabilizing the pelvis.

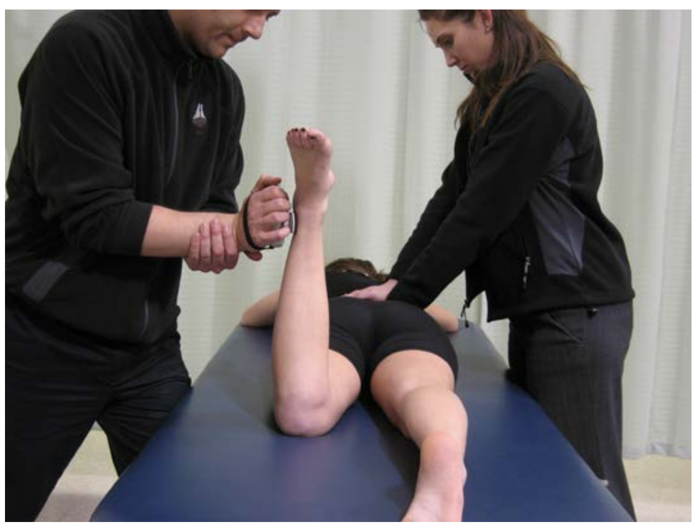


Figure 5. Hip Internal Rotation Strength

Figure 6. Hip External Rotation Strength

Ankle inversion and eversion were tested in side lying with the HHD placed at the distal end of the first or fifth metatarsal, respectively. The second tester stabilized the distal lower leg.

Figure 7. Ankle Inversion Strength

Figure 8. Ankle Eversion Strength

3.7.3.2 Isokinetic dynamometry for knee strength

Knee flexion and extension strength were tested using the Biodex isokinetic dynamometer. The Biodex was set up according to the manufacturers' guidelines prior to testing. The subjects sat in the Biodex chair with their knee joint center aligned with the dynamometer axis. Their lower leg was supported in the knee attachment and secured with Velcro straps. Additional straps were used to secure the thigh, waist and trunk to the Biodex chair to avoid extraneous movement of the body. Prior to testing, range of motion limits of knee flexion and extension were set for safety. For extension the subject straightened the knee fully and the limit was just below that position. For flexion the subject bent their knee fully and the limit was set just before that position. Subjects were allowed five practice trials at fifty and one hundred percent efforts to familiarize themselves with the test. Testing was completed at 60 degrees per second. Subjects started with the knee in the flexed position and performed five repetitions of consecutive extension and flexion at maximal effort. Subjects were encouraged throughout testing.

Figure 9: Knee Flexion and Extension Strength

3.7.3.3 Isokinetic dynamometry for trunk strength

Trunk muscular strength was assessed using the Biodex isokinetic dynamometer. The Biodex system was set up according to manufacturers' guidelines prior to testing. For testing of trunk flexion and extension, subjects sat in the Biodex chair with the dynamometer axis aligned with the superior edge of the iliac crest and the feet placed flat on the foot plate with the knees in approximately 10 degrees of flexion. Supports were adjusted so the lumbar pad was against the curve of the lumbar spine, upper back support at the level of the mid scapula, head support at a position just below the occiput so that the head and neck were in neutral alignment. Velcro straps were crossed and tightened across the subject's trunk, waist and thighs. These pad and strap placements were for subject safety and to help prevent extraneous movement during testing. For testing of trunk rotation the subject sat in the Biodex chair with the center of their head underneath the axis of rotation. The posterior supports were set behind the pelvis and leg supports strapped to the thighs to avoid excessive side to side motion of the lower body during testing. Straps were tightened around the shoulders to secure the upper torso to the chest pad. Prior to testing range of motion limits were set for safety. Each subject’s motion limits were set within their own range ability. For flexion and extension testing the range of motion limits were set just inside the maximum position to which the subject could bend forward towards their legs and lean backwards in the chair. For rotation testing, the range of motion limits were set just inside maximal rotation to the right and left. Subjects were allowed five practice trials at fifty percent effort and one hundred percent effort with one minute of resting in between practice and testing. Testing was completed at 60 degrees per second. For flexion and extension testing the subject started in the flexed position and then performed five repetitions of maximal effort trunk extension and flexion. For rotation testing the subject started fully rotated to the left and began by maximally rotating to the right and then back to the left for five trials. Subjects were cued to perform smooth consecutive motions and were encouraged throughout testing.

Figure 10: Trunk Flexion and Extension Strength

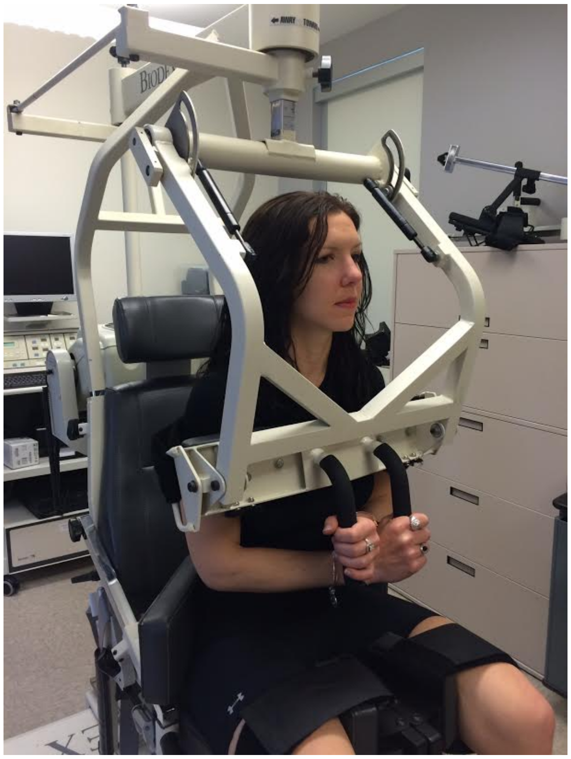


Figure 11: Trunk Rotation Strength

3.7.4 Postural Stability

Dynamic postural stability was measured using force plate technology. Ground reaction forces were collected in the x, y and z directions. A single leg jump landing protocol was used as the dynamic task. This task required subjects to jump from two feet over a 30cm hurdle from a distance of 40% of their height and land on the force plate on one foot. Subjects were asked to put their hands on their hips as soon as possible after they landed and felt stable. Subjects were allowed sufficient practice trials to feel comfortable performing the task on each leg. Trials were recollected if the subject's non-stance limb touched the stance limb or touched down onto the force plate, or if their stance foot rotated or hopped after landing. This was determined subjectively by the tester observing the trials. If there was some uncertainty as to if the subject rotated on the force plate, the tester opened the Vicon angle data to determine if the foot rotated more than 20 degrees, and recollected the trial if necessary. Three trials landing on each foot were collected. The force plate data was used to calculate the dynamic postural stability index (DPSI) which describes postural stability through analysis of ground reaction force variability upon landing from the jump. The DPSI is a composite postural stability score that is reflective of motion in all directions and normalized to the subjects' body weight, with higher scores indicating more movement and decreased postural stability. These procedures for the anterior jump and DPSI calculation have been found to be reliable with ICC (SEM) of 0.86 (0.01).[221]

Figure 12. Anterior Single Leg Jump Landing

3.7.5 Biomechanics

A custom model and marker set combining the trunk, lower extremity and the foot/ankle was used for this study. Double sided tape was used to place retro-reflective markers onto the subjects. Fourteen retro-reflective markers were placed onto the lower leg and foot, according to the Oxford Foot Model (OFM). The markers were placed at the most distal and medial aspect of the first metatarsal shaft, most proximal aspect of the fifth metatarsal shaft, most distal aspect of the fifth metatarsal shaft, midway between the second and third metatarsal heads, sustentaculum tali, lateral calcaneus, distal part of the calcaneus, posterior proximal calcaneus, peg marker between the heel and proximal calcaneus marker, medial malleolus, lateral malleolus, anterior aspect of the tibial crest, tibial tuberosity, and head of the fibula.[195,199,237] An additional 12 markers were placed on each leg on the thighs, pelvis and trunk at the lateral femoral epicondyles, mid lateral thighs, bilateral ASIS and PSIS, thoracic spinous process 10, xyphoid process, cervical spinous process 7, and sternal notch according to the lower extremity Plug in Gait Model with trunk markers.

The jump task performed is called a forward *grand jeté*. This is a basic dance movement with which dancers at all levels with a background of fundamental classical training are familiar. A tape mark was placed at a distance of 60% of the dancers' height away from the force plate. The dancer then took two steps back away from this mark and stood on their left foot with their right foot behind them. To complete the task the dancer stepped forward onto their right foot, then to the tape mark with their left foot where they jumped off of that foot and leaped forward onto the force plate landing on their right foot. The dancer continued forward off the force plate, and they were instructed to continue on as if they were progressing across the floor. The dancers were instructed to perform what they consider to be a typical or average *grand jeté* used in dance class or performance. The dancers were allowed to practice until they felt comfortable performing the jump landing on each leg and their starting position was marked with a second piece of tape. Landing limb order was randomized. The dancer performed five consecutive jumps landing on one leg and then the other. Trials were recollected if the subject appeared to pause at the jump position before leaping on to the force plate, failed to land on the force plate, failed to continue forward off the force plate after landing, or if the non-landing leg touched the force plate.

Figure 13. Dance Jump Task Kinematic Marker Set

3.8 DATA REDUCTION

3.8.1 Muscular Strength

The strength data collected using the HHD was normalized to subjects' mass by dividing the amount exerted against the HHD (kg) by the subject's mass (kg), and then multiplying by 100, so that the value was expressed as a percentage.

Equation 1: HHD Strength Normalization

Strength % Body Mass = (Kilograms Exerted / Kilograms Body Mass) * 100

Strength ratio variables were also calculated for each antagonistic muscle pair. The normalized strength values were used for the calculation of the ratios displayed in Table 4.

Table 4: Antagonist Pair Muscle Strength Ratios

Body Region	Ratio Pair Calculation
Trunk	Flexion / Extension
Trunk	Right Rotation / Left Rotation
Hip	Adduction / Abduction
Hip	Internal Rotation / External Rotation
Knee	Flexion / Extension
Ankle	Eversion / Inversion

3.8.2 Dynamic Postural Stability

The force plate data was filtered using a low pass Butterworth filter with a cutoff of 20Hz within the Vicon Nexus program. A custom MATLAB (v7.0.4, Natick, MA) script was used to process the ground reaction force data, average the three trials, and create an excel output file containing the DPSI score. Initial contact with the force plate was defined when the vertical ground reaction force exceeded 5% of the subject's body weight. Ground reaction force data from the first three seconds following initial contact in the x, y and z directions was used to calculate the dynamic postural stability index (DPSI). The DPSI utilizes mean square deviations in ground reaction forces from the 0 point along the frontal and sagittal axes of the force plate, as well as normalizing the score to subject body mass by standardizing the vertical ground reaction force along the force plate. The DPSI is a composite score of fluctuation in ground reaction forces in all three directions (mediolateral, anteroposterior and vertical) and is sensitive to change in all three directions.[87]

Equation 2. Dynamic Postural Stability Index

$$DPSI = \sqrt{}[\sum(0-x)^2 + \sum(0-y)^2 + \sum(\text{body weight} - z)^2/\text{number of data points}]$$

In this equation the "x" is the ground reaction force in the mediolateral direction, "y" in the anteroposterior direction, and "z" in the vertical direction. DPSI is the square root of the sum of the deviation of all "x" measurements from zero squared, plus the sum of the deviation of all "y" measurements from zero squared, plus the sum of the difference between the subjects bodyweight and the "z" measurements squared divided by the total number of data points.[87] Therefore, the DPSI equation accounts for variation in ground reaction forces about all three axes normalized to body weight across all data points of the trial.

3.8.3 Biomechanics

The retro-reflective markers were reconstructed and labeled in Vicon Nexus. The kinematic data was processed using a Butterworth filter with a low pass at 10Hz. Segment orientation (relative to the global reference frame) was calculated by creating a reference system embedded within each segment at the segment's center of gravity. A local coordinate system was established using Euler angles (y, x, z) to find the relative position of adjacent segments to each other.

The OFM was incorporated into the Vicon Nexus software with a custom Plug in Gait Model for the lower extremity and trunk, which created segments for the trunk, pelvis, femur, tibia, rearfoot, and forefoot. The kinematic data was synchronized with the force plate data within the Vicon system. A custom MATLAB code was used to identify the landing phase of the dance jump and determine lower extremity kinematic variables during landing. The landing of the jump was defined as initial contact to take off from the force plate. Initial contact was defined as the point where vertical ground reaction force exceeded 5% of body weight. The jump ended when the vertical ground reaction force was less than 5% of body weight, and called end contact. The code used these points in the kinetic measurements to identify the corresponding point in the kinematic measurements. The jump occurred from the point of initial contact to end contact with the force plate. The MATLAB code then calculated the joint angles in sagittal, frontal and transverse planes for the trunk, pelvis, hip, knee, ankle, and forefoot joints. The output excel file contained joint angles at initial contact and the maximum angle during landing of the jump (initial contact to end contact). The MATLAB code calculated the maximum jump height by finding the maximum position of the point in between the PSIS markers before initial contact with the force plate. The angles to be used for descriptive purposes and between group comparisons are displayed in Table 5. The angles used for regression analyses, chosen as specific potential risk factors for injury are listed in Table 6.

Table 5: Kinematic Variables for Between Group Comparisons

Body Region	Axis	Motion	Points in Dance Jump
Trunk	x	Flexion/extension	Initial Contact, Maximum
Trunk	y	Lateral tilt	Initial Contact, Maximum
Trunk	z	Rotation	Initial Contact, Maximum
Pelvis	x	Flexion/ extension	Initial Contact, Maximum
Pelvis	y	Lateral tilt	Initial Contact, Maximum
Pelvis	z	Rotation	Initial Contact, Maximum
Hip	x	Flexion/extension	Initial Contact, Maximum
Hip	y	Adduction/adduction	Initial Contact, Maximum
Hip	z	Rotation	Initial Contact, Maximum
Knee	x	Flexion/extension	Initial Contact, Maximum
Knee	y	Varus/valgus	Initial Contact, Maximum
Knee	z	Rotation	Initial Contact, Maximum
Ankle	x	Dorsi/plantarflexion	Initial Contact, Maximum
Ankle	y	Inversion/eversion	Initial Contact, Maximum
Ankle	z	Rotation	Initial Contact, Maximum
Forefoot	y	Dorsi/plantarflexion	Initial Contact, Maximum
Forefoot	z	Abduction/adduction	Initial Contact, Maximum
Forefoot	z	Internal/External Rotation	Initial Contact, Maximum

Table 6: Kinematic Variables for Regression Analyses

Body Region	Axis	Motion	Points in Dance Jump
Knee	y	Valgus	Initial Contact, Maximum
Ankle	y	Inversion	Initial Contact, Maximum
Forefoot	z	Pronation	Initial Contact, Maximum

3.9 DATA ANALYSIS

Data analyses was completed using IBM SPSS Statistics 22 (IBM Corporation, Armonk, New York). Descriptive data was presented as means and standard deviations, or median and interquartile range if not normally distributed. Statistical significance for all tests was set *a priori* at alpha = 0.05 (two-sided). Data for all variables was assessed for normality using the Shapiro Wilk test. Independent samples *t*-tests were used to determine differences between the professional group and the collegiate group for all variables. If the normality assumption was not met a Mann-Whitney U test was used. A Fisher's Exact test was used to determine differences in the proportion of subjects with injuries between the two groups.

To help interpret the differences between groups Cohen's standard effect sizes were calculated in the G-Power software program to determine the magnitude of difference between groups. Effect sizes can be interpreted as; small 0.2, medium 0.5, large 0.8.[196] For comparisons tested with the Mann Whitney U test, non-parametric effect sizes were calculated using Equation 3. These non-parametric effect sizes can be interpreted as; small 0.1, medium 0.3, large 0.5.[241]

Equation 3: Non-Parametric Effect Size Calculation

$$\text{Effect size} = \text{Zscore}/\sqrt{n_{total}}$$

Multiple linear regression statistical analyses were performed using STATA 14 (STATA Corp LP, College Station, Texas). The investigator's knowledge of subject matter was incorporated in the model building process. Statistical significance was set *a priori* at alpha = 0.05 (two-sided). Descriptive statistics were calculated for all variables. Scatter plots were created and correlation coefficients computed. Independent variables with collinearity issues were examined further for deletion. Separate multiple linear regression equations were fit for each of the dependent variables. Residuals were examined for linearity, heteroscedasticity, and outliers and influential points. Data transformations were performed if required. The multiple linear regression models were fit using the backwards stepwise method. Variance inflation factors (VIFs) and residual diagnostics were examined. Analyses were conducted to examine if additional variables could be dropped, and if new variables could be included in the model. If variables were dropped or added, then the model diagnostics were run again.

4.0 RESULTS

4.1 SUBJECTS

A total of 79 dancers were screened for the study, and 60 dancers were found to be eligible, volunteered, and were enrolled in the study. One collegiate female subject became injured in between her first and second day of testing, therefore her data was not used for analysis. Data was analyzed for 59 subjects (18 professional females, 12 professional males, 17 collegiate females, 12 collegiate males). A flow chart for subject enrollment is presented in Figure 14. There were equal proportions of female and male dancers in each group. In the professional group 60% were female and 40% were male. In the collegiate group 58.6% were female and 41.4% were male. No difference was found in the proportion of genders in each group (Chi-Square value = 0.012, p-value = 1.000).

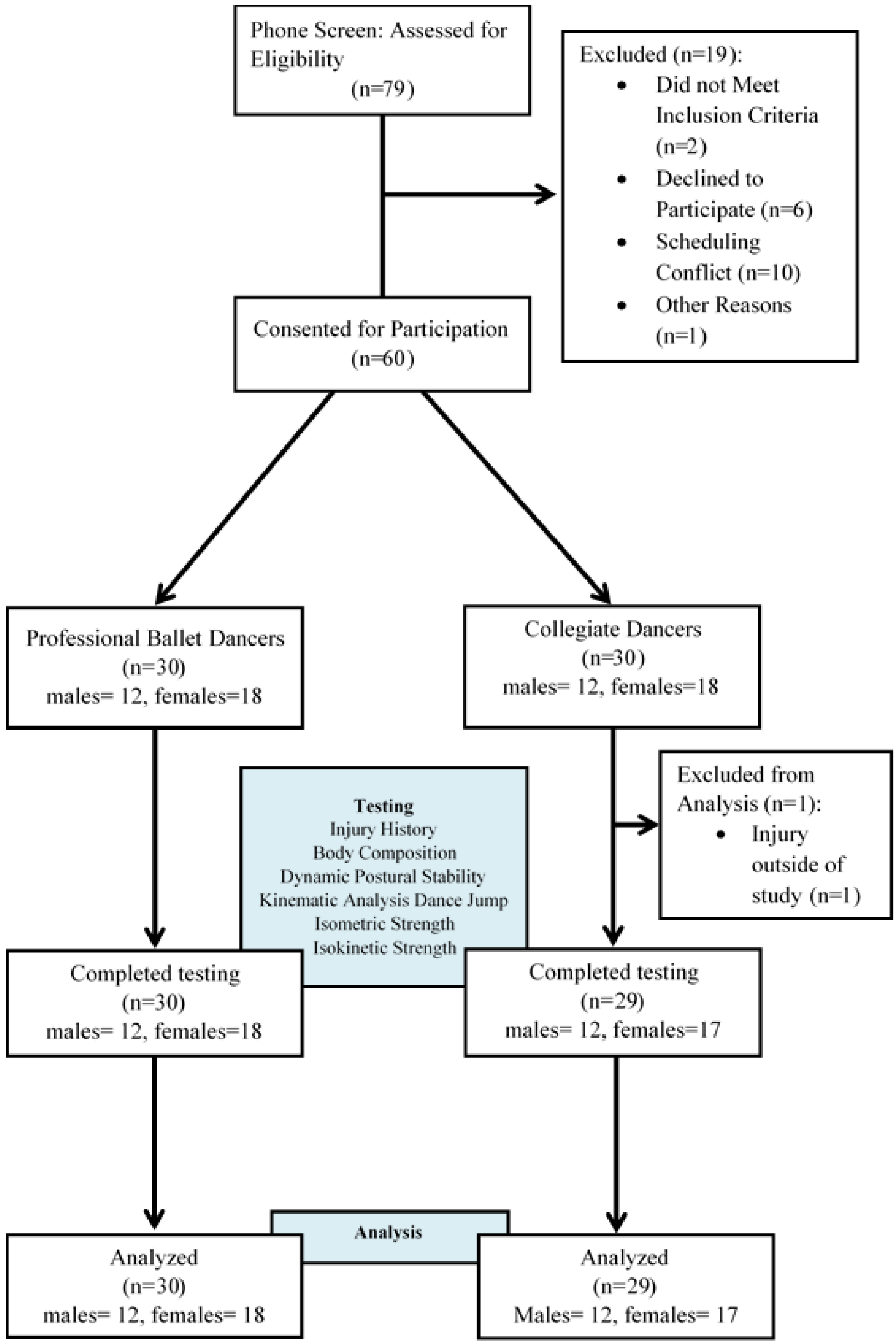


Figure 14: Subject Flow Chart

Professional ballet dancers came from several companies including three classical ballet and four contemporary ballet companies. Two dancers danced with both a classical and a contemporary ballet company. Two dancers were free-lance dancers currently working with a contemporary ballet company at the time of the study, who had previously danced as principal dancers in a classical company. The rank of the professional dancers in the study included apprentice (10.00%), corps de ballet (46.67%), soloist (10.00%), and dancer/director/choreographer (3.33%). 30.00% of the dancers did not work for a company with a ranking system. The average length of working or contract weeks reported by the professional dancers was 34.92 weeks. Professional dancers had an average of 6.083 years of professional dance experience. Professional dancers reported participating in an average of 8.19 hours of dance class a week and 23.67 hours of rehearsal a week. The typical number of hours in a performance week was difficult to collect because of variability between show and venue. None of the dancers were in a performance week at the time they participated in the study. Professional dancers reported performing in an average of 32.69 performances during the twelve months prior to participating in the study.

All collegiate dancers came from one of three prestigious dance institutions in the area, including Slippery Rock University (SRU), LaRoche College (LRC), or Point Park University (PPU). Slippery Rock University was ranked second best in the state of Pennsylvania by the 2014 Dance-Colleges.com national and state ranking list. LaRoche College was ranked eighteenth and PPU was rated twelfth in the state of Pennsylvania. All three dance programs have two 14 week semesters. Dance majors at all schools must participate in an audition to be accepted into the dance program. The degree from SRU is focused on modern dance, but all majors must demonstrate mastery in modern dance, ballet, and jazz to graduate from the program. At LRC the program is focused on contemporary ballet, but also requires modern and jazz technique. At PPU dance majors chose one or more concentrations in ballet, jazz and/or modern dance although they are required to be proficient in all types of dance to remain in the program. With all of these curriculum and admission requirement similarities, it can be accepted that the technical abilities of majors from both institutions are similar. The collegiate dancers included 34.48% freshman, 10.34% sophomores, 13.79% juniors, and 41.38% seniors. Their average time in collegiate dance was 2.55 years. Eight of the college dancers had some experience as a guest artist in performances with professional companies, but they had never been employed full time with a company. Collegiate dancers reported participating in an average of 18.07 hours of dance class a week and 9.06 hours of rehearsal a week. None of the dancers were in a performance week at the time they participated in the study. Collegiate dancers reported performing in an average of 8.82 performances in the twelve months prior to participating in the study.

All results for strength, dynamic postural stability and biomechanics of landing are for the dominant limb. Limb dominance was defined as the leg the dancer would use to kick a ball. 83% of subjects reported that the leg they would use to kick a ball was also their preferred gesture, or moving leg, in dance. Regarding limb dominance, 55 subjects (93.2%) were right leg dominant and 4 subjects (6.8%) were left leg dominant. Demographic data (age, height, weight) for all subjects is presented in Table 7.

Table 7: Subject Demographic Data

		Professional					Collegiate					
		N	Mean	SD	Med	IQR	N	Mean	SD	Med	IQR	p-value
Age (years)	All	30	25.0	3.3	25.0	22.0 - 28.0	29	20.2	1.3	20.0	19.0 - 21.0	<0.001†
	Female	18	24.5	3.2	24.0	22.0 - 27.0	17	20.2	1.3	20.0	19.0 - 21.0	<0.001†
	Male	12	25.7	3.5	27.0	22.0 - 28.8	12	20.2	1.3	20.5	19.0 - 21.0	<0.001
Height (cm)	All	30	172.6	9.1	173.9	164.0 - 180.0	29	169.2	9.6	166.9	162.1 - 177.3	0.171
	Female	18	166.9	6.6	165.2	162.5 - 173.6	17	165.0	7.0	165.5	160.3 - 167.8	0.396
	Male	12	181.0	4.6	181.5	177.6 - 182.2	12	175.2	9.9	175.8	167.0 - 182.9	0.084
Weight (kg)	All	30	62.2	11.0	59.6	52.3 - 71.2	29	66.1	12.7	64.3	55.3 - 70.8	0.254†
	Female	18	54.7	5.8	53.9	50.5 - 57.7	17	61.7	11.4	59.3	53.8 - 66.0	0.035†
	Male	12	73.5	6.2	74.0	68.0 - 78.8	12	72.2	12.4	69.6	63.4 - 81.0	0.754

N = number of subjects; SD = standard deviation; Med = median; IQR= interquartile range

† p-value from Mann Whitney U test

Normality was assessed for both groups, and the groups assessed for differences using independent samples *t*-tests or Mann-Whitney U tests (alpha = 0.05). No difference between groups were found for height or weight. There were no difference in height when comparing groups within genders. The professional females had lower body weight than the collegiate females. No differences were observed between professional and collegiate males. The professional group was found to be significantly older than the collegiate group (24.97 ± 3.33 years vs 20.17 ± 1.28 years, p-value < 0.001), also when stratified by gender. The age range of the collegiate group was much smaller than the professional group, 18-22 years and 20-33 years respectively. This accurately reflects age of collegiate dance majors, and therefore accurately represents each population of dancers, which is important in making between group comparisons, and for generalizability.

4.2 BETWEEN GROUP COMPARISONS OF PHYSICAL CHARACTERSITICS OF PROFESSIONAL BALLET AND COLLEGIATE DANCERS

4.2.1 Body Composition

Body composition testing was completed for all subjects (n = 59) using the Bod Pod® Body Composition System to measure percent body fat. All subjects completed procedures for measured lung volume tests. Some subjects were not able to satisfactorily complete the procedures for measured lung volume, as indicated by a high merit level demonstrating inconsistency between measurements. Lung volume for these subjects was predicted using the Bod Pod® software. 52.5% of the tests used measured lung volumes and 47.5% of the tests used predicted lung volumes. Body composition data were found to be normally distributed in both groups, and were compared using independent samples *t*-tests (alpha = 0.05). The body fat percentages and results of the between group comparisons are presented in Table 8.

Table 8: Body Fat Percentage of Professional and Collegiate Dancers

		Professional					Collegiate					
		N	**Mean**	**SD**	**Med**	**IQR**	**N**	**Mean**	**SD**	**Med**	**IQR**	**p-value**
Body Fat	All	30	14.14	5.67	13.55	9.60 - 17.53	29	18.20	7.63	19.20	11.95 - 23.10	0.024
(percentage)	Female	18	17.58	4.38	17.40	14.28 - 19.75	17	22.84	4.99	22.60	19.25 - 24.60	0.002
	Male	12	8.98	2.62	8.60	6.93 - 11.25	12	11.63	5.62	9.40	7.63 - 16.03	0.160

N = number of subjects; SD = standard deviation, Med = median; IQR = interquartile range

A significant difference was found in body fat percentage of professional and collegiate dancers, and the research hypothesis was supported. Professional dancers had significantly less body fat percentage than collegiate dancers (14.14% ± 5.67% vs 18.20% ± 7.63%, p-value = 0.024). Professional female dancers were found to have significantly lower body fat percentage than collegiate females (17.58% ± 4.38% vs 22.84% ± 4.99%, p-value = 0.002). Although the body fat percentage of professional males was lower than for collegiate males, there was no significant difference in body fat percentage observed within the males (8.98% ± 2.62% vs 11.63% ± 5.62%, p-value = 0.160). Effect sizes will be discussed in Chapter 5 and are available in Appendix E.

4.2.2 Muscular Strength

Tests completed using the HHD represent isometric strength and are reported in kg normalized to kg of body mass (kg % BM). Tests completed using the Biodex represent isokinetic strength and are reported in NM normalized to kg of body mass (NM % BM). Normality assessment of all strength data was completed for each group. All HHD and Biodex variables were normally distributed in both groups and independent sample *t*-tests were used to compare groups (alpha = 0.05).

4.2.2.1 Trunk Strength

Trunk strength testing was completed using the Biodex isokinetic dynamometer. Two dancers, (1 professional male, 1 collegiate female) did not complete isokinetic strength testing for trunk flexion and extension due to recent completion of rehabilitation for back injuries. These dancers met injury related inclusion criteria for the study, but the PI decided that due to their specific diagnoses it would be safer to forgo the trunk flexion/extension strength test. All subjects were able to complete trunk rotation testing. Therefore, trunk strength analyses were completed on 57 subjects. Trunk strength and between group comparisons are presented in Table 9.

Table 9: Isokinetic Dynamometry Trunk Strength Variables (NM % BM)

		Professional					Collegiate					
		N	**Mean**	**SD**	**Med**	**IQR**	**N**	**Mean**	**SD**	**Med**	**IQR**	**p-value**
Trunk Extension	All	29	283.49	81.53	271.93	225.43 - 328.72	28	239.84	82.37	226.26	190.73 - 298.10	0.049
	Female	18	259.08	69.06	252.78	219.71 - 313.96	16	241.74	74.89	220.76	204.38 - 298.10	0.488
	Male	11	323.44	87.62	314.03	266.90 - 371.84	12	237.31	94.83	247.45	172.86 - 308.68	0.035
Trunk Flexion	All	29	196.94	51.65	197.26	174.33 - 226.74	28	163.66	41.12	164.40	134.41 - 186.66	0.010
	Female	18	176.83	48.82	178.42	157.64 - 203.32	16	162.45	43.83	164.40	134.59 - 182.80	0.375
	Male	11	229.84	38.74	224.78	198.45 - 245.57	12	165.28	39.05	164.52	130.12 - 202.38	0.001
Trunk Flexion/ Extension Ratio	All	29	0.72	0.19	0.67	0.60 - 0.82	28	0.72	0.16	0.68	0.62 - 0.78	0.893†
	Female	18	0.70	0.14	0.67	0.59 - 0.83	16	0.68	0.09	0.66	0.63 - 0.75	0.722
	Male	11	0.76	0.26	0.67	0.60 - 0.81	12	0.76	0.21	0.75	0.59 - 0.85	0.976†
Right Trunk Rotation	All	30	102.94	38.93	96.45	76.91 - 126.78	29	92.66	27.23	91.93	70.36 - 116.61	0.246
	Female	18	86.50	24.23	83.82	75.69 - 105.44	17	91.59	27.69	89.70	72.50 - 119.67	0.566
	Male	12	127.60	44.52	141.85	79.10 - 154.55	12	94.17	27.71	97.17	68.80 - 112.57	0.038
Left Trunk Rotation	All	30	105.37	33.14	101.24	83.50 - 126.74	29	98.66	26.96	104.44	80.88 - 118.69	0.398
	Female	18	93.86	24.86	95.01	83.50 - 114.85	17	95.65	26.60	90.01	80.88 - 117.48	0.837
	Male	12	122.65	37.40	127.74	85.28 - 145.16	12	102.91	28.05	112.46	73.74 - 130.05	0.158
Right/Left Trunk Rotation Ratio	All	30	0.97	0.13	0.98	0.85 - 1.07	29	0.94	0.11	0.94	0.84 - 1.02	0.382
	Female	18	0.93	0.12	0.92	0.82 - 1.02	17	0.96	0.12	0.95	0.84 - 1.04	0.448
	Male	12	1.03	0.12	1.02	0.95 - 1.14	12	0.92	0.09	0.93	0.84 - 0.99	0.015

N = number of subjects; SD = standard deviation; IQR = interquartile range

† p-value from Mann Whitney U test

The research hypothesis that professional dancers would have higher trunk strength than collegiate dancers was partially supported. Differences between groups were found for trunk flexion and extension, but not for rotation. Professional dancers had stronger trunk extension than collegiate dancers (283.49 ± 81.53 vs 239.84 ± 82.37, p-value = 0.049). Professional dancers also had stronger trunk flexion than collegiate dancers (196.94 ± 51.65 vs 163.66 ± 41.12, p-value = 0.010). Higher trunk flexion and extension strength were observed for both female and male professional dancers than for female and male collegiate dancers, although this difference was only significant within males. No differences were found between groups for trunk rotation. For right trunk rotation, professionals and collegiate dancers were found to be similar (102.94 ± 38.93 vs 92.66 ± 27.23, p-value = 0.246). The same was true for left trunk rotation for professional and collegiate dancers respectively (105.37 ± 33.14 vs 98.66 ± 26.96, p-value = 0.398). The only difference overserved within genders was that collegiate male dancers had lower right trunk rotation strength than professional males. No differences were found between professional and collegiate dancers for trunk flexion/extension (0.72 ± 0.19 vs 0.72 ± 0.16, p-value = 0.886) or right/left trunk rotation (0.97 ± 0.13 vs 0.94 ± 0.11, p-value = 0.382). Effect sizes will be discussed in Chapter 5 and are available in Appendix E.

4.2.2.2 Hip Strength

All subjects completed all hip strength testing procedures (n = 59) with the HHD. Hip strength results and between group comparisons are presented in Table 10.

Table 10: Hand Held Dynamometry Hip Strength Variables (kg % BM)

		Professional					Collegiate					
		N	**Mean**	**SD**	**Med**	**IQR**	**N**	**Mean**	**SD**	**Med**	**IQR**	**p-value**
Hip	All	30	23.61	5.38	22.69	21.00 - 26.46	29	19.95	4.08	20.00	17.75 - 22.06	0.005
Abduction	Female	18	21.71	3.47	21.79	19.62 - 23.62	17	18.54	3.79	19.55	16.38 - 21.53	0.017†
(kg % BM)	Male	12	26.47	6.54	25.00	22.02 - 32.64	12	21.94	3.77	22.06	19.15 - 25.50	0.049
Hip	All	30	25.25	5.57	23.78	21.77 - 28.11	29	21.84	4.58	21.22	19.93 - 25.29	0.013
Adduction	Female	18	23.68	5.44	22.31	21.41 - 24.22	17	20.58	4.69	20.77	17.77 - 23.56	0.080†
(kg % BM)	Male	12	27.62	5.08	27.37	20.25 - 26.88	12	23.62	3.94	22.24	20.24 - 26.88	0.042
Hip Adduction/	All	30	1.08	0.15	1.07	1.00 - 1.20	29	1.12	0.24	1.08	0.94 - 1.26	0.690†
Abduction	Female	18	1.09	0.16	1.05	0.98 - 1.24	17	1.12	0.18	1.20	1.00 - 1.26	0.590
Ratio	Male	12	1.07	0.15	1.09	1.02 - 1.19	12	1.11	0.31	1.02	0.91 - 1.24	0.843†
Hip External	All	30	18.38	4.85	18.73	14.01 - 21.70	29	15.01	3.13	14.62	12.45 - 17.16	0.003
Rotation	Female	18	16.61	4.22	16.87	13.73 - 19.06	17	14.65	3.22	15.30	11.82 - 16.35	0.132
(kg % BM)	Male	12	21.02	4.66	21.26	19.28 - 23.81	12	15.53	3.07	14.39	12.78 - 18.62	0.003
Hip Internal	All	30	15.40	5.05	14.71	12.22 - 18.65	29	12.17	2.58	12.21	10.61 - 13.37	0.003
Rotation	Female	18	15.39	4.95	14.71	13.07 - 17.80	17	12.51	2.95	12.37	10.65 - 14.17	0.046
(kg % BM)	Male	12	15.41	5.44	14.73	12.01 - 19.66	12	11.68	1.95	11.97	10.52 - 13.02	0.042
Hip Internal/	All	30	0.86	0.25	0.88	0.62 - 0.98	29	0.83	0.20	0.79	0.70 - 0.96	0.657
External Rotation	Female	18	0.95	0.25	0.93	0.80 - 1.11	17	0.87	0.19	0.83	0.75 - 0.96	0.207†
Ratio	Male	12	0.73	0.17	0.70	0.60 - 0.90	12	0.78	0.21	0.72	0.64 - 0.98	0.503

N = number of subjects; SD = standard deviation; IQR = interquartile range

† p-value from Mann Whitney U test

For hip strength variables, the research hypothesis was supported and professional dancers were found to have stronger hip strength for all variables compared to collegiate dancers including; hip abduction (23.61 ± 5.38 vs 19.95 ± 4.08, p-value = 0.005), hip adduction (25.25 ± 5.57 vs 21.84 ± 4.58, p-value = 0.013), hip external rotation (18.38 ± 4.85 vs 15.01 ± 3.13, p-value = 0.003), and hip internal rotation (15.40 ± 5.05 vs 12.17 ± 2.58, p-value = 0.003). When stratified by gender, professionals were always stronger than their collegiate counterparts. This strength difference was significant for males for all muscles. The strength difference between female professional and collegiate dancers was significant for hip abduction and internal rotation, but not for hip adduction and external rotation. No differences were found between professional and collegiate dancers in the strength ratios hip adduction/abduction (1.08 ± 0.15 vs 1.12 ± 0.24, p-value = 0.682) or hip internal/external rotation (0.86 ± 0.25 vs 0.83 ± 0.20, p-value = 0.657). Effect sizes will be discussed in Chapter 5 and are available in Appendix E.

4.2.2.3 Knee Strength

All subjects completed all knee strength testing procedures (n = 59) in the Biodex. Knee strength results and between group comparisons are presented in Table 11.

Table 11: Isokinetic Dynamometry Knee Strength Variables (NM % BM)

		Professional					Collegiate					
		N	Mean	SD	Med	IQR	N	Mean	SD	Med	IQR	p-value
Knee	All	30	213.02	50.96	224.14	177.94 - 256.90	29	194.25	50.93	198.68	150.33 - 233.76	0.163
Extension	Female	18	199.83	48.37	215.95	157.15 - 233.80	17	189.53	51.35	184.81	143.84 - 223.90	0.546
(NM%BM)	Male	12	232.80	50.20	253.72	195.13 - 257.41	12	200.93	51.83	199.28	166.45 - 247.02	0.140
Knee	All	30	120.09	21.69	117.08	106.74 - 132.61	29	103.26	24.36	101.67	81.99 - 121.95	0.007
Flexion	Female	18	110.31	16.97	108.93	100.75 - 125.15	17	98.32	24.93	95.23	76.04 - 118.77	0.104
(NM%BM)	Male	12	134.77	20.10	130.84	116.68 - 151.53	12	110.26	22.70	110.88	90.82 - 122.79	0.010
Knee Flexion/	All	30	0.58	0.10	0.56	0.51 - 0.67	29	0.54	0.09	0.55	0.49 - 0.60	0.145
Extension	Female	18	0.57	0.09	0.55	0.49 - 0.66	17	0.53	0.08	0.55	0.47 - 0.59	0.165
Ratio	Male	12	0.60	0.11	0.58	0.52 - 0.67	12	0.57	0.10	0.54	0.50 - 0.61	0.494

N = number of subjects; SD = standard deviation; Med = median; IQR = interquartile range

The research hypothesis that professional dancers would have higher strength was partially supported. Although the professional group, overall and within genders, had stronger knee extension, this difference was not found to be significant (213.02 ± 50.96 vs 194.24 ± 50.93, p-value = 0.163). The professional dancers, however, were found to have significantly stronger knee flexion than collegiate dancers (120.09 ± 21.69 vs 103.26 ± 24.36, p-value = 0.007). This was observed for both females and males, however it was only a significant difference in the males. No differences were found between professional and collegiate dancers in the strength ratios for knee flexion/extension (0.58 ± 0.10 vs 0.54 ± 0.09, p-value = 0.145). Effect sizes will be discussed in Chapter 5 and are available in Appendix E.

4.2.2.4 Ankle Strength

All subjects completed all ankle strength testing procedures (n = 59). Ankle strength was assessed using a HHD. Ankle strength results and between group comparisons are presented in Table 12.

Table 12: Hand Held Dynamometry Ankle Strength Variables (kg % BM)

		Professional					Collegiate					
		N	**Mean**	**SD**	**Med**	**IQR**	**N**	**Mean**	**SD**	**Med**	**IQR**	**p-value**
Ankle	All	30	31.94	9.03	32.77	27.61 - 35.47	29	27.90	6.76	28.72	23.35 - 33.41	0.057
Inversion	Female	18	30.87	8.74	31.68	22.84 - 35.74	17	27.08	6.47	28.72	23.69 - 32.77	0.157
(kg%BM)	Male	12	33.55	9.61	33.55	31.22 - 35.14	12	29.05	7.28	27.64	23.05 - 35.26	0.319†
Ankle	All	30	27.32	6.51	27.40	22.88 - 31.40	29	24.64	6.12	24.81	21.46 - 29.05	0.109
Eversion	Female	18	27.01	7.79	25.39	21.58 - 32.41	17	23.90	7.04	24.81	17.66 - 26.29	0.225
(kg%BM)	Male	12	27.79	4.19	28.16	25.95 - 31.12	12	25.68	4.63	24.48	21.94 - 30.04	0.254
Ankle Eversion/	All	30	0.88	0.18	0.84	0.79 - 0.75	29	0.90	0.14	0.89	0.79 - 0.98	0.429†
Inversion	Female	18	0.89	0.17	0.87	0.78 - 1.03	17	0.89	0.15	0.90	0.78 - 0.99	0.965
Ratio	Male	12	0.87	0.21	0.82	0.80 - 0.87	12	0.90	0.13	0.88	0.81 - 0.95	0.219†

N = number of subjects; SD = standard deviation; IQR = interquartile range

† p-value from Mann Whitney U test

The research hypothesis that professional ballet dancers would have higher ankle strength than collegiate dancers was not supported. No significant difference was found between professional and collegiate dancers' ankle strength for ankle inversion (31.94 ± 9.03 vs 27.90 ± 6.76, p-value = 0.057) or ankle eversion (27.32 ± 6.51 vs 24.81 ± 6.12, p-value = 0.109). Although the professional group was stronger overall and within genders, this difference was small and not statistically significant. No differences were found between professional and collegiate dancers in the strength ratios for ankle eversion/inversion (0.88 ± 0.18 vs 0.90± 0.14, p-value = 0.422). Effect sizes will be discussed in Chapter 5 and are available in Appendix E.

4.2.3 Dynamic Postural Stability

All dancers completed dynamic postural stability testing. Four subjects were removed from the dynamic postural stability data set due to inability to properly perform the jump task, leaving 55 subjects to be analyzed. All of the excluded subjects were collegiate dancers; three female and one male. The dynamic postural stability data analyzed included 30 in the professional group (18 female, 12 male), and 25 in the collegiate group (14 female, and 11 male).

Dynamic postural stability indexes were calculated for the mediolateral (MLSI), anteroposterior (APSI), vertical (VSI), and overall composite (DPSI) performance. All scores were normally distributed in both groups and an independent samples *t*-test was used to assess for differences between the groups. Dynamic postural stability scores and results of the between group comparisons are presented in Table 13.

Table 13: Dynamic Postural Stability Scores of Professional Ballet and Collegiate Dancers

		Professional					Collegiate					
		N	**Mean**	**SD**	**Med**	**IQR**	**N**	**Mean**	**SD**	**Med**	**IQR**	**p-value**
DPSI	All	30	0.3285	0.0411	0.3261	0.30 - 0.35	25	0.3269	0.0313	0.3196	0.30 - 0.35	0.874
	Female	18	0.3131	0.0239	0.3149	0.30 - 0.34	14	0.3171	0.0299	0.3176	0.29 - 0.34	0.681
	Male	12	0.3514	0.0511	0.3533	0.30 - 0.40	11	0.3393	0.0297	0.3334	0.31 - 0.37	0.500
MLSI	All	30	0.0240	0.0052	0.0234	0.02 - 0.03	25	0.0216	0.0052	0.0216	0.02 - 0.03	0.092
	Female	18	0.0250	0.0050	0.0246	0.02 - 0.03	14	0.0223	0.0058	0.0235	0.02 - 0.03	0.158
	Male	12	0.0224	0.0053	0.0208	0.02 - 0.03	11	0.0207	0.0045	0.0210	0.02 - 0.02	0.408
APSI	All	30	0.1231	0.0083	0.1233	0.12 - 0.13	25	0.1247	0.0102	0.1221	0.12 - 0.13	0.536
	Female	18	0.1240	0.0078	0.1232	0.12 - 0.13	14	0.1229	0.0112	0.1214	0.11 - 0.13	0.755
	Male	12	0.1219	0.0091	0.1235	0.11 - 0.13	11	0.1269	0.0088	0.1256	0.12 - 0.13	0.189
VSI	All	30	0.3030	0.0434	0.2985	0.27 - 0.32	25	0.3011	0.0316	0.2962	0.28 - 0.32	0.854
	Female	18	0.2862	0.0244	0.2893	0.27 - 0.31	14	0.2912	0.0288	0.2918	0.26 - 0.31	0.596
	Male	12	0.3283	0.0537	0.3317	0.28 - 0.38	11	0.3136	0.0316	0.3047	0.29 - 0.35	0.441

N = number of subjects; SD = standard deviation; Med = median; IQR = interquartile range

The research hypothesis that professional dancers would have better dynamic postural stability than collegiate dancers was not supported, as no differences were found between groups for any of the variables. No differences were found between the overall DPSI composite scores of professional and collegiate dancers (0.3285 ± 0.0411 vs 0.3269 ± 0.0313, p-value = 0.874). No differences across genders were observed. No difference was found in MLSI scores of professional dancers compared to collegiate dancers (0.0240 ± 0.0052 vs 0.0216 ± 0.0052, p-value = 0.092), in APSI (0.1231 ± 0.0083 vs 0.1247 ± 0.0102, p-value = 0.536), or in VSI (0.3030 ± 0.0434 vs 0.3011 ± 0.0316, p-value = 0.854). No significant differences across genders were observed for any of these component DPSI scores. Effect sizes will be discussed in Chapter 5 and are available in Appendix E.

4.2.4 Biomechanics

All subjects completed motion analysis testing while they completed a dance jump task, the forward *grand jeté*. Data from landing on the dominant limb were analyzed. Kinematic data were lost for two subjects during processing, leaving 57 subjects for analysis; 28 professional dancers analyzed (17 female, 11 male) and 29 collegiate dancers (17 female, 12 male) for kinematic analysis.

Kinematic data were processed to reveal joint angles at initial contact and the maximum value during the landing of the jump in all three planes for the trunk, pelvis, hip, knee, rearfoot, and forefoot. All angles were assessed for normality and independent samples *t*-test or Mann Whitney U tests were used to assess for differences between the groups. Joint angles at initial contact and maximum during landing the jump and results of the between group comparisons are presented in Table 14 and Table 15. Overall, the results indicate that there were no differences in the landing kinematics of professional ballet and collegiate dancers. A few statistically significant differences were found, but given the high number of comparisons completed may result in increased risk of a type I error, and will be further discussed in Chapter 5. Effect sizes will be discussed in Chapter 5 and are available in Appendix E.

Table 14: Joint Angles at Initial Contact for Professional Ballet and Collegiate Dancers

		Professional					Collegiate					
		N	**Mean**	**SD**	**Med**	**IQR**	**N**	**Mean**	**SD**	**Med**	**IQR**	**p-value**
Trunk												
Flexion	All	28	0.09	5.18	-0.79	-3.91 - 4.57	29	-1.68	4.13	-1.85	-4.35 - 0.79	0.160
	Female	17	-1.24	4.87	-1.88	-4.16 - 2.59	17	-1.42	3.45	-1.69	-4.28 - 1.19	0.902
	Male	11	2.13	5.20	1.70	-2.14 - 7.4	12	-2.05	5.09	-2.01	-5.40 - 0.56	0.065
Lateral Flexion	All	28	-0.65	3.04	-0.80	-1.96 - 0.83	29	-0.90	3.83	-1.82	-3.88 - 0.74	0.423†
	Female	17	-1.71	2.42	-1.49	-2.72 - 0.11	17	-2.34	2.97	-2.69	-4.43 - -0.71	0.508
	Male	11	1.01	3.27	0.87	-1.73 - 4.33	12	1.13	4.11	0.41	-2.14 - 4.43	0.935

Table 14 (continued)

Rotation	All	28	3.02	12.08	2.86	-4.39 - 7.10	29	4.77	10.09	4.06	-0.88 - 11.21	0.555
	Female	17	2.31	8.46	2.72	-4.99 - 5.27	17	3.24	8.82	2.98	-2.24 - 8.54	0.755
	Male	11	4.12	16.66	4.29	2.85 - 15.54	12	6.93	11.72	5.73	-0.33 - 16.32	0.642
<u>Pelvis</u>												
Flexion	All	28	14.45	12.28	16.10	9.24 - 22.04	29	15.64	6.27	15.14	10.35 - 20.43	0.943†
	Female	17	15.20	6.56	14.58	9.60 - 21.62	17	14.72	5.39	14.63	10.06 - 18.81	0.815
	Male	11	13.28	18.32	17.49	4.88 - 25.29	12	16.93	7.41	16.25	11.18 - 24.49	1.000†
Lateral Flexion	All	28	0.30	5.18	0.48	-4.01 - 4.09	29	2.83	3.86	3.64	-0.053 - 6.00	0.041
	Female	17	2.12	4.75	1.51	-2.14 - 6.22	17	2.97	3.91	2.51	-0.21 - 6.56	0.573
	Male	11	-2.52	4.69	-2.71	-5.50 - 2.58	12	2.62	3.95	4.00	-1.55 - 6.10	0.010
Rotation	All	28	28.27	14.22	30.06	22.91 - 36.38	29	32.12	8.28	34.67	23.50 - 37.52	0.396†
	Female	17	30.12	6.19	29.53	23.90 - 35.32	17	30.92	8.03	29.03	22.19 - 37.10	0.745
	Male	11	25.43	21.67	31.59	18.60 - 40.22	12	33.82	8.68	35.13	26.90 - 40.17	0.347†
<u>Hip</u>												
Flexion	All	28	40.86	8.99	39.42	33.03 - 49.06	29	41.15	7.58	42.14	36.72 - 46.57	0.894
	Female	17	41.75	9.25	43.18	33.38 - 49.01	17	41.74	6.40	42.64	36.72- 45.52	0.997
	Male	11	39.48	8.82	36.35	32.0 - 49.13	12	40.32	9.23	39.23	33.95 - 48.93	0.608†
Abduction	All	28	-21.70	10.33	-22.09	-29.90 - -15.74	29	-21.48	9.32	-24.12	-27.60 - -13.62	0.934
	Female	17	-19.51	8.50	-21.14	-26.20 - -14.77	17	-19.65	9.08	-19.48	-27.37 - -12.50	0.963
	Male	11	-25.07	12.32	-26.54	-37.06 - -16.97	12	-24.07	9.43	-24.87	-31.43 - -18.21	0.828
Rotation	All	28	-19.68	11.27	-19.42	-28.67 - -9.44	29	-15.81	9.89	-18.42	-22.05 - - 9.36	0.174
	Female	17	-19.46	9.86	-19.74	-28.53 - -9.74	17	-18.03	7.81	-19.34	-24.10 - -13.94	0.642
	Male	11	-20.01	13.67	-17.65	-30.6 - -8.74	12	-12.67	11.91	-10.73	-21.33 - -5.83	0.183
<u>Knee</u>												
Flexion	All	28	15.71	8.68	17.30	10.66 - 20.17	29	15.58	7.38	16.66	10.76 - 21.85	0.951
	Female	17	19.88	7.08	19.72	15.52 - 26.19	17	17.57	6.48	18.33	12.32 - 22.06	0.330
	Male	11	9.27	6.94	10.64	2.71 - 16.18	12	12.75	7.92	12.62	6.39 - 19.91	0.277
Valgus	All	28	5.37	4.39	5.68	2.23 - 8.26	29	4.66	3.89	4.66	2.35 - 7.61	0.522
	Female	17	4.99	4.24	5.87	2.04 - 7.94	17	3.31	3.59	4.42	-0.65 - 5.81	0.222
	Male	11	5.97	4.74	4.82	2.66 - 10.66	12	6.58	3.59	6.54	3.06 - 9.54	0.727
Rotation	All	28	2.62	11.17	4.80	-7.27 - 11.66	29	2.59	7.73	0.31	-2.95 - 9.40	0.990
	Female	17	4.93	10.28	6.64	-4.16 - 13.10	17	5.75	7.13	1.14	0.14 - 11.54	0.059†
	Male	11	-0.94	12.03	0.98	-8.98 - 10.32	12	-1.88	6.40	-2.96	-8.01 - 2.10	0.821
<u>Ankle</u>												
Flexion	All	28	-40.90	5.23	-41.98	-43.18 - -37.87	29	-39.30	5.92	-37.87	-43.68 - -36.34	0.224†
	Female	17	-40.04	4.72	-41.79	-42.03 - -35.65	17	-40.24	6.55	-37.93	-44.94 - -34.98	0.920
	Male	11	-42.21	5.94	-42.61	-47.22 - -38.37	12	-37.97	4.82	-36.61	-42.53 - -33.49	0.073

Table 14 (continued)

		N	Mean	SD	Med	IQR	N	Mean	SD	Med	IQR	p-value
Inversion	All	28	-0.88	8.92	0.07	-7.21 - 5.88	29	-0.83	8.53	-2.62	-8.27 - 7.13	0.982
	Female	17	-0.51	9.42	0.17	-8.09 - 7.37	17	2.69	7.31	1.85	-2.87 - 8.25	0.278
	Male	11	-1.47	8.49	-0.02	-8.79 - 3.475	12	-5.82	7.82	-7.21	-10.00 - -3.23	0.215
Rotation	All	28	-22.75	8.87	-21.94	-25.03 - -12.95	29	-18.77	7.33	-18.21	-28.02 - -15.22	0.069
	Female	17	-25.06	9.77	-25.14	-34.13 - -16.09	17	-19.67	7.60	-20.73	-26.99 - -14.13	0.082
	Male	11	-19.19	6.05	-20.09	-24.33 - -14.07	12	-17.50	7.04	-15.61	-22.43 - -12.43	0.545
<u>Foot</u>												
Flexion	All	28	-18.74	3.93	-18.97	-21.18 - -15.15	29	-21.13	6.15	-20.92	-25.88 - -15.81	0.086
	Female	17	-18.67	4.41	-18.74	-22.28 - -14.69	17	-22.45	6.15	-21.94	-27.66 - -17.20	0.048
	Male	11	-18.86	3.25	-19.01	-21.18 - -17.31	12	-19.27	5.90	-18.15	-25.20 - -13.39	0.837
Inversion	All	28	2.57	3.03	2.76	-0.01 - 4.54	29	2.38	4.16	2.98	0.01 - 4.84	0.840
	Female	17	2.92	3.35	2.94	1.00 - 5.30	17	3.57	3.54	4.18	1.79 - 5.82	0.581
	Male	11	2.05	2.52	2.57	-0.94 - 3.53	12	0.68	4.53	2.44	-3.64 - 3.62	0.380
Rotation	All	28	0.10	6.14	-0.36	-4.75 - 4.63	29	-0.42	4.18	-1.39	-3.93 - 2.67	0.706
	Female	17	0.41	5.92	1.47	-2.87 - 4.60	17	-0.09	3.61	-1.05	-3.01 - 3.44	0.766
	Male	11	-0.38	6.71	-2.89	-5.97 - 4.72	12	-0.89	5.01	-2.03	-4.35 - 2.50	0.833†

N = number of subjects; SD = standard deviation; Med = median; IQR = interquartile range

† p-value from Mann Whitney U test

Table 15: Maximum Joint Angles during Landing for Professional Ballet and Collegiate Dancers

		Professional					Collegiate					
		N	**Mean**	**SD**	**Med**	**IQR**	**N**	**Mean**	**SD**	**Med**	**IQR**	**p-value**
<u>Trunk</u>												
Flexion	All	28	6.04	10.35	5.57	-2.15 - 11.22	29	3.54	6.58	3.36	-2.15 - 9.35	0.280
	Female	17	2.26	7.36	1.31	-2.90 - 9.39	17	2.72	6.38	2.30	-3.59 - 8.67	0.846
	Male	11	11.88	11.86	8.76	5.09 - 20.42	12	4.71	6.97	5.78	-0.12 - 9.65	0.088
Lateral Flexion	All	28	-0.65	3.59	-0.41	-2.62 - 1.28	29	-0.72	4.42	-1.48	-4.17 - 1.85	0.947
	Female	17	-1.66	3.26	-0.45	-4.04 - 0.67	17	-2.17	3.77	-2.29	-5.31 - 0.82	0.675
	Male	11	0.92	3.65	0.33	-2.41 - 3.79	12	1.34	4.59	0.04	-2.22 - 4.59	0.811
Rotation	All	28	6.66	12.16	5.64	1.90 - 15.4	29	10.02	10.26	9.42	1.75 - 20.26	0.264
	Female	17	7.63	9.44	5.70	2.80 - 15.83	17	11.31	10.86	10.98	2.69 - 20.47	0.300
	Male	11	5.16	15.89	5.59	-1.75 - 15.47	12	8.19	9.49	5.02	0.32 - 18.077	0.582
<u>Pelvis</u>												
Flexion	All	28	11.09	14.08	13.64	6.83 - 16.87	29	14.58	5.93	14.68	10.41 - 18.81	0.278†
	Female	17	12.58	5.64	13.72	8.12 - 15.94	17	16.06	5.85	16.14	11.00 - 21.20	0.087
	Male	11	8.78	21.79	9.21	6.36 - 21.45	12	12.47	5.61	11.67	8.18 - 15.29	0.880†

Table 15 (continued)

Lateral Flexion	All	28	1.55	6.23	1.75	-1.85 - 1.74	29	1.09	6.62	1.81	-2.46 - 6.75	0.787
	Female	17	3.03	5.94	2.69	0.03 - 9.55	17	-0.09	7.73	0.11	-7.87 - 7.26	0.196
	Male	11	-0.73	6.25	-1.28	-6.50 - 4.35	12	2.76	4.40	2.89	-1.24 - 6.85	0.133
Rotation	All	28	23.74	12.86	25.25	17.54 - 32.01	29	28.82	9.25	28.96	22.19 - 36.95	0.109†
	Female	17	23.95	7.81	24.48	18.40 - 30.91	17	29.92	8.62	29.40	22.20 - 36.95	0.042
	Male	11	23.40	18.67	26.01	16.33 - 36.79	12	27.26	10.26	27.94	20.08 - 37.23	0.541
<u>Hip</u>												
Flexion	All	28	58.46	19.72	55.18	45.74 - 75.89	29	52.18	13.57	50.59	45.13 - 57.88	0.166
	Female	17	61.67	21.56	59.24	48.99 - 76.07	17	51.41	12.86	50.59	45.66 - 57.77	0.104
	Male	11	53.48	16.18	51.77	41.39 - 63.66	12	53.27	15.03	52.57	40.53 - 63.34	0.974
Abduction	All	28	-20.88	10.22	-20.70	-29.21 --14.45	29	-23.01	9.79	-23.20	-30.30 - -16.11	0.184†
	Female	17	-19.41	7.27	-18.22	-24.09 - -13.64	17	-22.33	9.91	-23.20	-32.08 - -14.28	0.333
	Male	11	-23.17	13.72	-24.92	-32.49 - -15.35	12	-23.97	9.98	-22.96	-28.49 - -18.60	0.874
Rotation	All	28	-13.98	12.56	-11.56	-21.65 - -3.66	29	-10.76	11.57	-10.15	-19.48 - 0.40	0.319
	Female	17	-13.33	11.46	-11.80	-19.38 - -5.85	17	-17.13	9.35	-15.56	-23.63 - -9.92	0.297
	Male	11	-14.98	14.63	-10.34	-29.35 - -3.51	12	-1.74	7.88	0.73	-4.42 - 2.83	0.013†
<u>Knee</u>												
Flexion	All	28	52.04	9.22	51.04	44.73 - 59.05	29	52.18	9.66	51.11	46.25 - 58.57	0.953
	Female	17	53.02	6.99	51.12	48.11 - 58.90	17	51.93	10.58	49.20	46.49 - 59.36	0.725
	Male	11	50.52	12.13	45.62	41.36 - 59.36	12	52.55	8.62	54.24	45.20-58.91	0.647
Valgus	All	28	2.89	4.58	2.49	-0.52 - 5.79	29	1.94	8.25	1.62	-3.61 - 5.56	0.230†
	Female	17	1.55	3.60	2.47	-2.46 - 5.04	17	-1.42	4.81	-2.71	-3.99 - 2.05	0.050
	Male	11	4.97	5.29	2.91	1.14 - 9.11	12	6.70	9.86	4.47	0.16 - 12.44	0.610
Rotation	All	28	3.24	15.31	6.76	-10.87 - 13.53	29	9.24	15.05	5.54	-1.97 - 18.17	0.141
	Female	17	6.99	16.55	7.78	-11.19 - 17.88	17	13.81	15.45	10.01	2.65 - 26.03	0.223
	Male	11	-2.57	11.55	-2.78	-11.16 - 7.32	12	2.77	12.29	3.21	-7.36 - 12.81	0.296
<u>Ankle</u>												
Flexion	All	28	-27.42	31.72	-40.51	-50.08 - -6.17	29	-10.98	33.29	-13.97	-45.60 - 20.56	0.080†
	Female	17	-31.29	30.38	-45.99	-52.52 - -16.21	17	-6.63	36.80	12.57	-48.28 - 25.79	0.079†
	Male	11	-21.44	34.26	-39.68	-49.23 - 18.76	12	-17.13	27.94	-21.57	-42.48 - 10.43	0.608†
Inversion	All	28	7.78	9.27	9.15	0.60 - 15.22	29	9.06	10.31	9.38	3.54 - 14.85	0.624
	Female	17	7.64	8.59	8.83	-0.78 - 16.67	17	13.94	8.02	12.39	8.79 - 17.44	0.034
	Male	11	8.00	10.66	9.88	1.53 - 12.52	12	2.15	9.38	4.17	-7.24 - 10.83	0.176
Rotation	All	28	-21.24	14.53	-20.58	-32.56 - -6.17	29	-26.19	12.35	-24.40	-34.37 - -17.72	0.195†
	Female	17	-22.09	16.15	-20.22	-36.14 - -7.04	17	-30.06	13.34	-33.53	-40.44 - -18.01	0.126
	Male	11	-19.93	12.22	-20.93	-26.84 - -6.27	12	-20.71	8.59	-22.38	-25.29 - -13.24	0.861

Table 15 (continued)

Foot												
Flexion	All	28	-24.45	10.91	-27.94	-31.91 - -19.30	29	-25.79	14.15	-27.03	-36.96 - -18.47	0.596†
	Female	17	-24.37	12.26	-27.94	-32.97 - -19.38	17	-28.48	12.77	-27.03	-39.91 - -21.41	0.433†
	Male	11	-24.56	8.99	-27.94	-31.57 - -13.67	12	-21.97	15.66	-26.29	-36.48 - -10.90	0.636
Inversion	All	28	0.02	5.00	-0.43	-3.58 - 3.49	29	-0.13	6.57	-0.40	-5.58 - 5.25	0.923
	Female	17	1.05	4.29	-0.37	-2.63 - 4.17	17	-0.58	7.14	-1.14	-7.14 - 5.20	0.427
	Male	11	-1.58	5.78	-3.57	-4.10 - 3.62	12	0.50	5.92	-0.17	-4.80 - 6.27	0.406
Rotation	All	28	-3.25	5.31	-3.39	-2.16 - 11.22	29	-3.13	4.45	-3.52	-6.99 - 0.41	0.925
	Female	17	-3.31	5.90	-2.76	-7.20 - -0.22	17	-3.88	4.90	-6.25	-7.61 - 0.55	0.762
	Male	11	-3.16	4.52	-4.02	-7.01 - 1.49	12	-2.07	3.64	-2.61	-4.47 - 0.08	0.528

N = number of subjects; SD = standard deviation; Med = median; IQR = interquartile range

† p-value from Mann Whitney U test

4.2.5 Self-Reported Injury History

All dancers completed the self-reported injury history questionnaire. Dancers reported if they had ever had an injury that resulted in time loss from or modification of dance activities for at least one day after the injury occurred, and/or required formal treatment from a licensed professional at some point in their dance career, and if they had had this type of injury in the twelve months prior to participating in the study (1 year history). There was no difference between the professional and collegiate groups in regards to the proportion of subjects reporting at least one injury that met the operational definition, or any such injury in the prior one year (both p-values = 1.000). Results of Fisher's Exact tests are presented in Table 16. 93.3% of professional dancers and 93.1% of collegiate dancers reported that they had an injury in their total history, and 56.7% of professionals and 55.2% of collegiate dancers experienced an injury in their 1 year history.

Table 16: Proportion of Injured Subjects in Professional Ballet and Collegiate Dancer Groups

		Professional		Collegiate		
		N	**Percent**	**N**	**Percent**	**Fisher's Exact Test p-value**
Total Injury History	All	30	93.3	29	93.1	1.000
	Female	18	94.4	17	94.1	1.000
	Male	12	91.7	12	91.7	1.000
Injured in Past 1 Year	All	30	56.7	29	55.2	1.000
	Female	18	44.4	17	58.8	0.505
	Male	12	75.0	12	50.0	0.400

The locations of injures were also collected and the proportion of injured subjects with injuries at specific locations were compared between groups. Injury occurrence at all body regions are presented in Table 17. There were no differences in the proportion of injured subjects with injuries to various body regions in the professional and collegiate groups, except for at the foot and ankle. The proportion of professional dancers reporting ankle and foot/toe injuries was significantly higher than the proportion of collegiate dancers reporting injuries to those regions; 90.0% vs 51.7% (p-value = 0.002) and 60.0% vs 20.7% (p-value = 0.002) respectively. The proportions of injured subjects reporting injuries at each body region in the previous twelve months are reported in Table 18. No significant differences in the proportion of injured subjects with injuries at specific locations were found.

Table 17: Proportion of Injured Dancers with Injuries to Specific Body Regions

		Professional		Collegiate		
	Group	**N**	**Percent**	**N**	**Percent**	**Fisher's Exact Test p-value**
Neck	All	30	16.7	29	10.3	0.706
	Female	18	16.7	17	11.8	1.000
	Male	12	16.7	12	8.3	1.000
Upper Back	All	30	10.0	29	6.9	1.000
	Female	18	5.6	17	5.9	1.000
	Male	12	16.7	12	8.3	1.000
Lower Back	All	30	43.4	29	31.0	0.422
	Female	18	38.9	17	29.4	0.725
	Male	12	50.0	12	33.3	0.680
Ribs and Chest	All	30	16.7	29	6.9	0.424
	Female	18	22.2	17	5.9	0.338
	Male	12	8.3	12	8.3	1.000
Shoulder	All	30	33.3	29	20.7	0.213
	Female	18	27.8	17	23.5	1.000
	Male	12	58.3	12	41.7	0.371
Elbow/Wrist/Hand	All	30	10.0	29	10.3	1.000
	Female	18	0.0	17	5.9	0.486
	Male	12	25.0	12	16.7	1.000
Hip	All	30	20.0	29	24.1	0.761
	Female	18	35.3	17	16.7	0.264
	Male	12	25.0	12	8.3	0.590
Thigh	All	30	3.3	29	3.4	0.981
	Female	18	0.0	17	0.0	
	Male	12	8.3	12	8.3	1.000
Knee	All	30	26.7	29	31.0	0.711
	Female	18	41.2	17	11.1	0.060
	Male	12	50.0	12	16.7	0.193
Calf and Shin	All	30	30.0	29	13.8	0.129
	Female	18	17.6	17	27.8	0.691
	Male	12	33.3	12	8.3	0.317
Ankle	All	30	90.0	29	51.7	0.002
	Female	18	88.9	17	58.8	0.060
	Male	12	91.7	12	41.7	0.027

Table 17 (continued)

Foot and Toes	All	30	60.0	29	20.7	0.002
	Female	18	66.7	17	11.8	0.002
	Male	12	50.0	12	33.3	0.680

Table 18: Proportion of Injured Dancers with Injuries to Specific Body Regions in the Past One Year

		Professional		Collegiate		
	Group	**N**	**Percent**	**N**	**Percent**	**Fisher's Exact Test p-value**
Neck	All	30	3.3	29	0.0	1.000
	Female	18	0.0	17	0.0	
	Male	12	8.3	12	0.0	1.000
Upper Back	All	30	0.0	29	3.4	0.492
	Female	18	0.0	17	5.9	0.486
	Male	12	0.0	12	0.0	
Lower Back	All	30	43.3	29	31.0	0.422
	Female	18	38.9	17	29.4	0.725
	Male	12	50.0	12	33.3	0.680
Ribs and Chest	All	30	0.0	29	0.0	
	Female	18	0.0	17	0.0	
	Male	12	0.0	12	0.0	
Shoulder	All	30	6.7	29	0.0	0.492
	Female	18	5.6	17	0.0	1.000
	Male	12	8.3	12	0.0	1.000
Elbow/Wrist/Hand	All	30	3.3	29	0.0	1.000
	Female	18	0.0	17	0.0	
	Male	12	8.3	12	0.0	1.000
Hip	All	30	6.7	29	6.9	0.972
	Female	18	5.6	17	11.8	0.603
	Male	12	8.3	12	0.0	1.000
Thigh	All	30	3.3	29	0.0	1.000
	Female	18	0.0	17	0.0	
	Male	12	8.3	12	0.0	1.000
Knee	All	30	13.3	29	10.3	1.000
	Female	18	5.6	17	17.6	0.338
	Male	12	25.0	12	0.0	0.217

Table 18 (continued)

Calf and Shin	All	30	0.0	29	6.9	0.237
	Female	18	0.0	17	5.9	0.486
	Male	12	0.0	12	8.3	1.000
Ankle	All	30	26.7	29	24.1	1.000
	Female	18	22.2	17	17.6	1.000
	Male	12	33.3	12	33.3	1.000
Foot and Toes	All	30	16.7	29	6.9	0.424
	Female	18	22.2	17	5.9	0.338
	Male	12	8.3	12	8.3	1.000

4.3 REGRESSION ANALYSES OF THE ABILITY OF MUSCULAR STRENGTH TO PREDICT DYNAMIC POSTURAL STABILITY AND LANDING KINEMATICS

The purpose of specific aims 2 and 3 were to investigate the relationships between strength and dynamic postural stability and kinematic variables while landing from a dance jump. Specifically, the ability of strength performance to predict dynamic postural stability performance (Hypothesis 2a), knee valgus (Hypotheses 3a and 3b), ankle inversion (Hypotheses 3c and 3d), and foot pronation (Hypotheses 3e and 3f). Muscular strength independent variables of trunk and dominant lower extremity strength were assessed with handheld dynamometry and isokinetic dynamometry, and were reported relative to subject body mass. Independent strength variables were assessed on the dominant lower extremity. Dependent variables were also assessed on the dominant lower extremity and included the dynamic postural stability index score (DPSI), as well as the following kinematic variables; knee valgus at initial contact and maximum valgus angle during the dance jump, ankle inversion at initial contact and maximum inversion angle during the dance jump, and foot pronation angle at initial contact and maximum foot pronation angle during the dance jump. Univariate analyses are presented first, followed by bivariate analyses to determine the individual relationships between each pair of independent and dependent variables. Finally, multiple linear regressions are presented. Statistical significance was established at alpha = 0.05 *a priori*.

4.3.1 Univariate Analysis

4.3.1.1 Strength and Dynamic Postural Stability

The dependent variable was the dynamic postural stability index (DPSI). The independent strength variables chosen were trunk rotation strength, hip abduction strength, knee extension strength and knee flexion strength. DPSI scores were available for 55 dancers; therefore 55 subjects were included in this regression analysis. Descriptive statistics and normality assessment for DPSI and the independent strength variables are displayed in Table 19.

Table 19: Dynamic Postural Stability and Independent Strength Variables Normality Assessment and Descriptive Statistics of all Dancers

	N	Shapiro-Wilk	Mean	SD
Dynamic Postural Stability Index	55	0.257	0.328	0.037
Trunk Rotation Strength (NM %BM)	55	0.196	99.27	34.35
Hip Abduction Strength (kg %BM)	55	0.080	21.97	5.19
Knee Extension Strength (kg %BM)	55	0.280	206.30	50.19
Knee Flexion Strength (kg %BM)	55	0.530	113.67	23.21

N = number of subjects; SD = standard deviation

The normality assessment of DPSI and the independent strength variables trunk rotation strength, hip abduction strength, knee extension strength and knee flexion strength were also completed for each gender separately and are presented in Tables 20 and 21. The rationale for gender stratified univariate and subsequent bivariate and multiple linear regression was due to a potential interaction of the effect of gender and strength on DPSI that warranted further investigation. More detail is provided in the next section on bivariate analyses.

Table 20: Dynamic Postural Stability and Independent Strength Variables Normality Assessment and Descriptive Statistics of Male Dancers

	N	Shapiro-Wilk	Mean	SD
Dynamic Postural Stability Index	23	0.971	0.347	0.042
Trunk Rotation Strength (NM %BM)	23	0.205	112.01	49.60
Hip Abduction Strength (kg %BM)	23	0.533	24.29	5.82
Knee Extension Strength (kg %BM)	23	0.523	215.38	53.14
Knee Flexion Strength (kg %BM)	23	0.810	122.19	24.92

N = number of subjects; SD = standard deviation

Table 21: Dynamic Postural Stability and Independent Strength Variables Normality Assessment and Descriptive Statistics of Female Dancers

	N	Shapiro-Wilk	Mean	SD
Dynamic Postural Stability Index	32	0.987	0.315	0.026
Trunk Rotation Strength (NM %BM)	32	0.138	90.11	26.06
Hip Abduction Strength (kg %BM)	32	0.095	20.30	4.00
Knee Extension Strength (kg %BM)	32	0.136	199.78	47.74
Knee Flexion Strength (kg %BM)	32	0.962	107.55	20.14

N = number of subjects; SD = standard deviation

4.3.1.2 Strength and Knee Valgus Angles

The dependent variables were knee valgus angle at initial contact and maximum knee valgus angle during landing. The independent strength variables for the knee valgus regressions were hip external rotation strength, hip abduction strength, knee extension strength and knee flexion strength. Kinematic data was available for 57 dancers; therefore 57 subjects were included in these regression analyses. Descriptive statistics and normality assessment for the dependent kinematic variables and the knee independent strength variables are displayed in Table 22. Maximum knee valgus angle during landing was not normally distributed and will be assessed further.

Table 22: Dependent Knee Valgus Angle Variables and Independent Strength Variables Normality Assessment and Descriptive Statistics of all Dancers

Variable	N	Shapiro-Wilk	Mean	SD
Knee Valgus Angle at Initial Contact (degrees)	57	0.600	5.01	4.12
Maximum Knee Valgus Angle (degrees)	57	0.011	2.41	6.66
Hip External Rotation Strength (kg % BM)	57	0.428	16.63	4.45
Hip Abduction Strength (kg %BM)	57	0.044	21.84	5.15
Knee Extension Strength (NM %BM)	57	0.228	202.49	51.71
Knee Flexion Strength (NM % BM)	57	0.413	111.23	24.14

N = number of subjects; SD = standard deviation

The normality assessment of maximum knee valgus angle and the independent strength variables trunk rotation strength, hip abduction strength, knee extension strength and knee flexion strength were also completed for each gender separately and are presented in Tables 23 and 24. The rationale for separate univariate and subsequent bivariate and multiple linear regressions by gender was in response to an unexpected finding in the direction of the regression coefficients in the multiple linear regression. Analyses for each gender separately were completed to thoroughly investigate possible explanations for the unexpected results and are presented and discussed in subsequent sections.

Table 23: Dependent Maximum Knee Valgus Angle and Independent Strength Variables Normality Assessment and Descriptive Statistics of Male Dancers

Variable	N	Shapiro-Wilk	Mean	SD
Maximum Knee Valgus Angle (degrees)	23	0.226	5.87	7.88
Hip External Rotation Strength (kg % BM)	23	0.812	18.19	4.86
Hip Abduction Strength (kg %BM)	23	0.446	24.22	5.84
Knee Extension Strength (NM %BM)	23	0.582	215.10	52.93
Knee Flexion Strength (NM % BM)	23	0.787	121.17	24.05

N = number of subjects; SD = standard deviation

Table 24: Dependent Maximum Knee Valgus Angle and Independent Strength Variables Normality Assessment and Descriptive Statistics of Female Dancers

Variable	N	Shapiro-Wilk	Mean	SD
Maximum Knee Valgus Angle (degrees)	34	0.220	0.06	4.45
Hip External Rotation Strength (kg % BM)	34	0.706	15.57	3.87
Hip Abduction Strength (kg %BM)	34	0.085	20.24	3.95
Knee Extension Strength (NM %BM)	34	0.137	193.96	49.84
Knee Flexion Strength (NM % BM)	34	0.602	104.50	22.08

N = number of subjects; SD = standard deviation

4.3.1.3 Strength and Ankle Inversion Angles

The dependent variables were ankle inversion angle at initial contact and maximum inversion angle during landing. The independent strength variables for the inversion regressions were knee extension strength, knee flexion strength, ankle inversion strength and ankle eversion strength. Kinematic data was available for 57 dancers; therefore 57 subjects were included in this regression analysis. Descriptive statistics and normality assessment for the ankle dependent kinematic variables and the independent strength variables are displayed in Table 25. All variables were normally distributed.

Table 25: Dependent Ankle Inversion Angle Variables and Independent Strength Variables Normality Assessment and Descriptive Statistics

Variable	N	Shapiro-Wilk	Mean	SD
Inversion at initial contact (degrees)	57	0.529	-0.86	8.64
Maximum inversion angle (degrees)	57	0.627	8.43	9.74
Knee Extension Strength (NM %BM)	57	0.228	202.49	51.71
Knee Flexion Strength (NM %BM)	57	0.413	111.23	24.14
Ankle Inversion Strength (kg %BM)	57	0.084	30.09	8.21
Ankle Eversion Strength (kg %BM)	57	0.428	26.14	6.45

N = number of subjects; SD = standard deviation

4.3.1.4 Strength and Forefoot Pronation Angles

The dependent variables were foot pronation angle at initial contact and maximum pronation angle during landing, defined by the forefoot to rearfoot angle. The independent strength variables for the foot pronation regressions were knee extension strength, knee flexion strength, and ankle inversion strength and ankle eversion strength. Kinematic data was available for 57 dancers; therefore 57 subjects were included in this regression analysis. Descriptive statistics and normality assessment for the dependent foot kinematic variables and the independent strength variables are displayed in Table 26. All variables were normally distributed.

Table 26: Dependent Foot Pronation Angle Variables and Independent Strength Variables Normality Assessment and Descriptive Statistics

Variable	N	Shapiro-Wilk	Mean	SD
Pronation angle at initial contact (degrees)	57	0.725	-0.164	5.192
Maximum pronation angle (degrees)	57	0.410	-3.19	4.85
Knee Extension Strength (NM %BM)	57	0.228	202.49	51.71
Knee Flexion Strength (NM %BM)	57	0.413	111.23	24.14
Ankle Inversion Strength (kg %BM)	57	0.084	30.09	8.21
Ankle Eversion Strength (kg %BM)	57	0.428	26.14	6.45

N = number of subjects; SD = standard deviation

4.3.2 Bivariate Analysis

4.3.2.1 Strength and Dynamic Postural Stability

Each independent and dependent variable were plotted against each other, and the scatterplots are presented in Appendix B. Pearson correlation coefficients and corresponding p-values were calculated to determine the relationship between DPSI and each independent strength variable, as well as the relationship among the independent variables. A correlation matrix of all variables is presented in Table 27. Positive significant correlations were present amongst the pairs of dependent and independent variables. As strength increased there was a slight increase in DPSI score and this relationship will be investigated further. No strong correlations among independent variables were present.

Table 27: Pearson Correlations between DPSI and Independent Strength Variables

	Dynamic Postural Stability Index	Trunk Rotation Strength	Hip Abduction Strength	Knee Extension Strength	Knee Flexion Strength
	r **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**
Trunk Rotation Strength	0.41 (0.002)				
Hip Abduction Strength	0.284 (0.036)	0.337 (0.009)			
Knee Extension Strength	0.291 (0.031)	0.703 (<0.001)	0.348 (0.007)		
Knee Flexion Strength	0.326 (0.015)	0.668 (<0.001)	0.474 (<0.001)	0.777 (<0.001)	

Simple linear regressions were performed to better understand the relationship between the independent variables with the dependent variable DPSI. Results are presented in Table 28. Jackknife residuals were plotted against the fitted values and the scatterplots are presented in Appendix C. All scatterplots were randomly scattered around zero, with no patterns indicating that the assumptions of linearly and homoscedasticity had not been met. No obvious outliers were observed. Simple linear regression revealed that individually each independent strength variable was a significant predictor of the DPSI score. Trunk rotation strength accounts for approximately 17% of the variability in DPSI score (p-value = 0.002). Hip abduction and knee extension strength each accounted for approximately 8% of the variance in DPSI score (p-values

= 0.036 and 0.031 respectively). Knee flexion strength accounted for approximately 11% of the variability in DPSI score (p-value = 0.015).

Table 28: Simple Linear Regression Dynamic Postural Stability Index and Independent Strength Variables of all Dancers

Variable	R2	MSE	F value
Trunk Rotation Strength	0.1685	0.00114	F(1,53) = 10.74, Prob>F = 0.002
Hip Abduction Strength	0.0806	0.00126	F(1,53) = 4.65, Prob>F = 0.036
Knee Extension Strength	0.0844	0.00125	F(1,53) = 4.89, Prob>F = 0.031
Knee Flexion Strength	0.1060	0.00122	F(1,53) = 6.28, Prob>F = 0.015

The findings of the correlation and simple linear regressions between the depending variable DPSI score and the independent strength variables were not as expected. All analyses were significant and indicated that as strength increases that DPSI score also increases. It was not expected that as strength performance improved DPSI score would get worse. Although no gender comparisons were completed, observation of the data suggested that male dancers were stronger than female dancers, and female dancers had better DPSI scores. Therefore, the potential interaction of gender and strength on DPSI score was further investigated by plotting the dependent and independent variables and creating separate best fit lines for each gender. These graphs are included in Figures 15. Visual inspection revealed an interaction between gender and some strength variables. Due to this interaction, separate regression analyses were also completed for males and females.

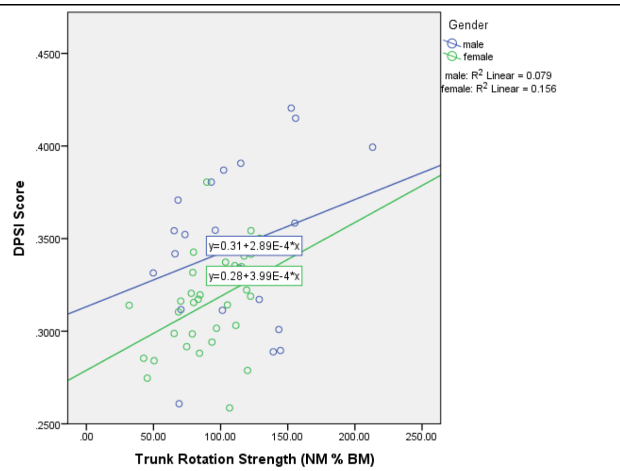
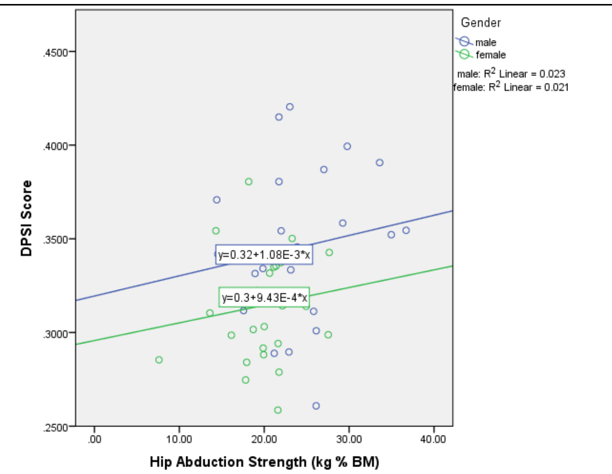
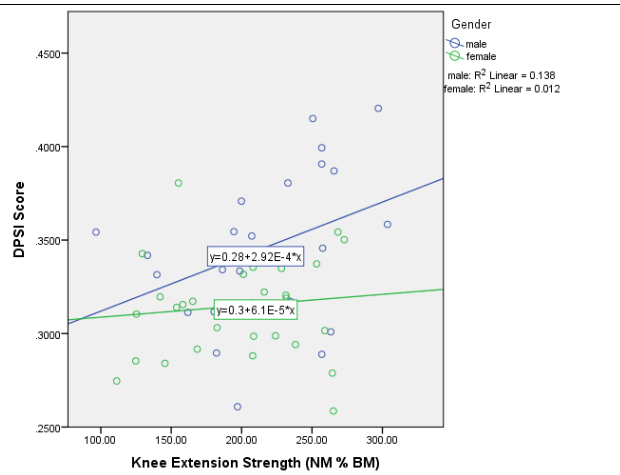
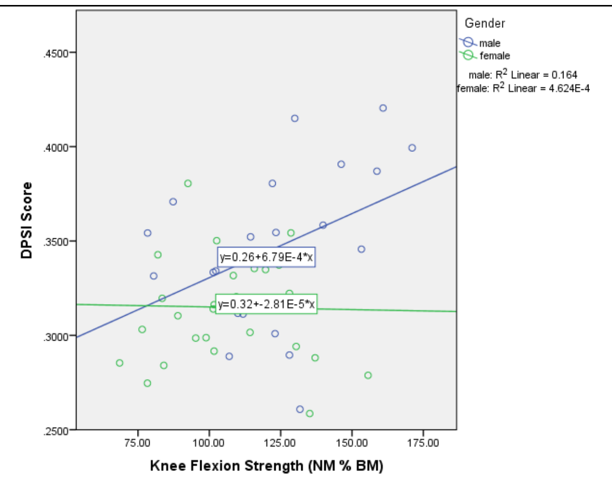
DPSI and Trunk Rotation Strength	DPSI and Hip Abduction Strength
	
DPSI and Knee Extension Strength	**DPSI and Knee Flexion Strength**
	

Figure 15: Scatter Plots for DPSI Score and Independent Strength Variables with Gender Lines

All pairs of dependent and independent variables were plotted in males and females separately and are presented in Appendix B. Pearson correlation coefficients and corresponding p-values were calculated to determine the relationship between DPSI and each independent strength variable, as well as the relationship among the independent variables, within each gender separately. A correlation matrix of all variables is presented in Tables 29 and 30. In the male dancers, positive but insignificant correlations were present amongst the pairs of dependent and independent variables. As strength increased there was an increase in DPSI score and this relationship will be investigated further. No strong correlations among independent variables were present. In the female dancers, one positive and significant correlation was found, indicating that as trunk rotation strength increased DPSI score did as well. Statistically insignificant correlations were present amongst the other pairs of dependent and independent variables. These correlations were also positive, except for knee flexion strength. For this variable as strength increased DPSI score decreased. In the female dancers no strong correlations among independent variables were present. With all variables except knee flexion, the direction of the correlation did not change when stratifying by gender. Even for knee flexion in females, the magnitude of the correlation coefficient was small (close to zero). Most correlations completed for genders separately were insignificant, likely do to smaller sample sizes when separating the dancers into two groups.

Table 29: Pearson Correlations between DPSI and Independent Strength Variables in Male Dancers

	Dynamic Postural Stability Index	Trunk Rotation Strength	Hip Abduction Strength	Knee Extension Strength	Knee Flexion Strength
	r **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**
Trunk Rotation Strength	0.281 (0.194)				
Hip Abduction Strength	0.150 (0.081)	0.289 (0.171)			
Knee Extension Strength	0.371 (0.081)	0.681 (<0.001)	0.351 (0.092)		
Knee Flexion Strength	0.405 (0.055)	0.678 (<0.001)	0.475 (0.019)	0.750 (<0.001)	

Table 30: Pearson Correlations between DPSI and Independent Strength Variables in Female Dancers

	Dynamic Postural Stability Index	Trunk Rotation Strength	Hip Abduction Strength	Knee Extension Strength	Knee Flexion Strength
	r **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**
Trunk Rotation Strength	0.395 (0.025)				
Hip Abduction Strength	0.143 (0.434)	0.170 (0.328)			
Knee Extension Strength	0.111 (0.546)	0.719 (<0.001)	0.242 (0.161)		
Knee Flexion Strength	-0.022 (0.907)	0.578 (<0.001)	0.294 (0.087)	0.784 (<0.001)	

Simple linear regressions were performed to better understand the relationship between the independent variables with the dependent variable DPSI score. Results are presented in Tables 31 and 32. Jackknife residuals were plotted against the fitted values and there was no obvious evidence of deviation from the assumptions of linearity and homoscedasticity, and no obvious outliers (Appendix C). In male dancers, simple linear regressions found no significant strength predictors of DPSI score. In female dancers, simple linear regression revealed that trunk rotation strength accounts for 15.63% of the variability in DPSI score (p-value = 0.025). In female dancers, none of the other independent strength variables were significant predictors of DPSI score with simple linear regression.

Table 31: Simple Linear Regression Dynamic Postural Stability Index and Independent Strength Variables in Male Dancers

Variable	R2	MSE	F value
Trunk Rotation Strength	0.0790	0.0017	F(1,21) = 1.80, Prob>F = 0.194
Hip Abduction Strength	0.0225	0.0018	F(1,21) = 0.48, Prob>F = 0.494
Knee Extension Strength	0.1376	0.0016	F(1,21) = 3.35, Prob>F = 0.081
Knee Flexion Strength	0.1640	0.0015	F(1,21) = 4.12, Prob>F = 0.055

Table 32: Simple Linear Regression Dynamic Postural Stability Index and Independent Strength Variables in Female Dancers

Variable	R2	MSE	F value
Trunk Rotation Strength	0.1563	0.0006	F(1,30) = 5.56, Prob>F = 0.025
Hip Abduction Strength	0.0205	0.0007	F(1,30) = 0.63, Prob>F = 0.434
Knee Extension Strength	0.0123	0.0007	F(1,30) = 0.37, Prob>F = 0.546
Knee Flexion Strength	0.0005	0.0007	F(1,30) = 0.01, Prob>F = 0.907

4.3.2.2 Strength and Knee Valgus

Each independent strength and dependent knee kinematic variable were plotted against each other, and scatterplots are presented in Appendix B. The plots for valgus angle at initial contact revealed a potential slight positive relationship that as strength increased the valgus angle at initial contact increased (less valgus). There was no evidence of potential outliers in the plots of knee valgus at initial contact and the strength variables. The plots for maximum valgus angle revealed little evidence of a relationship with strength. There were two potential outliers in the plots of maximum knee valgus with the strength variables, although not extreme. These two subjects had potentially higher angles, indicating their maximum valgus angle was actually in a greater position of varus and will be assessed further. Pearson correlation coefficients and corresponding p-values were calculated to determine the relationship between knee valgus angle at initial contact, maximum knee valgus angle with each of the independent strength variables. Correlations among the independent strength variable were also assessed. A complete correlation matrix of all variables is available in Table 33. None of the correlations between the dependent and independent variables were significant. No strong correlations among independent strength variables were present.

Table 33: Pearson Correlation Knee Valgus at Initial Contact and Maximum Knee Valgus with Independent Strength Variables

	Knee Valgus Angle at Initial Contact	Maximum Knee Valgus Angle	Square Root Maximum Knee Valgus Angle	Hip External Rotation Strength	Hip Abduction Strength	Knee Extension Strength	Knee Flexion Strength
	r (p - value)	*r* (p - value)	*r* (p - value)	*r* (p - value)	*r* (p - value)	*r* (p - value)	*r* (p - value)
Hip External Rotation Strength	0.213 (0.111)	0.156 (0.245)	0.175 (0.192)				
Hip Abduction Strength	0.186 (0.166)	0.118 (0.383)	0.143 (0.288)	0.622 (<0.001)			
Knee Extension Strength	0.052 (0.699)	-0.002 (0.990)	-0.027 (0.844)	0.503 (<0.001)	0.353 (0.007)		
Knee Flexion Strength	0.018 (0.893)	-0.026 (0.848)	-0.019 (0.891)	0.561 (<0.001)	0.474 (<0.001)	0.777 (<0.001)	

Simple linear regressions were performed to better understand the relationship between the independent strength variables with the dependent variables of knee valgus at initial contact and maximum knee valgus angle. Results are presented in Table 34 and Table35. Jackknife residuals were plotted against the fitted values and the scatterplots are presented in Appendix C. All scatterplots for knee valgus angle at initial contact and maximum knee valgus angle were randomly scattered around zero and no obvious outliers were identified. There were no patterns indicating that the assumptions of linearly and homoscedasticity had been violated. Simple linear regression revealed that individually none of the independent strength variables were a significant predictor of knee valgus at initial contact. Furthermore simple linear regressions revealed no significant predictors of maximum knee valgus angle.

Table 34: Simple Linear Regression Knee Valgus at Initial Contact and Independent Strength Variables

Variable	R2	MSE	F value
Hip External Rotation Strength	0.0455	16.490	F(1,55) = 2.62, Prob>F = 0.111
Hip Abduction Strength	0.0346	16.679	F(1,55) = 1.97, Prob>F = 0.166
Knee Extension Strength	0.0027	17.229	F(1,55) = 0.15, Prob>F = 0.699
Knee Flexion Strength	0.0003	17.271	F(1,55) = 0.02, Prob>F = 0.893

Table 35: Simple Linear Regression Maximum Knee Valgus and Independent Strength Variables

Variable	R2	MSE	F value
Hip External Rotation Strength	0.0245	44.029	F(1,55) = 1.38, Prob>F = 0.245
Hip Abduction Strength	0.0139	44.508	F(1,55) = 0.77, Prob>F = 0.383
Knee Extension Strength	0.0000	45.134	F(1,55) = 0.00, Prob>F = 0.990
Knee Flexion Strength	0.0007	45.104	F(1,55) = 0.04, Prob>F = 0.848

Though they were not significant, some of the correlations of dependent and independent strength variables were positive and some were negative. To thoroughly investigate the relationships between maximum knee valgus and strength variables, and ensure results were not due to an interaction of gender with muscular strength, separate bivariate analyses were performed for both genders. Maximum knee valgus was different between genders, and therefore plots of maximum knee valgus angle and strength independent variables were created with separate best fit lines for each gender and are presented in Figure 16. Visual inspection revealed no obvious interaction of gender and strength, except for hip abduction. With hip external rotation and knee extension strength, the direction did not change when stratifying by gender. With hip abduction, the direction of the correlation was opposite when stratified by gender. With knee flexion, the direction of the relationship with knee valgus was different when stratified by gender, but less obviously than with hip abduction.

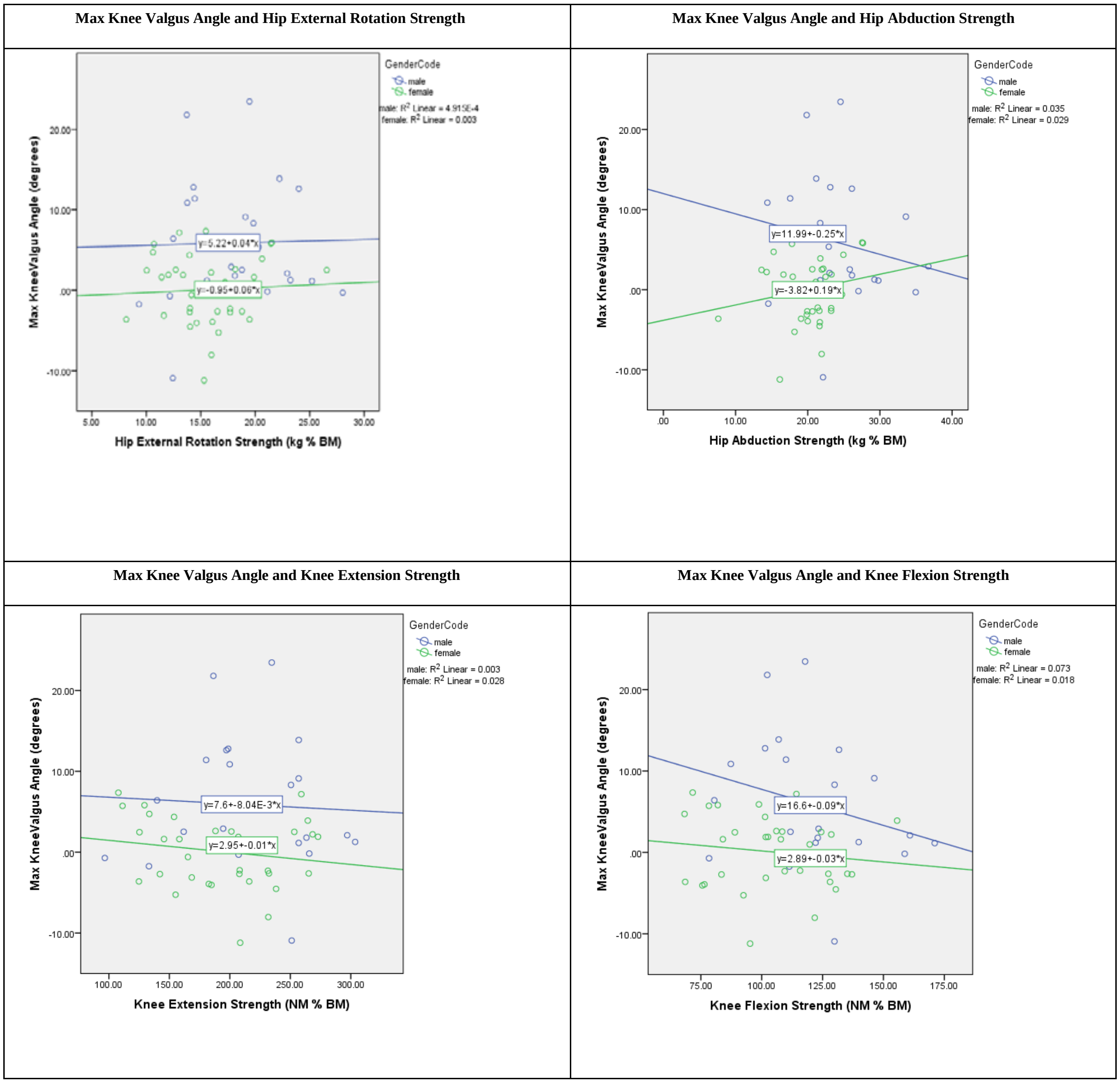


Figure 16: Scatter Plots for Maximum Knee Valgus Angle and Independent Strength Variables with Gender Lines

Maximum knee valgus angle was plotted with each independent strength variable, for each gender separately, and is presented in Appendix B. Pearson correlation coefficients and corresponding p-values were calculated to determine the relationship between maximum knee valgus angle and each independent strength variable, as well as the relationship among the independent variables, within each gender separately. A correlation matrix of all variables is presented in Tables 36 and 37. In the male dancers, a small positive but statistically insignificant correlation was present between hip external rotation and knee valgus angle. As hip external rotation strength increased knee valgus angle increased (less valgus). For the other strength variables, hip abduction, knee extension and knee flexion, negative but statistically insignificant correlations were present. As strength increased there was a slight decrease in maximum knee valgus angle (more valgus). No strong correlations among independent variables were present. In the female dancers, positive and insignificant correlations were found between maximum knee valgus angle and both hip strength variables. As hip external rotation and hip abduction strength increased knee valgus angle increased (less valgus). In female dancers, as in male dancers, small insignificant negative correlations were present between knee extension strength and knee flexion strength and maximum knee valgus angle. As knee strength increased the knee valgus angle decreased (more valgus). In the female dancers no strong correlations among independent variables were present. All correlations completed for genders, as well as all subjects, were insignificant.

Table 36: Pearson Correlations between Maximum Knee Valgus Angle and Independent Strength Variables in Male Dancers

	Max Knee Valgus Angle	Hip External Rotation Strength	Hip Abduction Strength	Knee Extension Strength	Knee Flexion Strength
	r **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**
Hip External Rotation Strength	0.022 (0.920)				
Hip Abduction Strength	-0.187 (0.392)	0.656 (0.001)			
Knee Extension Strength	-0.054 (0.807)	0.583 (0.004)	0.358 (0.093)		
Knee Flexion Strength	-0.270 (0.213)	0.623 (0.002)	0.497 (0.016)	0.743 (<0.001)	

Table 37: Pearson Correlations between Maximum Knee Valgus Angle and Independent Strength Variables in Female Dancers

	Max Knee Valgus Angle	Hip External Rotation Strength	Hip Abduction Strength	Knee Extension Strength	Knee Flexion Strength
	r **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**
Hip External Rotation Strength	0.056 (0.751)				
Hip Abduction Strength	0.170 (0.335)	0.568 (<0.001)			
Knee Extension Strength	-0.167 (0.345)	0.381 (0.026)	0.256 (0.144)		
Knee Flexion Strength	-0.134 (0.449)	0.417 (0.014)	0.295 (0.090)	0.788 (<0.001)	

Simple linear regressions for each gender were performed to better understand the relationship between the independent variables with maximum knee valgus angle. Results are presented in Tables 38 and 39. Jackknife residuals were plotted against the fitted values and there was no obvious evidence of deviation from the assumptions of linearity and homoscedasticity, and no obvious outliers (Appendix C). In male dancers, simple linear regressions found no significant strength predictors of maximum knee valgus angle. In female dancers, simple linear regressions found no significant strength predictors of maximum knee valgus angle.

Table 38: Simple Linear Regression for Maximum Knee Valgus Angle and Independent Strength Variables in Male Dancers

Variable	R2	MSE	F value
Hip External Rotation Strength	0.0005	65.065	F(1,21) = 0.01, Prob>F = 0.920
Hip Abduction Strength	0.0351	62.814	F(1,21) = 0.76, Prob>F = 0.392
Knee Extension Strength	0.0029	64.907	F(1,21) = 0.06, Prob>F = 0.807
Knee Flexion Strength	0.0730	60.347	F(1,21) = 1.65, Prob>F = 0.213

Table 39: Simple Linear Regression for Maximum Knee Valgus Angle and Independent Strength Variables in Female Dancers

Variable	R2	MSE	F value
Hip External Rotation Strength	0.0032	20.327	F(1,32) = 010, Prob>F = 0.751
Hip Abduction Strength	0.0291	19.800	F(1,32) = 0.96, Prob>F = 0.335
Knee Extension Strength	0.0279	19.824	F(1,32) = 0.92, Prob>F = 0.345
Knee Flexion Strength	0.018	20.224	F(1,32) = 0.59, Prob>F = 0.449

4.3.2.3 Strength and Ankle Inversion

Each independent strength and dependent ankle inversion variable was plotted against each other, and the scatterplots are presented in Appendix B. In general, the plots for inversion angle at initial contact and maximum inversion angle revealed little evidence of a relationship with the independent strength variables. Pearson correlation coefficients and corresponding p-values were calculated to determine the relationship between inversion angle at initial contact and maximum inversion angle with each independent strength variable, as well as the relationship among independent variables. A complete correlation matrix of all variables is available in Table 40. No significant correlations were found between the dependent and independent variables. No strong correlations among the independent variables were present.

Table 40: Pearson Correlations Ankle Inversion at Initial Contact and Maximum Ankle Inversion Angle with Independent Strength Variables for all Dancers

	Ankle Inversion at Initial Contact	Maximum Ankle Inversion	Knee Extension Strength	Knee Flexion Strength	Ankle Inversion Strength	Ankle Eversion Strength
	r **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**
Knee Extension Strength	0.237 (0.076)	0.178 (0.186)				
Knee Flexion Strength	0.023 (0.862)	0.131 (0.331)	0.777 (<0.001)			
Ankle Inversion Strength	0.128 (0.343)	0.100 (0.458)	0.488 (<0.001)	0.537 (<0.001)		
Ankle Eversion Strength	0.006 (0.965)	0.016 (0.905)	0.440 (0.001)	0.474 (<0.001)	0.761 (<0.001)	

Simple linear regressions were performed to better understand the relationship between the independent variables with the dependent variables of inversion at initial contact and maximum inversion angle. Results are presented in Table 41 and Table 42. Jackknife residuals were plotted against the fitted values. All scatter plots were randomly scattered around zero with no obvious evidence of deviation from the assumptions of linearity and homoscedasticity, and no obvious outliers. The scatterplots are presented in Appendix C. Simple linear regression revealed that individually none of the independent strength variables were significant predictors of ankle inversion at initial contact or of maximum inversion angle during landing.

Table 41: Simple Linear Regression Ankle Inversion at Initial Contact and Independent Strength Variables for all Dancers

Variable	R2	MSE	F value
Knee Extension Strength	0.0560	71.79730	F(1,55) = 3.26, Prob>F = 0.076
Knee Flexion Strength	0.0006	76.01440	F(1,55) = 0.03, Prob>F = 0.862
Ankle Inversion Strength	0.0164	74.81150	F(1,55) = 0.92, Prob>F = 0.343
Ankle Eversion Strength	≤0.0001	76.05370	F(1,55) = 0.00, Prob>F = 0.966

Table 42: Simple Linear Regression Maximum Ankle Inversion and Independent Strength Variables for all Dancers

Variable	R2	MSE	F value
Knee Extension Strength	0.0315	93.61910	F(1,55) = 1.79, Prob>F = 0.1864
Knee Flexion Strength	0.0172	95.00380	F(1,55) = 0.96, Prob>F = 0.331
Ankle Inversion Strength	0.0100	95.69560	F(1,55) = 0.56, Prob>F = 0.458
Ankle Eversion Strength	0.0003	96.64190	F(1,55) = 0.01, Prob>F = 0.9054

4.3.2.4 Strength and Forefoot Pronation

Each independent strength variable and dependent kinematic foot pronation variable were plotted against each other, and the scatterplots are presented in Appendix B. In general, the plots for pronation angle at initial contact and maximum inversion angle revealed little evidence of associations with the independent strength variables. Pearson correlation coefficients and corresponding p-values were calculated to determine the relationship between inversion angle at initial contact and maximum inversion angle with each independent strength variable, as well as the relationships among each pair of independent variables. A correlation matrix of all variables is available in Table 43. No significant correlations were found amongst the pairs of dependent kinematic and independent strength variables. No strong correlations among independent variables were present.

Table 43: Pearson Correlations for Foot Pronation at Initial Contact and Maximum Foot Pronation Angle with Independent Strength Variables for all Dancers

	Foot Pronation at Initial Contact	Maximum Foot Pronation	Knee Extension Strength	Knee Flexion Strength	Ankle Inversion Strength	Ankle Eversion Strength
	r **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**	***r*** **(p - value)**
Knee Extension Strength	-0.095 (0.480)	-0.061 (0.655)				
Knee Flexion Strength	-0.141 (0.295)	-0.018 (0.897)	0.777 (<0.001)			
Ankle Inversion Strength	0.064 (0.638)	-0.036 (0.789)	0.488 (<0.001)	0.537 (<0.001)		
Ankle Eversion Strength	0.104 (0.440)	-0.006 (0.966)	0.440 (0.001)	0.474 (<0.001)	0.761 (<0.001)	

Simple linear regressions were performed to better understand the relationship between the independent variables with the dependent variables of pronation at initial contact and maximum pronation angle. Results are presented in Table 44 and Table 45. Jackknife residuals were plotted against the fitted values and the scatterplots are presented in Appendix C. All scatterplots for pronation angle at initial contact were randomly scattered around zero with no patterns indicating that the assumptions of linearly and homoscedasticity had been violated. There was one possible outlier that will be investigated further. Simple linear regression revealed that individually none of the independent strength variables were significant predictors of foot pronation angle at initial contact or of maximum pronation angle.

Table 44: Simple Linear Regression for Foot Pronation Angle at Initial Contact and Independent Strength Variables for all Dancers

Variable	R2	MSE	F value
Knee Extension Strength	0.0091	27.198	F(1,55) = 0.51, Prob>F = 0.480
Knee Flexion Strength	0.0199	26.902	F(1,55) = 1.12, Prob>F = 0.295
Ankle Inversion Strength	0.0041	27.337	F(1,55) = 0.22, Prob>F = 0.638
Ankle Eversion Strength	0.0109	27.150	F(1,55) = 0.60, Prob>F = 0.440

Table 45: Simple Linear Regression for Maximum Foot Pronation Angle and Independent Strength Variables for all Dancers

Variable	R2	MSE	F value
Knee Extension Strength	0.0037	23.81910	F(1,55) = 0.22, Prob>F = 0.655
Knee Flexion Strength	0.0003	23.89920	F(1,55) = 0.02, Prob>F = 0.897
Ankle Inversion Strength	0.0013	23.87520	F(1,55) = 0.07, Prob>F = 0.789
Ankle Eversion Strength	≤0.001	23.90580	F(1,55) ≤ 0.001, Prob>F = 0.966

4.3.3 Multiple Linear Regression Models

4.3.3.1 Strength and Dynamic Postural Stability

The final regression model for DPSI score (Hypothesis 2a) included gender, group, and trunk rotation strength and is presented in Table 46. A multiple linear regression model demonstrated that gender, group, and trunk rotation strength statistically significantly predict DPSI score ($F(3, 51) = 5.99$, $p = 0.002$). Gender, group and trunk rotation strength were responsible for 26.07 % of the explained variability in DPSI score. The fitted multiple linear regression model was: DPSI = 0.0256 – 0.0236 (Gender) – 0.0001 (Group) + 0.0003 (trunk rotation strength). In the fitted multiple linear regression equation, gender and trunk rotation strength were significant predictors of DPSI score. With all other variables held constant, females tended to have lower DPSI scores by 0.0236, and the DPSI score increased 0.0003 for every one NM % BW increase in right trunk rotation strength.

Jackknife residuals were plotted against the fitted values and there was no obvious evidence of deviation from the assumptions of linearity and homoscedasticity, and no obvious outliers (Appendix D). The results of the Shapiro Wilk test indicated that residuals were normally distributed ($p = 0.328$). Examination of VIFs and Cook's D revealed no issues with multicollinearity, or influential points, respectively.

Table 46: Multiple Regression Model for DPSI Score in all Dancers

Source	SS	df	MS		
Model	0.01891	3	0.0063	Observations	55
Residual	0.05364	51	0.00105	F(3,51)	5.99
Total	0.07255	54	0.00134	Prob>F	0.0014
				R2	0.2607
				Adjusted R2	0.2172

Predictor Variables	Coefficients	t	p-value	95% Confidence Interval
Gender	-0.0236	-2.51	0.015	-0.042, -0.005
Group	-0.0001	-0.02	0.988	-0.018, 0.018
Trunk Rotation Strength	0.0003	2.41	0.020	0.000, 0.001
Constant	0.0256	12.97	0.000	0.281, 0.384

Separate multiple linear regressions for each gender were performed to understand the effect of gender on the relationship between strength and DPSI score. The final regression models for DPSI score (Hypothesis 2a) are presented in Table 47 and 48.

For male dancers, a multiple linear regression model for DPSI score, was not statistically significant ($F(2, 20) = 2.06$, $p = 0.154$). Jackknife residuals were plotted against the fitted values and there was no obvious evidence of deviation from the assumptions of linearity and homoscedasticity, and no obvious outliers (Appendix D). The results of the Shapiro Wilk test indicated that residuals were normally distributed ($p = 0.762$). Examination of VIFs and Cook's D revealed no issues with multicollinearity, or influential points, respectively.

For females dancers, a multiple linear regression model demonstrated that group, trunk rotation strength, and knee flexion strength statistically significantly predict DPSI score ($F(3, 28)= 3.43$, $p = 0.031$). Group, trunk rotation strength, and knee flexion strength were responsible for 26.85 % of the explained variability in DPSI score. The fitted multiple linear regression model was: DPSI = 0.3071 + 0.0053 (Group) + 0.0007 (trunk rotation strength) – 0.006 (knee flexion strength). In the fitted multiple linear regression equation, trunk rotation strength was a significant predictor of DPSI score. With all other variables held constant, the DPSI score increased 0.0007 for every one NM % BW increase in trunk rotation strength.

Jackknife residuals were plotted against the fitted values and there was no obvious evidence of deviation from the assumptions of linearity and homoscedasticity, and no obvious outliers (Appendix D). The results of the Shapiro Wilk test indicated that residuals were normally distributed (p = 0.476). Examination of VIFs and Cook's D revealed no issues with multicollinearity, or influential points, respectively.

Table 47: Multiple Regression for DPSI and Independent Strength Variables in Male Dancers

Source	SS	df	MS		
Model	0.0066	2	0.0033	Observations	23
Residual	0.0319	20	0.0016	F(2,20)	2.05
Total	0.0384	22	0.0017	Prob>F	0.154
				R2	0.1709
				Adjusted R2	0.0880

Predictor Variables	Coefficients	t	p-value	95% Confidence Interval
Group	-0.0081	-0.41	0.687	-0.049, 0.033
Knee Flexion Strength	0.0008	1.90	0.073	≤ -0.001, 0.002
Constant	0.2641	6.19	≤0.001	0.175, 0.353

Table 48: Multiple Regression for DPSI and Independent Strength Variables in Female Dancers

Source	SS	df	MS		
Model	0.0058	3	0.0019	Observations	32
Residual	0.0157	28	0.0006	F(3,28)	3.43
Total	0.0214	31	0.0007	Prob>F	0.031
				R2	0.2685
				Adjusted R2	0.1901

Predictor Variables	Coefficients	t	p-value	95% Confidence Interval
Group	0.0053	0.59	0.561	-0.01, 0.02
Trunk Rotation Strength	0.0007	3.17	0.004	≤0.001, 0.001
Knee Flexion Strength	-0.0006	-2.07	0.048	-0.001, ≤ -0.001
Constant	0.3071	12.04	≤0.001	0.255, 0.359

4.3.3.2 Strength and Knee Valgus

The final regression model for knee valgus angle at initial contact (Hypothesis 3a) is summarized in Table 49 and was not found to be significant (p-value = 0.139). Jackknife residuals were plotted against the fitted values and there was no obvious evidence of deviation from the assumptions of linearity and homoscedasticity, and no obvious outliers (Appendix D). The results of the Shapiro Wilk test indicated that residuals were normally distributed (p = 0.714). Examination of VIFs and Cook’s D revealed no issues with multicollinearity, or influential points, respectively.

Table 49: Multiple Regression for Knee Valgus Angle at Initial Contact in all Dancers

Source	SS	df	MS		Observations	57
Model	116.589	4	29.147		F(4, 52)	1.82
Residual	833.617	52	16.031		Prob>F	0.139
Total	950.206	56	16.968		R2	0.1227
					Adjusted R2	0.0552

Predictor Variables	Coefficients	t	p-value	95% Confidence Interval
Gender	-2.2516	-1.91	0.062	-4.623, 0.111
Group	0.6894	0.58	0.562	-1.682, 3.061
Hip External Rotation Strength	0.2177	1.43	0.158	-0.087, 0.522
Knee Flexion Strength	-0.0401	-1.43	0.160	-0.096, 0.016
Constant	8.4162	2.17	0.035	0.629, 16.203

The final regression model for maximum knee valgus angle during landing (Hypothesis 3b) included gender, group, and trunk rotation strength and is presented in Table 50. A multiple linear regression model demonstrated that gender, group, hip external rotation strength and knee flexion strength statistically significantly predict maximum knee valgus angle ($F(4,52)= 4.53$, $p = 0.003$). Gender, group, hip external rotation strength and knee flexion strength were responsible for 25.85% of the explained variability in maximum knee valgus angle. The fitted multiple linear regression model was: maximum knee valgus angle = 16.9753– 6.7965 (Gender) + 1.8645 (Group) + 0.2076 (hip external rotation strength) – 0.0894 (knee flexion strength). In the fitted multiple linear regression equation, gender and knee flexion strength were significant predictors of DPSI score. With all other variables held constant, females tended to have lower knee valgus angles (more valgus) by 6.7965 degrees and the knee valgus angle decreased 0.0894 degrees for every one NM % BW increase in knee flexion strength.

Jackknife residuals were plotted against the fitted values and there was no obvious evidence of deviation from the assumptions of linearity and homoscedasticity, and no obvious outliers (Appendix D). The results of the Shapiro Wilk test indicated that residuals were not normally distributed (p = 0.042), and will be investigated further. Examination of VIFs and Cook's D revealed no issues with multicollinearity, or influential points, respectively.

Table 50: Multiple Regression for Maximum Knee Valgus Angle during Landing in all Dancers

Source	SS	df	MS		
Model	641.632	4	160.408	Observations	57
Residual	1840.77	52	35.399	F(4, 52)	4.53
Total	2482.403	56	44.329	Prob>F	0.003
				R2	0.2585
				Adjusted R2	0.2014

Predictor Variables	Coefficients	t	p-value	95% Confidence Interval
Gender	-6.7965	-3.87	≤0.001	-10.321, -3.272
Group	1.8645	1.06	0.293	-1.660, 5.389
Hip External Rotation Strength	0.2076	0.92	0.362	-0.245, 0.660
Knee Flexion Strength	-0.0894	-2.14	0.037	-0.173, -0.006
Constant	16.9753	2.94	0.005	5.404, 28.546

Because the results of the Shapiro Wilk test indicated that residuals were not normally distributed, several transformations of maximum knee valgus angle were performed (reciprocal, square root and logarithmic) and all regression analyses were tried on these transformed variables. None of the transformations improved normality of the residuals of the final multiple linear regression model. Therefore, a regression with robust standard errors was performed, and the results did not change. A linear regression with robust standard errors demonstrated the same outcome as the previous model (F(4, 52) = 4.02, p = 0.007), with gender, group, hip external rotation strength and knee flexion strength being responsible for 25.85% of the explained variability in maximum knee valgus angle. Gender and knee flexion strength were the only significant predictors of maximum knee valgus angle within the model. Therefore, the regression equation and interpretation hold true in the regression with robust standard errors.

A multiple linear regression was completed for maximum knee valgus angle in each gender separately due to the unexpected finding that increased strength predicated more knee valgus. These regressions are summarized in Tables 51 and 52. Neither were found to be significant (male p-value = 0.139, female p-value = 0.139). Jackknife residuals were plotted against the fitted values and there was no obvious evidence of deviation from the assumptions of linearity and homoscedasticity, and no obvious outliers (Appendix D). For male dancers the results of the Shapiro Wilk test indicated that residuals were normally distributed (p = 0.320). Examination of VIFs and Cook's D revealed no issues with multicollinearity, or influential points, respectively. For female dancers the results of the Shapiro Wilk test indicated that residuals were normally distributed (p = 0.872). Examination of VIFs and Cook's D revealed no issues with multicollinearity, or influential points, respectively. These findings will be discussed in the next chapter.

Table 51: Multiple Regression for Maximum Knee Valgus Angle During Landing in Male Dancers

Source	SS	df	MS		
Model	253.403	4	63.351	Observations	23
Residual	1113.637	18	61.869	F(4, 18)	1.02
Total	1367.041	22	62.138	Prob>F	0.422
				R2	0.1854
				Adjusted R2	0.0043

Predictor Variables	Coefficients	t	p-value	95% Confidence Interval
Group	-1.5750	-0.38	0.707	-10.238, 7.088
Hip External Rotation Strength	0.8448	1.54	0.141	-0.308, 1.997
Hip Abduction Strength	-0.3867	-1.00	0.329	-1.196, 0.422
Knee Flexion Strength	-0.1319	-1.44	0.167	-0.325, 0.061
Constant	18.1811	1.98	0.063	-1.117, 37.480

Table 52: Multiple Regression for Maximum Knee Valgus Angle During Landing in Female Dancers

Source	SS	df	MS		
Model	112.862	2	56.431	Observations	34
Residual	539.689	31	17.409	F(2, 31)	3.24
Total	652.551	33	19.774	Prob>F	0.053
				R2	0.1730
				Adjusted R2	0.1196

Predictor Variables	Coefficients	t	p-value	95% Confidence Interval
Group	3.5966	2.41	0.022	0.552, 6.641
Knee Flexion Strength	-0.0505	1.47	0.151	-0.120, 0.019
Constant	-0.0524	-0.01	0.989	-7.633, 7.528

4.3.3.3 Strength and Ankle Inversion

The final regression model for ankle inversion angle at initial contact (Hypothesis 3c) is presented in Table 53. The variables chosen for this regression were gender and group that were forced into the model, as well as the strength variables for knee extension, knee flexion, ankle inversion and ankle eversion. A multiple linear regression model demonstrated that gender, group, knee extension strength, knee flexion strength, ankle inversion strength, and ankle eversion strength statistically significantly predict ankle inversion angle at initial contact ($F(6, 50) = 2.42$, $p = 0.039$). Gender, group, knee extension strength, knee flexion strength, ankle inversion strength, ankle eversion strength were responsible for 22.53% of the explained variability in ankle inversion angle at initial contact. The fitted multiple linear regression model was: ankle inversion at initial contact = -13.8122 + 5.0722 (Gender) – 0.1138 (Group) + 0.0.838 (knee extension strength) – 0.1026 (knee flexion strength) + 0.2850 (ankle inversion strength) – 0.3482 (ankle eversion strength). In the fitted multiple linear regression equation, gender and knee extension strength were significant predictors of ankle inversion at initial contact. With all other variables held constant, at initial contact females tended to have higher ankle inversion angles by 5.0722 degrees and the ankle inversion angle increased 0.2850 degrees for every one NM % BW increase in knee extension strength.

Jackknife residuals were plotted against the fitted values and there was no obvious evidence of deviation from the assumptions of linearity and homoscedasticity, and no obvious outliers (Appendix D). The results of the Shapiro Wilk test indicated that residuals were normally distributed ($p = 0.189$). Examination of VIFs and Cook's D revealed no issues with multicollinearity, or influential points, respectively.

Table 53: Multiple Regression for Ankle Inversion Angle at Initial Contact

Source	SS	df	MS		
Model	942.439	6	157.073	Observations	57
Residual	3240.66	50	64.813	F(6,50)	2.42
Total	4183.09	56	74.6981	Prob>F	0.039
				R2	0.2253
				Adjusted R2	0.1323

Predictor Variables	Coefficients	t	p-value	95% Confidence Interval
Gender	5.0722	2.14	0.037	0.315, 9.829
Group	-0.1138	-0.05	0.962	-4.849, 4.622
Knee Extension Strength	0.0838	2.45	0.018	0.015, 0.153
Knee Flexion Strength	-0.1026	-1.25	0.218	-0.268, -0.063
Ankle Inversion Strength	0.2850	1.33	0.188	-0.144, 0.714
Ankle Eversion Strength	-0.3482	-1.34	0.186	-0.870, 0.173
Constant	-13.8122	-1.79	0.079	-29.300, 1.674

Backwards stepwise regression was performed for maximum inversion angle and six independent variables. The same as for ankle inversion at initial contact model, the independent variables included gender, group, knee extension strength, knee flexion strength, ankle inversion strength and ankle eversion strength. The final regression model for maximum inversion angle (Hypothesis 3d) is presented in Table 54. A multiple linear regression model demonstrated that gender, group, knee extension strength, knee flexion strength, ankle inversion strength, and ankle eversion strength statistically significantly predict maximum ankle inversion angle ($F(3, 53)= 3.90$, $p = 0.014$). Gender, group, knee extension strength, knee flexion strength, ankle inversion strength, ankle eversion strength were responsible for 18.07% of the explained variability in maximum ankle inversion angle. The fitted multiple linear regression model was: maximum ankle inversion angle = -14.3661+ 8.2021 (Gender) – 3.6632 (Group) + 0.1364 (knee flexion strength). In the fitted multiple linear regression equation, gender and knee flexion strength were significant predictors of maximum ankle inversion. With all other variables held constant, at initial contact females tended to have higher ankle inversion angles by 8.2021 degrees and the ankle inversion angle increased 0.1364 degrees for every one NM % BW increase in knee flexion strength.

Jackknife residuals were plotted against the fitted values and there was no obvious evidence of deviation from the assumptions of linearity and homoscedasticity, and no obvious outliers (Appendix D). The results of the Shapiro Wilk test indicated that residuals were normally distributed (p = 0.195). Examination of VIFs and Cook's D revealed no issues with multicollinearity, or influential points, respectively.

Table 54: Multiple Regression for Maximum Ankle Inversion Angle

Source	SS	df	MS		
Model	960.577	3	32.192	Observations	57
Residual	4345.104	53	82.191	F(6,50)	3.90
Total	5316.682	56	94.941	Prob>F	0.014
				R2	0.1807
				Adjusted R2	0.1343

Predictor Variables	Coefficients	t	p-value	95% Confidence Interval
Gender	8.2021	3.11	0.003	2.914, 13.490
Group	-3.6632	-1.42	0.162	-8.847, 1.520
Knee Flexion Strength	0.1364	2.37	0.021	0.021, 0.252
Constant	-14.3661	-1.70	0.095	-31.340, 2.608

4.3.3.4 Strength and Forefoot Pronation

The final regression model for foot pronation angle at initial contact (Hypothesis 3e) is summarized in Table 55 and was not found to be significant (p-value = 0.466). Jackknife residuals were plotted against the fitted values and there was no obvious evidence of deviation from the assumptions of linearity and homoscedasticity, and no obvious outliers (Appendix D). The results of the Shapiro Wilk test indicated that residuals were normally distributed (p = 0.613). Examination of VIFs and Cook's D revealed no issues with multicollinearity, or influential points, respectively.

Table 55: Multiple Regression for Foot Pronation Angle at Initial Contact

Source	SS	df	MS		
Model	98.538	4	24.634	Observations	57
Residual	1411.130	52	27.137	F(6,50)	0.91
Total	1509.670	56	26.958	Prob>F	0.466
				R2	0.0653
				Adjusted R2	-0.007

Predictor Variables	Coefficients	t	p-value	95% Confidence Interval
Gender	-0.0177	-0.01	0.991	-3.068, 3.033
Group	0.9609	0.65	0.522	-2.028, 3.950
Ankle Eversion Strength	0.1702	1.38	0.174	-0.077, 0.418
Knee Flexion Strength	-0.0588	-1.61	0.114	-0.132, 0.015
Constant	0.5252	0.11	0.917	-9.481, 10.531

The final regression model for maximum foot pronation angle (Hypothesis 3f) is summarized in Table 56 and was not found to be significant (p-value = 0.749). Jackknife residuals were plotted against the fitted values and the residuals follow a dichotomous pattern, as group and gender were the only variables remaining in the model. There were no obvious outliers. The results of the Shapiro Wilk test indicated that residuals were normally distributed (p = 0.303). Examination of VIFs and Cook's D revealed no issues with multicollinearity, or influential points, respectively.

Table 56: Multiple Regression for Maximum Pronation Angle during Landing

Source	SS	df	MS		
Model	14.006	2	7.003	Observations	57
Residual	1300.860	54	24.090	F(2,54)	0.29
Total	1314.862	56	23.450	Prob>F	0.749
				R2	0.0107
				Adjusted R2	-0.026

Predictor Variables	Coefficients	t	p-value	95% Confidence Interval
Gender	-1.0029	-0.76	0.453	-3.660, 1.654
Group	-0.1013	-0.08	0.938	-2.709, 2.506
Constant	-1.4361	-0.49	0.624	-7.277, 4.405

5.0 DISCUSSION

This study helped to more thoroughly describe the physical characteristics and orthopaedic injury histories of both professional ballet dancers and collegiate dancers, including lower extremity and trunk muscular strength, dynamic postural stability, and kinematics landing from a dance jump. Data on these characteristics are currently limited, and the differences between professional and collegiate dancers are largely unknown. Results demonstrate that professional dancers have significantly less body fat percentage, and they are significantly stronger than collegiate dancers for most muscle groups tested. No significant differences were found between professional ballet and collegiate dancers for dynamic postural stability and minimal differences in kinematics. No differences were found in the self-reported injury histories, except that a greater proportion of professional dancers reported injuries to the ankle, and foot and toe regions. These findings from between group comparisons will be helpful for clinicians working with different types of dancers by determining which characteristics may need to be addressed with rehabilitation or supplemental training programs. These types of programs may need to be different for different types of dancers, depending on the variables where significant differences are found. It will be important to consider types of dancers (professional verses collegiate) separately, or control for group, in future work including variables where differences were found.

This study also makes significant contributions to dance medicine literature because it investigates the relationship among physical and performance characteristics; specifically if strength can predict dynamic postural stability and landing kinematics that may increase the risk for knee and ankle injury. This information provides insight into the relationships among variables and help explain if performance in one area predicts performance in another. Regression analyses revealed that gender and trunk rotation strength predicted dynamic postural stability. Gender and knee flexion strength predicted maximum knee valgus angle. Gender and knee extension strength predicted ankle inversion angle at initial contact and, gender and knee flexion strength predicted maximum inversion angle. No significant predictors of foot pronation angle were found. Some of these results were unexpected and suggest that improved strength performance does not predict improved DPSI or knee valgus angle. Further research should investigate the relationships among physical characteristics and performance variables in each gender separately, as well as seek to find additional variables that explain the relationship between strength and dynamic postural stability and kinematics.

5.1 BETWEEN GROUP COMPARIONS IN PHYSICAL CHARACTERISTICS OF PROFESSIONAL BALLET AND COLLEGIATE DANCERS

The purpose of the first specific aim of this study was to determine if professional ballet and collegiate dancers were different in various physical and neuromuscular characteristics, as well as self-reported injuries (hypotheses 1a – 1g). Several differences between professional ballet and collegiate dancers were found, including body composition, trunk flexion and extension strength, hip strength, and knee flexion strength. No differences were found between the groups for trunk rotation strength, knee extension strength, or ankle strength. No differences were found between groups for dynamic postural stability or kinematics during the dance jump task of forward *grand jeté*. No differences were found between groups for self-report of a time loss musculoskeletal injury in the dancers' total or one year injury history. A greater proportion of professional dancers reported injuries to their ankle, and foot and toe regions in their total injury history, but not in the past one year, as compared to collegiate dancers.

5.1.1 Body Composition

Professional dancers were found to have significantly lower percentages of body fat than collegiate dancers, which is in support of the hypothesis. The average percent body fat was 4.06% lower in the professional group. This was observed across the female and male groups, although only statistically significant in the professional females. Within the females the professional dancers had 5.26% lower body fat percentage and within males the professionals had 2.65% lower body fat percentage. There may be important health and performance implications emerging from the data in this study regarding the relationship between body weight and percent body fat in different types of dancers.

In the professional dancers the female average of 17.58% can be considered lean, and very close to other athletic populations, according to the American College of Sports Medicine (ACSM). The ACSM categorizes female body types by percentage of body fat as follows: athletes (<17%), lean (17-22%), normal (22-25%), above average (25-29%), over-fat (29-35%), and obese (>35%).[242] One of the female dancers was categorized as having an above average body fat percentage of 27.4%. Her body fat may have been higher because she had given birth within the past year. None of the professional female dancers would be categorized as over-fat or obese. However, some of the dancers may have body fat percentages lower than recommended for good health. The American Council on Exercise (ACE) recommends women have at least 10-13% body fat as essential fat.[243] Although none fell below 10% body fat, three of the professional female dancers (16.7% of this subgroup) had body fat percentages in this essential fat only category. This shows that a proportion of professional female dancers may have unsafe body fat percentages. In this subgroup, promoting a body fat percentage that is both healthy and allows for the desired aesthetic is needed. It may be that the professional ballet dancers are trying to maintain an unhealthy physique and body size. Recently, deSilva, et al., reported that 40% of professional female ballet dancers have moderate to severe altered perception of their body, meaning they do not accurately perceive their body often resulting in poor body image. Additionally, 60% would like to have a silhouette that is smaller than the one they perceive themselves to be, indicating a persistent desire to be a different body size and shape.[244] A study on adolescent female ballet dancers found that this group had higher levels of poor body image and low self-esteem than age and gender matched controls as well as adolescent male ballet dancers. The authors recommended interventions focused on improving self-esteem to help prevent psychological problems for the female dancers in the future.[245] Promoting a safe and healthy physique, as well as a positive and accepting body image, is likely warranted in female ballet dancers.

Special consideration of these unhealthy physical findings is needed to help improve health in female ballet dancers. A positive finding from the current study is that the average body fat percentage in professional female ballet dancers is within normal limits for an athletic population. Most professional female dancers were able to achieve the desired lean aesthetic and still be healthy, although any underlying psychological issues or the dancers' perception of their actual verses desired size is unknown. The average professional female body fat percentage of 17.58% from the current study is similar, if not slightly higher than previous findings. Several earlier studies that found lower body fat percentages in female professional dancers ranging from 12.7 to 14.6%, used skinfold methods.[155,246-248] More accurate measures of body composition testing in professional female ballet dancers have results similar to those of this study; 19.1% using bioelectrical impedance, 16.4% using dual X-ray absorptiometry (DXA), and 17.4% using underwater weighing.[143,246] Underwater weighing and DXA are considered gold standards for measuring body composition. The current study's results were essentially the same, validating that it was able to accurately describe the body fat percentage of professional female ballet dancers. The data from this study, combined with previous work using the best methods for body composition assessment indicate that the body fat percentage of professional female ballet dancers is around 17%.

In the professional dancers, the male average was 8.98% and would be categorized as athletic by the ACSM. For males, body type categories by body fat percentage are as follows: athlete (<10%), lean (10-15%), normal (15-18%), above average (18-20%), over-fat (20-25%), and obese (>25%).[242] For men 2-5% body fat is essential fat.[243] Only one professional male dancer had a very low body fat percentage of 4.8%, which falls below 5%, potentially putting him at increased health risk. None of the professional male dancers had a body fat percentage greater than 12%, indicating that all would be considered lean.[242] Data on body fat percentage in professional male dancers is limited. To the author's knowledge, only one study had reported body composition in this group. Micheli et al., found that professional male ballet dancers had an average body fat percentage of 6.5% using skinfold methods.[247] To the author's knowledge, other body composition data on professional male ballet dancers using more accurate methods such as air-displacement plethysmography, DXA, or hydrostatic weighing are not available. It appears that professional male dancers remain lean, but are less likely to have body fat percentages that are too low and put them at health risk as in the professional female dancers. Also, consideration should be paid to male dancers who may be suffering from issues with body image. Although a lower percentage than in females, approximately 20% of professional male ballet dancers had an alteration in the way they perceived their bodies and 80% wished to have a different silhouette. Some men wished for a larger and some for a smaller body shape.[244] Clinicians should help male dancers accept their bodies and provide services/training to achieve a healthy and fit physiological and psychological state.

In the female collegiate dancers, average body fat percentage was 22.84%, which could be categorized as on the border of lean and normal by the ACSM.[242] 17.6% of the collegiate dancers were categorized as being lean, the category of the average female professional dancer. None of the collegiate females fell in the at risk/essential body fat only category. One female collegiate dancer had a body fat percentage of 35.9%, which is considered obese and outside of normal healthy recommendations for the general adult female population.[242] The collegiate female dancers had a higher body fat percentage than the professional female dancers, falling at the low end of the normal range for the general population.[242] The collegiate female dancers in this study fell into the suggested range by Chmelar and Fitt of 17% to 23% body fat.[249] The average body fat percentage of the female collegiate level dancers seemed to vary across studies. Values from previous studies that are lower than those in the current study were 14.2% using skinfold methods, 19.1% using bioelectrical impedance, to 19.9% using DXA.[246,250] A recent study with body composition results more similar to that of this study looked at different types of Korean dance majors using DXA and had slightly higher body fat percentages than those in this study; 24.8% ± 3.12% for ballet dancers, 24.5% ± 4.57% for contemporary dancers, and 27.7% ± 4.64% for traditional Korean dancers.[251] Their results are similar to Friesen et al., who found the body composition of collegiate modern dancers to be 25.9% ± 4.2%.[145] All of these studies indicate that female dancers are still successful at the collegiate level with a higher body fat percentage, as compared to professional dancers. It is unknown which dancers will go on to have a professional career after college and if body fat percentage, or related aesthetic, influences this. It is also unknown if the collegiate dancers in this study suffered from body dysmorphia, psychological, or self-esteem disorders.

The collegiate male dancer's average body fat percentage was 11.63%, which placed them into a lean category, as compared to the professional males whose average could be categorized as athletic.[242] The difference between professional and collegiate male dancers was not found to be statistically significant; however, this finding may be clinically significant. Two collegiate male dancers (16.7%) fell into the athletic category and one had a risky body fat percentage below 5%. One collegiate male dancer had excessive body fat of 23%. To the author's knowledge, no other data on collegiate male dancers was available for comparison to this study.

In addition to having less body fat percentage, the female professional dancers also had significantly lower total body mass than collegiate female dancers. In the male dancers there was no difference in body mass between professional and collegiate groups. It was supported that male collegiate dancers have higher body fat percentages than professional male dancers, but similar body mass, however further investigation is needed. Similarly, Liiv et al., also found female ballet dancers to have lower body mass, BMI, and body fat percentage, measured by DXA, when compared to contemporary dancers and dance-sport dancers. Contemporary dancers were more muscular than both ballet dancers and dance-sport dancers, and the ballet dancers had the lowest aerobic capacity of the three groups.[252] Lim et al., reported on body fat percentage and muscular strength of female collegiate dancers. The dancers with lower body fat percentages (approximately 24-25%) had higher quadriceps and hamstring muscular strength than dancers and controls who had higher body fat percentages (approximately 27-30%).[251] However, no statistical tests were run to determine the relationships among these variables and further investigation is required. It has been proposed that dancers can be encouraged to be "fit for a purpose" to promote healthy body composition, as well as other physiological factors, for better dance performance.[32] It has been recommended that optimal body fat percentages for female collegiate level dancers be between 17% and 23%.[249] However, further analyses and future investigations should be done to determine the relationship between body fat percentage and various physical and performance characteristics to validate if this is the optimal body fat percentage for health and performance in all types, levels and genders of dancers.

5.1.2 Muscular Strength

5.1.2.1 Trunk Strength

The hypothesis that the trunk strength would be higher in professional ballet dancers than collegiate dancers was partially supported. The trunk extension and flexion strength of the professional group was significantly higher than the collegiate group. The professional dancers had an average trunk extension strength of 43.65 NM % BW more than the collegiate group. For trunk flexion they had 33.28 NM % BW body weight more than collegiate dancers. The difference between trunk flexion and extension strength of professional and collegiate dancers had effect sizes of 0.53 for extension and 0.71 for flexion. This difference is also likely a clinically meaningful finding in the difference in trunk strength of professional and collegiate dancers.

Professional dancers were stronger than collegiate dancers within both female and male dancers, however the difference was statistically significant only in the male group. The difference between the professional and collegiate male groups was 86.13 NM% BW for trunk extension and 64.56% NM% BW for trunk flexion. Professional female's average strength for trunk extension was 17.34 NM% BW higher, and their trunk flexion 14.38 NM % BW higher than the collegiate females. The magnitude of these differences between male professional and collegiate dancers were large; 0.94 for extension and 1.66 for flexion. For females, the effect sizes were smaller being 0.24 for extension and 0.310 for flexion. While professional dancers are always on average stronger than collegiate dancers, the difference is much more pronounced in the males.

Dancers in the present study were found to be stronger than those previously reported. The hierarchy of strength of different groups of dancers is the same, with the exception of collegiate males; professional males > professional females > collegiate females. To the author's knowledge, no studies reporting on trunk strength of collegiate males were available for comparison. Cale-Benzoor, et al., also investigated the trunk strength of ballet dancers using isokinetic dynamometry, but did not include any collegiate male dancers. Their data was reported in foot pounds % body weight in pounds, and have been converted to NM % BM for comparison to the current study. Professional male dancers peak trunk extension strength was

199.31 NM % BM and peak trunk flexion strength was 135.58 NM % BM, as compared to 323.44 NM % BM and 229.84 NM %BM in the current study. Professional female dancers peak trunk extension was 173.55 NM % BM and peak trunk flexion strength was 101.9 NM % BM, compared to 259.08 NM % BM and 176 NM % BM in the current study. Collegiate female dancers peak trunk extension was 141.01 NM % BM and peak trunk flexion strength was 89.48 NM % BM, compared to 241.74 NM % BM and 162.45 NM % BM.[57] The previous study reported strength as the peak force from six trials, and the current study reported the average peak torque of five trials. Peak force values are usually expected to be slightly higher than average peak force, also supporting that the dancers in the current study are stronger than those previously reported. The increased strength of the dancers in our study may be because of the testing position. The dancers in the former study were tested in standing whereas the current study utilized a semi standing position. The current testing position is safer and will allow subjects to exert their maximal force. This testing position has been used in other groups in sports medicine literature, allowing for assessment to be made of how dancers compare to other athletes.

Previous work has reported isokinetic trunk extension and flexion strength, tested in semi-standing at 60 degrees per second, of collegiate level wrestlers and judokas.[253] These male athletes were stronger then the male dancers in the present study. Their strength for trunk extension ranged from 530 to 650 NM % BM and trunk flexion ranged from 270 to 280 NM % BM, with the wrestlers being stronger, likely because of the demand of their sports where fighting and exerting great force to dominate an opponent is required.[253] The trunk strength requirements of dance are not fully understood, although for males, lifting partners overhead is required. The same testing methods of the current study were also used by Sell et al., to assess strength in athletic adults. Professional male dancers had similar strength to recreationally active males. These males had trunk extension strength of 384.71 NM % BM, and the professional male dancers had 323.44 NM % BM. In the previous study the males had trunk flexion strength of 220.21 NM % BM and the professional male dancers had trunk flexion strength of 229.84 NM % BM.[254] Professional male dancers have similar strength to the athletic males in this previous study. Trunk strengthening may be beneficial for professional male dancers so that they can achieve greater strength than recreationally active males, who are not likely required to lift others overhead. The collegiate males were much weaker compared to athletic males, with trunk extension strength of 237.31 NM % BM and trunk flexion strength of 165.28 NM % BM. This indicates they are a weak subgroup of dancers requiring additional trunk strengthening. Further investigation of injuries in collegiate male dancers, and consideration of the dance requirements is needed. Collegiate male dancers may or may not do as much partnering as professional male dancers. If they do, they may not have adequate strength.

Less information on the trunk strength of female athletes is available for comparison to the female dancers in the present study. Sell et al., did include athletic females, most of which (8/10) were collegiate gymnasts, who are often thought to be more similar to dancers than other types of athletes. The trunk extension and flexion strength of these females were 226. 83 NM % BM and 138.30 NM % BM respectively.[254] Both female professional ballet and collegiate dancers, who were determined to have no differences in trunk extension and flexion strength, had slightly stronger trunk extension and flexion compared to the other athletes. The trunk extension strengths were 259.08 NM % BM and 241.74 NM % BW for professional and collegiate dancers respectively. Female dancers, both professional and collegiate, are similar if not slightly stronger than athletic females, including gymnasts.

No differences in trunk rotation strength were found between professional and collegiate dancers. The average right and left rotation strength values were approximately 6-10 NM % BW higher in the professional group, however this difference was not statistically significant. The effect sizes were 0.31 for right rotation and 0.22 for left rotation. An interesting observation in trunk rotation strength when looking across all gender subgroups is that the professional men were the strongest and the professional women were the weakest. There was very little difference between the collegiate females and males. There was however, a difference observed in the trunk rotation strength of male professional and male collegiate dancers. The professional males were stronger in both right and left trunk rotation. This difference was significant on the right but not the left. The difference in both directions is likely clinically significant. The effect size between professional and collegiate males is 0.90 to the right and 0.59 to the left. Differences in trunk rotation strength of the professional and collegiate male dancers range from 19.74 NM % BM on the left to 33.43 NM % BM on the right. A significant difference found for male right rotation strength is due to the fact that professional males were stronger to the right and collegiate males were stronger to the left, increasing the difference on the right side and narrowing the difference on the left.

To the author's knowledge, isokinetic trunk rotation strength of dancers has not been previously studied. The dancers in the current study were weaker compared to a general military population. Right and left trunk strength values of the dancers were averaged for comparison. Male soldiers trunk strength was 145.1 NM % BM compared to 125.1 NM % BM for professional male dancers.[255] Female soldiers trunk strength was 110.5 NM % BM compared to 90.18 NM % BM for professional female dancers.[255] Male and female collegiate dances had similar trunk rotation strength which ranged from 91.6 to 102.9 NM % BM, and are also weaker than soldiers. Dancers may have weakness of their trunk rotation musculature as their strength values were lower than the soldiers. The soldiers in this study would be representative of a physically active adult group, and since dancers are very athletic, performing many movements with their torsos, lifting and partnering, they may benefit from higher strength.

Another comparison group for trunk rotation strength comes from Sell et al., who also used the same methods as the current study and reported on trunk rotation of athletic and recreationally active individuals. Recreationally active males had average right and left trunk rotation strength of 136.23 NM % BM and 126.11 NM % BM respectively.[254] These are closer to the values seen in the professional male dancers in the current study; 127.60 NM % BM and 122.65 NM % BM for right and left rotation respectively. The collegiate male group showed weakness compared to recreationally active males. Their right and left trunk rotation strength were 94.17 NM % BM and 102.91 NM % BM respectively. This further supports the hypothesis that collegiate male dancers may be a subgroup of dancers with trunk weakness. The female group in the study by Sell et al. is of particular interest because 8 of the 10 females were Division 1 gymnasts, and the remaining 2 were recreationally active. Gymnasts are thought to be more similar to dancers than other types of athletes. The right and left rotation strength of the females were 82.22 NM % BM and 79.55 NM % BM respectively.[254] Both female professional ballet and collegiate dancers, who were determined to have similar trunk rotation strength, had slightly stronger trunk rotation strength than this comparison group. The right trunk rotation strength of the female dancers was 86.50 NM % BM for the professionals and 91.59 NM % BM of the collegiate dancers. The left trunk rotation strength of the female dancers was 93.86 NM % BM for the professionals and 95.65 NM % BM for the collegiate dancers. The differences between the dancers and female athletes may not be clinically significant. Both groups may have adequate trunk rotation strength, or potentially, both groups have weakness of their trunk rotation musculature.

Overall the strength balance of the trunk extensor and flexors was very good in both groups of dancers, reflected by the strength ratios. There were no differences between groups in the trunk flexion/extension ratio or the right/left trunk rotation ratio. The average ratio for both professional and collegiate dancers was 0.72. The females had slightly lower ratios of 0.70 in the professionals and 0.68 in the collegiate dancers. The ratios in males were slightly higher, with an average trunk flexion/extension ration of 0.76 in both groups. This indicates that their trunk flexors were weaker than there trunk extensors. This is normal and expected. It also indicates that dancers do not have suboptimal strength balance of their trunk flexors and extensors, despite potential weakness. The right/left trunk rotation were also very balanced in both groups, with no statistical differences found. The right/left trunk rotation strength ratios were 0.97 in the professional group and 0.94 in the collegiate group. This indicates that the right trunk rotators were slightly weaker than the left. A rotation ratio of 1.0 would indicate equal strength on both sides. One statistical difference was found when comparing male dancers in each group. In the professional males the ratio was 1.03 indicating that the left rotators were slightly stronger and in the collegiate males the ratio was 0.92. This statistical difference may also be present because the collegiate male's left trunk rotation strength was found to be significantly lower than the professionals. Within the females the professional's rotation strength ratio was 0.93 and collegiate dancer's ratio was 0.96, and was not statistically significant. All of the trunk rotation strength ratios were very close to one, indicating good muscle balance with no clinically meaningful difference between groups.

In summary, professional dancers have greater trunk strength for trunk flexion and extension. The professional trunk rotation strength average is higher than the collegiate group, but not statistically significant. The strength differences observed may be coming largely from the strength of the professional males. The professional female and collegiate male and female dancers all appear to be similar. Because males are expected to be stronger than females, this may indicate that collegiate male dancers have weakness of their trunk musculature. Both groups of dancers have good trunk muscular strength balance of antagonist muscle groups; extension/flexion and right/left rotation. Overall, dancers have trunk strength similar to active adults. They may require more trunk strength for better performance and injury prevention.

5.1.2.2 Hip Strength

The hypothesis that professional dancers would be stronger than collegiate dancers was supported. Professional dancers were significantly stronger than collegiate dancers in all hip strength variables, which included abduction, adduction, external rotation, and internal rotation. The professional dancers had average hip abduction strength of 3.66 kg % BM greater than the collegiate group with an effect size of 0.77. For hip adduction the professional's strength was 3.71 kg % BW greater than the collegiate group, which corresponded with an effect size of 0.67. Similar results were found for hip external and internal rotation. For hip external rotation the professional group's average hip strength was 3.37 kg % BW higher than the collegiate dancers, and was 3.26 kg % BW higher for internal rotation. The magnitudes of these differences were large, being 0.82 for external and 0.81 for internal rotation.

On stratification by gender, professional dancers remained stronger than collegiate dancers. For hip abduction and hip internal rotation the professional females were statistically significantly strength than collegiate female dancers with differences of 3.17 kg % BM and 3.02 kg % BM respectively. The differences between females in each group of 3.1 kg % BM for hip adduction and 1.96 kg % BM for hip external rotation were not statistically significant. They may all, however, be clinically significant. The effect sizes, from calculations for non-parametric tests, for the difference between the females in each group were 0.40, 0.30 for hip abduction and adduction respectively. Using traditional effect size calculations, effect sizes for external and internal rotation strength were 0.52, and 0.71 respectively. Professional male dancers were significantly stronger than collegiate male dancers for all tests. The professional male dancers were 4.53, 4.00, 5.49, and 3.73 kg % BM stronger than male collegiate dancers for hip abduction, adduction, external rotation and internal rotation respectively, with large effect sizes of 0.85, 0.88, 1.39, and 1.19 respectively. The magnitude of the difference between male professional and collegiate dancers is greater than for female comparisons. It is also likely more clinically meaningful. Collegiate male dancers show greater weakness compared to their professional counterparts than the collegiate females do compared to professional dancers. Furthermore, the difference between professional and collegiate dancer groups as a whole may be more influenced by the male dancers than the female dancers.

One interesting observation with hip internal rotation strength is a lack of gender difference. Usually it is expected that male dancers will be stronger than female dancers. Within the professional group, male dancers were stronger than females in all hip strength variables. The difference in hip internal rotation between male and female professional dancers, however, was only 0.02 kg % BW. In the collegiate group the males were stronger with all variables except hip internal rotation. The collegiate female dancers were 0.83 kg % BW stronger than the male dancers. These differences are very small and not likely to be clinically significant. Therefore, there may not be any gender difference with hip internal rotation strength. This may potentially be because this is a movement with which the dancers are unfamiliar with. Dancers will very rarely perform movement into internal rotation, especially active or weighted movements requiring muscular strength in this direction. The hip internal rotators may act as stabilizers rather than primary movers. Any movements into that direction would not be likely to be powerful movements. This may be why strength of the internal rotators is the lowest of the hip muscles and lacks a gender difference.

To the authors' knowledge only one previous study has reported on hip strength of professional dancers, and none on collegiate dancers. Hamilton et al., reported isokinetic hip strength values of the male professional ballet dancers for hip abduction and adduction to be 112.1 ± 19.0 foot pounds and 96.4 ± 23.6 foot pounds respectively, with a hip abduction to adduction ratio of 1.2 ± 0.02. The female professional ballet dancers hip abduction strength was 89.4 ± 15.8 and hip adduction strength was 80.7 ± 17.2 with an abduction to adduction ratio of 1.5 ± 0.2. These strength values were not normalized to body weight.[59] Hamilton et al., reported that the dancers in their study had weakness of hip adductors but not abductors when compared to normal. This led to a reversal of the expected hip abduction to adduction ratio, in that the abductors were stronger than the adductors as typically seen.[59]

The muscle strength (hip abduction and adduction) of the dancers in the current study cannot be directly compared to those in this previous study because of differing testing methods (isometric verses isokinetic). However, the strength ratios can be compared. For the purposes of comparison the ratios of the professional ballet dancers in the current study were recalculated as abduction/adduction and were found to be 0.95 for the male dancers and 0.92 for the female dancers. Hamilton et al., suggested that the hip abductors may be stronger because of a substantial amount of isometric training in dance, where dancers will use their hip abductors to stabilize their standing limb and/or hold their moving limb out to the side in an abducted position.[59] This isometric function supports the use of isometric testing of the hip musculature, which was performed in the current study. Potentially, the use of isometric muscle testing as opposed to isokinetic testing could explain the difference in ratios. The dancers in the present study have the expected strength ratio where the adductors are stronger than the abductors.[214] Both groups of professional ballet dancers, however, display good muscle balance of their hip abductors and adductors.

Beyond the strength ratios, direct comparisons to the dancers in previous work cannot be made, however, the dancers in the current study can be compared to other athletes. Faherty et al., used the same isometric testing methods as in the current study and found that Division I collegiate soccer players had hip strength reported in kg % BM, of 22.77 ± 5.22, 23.76 ± 9.63, 18.32 ± 3.67, 15.83 ± 4.20 for hip abduction, hip adduction, hip external rotation and hip internal rotation respectively.[256] These values are very similar to the strength of the professional dancer group for hip abduction and adduction, but the hip external and internal rotation strength of the professional dancers appears less. In comparison, the collegiate dancer group is weaker than these Division I soccer players for all hip strength measurements. When comparing within specific genders the male professional dancers appear stronger than the male soccer players, but the male collegiate dancers appear weaker. The male soccer players had hip strength values of 21.91 ± 6.09, 24.73 ± 13.24, 18.47 ± 3.70, 14.90 ± 3.78 for hip abduction, hip adduction, hip external rotation and hip internal rotation respectively.[256] The female soccer players had hip strength values of 23.56 ± 4.22, 22.85 ± 4.12, 18.17 ± 3.69, 16.67 ± 4.44 for hip abduction, hip adduction, hip external rotation and hip internal rotation respectively.[256] Both the female professional and collegiate dancers are weaker than the female collegiate soccer players, but the difference is less apparent with the professional female dancers. Overall, these comparisons suggest that collegiate dancers are the weakest compared to other athletes, and they may benefit from increased hip strength. However, professional dancers may also benefit from hip strength if it is important for them to be stronger than collegiate athletes.

In summary, professional dancers have greater hip strength than collegiate dancers in all motions tested; abduction, adduction, internal and external rotation. This difference was also observed within genders, although only significant for two of the four tests in female dancers. This study provides assessment of isometric hip strength in the dance population that has previously not been reported. This study indicates that dancers have slightly stronger hip adduction than abduction and is different from what has previously been reported in professional ballet dancers.[59] Dancers may have weakness of their hip musculature compared to other athletes, especially in hip external and internal rotation.[256] This may be of concern because dancers spend a significant amount of time standing and balancing on one leg, in an externally rotated position, requiring strength of the hip rotators for stabilization of the hip and pelvis.[59] Collegiate dancers appear to be weak in all directions compared to both soccer players and professional dancers. Strengthening of the hip musculature may be especially important in this group of dancers.

5.1.2.3 Knee Strength

The hypothesis that professional dancers would have greater knee strength was partially supported. A statistically significant difference between groups was not found for knee extension. Professional dancers' knee extension strength average was 18.77 NM % BM greater than collegiate dancers and the effect size was 0.37. A significant difference was found for knee flexion, with professional dancers having an average of 16.83 NM % BM and corresponded with an effect size of 0.73.

When comparing professional to collegiate dancers within genders there are no significant differences between groups for knee extension. Professional female dancers are 10.3 NM % BM stronger than female collegiate dancers on average. The effect size was 0.21. The male professional dancers' average knee extension strength was 31.87 NM % BM higher than the male collegiate dancers, with an effect size of 0.62. This difference may be clinically significant. For knee flexion, there was a significant difference between males in the two groups. The professional male dancers were 24.51 NM % BM stronger than the male collegiate dancers with a large effect size of 1.14. For knee flexion, there was no statistically significant difference between female dancers in the professional and collegiate groups. The female professional dancers were 11.99 NM % BM stronger than the collegiate dancers, with an effect size of 0.56. This difference may, however, be clinically meaningful. In general the magnitude of the difference between male dancers in the different groups is larger than the females. This likely means that the collegiate male dancers are weak and may benefit from strengthening programs.

Overall the results of this study indicate that professional dancers have stronger knee musculature than collegiate dancers. Observation of previous data shows similar results to our study, but none of the previous between group comparisons were tested statistically. In previous work, professional male dancers are the strongest compared to professional female and collegiate female dancers.[32] To the authors' knowledge, no previous studies have presented data on collegiate male dance majors. Previous studies show that professional female dancers were stronger, or equal in strength, to female collegiate dancers depending on the data set.[32,34,36,52,59]

Previous work examining knee extension (KE) and knee flexion (KF) muscular strength of professional ballet dancers also used isokinetic methods collected at 60 degrees per second. Unfortunately, this study did not report strength normalized to body mass, therefore we have used the raw strength values, of the right limbs, of the professional dancers in the current study for comparison. The findings of Hamilton et al., have also been converted from foot pounds to newton meters. They found professional male ballet dancers to have knee extension strength of 127.4 NM ± 17.3 NM and knee flexion strength of 75.8 NM ± 9.0 NM. The professional female dancers in this study had knee extension and flexion strength of 95.1 NM ± 7.1 NM and 52.9 NM ± 7.5 NM respectively.[59] The dancers in the current study appeared to be stronger, with un-normalized strength values for the right lower extremity as follows: male KE = 169.89 ± 34.78 NM, male KF = 98.98 ± 16.48 NM, female KE = 107.06 ± 28.02 NM, female KF = 59.83 ± 9.91 NM.

A study by Chmelar et al., investigated the strength of female dancers, including both professional ballet and collegiate dancers. They also tested isokinetic knee strength at 60 degrees per second. Values were converted from foot pounds % BW to NM % BM for comparison to the current study. Chmelar et al., found that professional ballet dancers had knee extension and flexion strength of 99.92 NM % BM ± 16.8 and 68.5 NM % BM ± 9.1 NM % BM respectively.[52] These dancers are weaker than the professional dancers in the current study (professional ballet female KE = 199.83 NM % BM, female KF = 110.31 NM % BM). The female collegiate dancers in the study by Chmelar, et al., had knee extension strength of 104.06 NM % BM and knee flexion strength of 61.89 NM % BM.[52] These female collegiate dancers were also weaker than the female collegiate dancers in the current study (collegiate female KE = 189.53 NM % BM, KF = 98.32 NM % BM). The results of the strength of female collegiate dancers in the present study are more similar to a more recent study by Lim, et al. They investigated the strength of collegiate dance majors and found that there were differences between three types of female dancers (traditional Korean dancer, ballet, and contemporary). These subjects were also tested on an isokinetic dynamometer at 60 degrees per second. Quadriceps strength of these dancers ranged from 170.6 NM %BW to 184.3 NM %BW depending on side and group.[251]

In comparison to other athletes, two previous works by Kirkendall and their colleagues, investigated the knee muscular strength of professional ballet dancers and compared them to several other groups of athletes including, figure skaters, swimmers, cross country athletes, skiers, and basketball, hockey, American football, and volleyball players. They used isokinetic testing at 45 degrees per second, reported in foot pounds relative to fat free mass. They also used the Hill's hyperbola equation to estimate strength at 30 degrees per second for comparison to the other athletes who were collected at that speed.[31] They found that both male and female professional dancers were weakest of all groups compared to their respective genders in other athletic groups. The deficit of the male dancers in comparison to other athletes was less pronounced than for the female dancers who had the lowest strength of all groups.[9,31] Chmelar at al., compared the professional and collegiate female dancers in their study to collegiate basketball players and track athletes, and found the dancers to be similar to the basketball players, but weaker than the track athletes when tested at 180 degrees per second.[52]

When comparing the dancers in the present study to other groups of athletes, it appears that they are probably less weak than previously thought. When compared to adult males in other studies using isokinetic methods collected at 60 degrees per second expressed as NM % BM, male professional dancers have similar KE strength and higher KF strength compared to male Army soldiers (male professional dancer KE = 232.80, KF = 134.77 vs male Army soldiers KE =

236.12, KF 114.81), Female professional dancers have stronger KE and KF than female Army soldiers (female professional dancer KE = 199.83, KF = 110.31 vs female Army soldiers KE = 191.30, KF = 92.98).[257] The collegiate dancers were weaker than the Army soldiers (male collegiate dancer KE = 200.93, KF = 110.26, and female collegiate dancer KE = 189.53, KF 98.32). The professional ballet dancers, collegiate dancers, and the Army soldiers had weaker thigh musculature than triathletes (male triathlete KE = 242.09, KF = 128.00 and female triathlete KE = 216.53, KF = 115.47).[257] However, when comparing to collegiate basketball and soccer players the (male collegiate athlete KE = 271.69, KF 131.72, and female collegiate athlete KE = 222.93, KF = 113.74), the professional dancers, collegiate dancers, and Army soldiers were all weaker.[89]

It is unclear why the dancers in previous studies were weaker than those in more recent studies. The current and previous studies include similar types of dancers, and report the same methods for testing regarding test set up, warm up, test instructions, and encouragement given during testing. The results of this study indicate that dancers, especially females, may have less strength deficit of their knee musculature than previously thought. Another potential explanation for the seeming increase in dancer strength may be that dancers, especially female dancers, have had increasing strength over the years. Most previous work was published in the 1980s and early 1990s. Since that time research refuting the fear among dancers that strength training leads to an unwanted “bulky appearance” has been published.[36] It is possible that dancers as a group of athletes have been becoming stronger, but this warrants further investigation.

Another interesting finding of the present study is that the dancers did not have as high of hamstring to quadriceps strength ratios (H:Q), as had previously been reported. It is accepted that the hamstrings should be approximately two thirds as strong as the quadriceps; a ratio of 0.67 or

67%.[166] Others suggest this ratio can range from 50-80% depending on the speed of isokinetic testing.[258] Previous studies on dancers found that this population had optimal ratios. These ratios ranged from 0.59 to 0.67 in male professional dancers.[31,59] The H:Q strength ratios for female professional ballet dancers included 0.55, 0.68, and 0.69.[31,52,59] Female collegiate dancers were reported to have a H:Q ratio of 0.59.[52] With the exception of the dancers in the study by Hamilton et al., both the professional and collegiate groups had slightly lower ratios than previously reported (professional ratio 0.58, collegiate ratio 0.54). The males within both groups had more favorable ratios than the females (male professional 0.60, male collegiate 0.57, and female professional 0.55, female collegiate 0.54). Overall the dancers had better H:Q ratios than those reported for collegiate athletes tested at the same speed. Rosene, et al., reported the average H:Q of male and female soccer, softball, volleyball, and basketball athletes to be 0.50. The ratios ranged from 0.47 to 0.55 in the different athlete groups, with softball having the lowest H:Q ratio and basketball the highest.[258]

In summary, professional dancers have significantly stronger knee flexion than collegiate dancers. Professional dancers may have a clinically meaningful increased strength in knee extension compared to collegiate dancers, however it was not found to be statistically significant. Because of these differences, it is recommended that professional and collegiate dancers be considered separately in making clinical judgments and conducting research. Professional male dancers appear to be strongest, followed by professional females, who are similar to collegiate females. Collegiate males have the lowest thigh muscular strength in relation to the other groups. This group, especially, may benefit from thigh strengthening. All dancers seem to have good balance, of thigh muscular strength, although it could still be improved for better performance and injury prevention. Overall, professional dancers and collegiate female dancers may be stronger than previously reported, and they may not be as different from other athletes as previously thought. However, if the strength of dancers is adequate to meet dancing demands and prevent injury is unknown.

5.1.2.4 Ankle Strength

The hypothesis that professional dancers would have stronger ankle musculature was not supported. No significant differences were found between professional and collegiate dancers for ankle inversion or eversion strength. For ankle inversion the professional dancers were 4.04 kg % BM stronger, and for ankle eversion they were 2.68 kg % BM stronger. The effect sizes were 0.51 for inversion and 0.42 for eversion. The same is true when comparing within genders. The male professional dancers had 4.5 and 2.11 kg % BW more strength for ankle inversion and eversion respectively with effect 0.21 (non-parametric) and 0.48 (parametric). Within the female dancers, professional dancers had 3.79 kg % BM more ankle inversion strength and 3.11 kg % with effect sizes of 0.49 and 0.42 respectively. There may be a small clinically meaningful difference between the professional and collegiate dancer's ankle muscular strength, however it is less pronounced than in other muscle groups. In regard to muscle balance on the ankle musculature, there was no difference between professional and collegiate dance groups for eversion/inversion strength ratio. The eversion/inversion ratios are both approximately 0.90. This demonstrates good muscle balance as the ankle inverters are expected to be slightly stronger than the ankle evertors.[259,260] Overall, the results indicate no difference in ankle strength between professional and collegiate dancers.

An interesting observation from the ankle strength results is that in addition to a lack of difference between professional and collegiate dancers, there is an apparent lack of strength difference between male and female dancers. For ankle inversion and eversion, all groups and gender subgroups appear very similar. Within the professional dancers, there is approximately a 1-2 kg % BM difference with males being stronger in ankle inversion, and a negligible difference of only a few decimals for ankle eversion. Within the collegiate dancers there is a 1-2 kg % BM difference with males being slightly stronger for both ankle inversion and eversion. This lack of gender difference may be because female dancers train and perform *en pointé*.[1] The increased amount of time spent dancing on the tips of their toes (wearing specialized shoes) may have contributed to female dancers developing strength similar to males.

To the author's knowledge, no other studies have looked at ankle inversion and eversion muscular strength in dancers. Some have looked at isokinetic ankle dorsiflexion and plantar flexion strength.[58,59] A study by Hamilton et al., found the ankle plantar and dorsiflexion strength to be sufficient compared to normal, as well as having good muscle balance/strength ratio.[59] The findings of the current study are supported by Liederbach et al., who found that dancers had lower strength values than expected when compared to controls. They thought that dancers should have higher dorsi and plantar flexion strength than controls due to the high demand on the ankle musculature in dance.[58] Furthermore, they found that there was an imbalance between the dorsi and plantar flexors, with the dorsiflexors being much weaker. It was proposed that along with loss of dorsiflexion ROM, the weakness of dorsiflexors and inverters may be related to the high amount of ankle injuries in dancers.[58] Because of this, and the relationship between ankle inversion and eversion ankle strength with ankle pathology proposed by Ritter et al., it was considered most important to investigate the strength of the medial and lateral ankle musculature.[168]

When comparing the professional and collegiate dancers in this study to other athletes, they appear to be similar to soccer players. Using the same testing methods as the current study, Division I soccer players were found to have ankle inversion strength of 29.90 ± 6.49 kg % BM and ankle eversion strength of 29.05 ± 5.47 kg % BM.[256] The ankle strength of the soccer players was also similar to the dancers in that there was no apparent gender difference. The strength of the male soccer players was 30.08 ± 6.69 kg % BM for ankle inversion and 28.98 ± 5.58 kg % BM for ankle eversion. The strength of the female soccer players was 29.73 ± 6.38 and 29.11 ± 5.42 kg % BM for ankle inversion and eversion respectively.[256] The ankle inversion strength of these soccer players was in-between the inversion strength of the professional and collegiate dancers. The soccer players' ankle eversion strength, however, was slightly higher than both groups of dancers (Table 11). These results and comparisons suggest that dancers have similar ankle strength compared to other athletes. However, given that dancing places a high demand on the ankle it may be expected that dancers should have greater strength of their ankle musculature than other athletes.[1,58]

In summary, this study presents a new descriptive overview of ankle inversion and eversion strength in professional and collegiate dancers. Unlike most other body regions (trunk extension and flexion, all hip muscle groups, and knee flexion), there are no strength differences between the groups. Furthermore, both groups of dancers have similar ankle inversion and eversion strength to collegiate soccer players. Because dancers likely require a high amount of ankle strength, the fact that professional dancers are not stronger than collegiate dancers or other athletes may be of concern. The ankle and foot regions are where dancers sustain most of their injuries, so this may be an area where they need more strength.[4] Future research should seek to find the true strength demands of dancing, if dancers have adequate strength to meet these demands, and the relationship between strength and injury in dancers.

5.1.3 Dynamic Postural Stability

The hypothesis that professional ballet dancers would have better dynamic postural stability than collegiate dancers was not supported. No differences were found between the groups for the overall score (DPSI), mediolateral component score (MLSI), anteroposterior component score (APSI), or vertical component score (VSI). No differences were observed within genders between the two groups. The professional dancers had 0.0016 higher DPSI scores, 0.0034 higher MLSI, 0.0016 lower APSI, and .0019 higher VSI scores. The effect sizes were small to medium for DPSI, MLSI, APSI, and VSI, being 0.15, 0.50, 0.11, and 0.19 respectively. There is not any statistically significant, or likely clinically meaningful difference between the groups.

Little research has been done on the dynamic postural stability of dancers, and to the authors knowledge, none have used the same task and stability calculation. Comparing to the same dynamic postural stability task, the dancers performed similar to healthy male and female recreationally active individuals, with an average DPSI score of 0.348 ± 0.035.[221] In other literature using the same dynamic postural stability task and calculation as the present study, more information is available for male subjects. Both professional and collegiate male dancers performed similarly or slightly worse than professional rugby players who had scores as follows: DPSI = 0.32 ± 0.03, MLSI = 0.03 ± 0.01, APSI = 0.12 ± 0.01, VSI = 0.29 ± 0.04.[261] The male dancers also performed worse than male Army soldiers who had scores as follows: DPSI = 0.324 ± 0.041, MLSI = 0.025 ± 0.006, APSI = 0.119 ± 0.011, VSI = 0.299 ± 0.041.[262] These comparisons, however, should be interpreted with caution because the dancers performed the dynamic task without shoes on, and all of the subjects in the other studies performed the task wearing athletic shoes. The primary purpose of the current study was to describe and compare dancers who do not perform their activity wearing athletic shoes. Therefore it was more relevant to have the dancers perform the task without shoes. Zech, et al., found that runners had significantly worse dynamic balance during barefoot compared to shod conditions.[263] If dancers performed the task with shoes on they may have done better, or the other groups without shoes on may have done worse. If this were the case, the suspicion that dancers would have better dynamic postural stability may be true. The difference between dancers and other groups should be investigated with all subjects being tested with the same testing conditions.

The finding that professional dancers did not have better postural stability than collegiate dancers was not expected. Even though statistically differences were not found, the professional dancers had worse postural stability in most of the dynamic postural stability scores. This is in opposition to previous literature. Rein, et al., had found professional dancers to have better static postural stability than amateur dancers and healthy controls while standing on both feet, the right foot and the left foot, when assessed with stability index scores.[7] The findings of the present study may support what was previous found by Rein, et al., in that the professional dancers had better stability in the anteroposterior direction (although not statistically significant). Rein et al., found that the professional dancers balanced predominantly in the anteroposterior portions of their feet, as opposed to the mediolateral portion used by the amateur dancers.[7]

The SEM for the DPSI is 0.01, and all of the differences were to the hundredth of a decimal. It may also be that the DPSI and component scores do not adequately describe complex strategies used to maintain postural stability. Schmit, et al., studied dancers and track athletes and found that there were no differences in static postural stability between the groups with traditional variability measures, similar to the DPSI. However, when they used analyses to describe dynamic patterns of postural sway, including recurrence, maxline stability, entropy, and absolute trends in the force plate data, they found that dancers did in fact have superior postural stability.[70] This suggests that the way in which dancers maintain postural stability is more complex than described with traditional linear methods. This may prove to be even more important when dynamic tasks, as opposed to static tasks, are being performed. Future research investigating the difference between professional and collegiate dancers should utilize variables which describe the dynamic patterns used to maintain postural stability. Furthermore, the clinical significance of dynamic postural stability ability in relation to dance performance, successful task completion and injury should be investigated.

5.1.4 Biomechanics

Overall, very few differences were found in the landing kinematics of professional and collegiate dancers. This indicates that at most joints, professional and collegiate dancers have similar landing patterns. A small number of significant differences were found between groups overall, as well as within genders between the two groups, which could be because of chance It is also possible that these few differences indicate areas where professional collegiate dancers have differences in landing patterns, despite being similar in most other areas. A statistically significant difference was found between the professional dancers and the collegiate dancers for lateral flexion of the pelvis at initial contact, with professional dancers having 2.5 degrees less lateral flexion. These values indicate that the professional dancers had less lateral tilt of their pelvises. The effect size is 0.55. Professional dancers may land with slightly less lateral tilt of their pelvis.

A few statistically significant differences were also found between groups when comparing across genders. Female professional dancers were found to have 3.77 degrees less plantar flexion of the forefoot relative to the rearfoot at initial contact than female collegiate dancers. The effect size is 0.20 and it cannot be certain that there is any great magnitude of difference between the females in each group. Female professional dancers were found to have 6.60 degrees less inversion than female collegiate dancers with an effect size of 0.76. Finally, a statistically significant difference was found between females in each group for maximum pelvis rotation. Female professional dancers had 5.67 degrees less pelvis rotation than collegiate dancers. This is potentially indicative of better mechanics, as the desired aesthetic and theoretically less risky movement pattern would be the keep the pelvis closer to a neutral position. The difference in the pelvis rotation of females had an effect size of 0.73. One difference was found when comparing males between groups for lateral flexion of the pelvis at initial contact (-2.52 ± 4.69 vs 2.62 ± 3.95), indicating that the male dancers in each group had a small amount of tilt but in opposite directions.

One of the reasons why this study may not have found differences between professional and collegiate dancers is that the kinematic variables look at the angle at a single point during the jump. At initial contact, this method would be appropriate to accurately define the position at that point in time. The fact that professional dancers and collegiate dancers display similar kinematics at initial contact is likely an important finding. However, finding the absolute maximum angle at a specific joint in a given direction may not be the best way to most accurately describe kinematic patterns that are important. For example, dancers have an average maximum knee angle in the frontal plane of varus. This was observed in both male and female dancers. This places dancers, as a group, into a category of athletes who do not land with a risky knee position of valgus, as traditionally described. Variables that describe excursions of motion in the different planes may be more useful. A dancer that moves through both varus and valgus positions during landing may be more at risk than those who stay more consistently in a varus position. It is also possible that the phase of the jump where a potential injurious movement occurs could also be important. For example, if increased valgus occurred during the weight acceptance phase versus the take-off phase of jumping, it could potentially be important. Looking at kinematics variable, which describe patterns of movement, may identify differences between groups.

There are other potential limitations of the current methodology. One is that the speed at which the dancers completed the dance jump task was not controlled. Other studies investigating biomechanics during dance movements had controlled for speed and timing by using music or a metronome.[264,265] If this has been incorporated it would have been more similar to a real dance situation, allowing all dancers to be compared equally. Another limitation is that the study did not control for jump height. Dancers who jumped higher may potentially display different landing kinematics from those who did not jump as high. However, it is not common for jump height to be specified during dance performance. Different dancers performing the same dance steps will self-select how high they jump, which is accurately reflected in the way the dancers performed the task for this study. Though controlling for jump height, if it had been based on dancer height, would have allowed each dancer to be compared equally, it does not represent what actually occurs during dance activity. By allowing dancers to perform the jump task in their usual way, a true representation of how each individual usually jumped and landed was likely achieved.

Although this study found no major differences in landing kinematics of professional and collegiate dancers, it does provide a thorough description of landing a dance jump task; the forward *grand jeté*. Since minimal differences were found between groups, a summary description of the landing positions will be summarized with both groups together. The summary will progress from the top to the bottom of the kinetic chain, for positions at initial contact and then maximum angles during landing. At initial contact dancers landed with a very upright position of the torso. The trunk segment was in approximately zero to two degrees of extension, less than one degree of lateral flexion, and no greater than five degrees of internal rotation. At the pelvis, dancers had approximately fifteen degrees of anterior pelvic tilt, zero to three degrees of lateral flexion, and twenty eight to thirty two degrees of rotation. At initial contact dancers had approximately forty one degrees of hip flexion, twenty one degrees of hip abduction, and sixteen to twenty degrees of external rotation. The dancers' knee position was in approximately fifteen degrees of flexion, five degrees of varus, and two degrees of internal rotation at initial contact. At initial contact the ankle was found to have an approximate position of thirty eight to forty two degrees of plantar flexion, one degree of eversion, and eighteen to twenty two degrees of rotation. The position of the foot, defined by the position of the forefoot relative to the rearfoot, was in approximately twenty degrees of plantar flexion, three degrees of inversion, and zero degrees of rotation.

To summarize the maximum joint angles during landing, the dancers' average maximum trunk position was approximately four to six degrees of flexion, zero degrees of lateral flexion, and six to ten degrees of rotation internal rotation. At the pelvis, dancers' maximum position was approximately twelve to fifteen degrees of anterior pelvis tilt, one to two degrees of lateral flexion, and twenty three to twenty nine degrees internal rotation. The maximum angles at the hip were approximately fifty two to fifty nine degrees of flexion, twenty to twenty three degrees of hip abduction, and ten to fourteen degrees of external rotation. At the knee the maximum positon of flexion was approximately fifty two degrees, two to three degrees of varus, and three to ten degrees of internal rotation. For the ankle, the average amount of flexion was approximately eleven to twenty seven degrees of plantar flexion, eight to nine degrees of inversion, and twenty degrees of rotation. It is interesting to note that although the difference in ankle flexion in the sagittal place was not found to be statistically significant there is a large difference between the groups. The maximum value achieved during landing was in a great deal of plantar flexion for the professional group, and much closer to dorsiflexion for the collegiate group. This may indicate a potential difference in landing pattern of the group that may be better described by looking at the pattern of motion or excursion. The likely pattern is that collegiate dancers move through full dorsiflexion, and potentially greater dorsiflexion, than professional dancers. Professional dancers tend to stay in a more plantar flexed position, on the balls of their feet with heels not touching the ground, during landing than the collegiate dancers. For the position of the foot, defined by the relative positions of the rearfoot and forefoot, dancers' displayed approximately twenty four to twenty six degrees of plantar flexion, zero to one degree of inversion, and three degrees of rotation into pronation.

5.1.5 Self-Reported Injury History

Our hypothesis that there would be a higher proportion of professional dancers with self-reported injuries for their total injury history was not supported. A high proportion of injured subjects were found for total history in professional and collegiate dancer groups; at 93.3% and 93.1% respectively. One study found that 47% of dancers surveyed reported having a performance limiting injury in their lifetime.[266] Previous studies have not often reported on the total injury history of dancers. This study supports a generally accepted assumption that most dancers have had, or will sustain an injury, at some point in their career. This assumption is based on the observation that there is a high injury incidence in companies and groups of dancers each year. In our study the proportion of injured dancers in the past one year was not different between groups. The proportion of injured subjects was 56.7% in the professional dancers and 55.3% in the collegiate dancers. This percentage is lower than what was expected for the professional group, in which previous studies have reported the percentage of dancers injured in a one year period to range from 67% to 95%.[6,15-19] In a previous study on collegiate dancers, 62% reported having an injury in the past year that affected their dancing.[5]

Differences between studies are likely due to the variety of injury definitions used. The definition used in the current study is consistent with that used by Allen et al. who followed the recommendations of the NCAA, and includes injuries that prevented full participation in dance activity for at least one day after the injury occurred.[20] These are in accordance with a time loss definition supported by Liederbach et al. However according to these recommendations of the IADMS Standard Measures Conesus, some of the injuries included in the Allen study and the present study would be considered musculoskeletal complaints rather than injuries.[267] The difference in definition allows injuries that prevent the dancer from participating fully, for example not being able to jump or needing to modify their movements based on recommendations of their health care provider. The later definition would only include injuries that kept the dancer out of all dance activities. The concern is that this definition does not accurately encompass all musculoskeletal injuries, especially in a performance environment where dancers need to participate as much as possible to meet artistic demands of their occupation. The current definition is supported by the Dance USA Task Force on Dancer Health. They recently reported data from eight professional dance companies using the same definition and because it was felt that an injury or complaint that prevented full participation in activity was significant enough to consider as time loss, even if the dancer was able to do some dance activity.[268]

Our study refutes a previous suggestion that collegiate dancers may sustain less injuries because they spend less time dancing.[107] The professional dancers reported that they spent an average of 8.19 hours in class and 23.67 hours in rehearsal each week. The collegiate dancers reported that they spent 18.07 hours in class and 9.06 hours in rehearsal each week. We were unable to account for the amount of time in performance. Galbratith at al., recently reported that most injuries in professional dancers were sustained in class and rehearsal rather than performance, so it is likely this study was able to capture most injuries.[268] The study by Galbraith at al., did not include collegiate dancers so it is unknown if collegiate dancers would follow the same pattern in the dance activity where they are most often injured. The finding that collegiate dancers in this study spent less time dancing, but still experience the same amount of injuries may be explained by an underutilization of or lack of health care resources. Another study of dancers at a collegiate institution found the proportion of dancers who reported being injured was higher than clinical chart reviews.[54] Anecdotally, some of the collegiate dancers voluntarily reported not feeling comfortable accessing the health care provided on site at their university, without any questioning about the topic. The other two universities where collegiate dancers were recruited from do not have any on site health care. Collegiate dancers may have difficulty accessing health care when services are not provided at their university because of out of network health care coverage policies if they are not attending school in their home area. Of the professional dancers in the study, the ones from Pittsburgh Ballet Theater do have on site care on a daily basis. The dancers in the other companies do not. However, they would likely have personal health insurance that could be used in the area where they live and work. These reasons all warrant consideration and formal investigation in future studies. Collegiate dancers may potentially be an underserved population in the dance community. Lack of service and barriers to accessing service could be investigated further to help reduce injury and improve care in collegiate dancers.

When examining the injury locations this study found that similar proportions of subjects reporting injuries at various anatomical regions including the neck, upper back, lower back, hip, thigh, knee, and the calf and shin in each group. The proportions of subjects with injuries at each region is consistent with what has previously been reported.[4] Professional and collegiate dancers sustain injuries to similar body parts. The basic demands of dance may be similar, and both groups are skeletally mature, leading the areas injured to be different than in children and adolescent dancers.[14,25,105,106] In the present study the only differences found between groups were at the ankle and the foot and toe regions. Professional dancers reported higher numbers of injuries to these last two regions than collegiate dancers in their total injury history, but not their past one year injury history.

The proportion of professional dancers reporting ankle, and foot and toe injuries was higher, and may be because of a potentially higher demand put on the ankle, foot and toes in ballet. This may also be because of the foot type required or desired in classical ballet. A high arched foot with increased plantar flexion ability is desired for ballet dancers, as well as being more prevalent in this population compared to controls.[269] In young dancers inadequate plantar flexion is a risk factor for future injury, likely because it is needed for ballet.[25] However, dancers who have inadequate plantar flexion are unlikely to have advanced to the professional level.[59,269] Because this foot type is so prevalent in professional dancers, especially females, it is difficult to tell if it leads to increased injury. The collegiate dance culture may be more accepting of a foot type with less extreme plantar flexion. It may also be that female professional ballet dancers are spending more time dancing in *pointé* shoes than female collegiate dancers. Although time in *pointé* shoes was not collected as a variable, female professional ballet dancers likely spending a majority of their time doing classical ballet requiring *pointé* shoes and performing the corresponding dance steps on *pointé*. Collegiate dancers spend a more equal time in ballet, modern and jazz dance activities. The latter of which do not require *pointé* work. Another explanation as to why a greater proportion of the professional dancers sustained injuries to their ankle and foot/toe regions is that they have a higher demand but no increased strength of their ankle musculature. There was no significant difference between the ankle strength of the two groups.

5.2 REGRESSION ANALYSES OF THE ABILITY OF MUSCULAR STRENGTH TO PREDICT DYNAMIC POSTURAL STABILITY AND LANDING KINEMATICS

5.2.1 Strength Predictors of Dynamic Postural Stability

This study found significant predictors of DPSI in professional and collegiate dancers. The final regression model for DPSI score (Hypothesis 2a) was significant and included gender, group, and trunk rotation strength (Table 35). Together these variables explained approximately 26% of the variance in DPSI score. Being a female dancer predicted a lower and better DPSI score by 0.0236. Group, which was forced into the model, was not a significant predictor within the model. This indicates that professional dancers do not have better balance than collegiate dancers, which is supported by the between group comparisons presented in earlier sections of this dissertation. Having stronger trunk rotation was a significant predictor in the model. The result that increased trunk rotation strength is associated with a higher, and worse DPSI score was unexpected. The final model found that DPSI score increased 0.0003 for every one NM % BW increase in trunk rotation strength. This coefficient for trunk rotation strength is very small, making it difficult to determine the clinical meaningfulness of this result. However, this unexpected finding warrants further investigation.

To the author's knowledge, no studies have investigated or have had findings indicating a gender difference in postural stability of dancers. This is largely due to the fact that most studies have used only female dancers. Those that have used males, had small sample sizes (five males and five females) and did not present data by gender. Studies investigating gender differences in postural stability in other populations have had differing results. Similar to this present study, Allison, et al., found that female Army soldiers had better static postural stability.[255] However, it may be important to compare static and dynamic tasks separately. Wikstrom, et al., investigated dynamic postural stability in males and females using a similar task and same calculation of score as the current study. They found that male subjects had significantly better DPSI scores.[270] All subjects in this study were healthy and injury free, however, no information was provided regarding their athletic ability or sport participation. It is unknown if this would influence the subjects' dynamic postural stability performance if there was a difference in athletic ability between the groups. When athletic ability is considered, results seem to be similar to the present study in that female subjects appear to have better dynamic postural stability than males. Dallinga, et al., recently found that female athletes had better DPSI scores than male athletes, including volleyball, basketball and korfball players.[271] The subjects in this study performed a similar jump task to the dancers in the current study, and a similar calculation of DPSI was used.

This regression model shows that being a female dancer predicts a better (lower) DPSI score. Although the potential interaction with gender and strength variables when both genders are included in the regression model could hinder the ability to identify meaningful predictors of DPSI score, the finding that female dancers have better postural stability is novel. In the initial regression, which included all dancers, trunk rotation strength may have been included in the model because male dancers, who have worse DPSI scores, are stronger than female dancers. Bivariate analysis revealed that all strength variables had small positive significant correlations with DPSI score. With the simple linear regressions, all of the strength variables were found to be significant predictors. Trunk rotation strength had the highest R^2 value, accounting for 16.85% of the variance in DPSI score. The other strength variables accounted for 8 to 10% of the variance of DPSI score in simple linear regression. It is interesting to note that for all of strength variables, higher strength predicted a higher and worse DPSI score. Furthermore, for trunk rotation strength, the male professional dancers were much stronger in comparison to female professional dancers and both male and female collegiate dancers. For this strength variable female professional dancers had the lowest strength values.

Due to the possibility of interactions between strength variables and gender (Figure 15), separate regressions for strength predictors of DPSI score in male and female dancers were completed. In male dancers no significant model was found with multiple linear regression. Furthermore, no significant correlations or relationships with simple linear regressions were found between strength and DPSI score in male dancers. The ability to find significant results within the male group may have been limited by sample size, as only 23 male dancers were included in the analyses. In the female dancers, a multiple linear regression found that approximately 26% of the variance in DPSI score could be explained by group, trunk rotation strength, and knee flexion strength. In this model only the strength variables were significant, and not group. This indicates that the level of dancer, (professional verses collegiate) was not important in predicting DPSI score; the same as in the model including both genders, and as supported by the between group comparisons. The result that stronger trunk rotation predicted worse DPSI performance remained in the female only regression, indicating that for this variable the interaction with gender may not be important. The finding that increased knee flexion strength predicted better DPSI score is what would be expected. With correlation and simple linear regression, trunk rotation strength had the only significant relationship with DPSI score.

The finding that increased strength would significantly predict a worse DPSI score was not expected based on clinical judgement, and found in both the combined gender model and the female only model. However, because this unexpected finding holds true in regression separated by gender, there is evidence that the finding is true and not related to interaction between strength variables and gender. There is evidence however, of this result in another population. To the author's knowledge, only one previous study has looked at the ability of strength to predict DPSI score. The author of this dissertation and their colleagues, found that a model including knee extension, knee flexion, ankle inversion and ankle eversion strength, and ankle dorsiflexion significantly predicted approximately 19% of the variance in DPSI score in a group of male Army soldiers.[272] Within the multiple linear model, only the strength predictors were significant. In this study, it was also observed that increased strength of some variables increased DPSI score, while others decreased DPSI score. In the model knee extension strength and ankle eversion strength increased DPSI score, while knee flexion strength and ankle inversion strength decreased DPSI score. In this study, none of the strength variables were significant predictors with simple linear regressions.[272] This study only included male subjects, whereas the current study included subjects of both genders. However, both indicate that the relationship between strength and dynamic postural stability is complex, and does not necessarily follow the hypothesis that better performance in one domain predicts better performance in another.

The relationship revealed that increased strength of some variables is related to worse DPSI score is interesting and unexpected. Both increased strength and increased dynamic postural stability are important for dancers, but better performance in one does not indicate better performance in the other. The finding could potentially be explained by other factors not examined in this study. DPSI incorporates motion variability in all directions normalized to body weight. However, it could be influenced by a very high or low variability in one direction affecting the score. Further analyses could include regression for each component score (MLSI, APSI, VSI) separately. Non-linear analyses of dynamic postural stability could also be used as the outcome variable. It is possible that stronger dancers use different patterns to maintain postural stability. Calculation of DPSI does not include a component for how high the subjects jump. The jump task for dynamic postural stability standardized minimum jump height, but not maximum jump. Subjects who jump higher may have different DPSI scores, and maybe this is related to their strength. Incorporation or simultaneous collection of jump height during the jump task could be included in future studies to see if it explains the results. More subjects are needed for regressions investigating genders separately, for adequate power. Also, these analyses should be conducted in other populations, including both genders, to see if the relationships between strength and DPSI score hold true. There could also be another extraneous confounding variable, which has not been determined at this time.

In summary, it appears that gender is an important factor is predicting dynamic postural stability in dancers. Female dancers have better postural stability that males dancers, which is also seen in other groups of athletes.[255,271] Finding strength predictors of dynamic postural stability within each genders would be important. Other variables to explain the finding that increased strength was associated with higher DPSI score should be explored in future studies. Future studies should also investigate the ability of the DPSI score to predict injury, or look at the influence of previous injury on performance.

5.2.2 Strength Predictors of Knee Valgus during Landing of a Dance Jump

No significant model was found for predicting knee valgus angle at initial contact (Hypothesis 3c). However, a significant model was found for predicting maximum knee valgus angle during landing (Hypothesis 3d). Gender, group, hip external rotation strength and knee flexion strength were found to be significant predictors of maximum knee valgus angle and accounted for approximately 26% of the variance in maximum valgus angle. It is important to note that for both angle at initial contact and maximum angle during landing, the average of all dancers was in a position of varus rather than valgus. Negative angles represent valgus positive angles varus. At initial contact the average joint knee position in degrees the frontal plane was 5.01 ± 4.12 and ranged from -2.50 to 14.27 degrees. The average maximum angle of valgus for all dancers was 2.41 ± 6.66 and ranged from -11.20 to 23.45 degrees. Even when stratified by gender the average remained in slight varus. It may be that no significant model identified predictors of knee valgus angle at initial contact was found because dancers do not land with a great deal of valgus. Significant predictors of maximum knee valgus may have been found because more valgus was observed for that variable. Dancers do not tend to land with a great degree of valgus, which is supported by previous literature on other jumping tasks, although this study did demonstrate gender differences identified by the regression for maximum valgus angle when previous studies did not.[2,3]

In the final multiple linear regression gender and knee flexion strength were significant predictors of maximum knee valgus. Female gender increased knee valgus by 6.7965 degrees. The task used in this study may have been important in identifying influence of gender, because the drop landing task used in previous work may not have been difficult or specific enough to dance activity to elicit knee valgus in female dancers.[2] Another interesting finding from this regression analysis is that increased knee flexion strength increased maximum knee valgus angle by 0.0894 degrees. This was surprising because it was expected that increased strength for any muscle group would predict less knee valgus. The influence of knee flexion strength on maximum valgus angle is very small. Further investigation into the meaningfulness of this small amount of change and potential interaction of variables in warranted, because even though only knee flexion strength was significant, hip external rotation strength was also included in the model. Future regression in separate genders could help find the most important strength predictors specific to each. The preliminary analyses performed to check for interaction of strength and gender did not elicit any significant models. This may be due to inadequate sample sizes when stratified by gender. When observing the models, however, the finding of a negative constant value for knee flexion remains in both genders, as well as in the bivariate analyses for both genders. Therefore, the unexpected finding is not likely due to an interaction of strength and gender.

The unexpected finding with knee flexion is similar to the findings of the present study for DPSI score. Increased strength is associated with outcomes thought to increase injury risk; increased DPSI score and increased maximum knee valgus. These findings are likely indicative of some other performance variable not looked at in the present study. It may be that those with higher strength are jumping differently. Dancers in this study were asked to perform what they felt was their typical forward *grand jeté*, and therefore self-selected their jump height. This accurately represents what occurs in dance activities. Potentially, stronger dancers may jump higher and land with more valgus. This variable could be explored in future analyses. Also, even the lowest knee valgus angle observed, -11.20 degrees in a female dancer, is higher than the valgus angles observed on the injured limbs of female athletes who went on to sustain ACL injury (approximately 20 degrees of valgus).[88] The amount of valgus that is important in predicting other types of knee injuries and pain is needed to determine the degree of valgus that may lead to non-traumatic overuse problems, which are more common in dancers than traumatic injures such as ACL tears.[4,16,20,82,109]

One other study has looked at the ability of lower extremity strength to predict knee valgus during landing in an adult population. In a recent dissertation study, Heebner reported that peak knee extension and flexion strength did not predict knee valgus angle at initial contact or peak knee valgus with correlation, simple linear regression, or as variables in multiple regression in female active adults.[273] This study is similar to the current study in that knee extension and flexion strength was not important for prediction of knee valgus at initial contact. The study by Heebner is different in that they did not find knee flexion strength to be an important variable in predicting maximum knee valgus as a part of a multiple linear analysis. This difference may be because the study by Heebner did not include other strength variables, but potentially knee flexion strength is important when interacting with the strength of other lower extremity musculature like the hip. Heebner included knee strength with other sensorimotor characteristics including proprioception.[273] Also, Heebner tested isokinetic strength at a much higher speed (240 degrees per second). While this speed is closer to the speed at which athletic activity occurs, it may be too fast to allow the subjects to exert a maximal force indicative of their overall strength.[273] Heebner studied active females. Potentially strength is important in dancers but not this other population. The task in Heebner's study was normalized to maximum vertical jump height, but was a double leg rather than a single leg landing.[273] Difference in task could also potentially explain the differences between the studies.

Other studies have also investigated the ability of strength to predict knee valgus during non-jumping tasks. Akins et al., investigated the ability of lower extremity strength and dynamic postural stability to predict maximum knee valgus and found no significant predictors.[261] This only investigated knee valgus angle at initial contact during landing a single leg drop landing and is similar to the present study in that no strength predictors were identified. Three of the same variables were included in the regressions; knee extension, knee flexion and hip abduction strength.[261] The findings of Akins et al., for maximum knee valgus angle are dissimilar to the present study. They did not find any significant strength predictors of maximum knee valgus angle in elite male rugby players, who may have different abilities than the dancers in the current study.[261] Similarly, Sigward et al., studied young female soccer players during a single leg squat task and did not find any significant strength predictors of maximum knee valgus.[274] Both of these studies investigated maximum angles during a single leg squat rather than a jumping or landing task, which may elicit different degrees of valgus and have a different relationship with strength.

One study that did identify a relationship between strength and knee valgus was performed by Claiborne et al., who investigated valgus during a single leg squat.[275] Claiborne also studied adult male and female subjects, who were healthy but not specified as athletes. In this study, increased knee strength was identified as the only significant predictor in a multiple linear model that also included hip rotation and abduction strength. These findings were opposite of the present study in that increased strength was associated with less knee valgus.[275] The difference in outcome may be explained by the task used. A single leg squat may have different requirements than a jumping and landing task. This difference may also potentially be explained by the knee valgus variable used. Claiborne et al., used an excursion variable whereas the present study used a peak variable.[275] Excursion would explain the amount of motion into the valgus directions, where finding the maximum value describes a single point in time. It is possible that stronger dancers achieve a degree of greater valgus, but it is unknown if their excursion into valgus, or total movement variability at the knee is also greater. Other types of non-linear analyses may also provide insight into landing patterns of stronger verses weaker dancers and could be included in future studies.

5.2.3 Strength Predictors of Ankle Inversion during Landing of a Dance Jump

This study found significant predictors of ankle inversion angle at initial contact, and maximum inversion angle, in professional ballet and collegiate dancers. The final regression model for ankle inversion angle at initial contact (Hypothesis 3c) was significant and included gender, group, knee extension strength, knee flexion strength, ankle inversion strength, and ankle eversion strength and explained approximately 22% of the variance in ankle inversion angle at initial contact. The only significant variables in the model for ankle inversion angle at initial contact were gender and knee extension strength. Being a female dancer increased the inversion angle at initial contact by 5.0722 degrees. Greater knee extension strength increased the angle of inversion by 0.0838 degrees. Interestingly, some muscular strength variables had positive constant values, and some had negative. Perhaps this effect of muscular strength variables could be better explained by using strength ratios which reflect muscle balance. Future analyses could be done using strength ratios as muscle strength independent variables. For maximum ankle inversion angle, the final model was significant (Hypothesis 3d) and included gender, group and knee flexion strength and explained approximately 18% of the variance in ankle maximum inversion angle. In this model gender and knee flexion strength were significant predictors. Being a female dancer increased maximum inversion angle by 8.2021 degrees. Knee flexion strength increased maximum ankle inversion angle 0.1364 degrees for every one NM % BM. Interestingly, increased knee flexion strength increased maximum inversion angle, whereas it decreased the angle in the model for inversion at initial contact, although it was not a significant predictor in the first model.

Further investigation into the amount of ankle inversion, and when during landing risk for injury occurs is needed to better understand the relationships among strength and joint position. The finding that females land with greater inversion angle, and that increased knee strength increases inversion angle is interesting and somewhat unexpected because the original hypothesis was that increased inversion would be a risk factor for injury. Increased inversion was chosen because it could potentially lead to an ankle sprain.[94,95] However, some ankle inversion is excepted as it is a part of normal landing kinematics. Other studies of dancers landing kinematics have reported a position of inversion at initial contact, ranging from approximately 5 to 12 degrees of inversion depending on the study.[100,276] At initial contact the dancers in the current study actually had an average position of slight eversion. Ankle inversion angle at initial contact was -0.86 ± 8.64 and ranged from -19.28 to 18.68 degrees. A cadaveric study revealed that the ankle was most unstable in full plantar flexion with inversion.[277] Since the dancers in the present study landing in plantar flexion, the slight eversion may potentially be increasing the stability of ankle.

The dancers in the current study landed with less inversion at initial contact than previously reported. This could potentially be due to the landing task performed, which included a *suaté* and a *saut de chat* task.[100,276] The *suaté* task requires a much simpler position of the leg and foot and is a non-traveling task, so it may elicit a different foot position. The *saut de chat* task, however, is similar to the *grand jeté* task used in the current study. The difference in inversion angle at initial contact may be explained by the type of dancers. In the previous study by Kulig et al., pre-professional high school aged subjects were analyzed.[100] These dancers are younger and would perform at a lower level than the professional dancers and collegiate dance majors of the current study, which may explain the kinematic differences in landing. Dancer's average maximum inversion ankle was 8.43 ± 9.74 and ranged from -14.34 to 36.91 degrees. Potentially, the maximum angle is great enough to be a risk factor for injury, whereas the average is not likely so. It is possible that a non-linear relationship exists for ankle inversion and injury, where extreme excursion into either direction is problematic but some excursion into both directions is normal. More research is needed to truly determine how much, and in which direction, motion at the ankle is important as a risk factor for injury. It is unknown how much inversion, or eversion, is a risk factor for injury.

5.2.4 Strength Predictors of Foot Pronation during Landing of a Dance Jump

No significant predictors of foot pronation at initial contact or maximum angle during landing were found with multiple regression (Hypotheses 3e and 3f). The predictor variables chosen were gender, group, knee extension strength, knee flexion strength, ankle inversion strength and ankle eversion strength. None of the independent strength variables were correlated with the dependent variables, and none were significant individual predictors of variance in foot pronation with simple linear regression. Dancers did not display a large amount of pronation during the task. The axis chosen to define pronation was z axis, about which rotation occurs. At initial contact, the midfoot defined by the positon of the forefoot in relation to the rearfoot, was in a very neutral position for both the professional and collegiate groups (professional = 0.10º, collegiate = -0.42º). The maximum angle of pronation in each group were very similar and only indicate a small amount of pronation (professional = -3.25º, collegiate = -3.13º).

Other studies have investigated motion of the foot using a multi-segment foot model. Allowing a joint for the foot to be created can more accurately describe what is occurring through the many anatomical joints of the foot and are thought to most closely estimate the midfoot position.[195] The foot pronation position, defined in the transverse plane, of the dancers in this study are different than previously reported by Yan, et al., who described dancers performing a jump in second position.[276] Though they did not report angles at initial contact and maximum angle, they did provide graphs showing midfoot position as a percentage of the jump. Upon observing the graph it appears the dancers were in approximately negative five degrees of external rotation at initial contact. At initial contact this type of rotation would indicate more of the medial side of the foot (great toe) towards the floor. In the current study, the average angle at initial contact was approximately zero, indicating a neutral position of the foot. In the study by Yan, et al., the foot moved through to approximately five degrees of internal rotation (onto the lateral side of the foot), and then back to external rotation of slightly more than negative five degrees at end contact. It appears as though the negative values are slightly greater, indicated the maximum value was into external rotation [276] The maximum foot angle in the transverse plane in the current study is approximately negative three degrees, however, the phase of the jump in which the maximum foot pronation angle occurred is unknown. The differences in foot angles between the two studies may be due to differences in the jump performed. The dancers in the study by Yan, et al., performed a basic jump where the dancers' legs are fully externally rotated and abducted so that they look like an inverted "V" (see "second position" in Figure 1). The dancer will stay in one place on the floor and jump straight up and land in the same position. In the current study the dancer is moving in a forward directly and the legs would not be fully externally rotated. This difference in the plane in which the motion is performed (frontal verses sagittal) may explain differences in foot position during landing. Future research could seek to better explain potential differences in foot positions during different dance steps. Differences may also be explained by the use of different multi-segment foot models.

A reason that this study did not find any significant predictors of foot pronation at initial contact or maximum pronation angle may be that pronation is a complex motion to describe. This study chose to define pronation in the plane of rotation of the foot because it was thought that this would most closely relate to the most common plane thought to describe pronation during closed chain activity like walking, because it had previously been found that those with flat arches (more pronation) had the greatest difference from those with normal arches in the horizontal plane.[195] However, pronation does involve motion in the sagittal and frontal planes as well. In addition to the rotation of the medial foot towards the floor, as examined in this study, pronation also involves plantar flexion and eversion of forefoot relative to the rearfoot. It may be that choosing one of these other planes to investigate would have been more appropriate. Similar to the small amount of external rotation observed, the dancers' displayed a small amount of eversion, the motion in the frontal plane corresponding to pronation. The dancers in this study displayed a greater amount of maximum plantar flexion, which would correspond with pronation. This may have been a better angle to choose to describe pronation. Another potentially better way to describe pronation of the foot would be to look at the motion in all three planes together. Furthermore, it is possible that foot pronation cannot be accurately described at a single time point, as in finding the absolute maximum angle. Describing the dynamic pattern that the foot moves through during landing is likely a better way to describe foot pronation.

A significant model for predicting foot pronation may have been found if other independent strength variables had been used in the model. The strength variables included in this model were ankle inversion and eversion, as well as knee strength (extension and flexion). Ankle strength was chosen because it was thought that its primary role in moving the foot would be important to consider. Knee extension and flexion strength were chosen because they are the proximal limb musculature closest to the foot. It is possible that other proximal musculature, or combinations, could have predicted foot pronation. Future studies should look at the influence of trunk and hip strength on the model.

5.3 LIMITATIONS

This study is not without limitations. The study was adequately powered when genders were combined with equal proportions of each gender in each group. Stratification by gender allowed for a more thorough understanding of the unexpected results seen. However, when stratified by gender, analyses are not adequately powered. Therefore, this study can be generalized to the professional ballet and collegiate dance populations as a whole, but more data should be collected on specific gender subgroups. This study should not be generalized to other groups of professional dancers (modern, sport dance, hip hop, etc.), intermural collegiate dancers, recreational dancers, pre-professional, or school aged dancers. This study included dancers that were currently free of injury, and should not be generalized to dancers who are currently injured. This study does not provided information on dancers with history of specific injuries and how they may be different from others. The injury history information included all injuries that resulted in completed time loss of activity modification and should only be compared to data using the same definition.

The task used for kinematic analysis in the current study was a forward *grand jeté*. It is a dance specific task, but should not be directly compared to other studies using other tasks. Furthermore, future studies should control for the timing of the jump. Potentially, jump height should be controlled although the impact that this would have on the ability to study the dancers' usual performance should be considered. In addition to the task chosen for kinematic analyses, the variables calculated may not fully describe the biomechanics of this dance jump. The biomechanical variables do not include any kinetic variables, or kinetic variables describing excursion, variability or patterns of motion, all of which are potentially difference in professional and collegiate dancer and may also be potential risk factors for injury.

5.4 CLINICAL SIGNIFICANCE

This study thoroughly describes the physical characteristics and orthopaedic injury histories of both professional ballet and collegiate dancers, including lower extremity and trunk muscular strength, dynamic postural stability, and kinematics landing from a dance jump. Professional dancers were stronger than collegiate dancers for most variables tested. Strengthening programs may be needed, especially in collegiate dancers. Professional dancers did not have higher ankle strength than collegiate dancers, and there was a significantly greater portion of subjects with ankle, foot and toes injures in this group, indicating that the ankle may be an important area to address in professional dancers. This study found that gender was a significant predictor of dynamic postural stability, maximum knee valgus angle, and ankle inversion angle at initial contact and maximum angle during landing. Previous studies had not investigated dynamic postural stability between genders, and had not identified kinematic differences between genders. When considering these variables as indicators of performance or as injury risk factors, genders should be considered separately. This study provides insight into the relationships among variables and found that within the scope of the variables that were analyzed in this study, in general, increased strength does not indicate better performance with the neuromuscular variables.

5.5 SUGGESTIONS FOR FUTURE RESEARCH

Future research should further investigate physical characteristics of professional ballet and collegiate dancers in each gender separately. This would allow for gender comparisons within each group, as well as comparing within genders between each group. Future regression analyses should be completed in each gender separately to avoid possible interaction of independent variables with gender on the dependent variable. Future studies could also seek to find if there are differences in strength, dynamic postural stability and landing kinematics between dancers who have experienced different kinds of injuries. Furthermore, the ability of these characteristics to predict injury in prospective studies would be useful.

Future research should also seek to explain the unexpected finding that increased strength predicted worse dynamic postural stability by collecting and including other variables not currently investigated. Future work investigating the relationship between strength and neuromuscular characteristics such as dynamic postural stability and kinematics should include larger sample sizes so that additional strength variables can be included in the model. This would allow the seemingly complex relationships between strength and neuromuscular variables to be better investigated. Furthermore, the amount of motion in a given direction that increases injury risk should be further investigated.

Other outcome variables to describe dynamic postural stability and kinematics should be considered in future work. Other potential postural stability outcomes include variables describing dynamic patterns of postural sway, including recurrence, maxline stability, entropy, and absolute trends in the force plate data. The position in each plane should be considered when investigating joint position of the foot. Other variables describing kinematic data such as motion excursion and variability should be considered and may identify differences between professional ballet and collegiate dance majors. Non-linear analyses to determine if there are differences in patterns of motion between the two groups may provide more insight. Furthermore, there may be differences between groups in kinetic variables such as joint forces, moments and ground reaction force upon landing, and these could be investigated in future work.

5.6 CONCLUSIONS

The purpose of this study was to investigate differences in physical characteristics of professional ballet and collegiate dance majors. It found that professional dancers had significantly lower body fat percentages, and had significantly stronger trunk extension and flexion, hip abduction, adduction, internal and external rotation, and knee flexion strength. No differences were found between professional and collegiate dancers for trunk rotation, knee extension, ankle inversion or ankle eversion strength. The magnitude of the difference in strength variables are important to consider, and indicate that professional dancers were stronger in all tests even when statistical significance was not found. Based on the differences between these groups, it is suggested that professional and collegiate dancers be considered separately, or controlled for, in studies investigating strength. No differences were found between professional and collegiate dancers in dynamic postural stability. Only one difference was found between groups in kinematic variables during landing, therefore overall there are no differences between the groups. In general, no significant differences were found in the proportion of subjects reporting they had experienced an injury limiting their participation in dance activities, in either their total injury history or within the past one year. There was a significantly higher proportion of professional dancers who reported injury to their ankle, foot and toe regions in their total injury history, as compared to collegiate dancers.

Regression analyses revealed a novel finding that gender was a significant predictor of better dynamic postural stability. Unexpectedly, increased trunk rotation strength predicted worse dynamic postural stability in analyses of all subjects and when stratified by gender. This may indicated that better performance in one performance domain is not related to postural stability performance, and that other variables to explain this finding need to be considered in future work. Regression analyses revealed that female gender was a significant predictor of increased maximum knee valgus. Previous research had not identified a gender difference in landing kinematics, and may be explained by the use of a dance specific task in the present study.[2,3,8] An unexpected finding was that increased knee flexion strength predicted more maximum knee valgus, however no significant strength predictors or multiple linear models were found when stratified by gender. Similar to dynamic postural stability, additional variables need to be collected and considered to understand this finding and the relationship between strength and maximum knee valgus. Gender was also a significant predictor of ankle inversion at initial contact and maximum inversion angle; female dancers had increased ankle inversion. In the multiple linear regression models, increased knee extension strength predicted increased ankle inversion at initial contact, and increased knee flexion strength predicted increased maximum inversion angle, in addition to gender. The amount of inversion that is normal verses a risk factor for injury requires further investigation before these findings can be fully understood. No significant models for knee valgus angle at initial contact, foot pronation angle at initial contact or maximum foot pronation angle were identified.

APPENDIX A

Dancer Demographic, Orthopaedic Injury History and Supplemental Training Information

ID Number: _____

Date:

Date of birth (month/year): ______/

Gender: M F

Dance Background Information:

Current Dance Institution: ______________

Position in Company/year in school: _____

Years with current company/year in school: _____

Previous experience as a professional/collegiate dancer: __________________________

Years of professional/collegiate dancing:_____________________

Current Dance Activity Information:

Typical participation in dance activities (hours):
Class:_____________________________
Rehearsal:_________________________
Performance:______________________

Start date of my current season/semester (if applicable): __________________________

Numbers of weeks of my contract season(s)/semester(s):________________________________

Number of performances I have danced in so far this current dance season/semester: _______

Number of performances I have danced in the past 12 months: _______

Orthopedic History/Total Dance Career

Check "yes" or "no."

Yes	No		
☐	☐	1.	Have you ever had an injury, like a sprain, strain or any other injury that caused you to miss or modify your dance activities (class, rehearsal, performance), or that resulted in treatment from a medical professional
☐	☐	2.	Have you ever had any broken or fractured bones or dislocated joints?
☐	☐	3.	Have you ever had surgery for a dance related injury?
☐	☐	4	Have you ever been diagnosed with a stress fracture? Where?
☐	☐	5.	Have you ever sprained your ankle? ☐Right ☐Left

Please indicate what body part was affected in the boxes below

Neck	Upper Back	Lower Back	Rib/Chest	Shoulder	Elbow/Wrist/Hand
☐Right ☐Left ☐Middle	☐Right ☐Left ☐ Middle	☐Right ☐Left ☐Middle	☐Right ☐Left ☐Middle	☐Right ☐Left	☐Right ☐Left
Hip	**Thigh**	**Knee**	**Calf/shin**	**Ankle**	**Foot/Toes**
☐Right ☐Left	☐Right ☐Left	☐Right ☐Left	☐Right ☐Left	☐Right ☐Left	☐Right ☐Left

1 Year Orthopedic History/Past 12 months

Check "yes" or "no."

Yes	No		
☐	☐	1.	Have you ever had an injury, like a sprain, strain or any other injury that caused you to miss or modify your dance activities (class, rehearsal, performance), or that resulted in treatment from a medical professional

Please indicate what body part was affected in the boxes below

Neck	Upper Back	Lower Back	Rib/Chest	Shoulder	Elbow/Wrist/Hand
☐Right ☐Left ☐Middle	☐Right ☐Left ☐ Middle	☐Right ☐Left ☐Middle	☐Right ☐Left ☐Middle	☐Right ☐Left	☐Right ☐Left
Hip ☐Right ☐Left	Thigh ☐Right ☐Left	Knee ☐Right ☐Left	Calf/shin ☐Right ☐Left	Ankle ☐Right ☐Left	Foot/Toes ☐Right ☐Left

**Please indicate the type of injury to the best of your knowledge in the appropriate box for the "1Year Orthopedic History/Past 12 months". Examples are: fracture, tendinitis, bursitis, dislocation, etc.

**Please ask for help if you need when filling out this form

<u>**Supplemental Training (past 6 months)**</u>

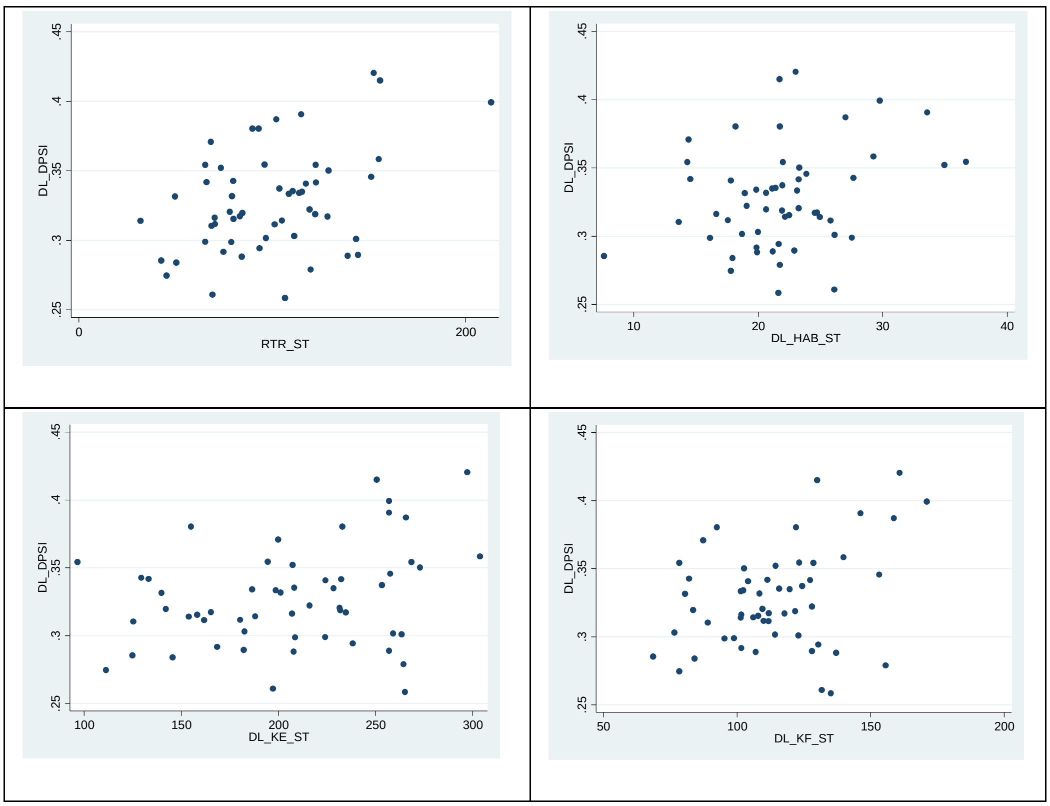
Please indicate any non-dance physical training in which you have regularly participated in during past 6 months. Please provide detail for type of training if you do a specific kind of training in the categories provided.

Type of Training	Minutes per session	Sessions per week	Weeks per month	Number of Months
<u>Pilates</u>				
<u>Gyrotonics</u>				
<u>Yoga</u>				
<u>Cardio exercise</u>				
<u>Strength/resistance Training</u>				
<u>Other (please specify)</u>				

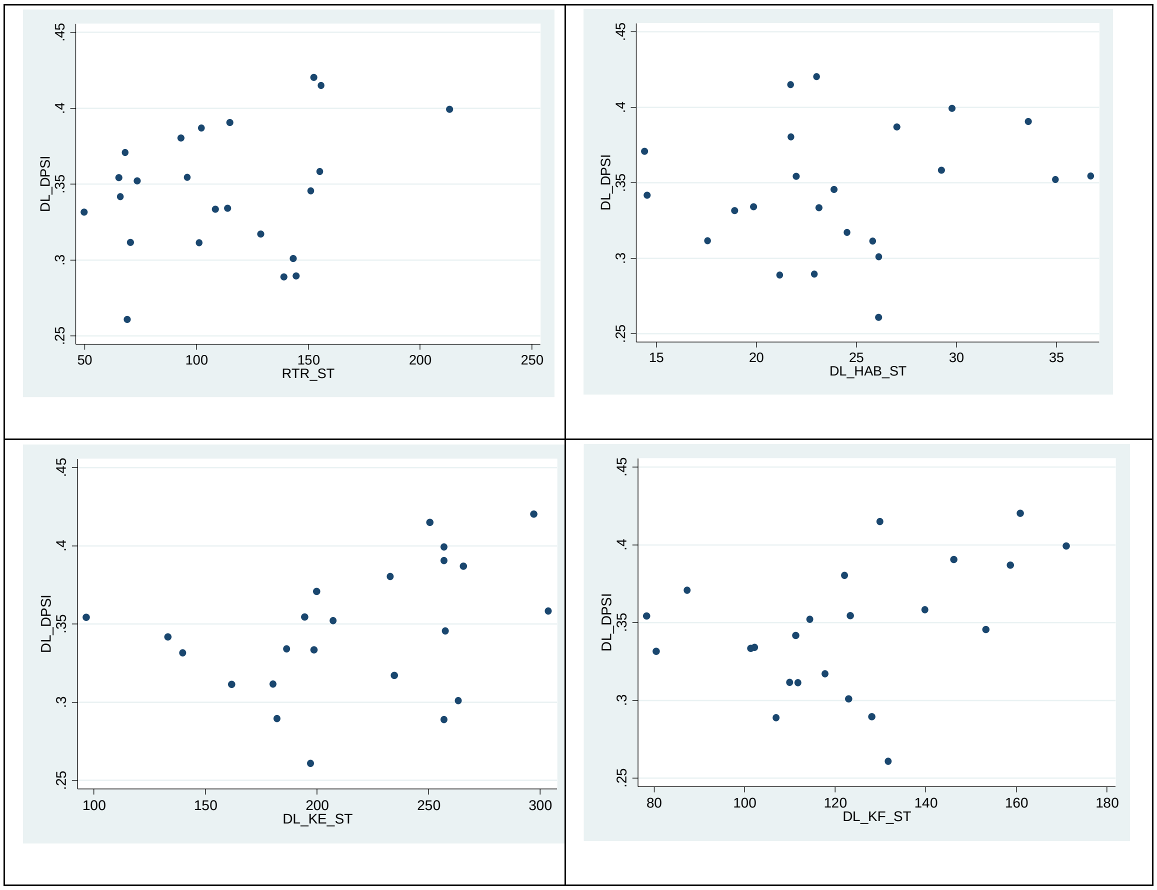
APPENDIX B

SCATTER PLOTS FOR EACH DEPENDENT AND INDEPENDENT VARIABLE

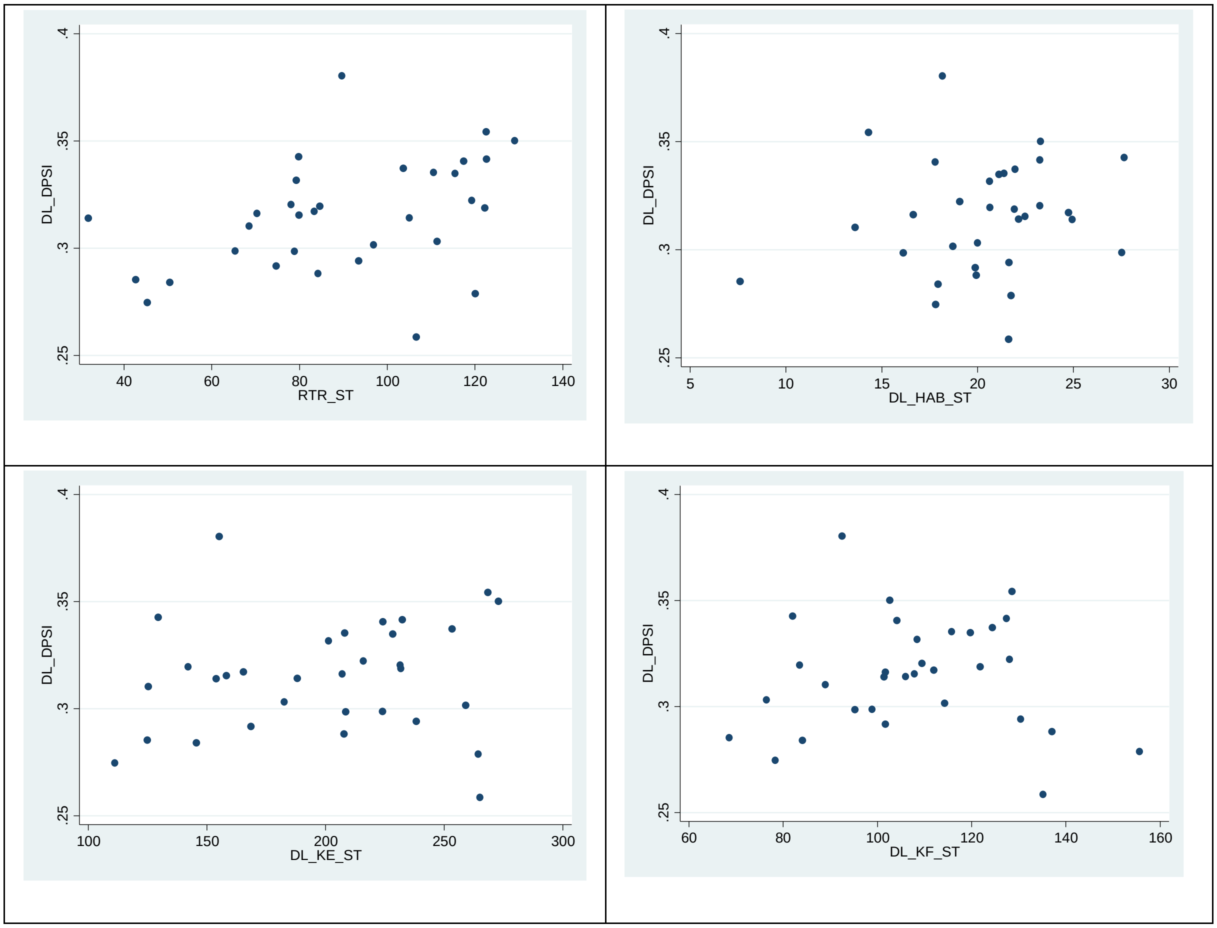
B.1 DPSI AND INDEPENDENT STRENGTH VARIABLES



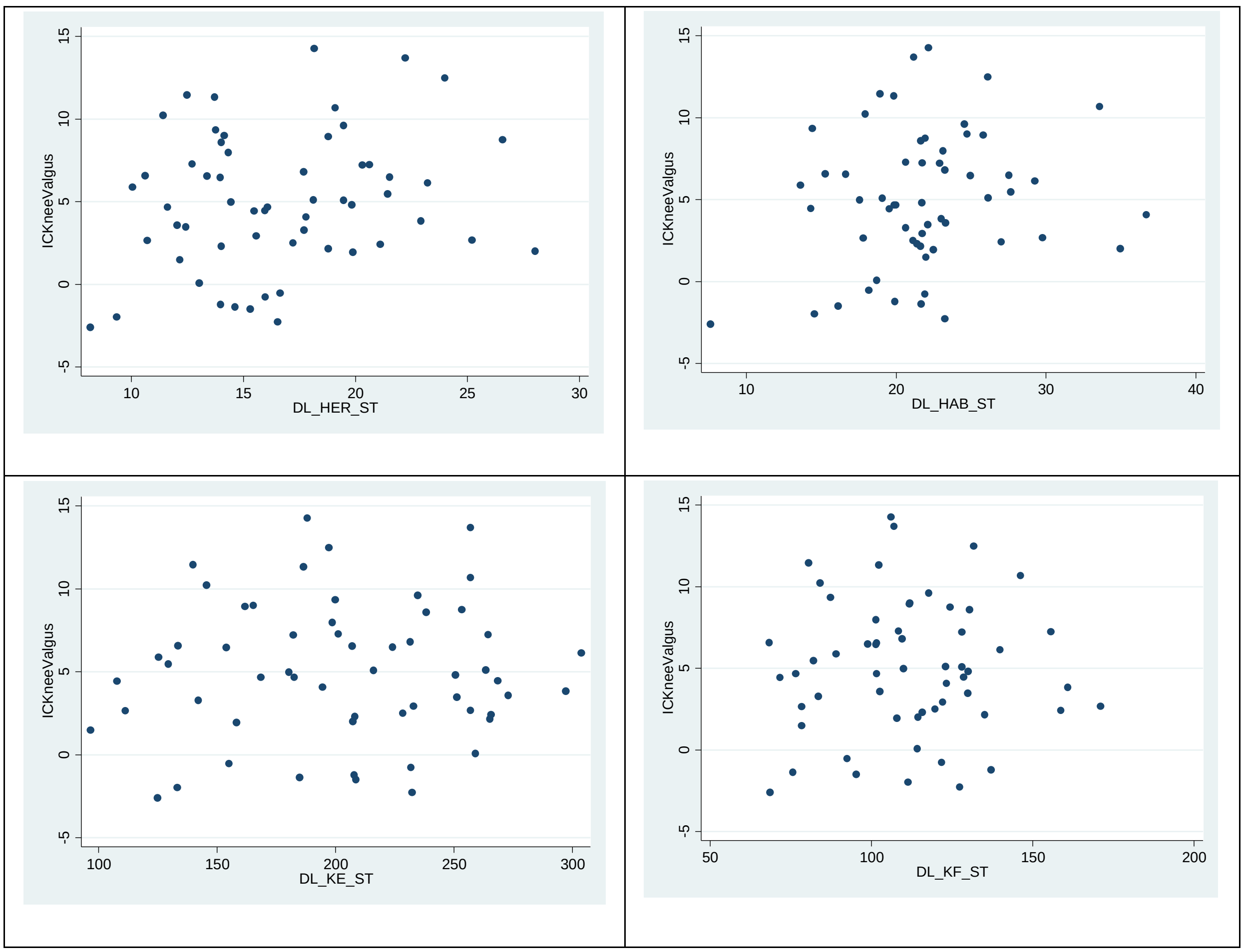
DPSI AND INDEPENDENT STRENGTH VARIABLES IN MALE DANCERS



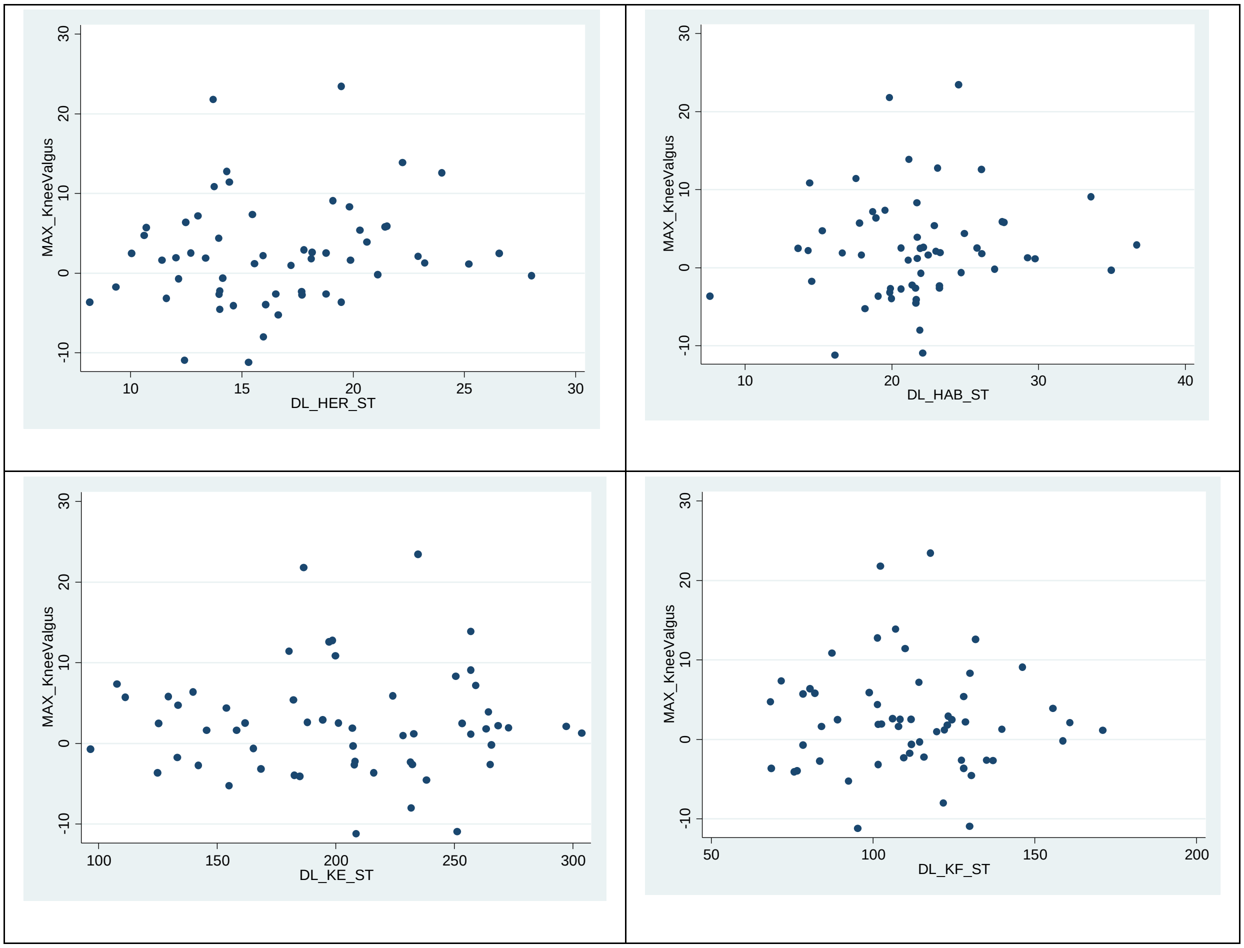
DPSI AND INDEPENDENT STRENGTH VARIABLES IN FEMALE DANCERS



B.2 KNEE VALGUS ANGLE AT INITIAL CONTACT AND INDEPENDENT STRENGTH VARIABLES

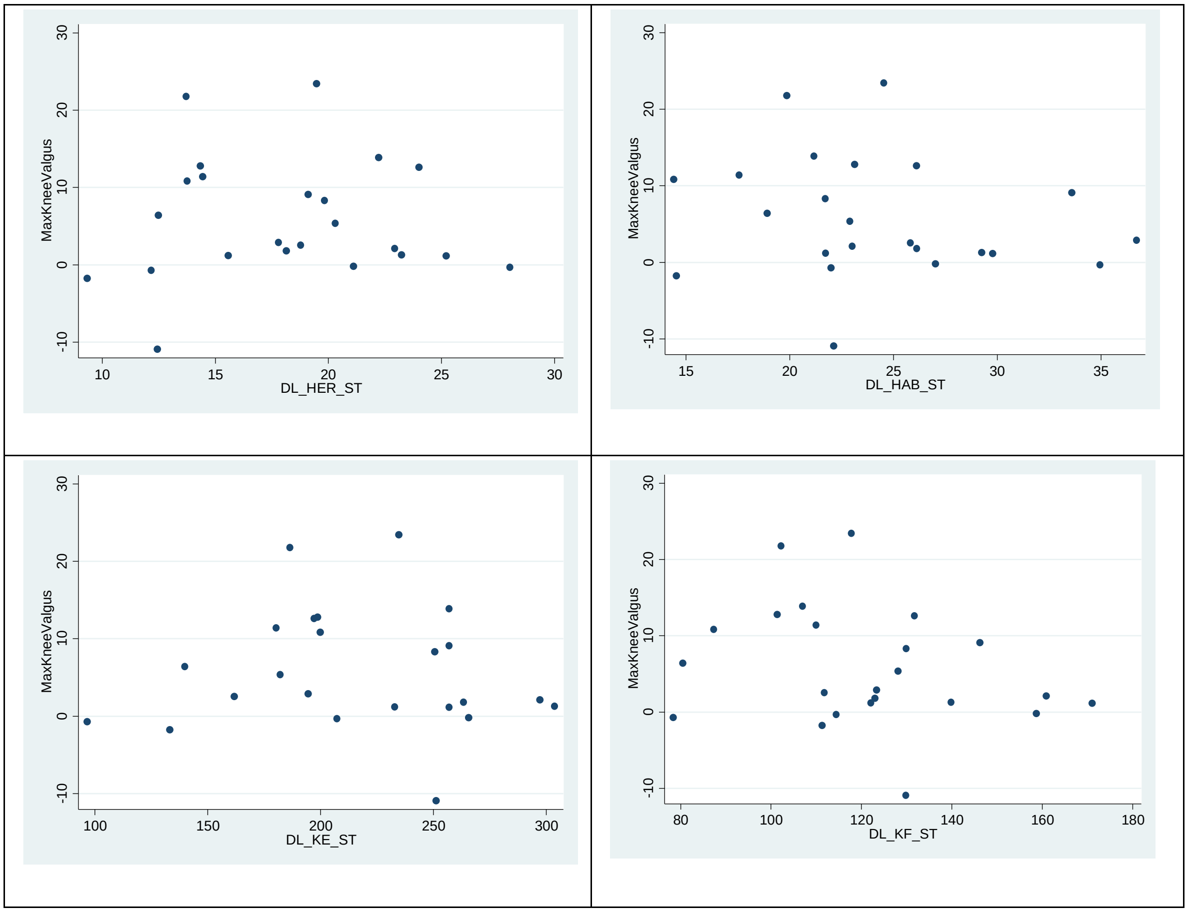


B.3 MAXIMUM KNEE VALGUS ANGLE AND INDEPENDENT STRENGTH VARIABLES



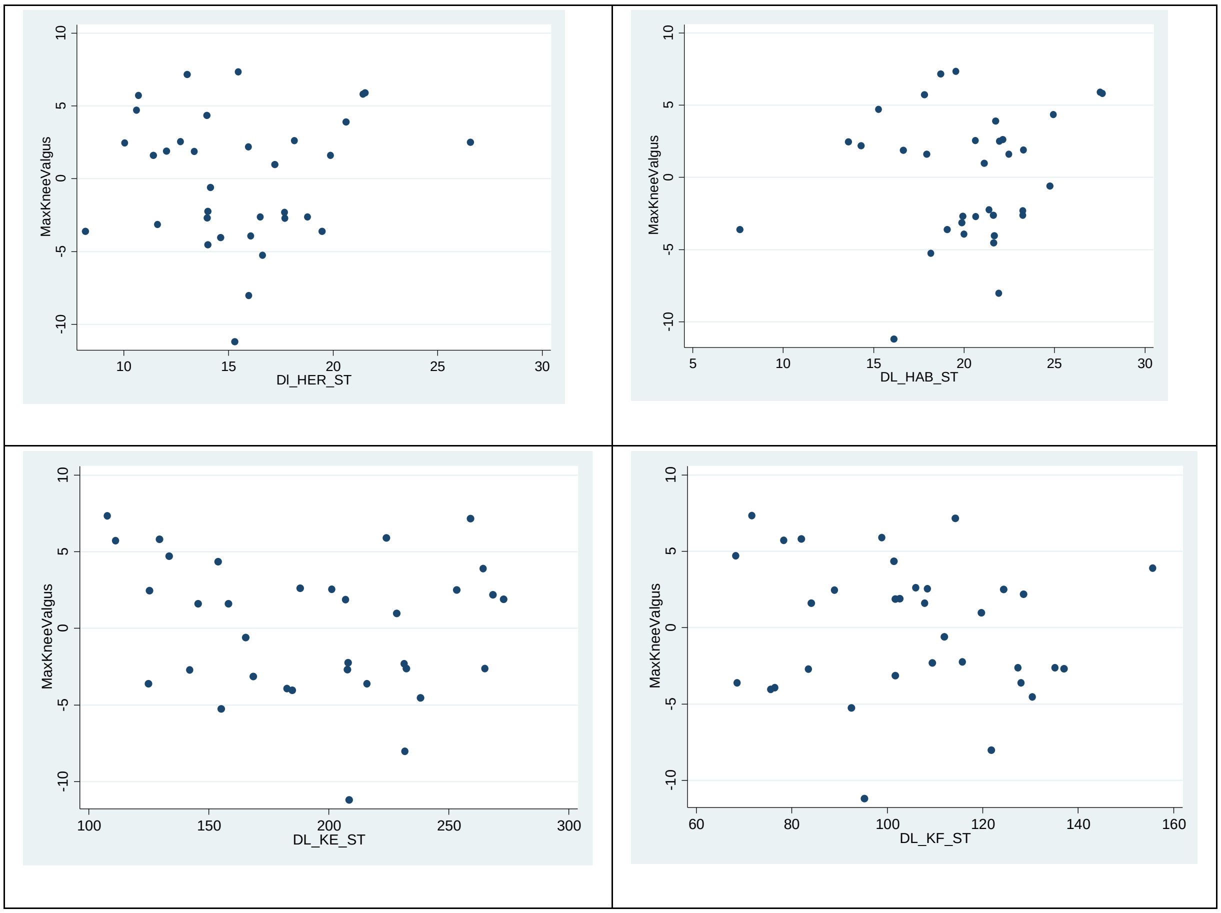
MAXIMUM KNEE VALGUS ANGLE AND INDEPENDENT STRENGTH VARIABLES

IN MALE DANCERS

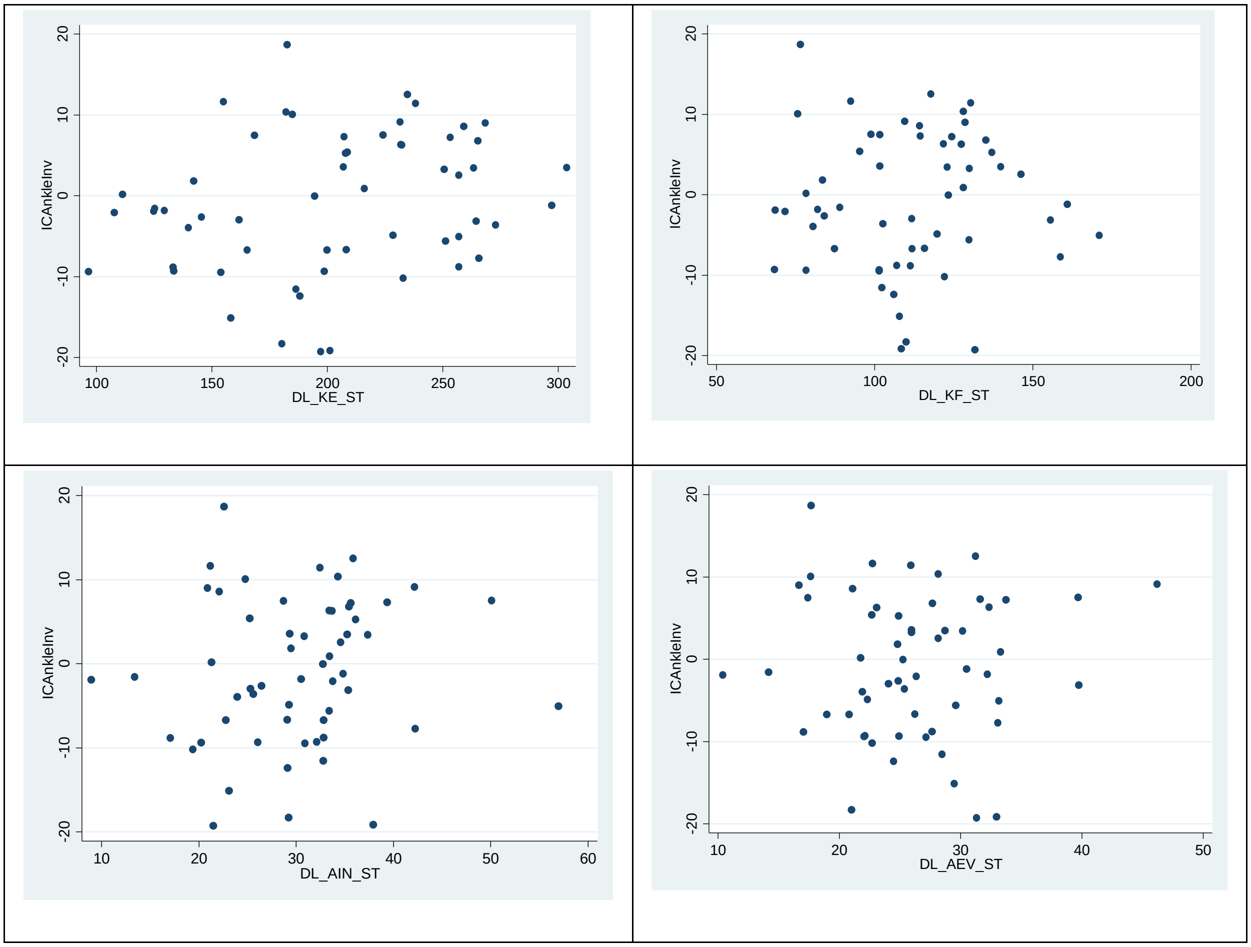


MAXIMUM KNEE VALGUS ANGLE AND INDEPENDENT STRENGTH VARIABLES

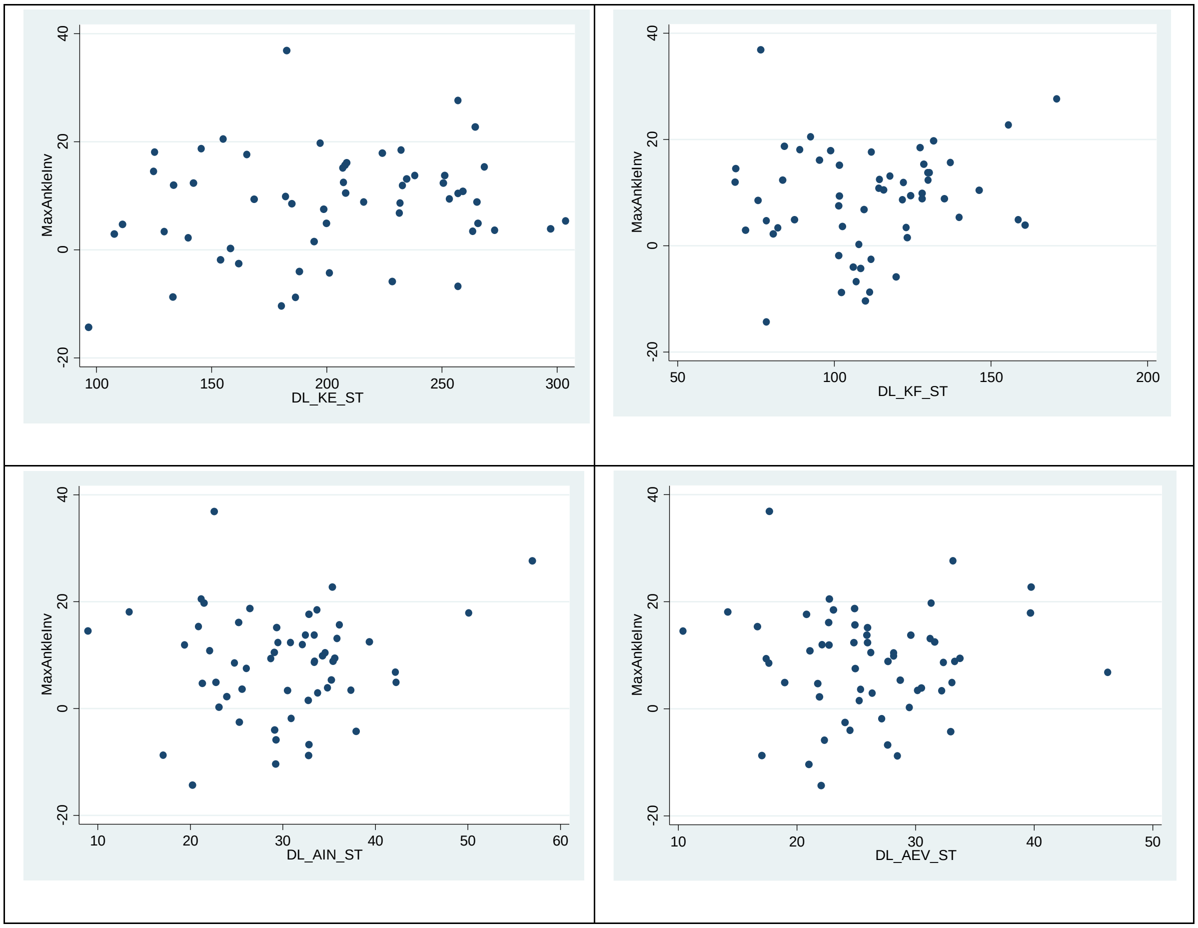
IN FEMALE DANCERS



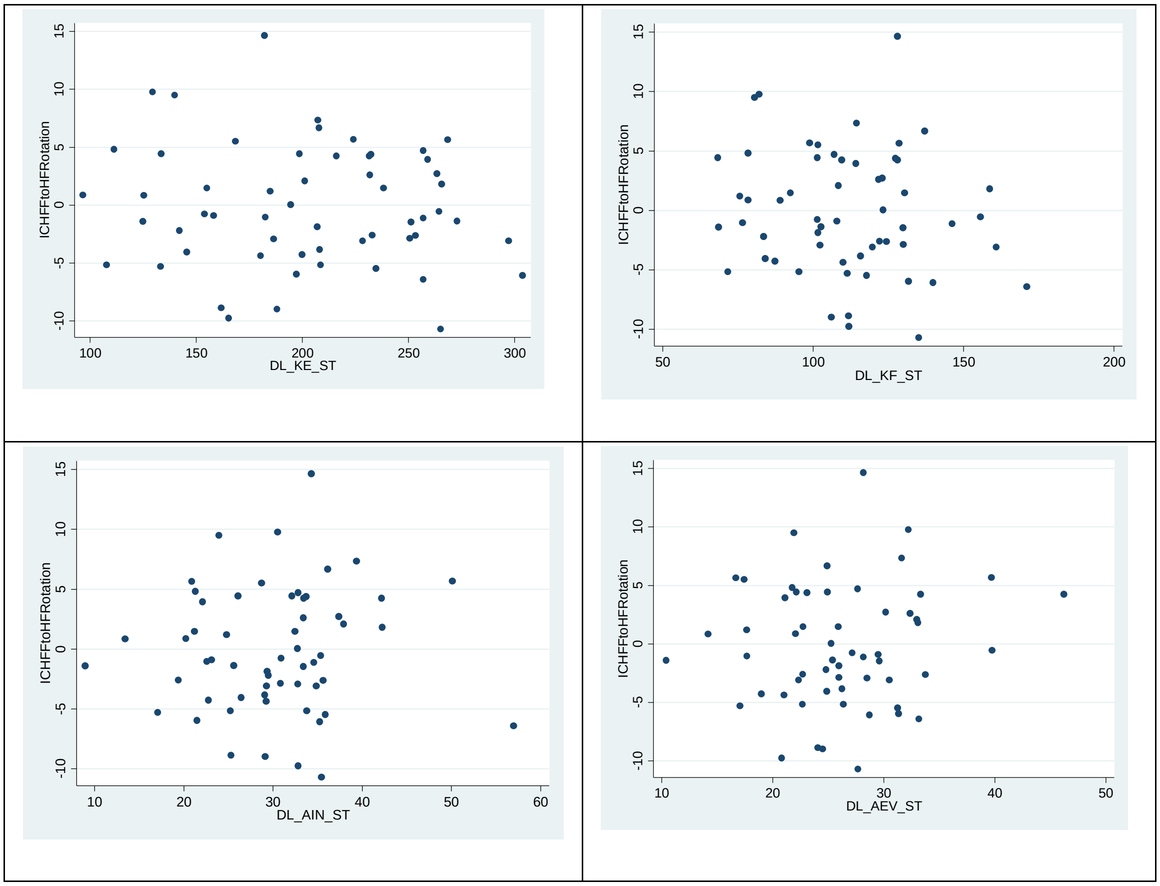
B.4 ANKLE INVERSION AT INITIAL CONTACT AND INDEPENDENT STRENGTH VARIABLES



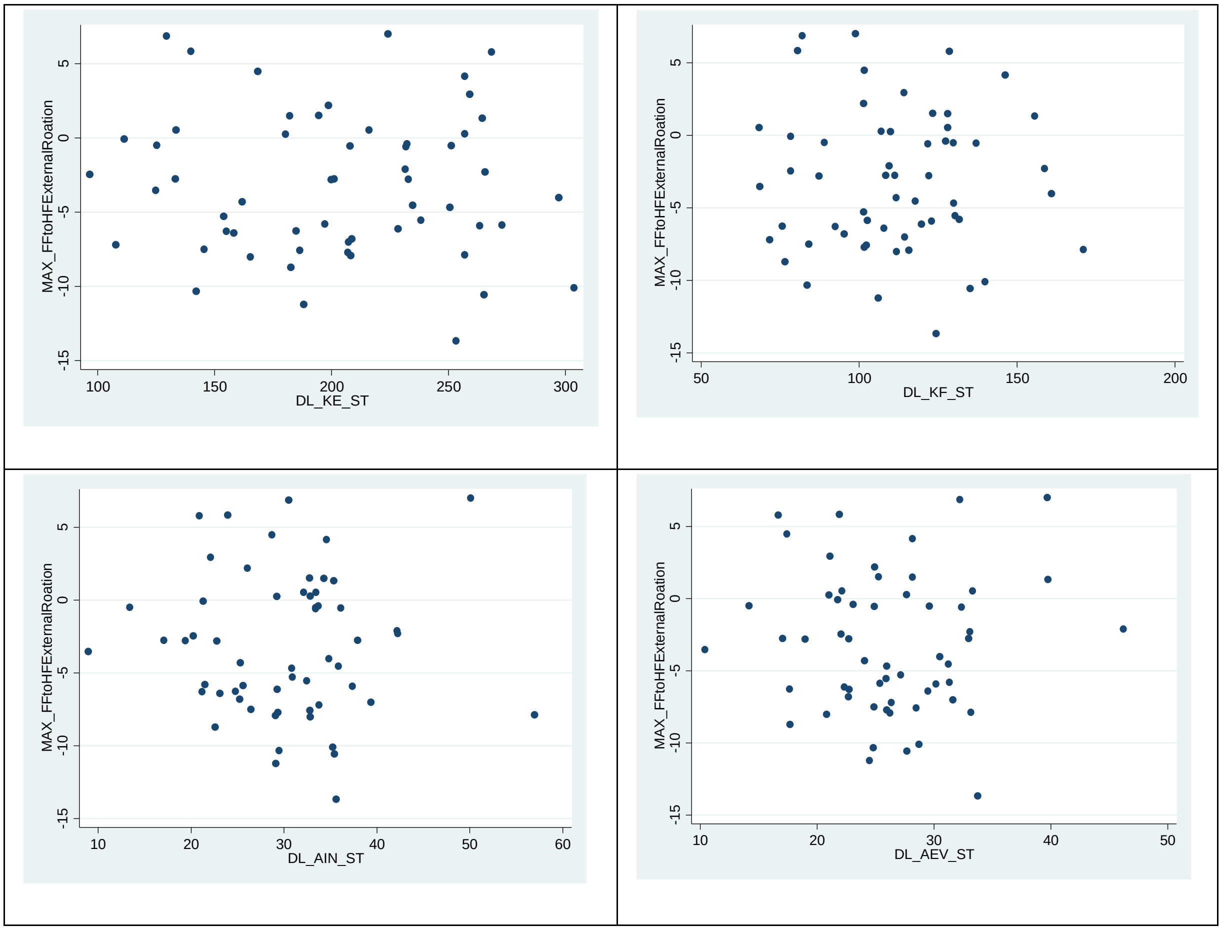
B.5 MAXIMUM ANKLE INVERSION ANGLE AND INDEPENDENT STRENGTH VARIABLES



B6. PRONATION ANGLE AT INITIAL CONTACT AND INDEPENDENT STRENGTH VARIABLES



B.7 MAXIMUM PRONTATION ANGLE AND INDEPENDENT STRENGTH VARIABLES

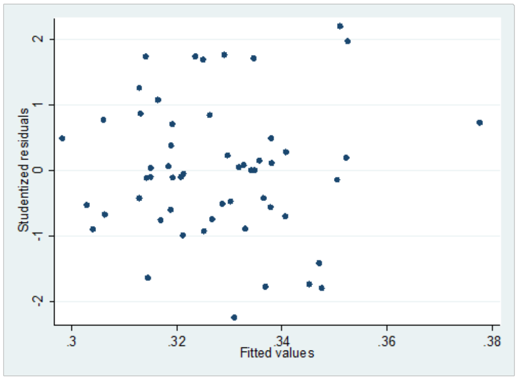


APPENDIX C

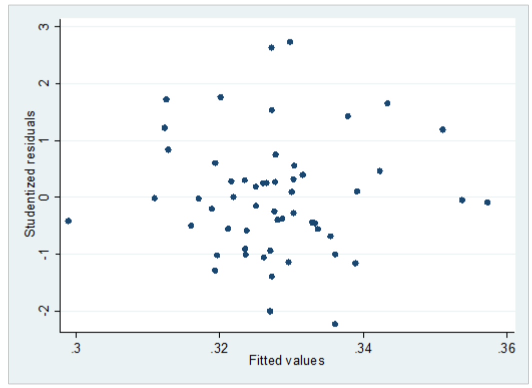
SCATTER PLOTS OF THE RESIDUALS AND FITTED VALUES FOR EACH PREDICTOR AND OUTCOME VARIABLE

C.1 RESIDUAL PLOTS FOR DPSI AND INDEPENDENT STRENGTH VARAIABLES

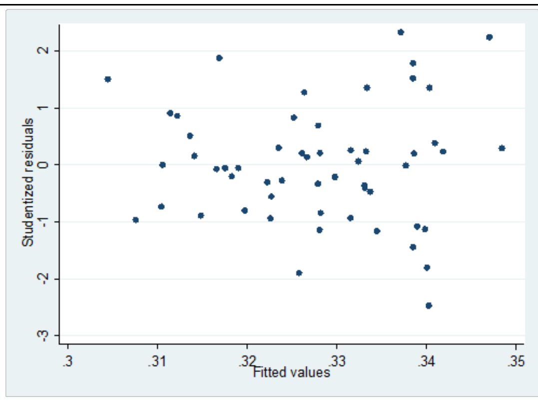
DPSI and Right Trunk Rotation Strength



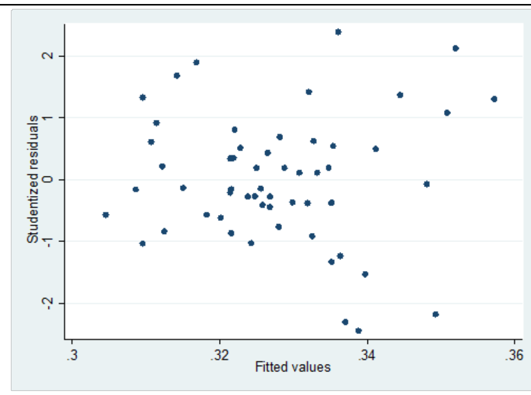
DPSI and Hip Abduction Strength



DPSI and Knee Extension Strength

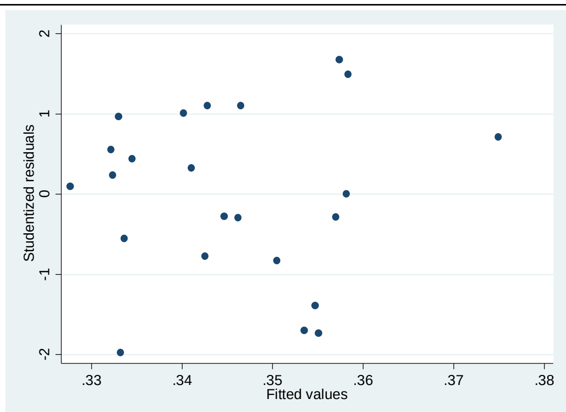
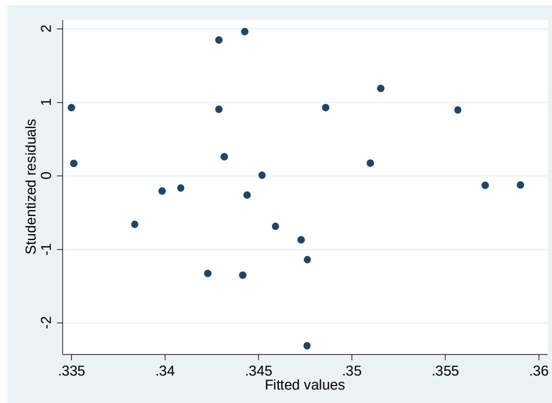
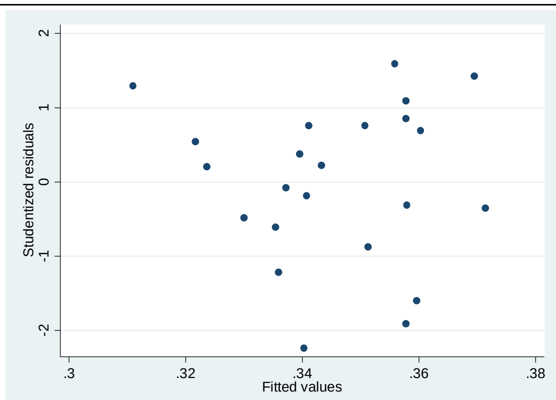
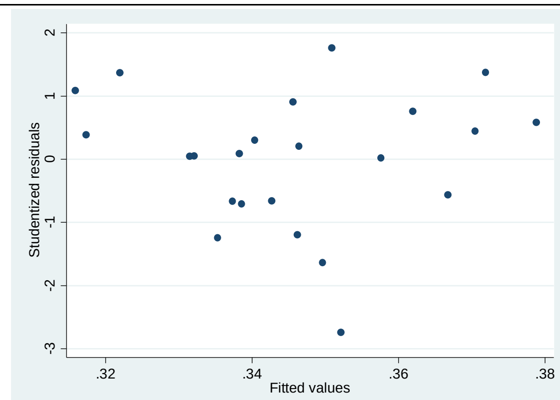


DPSI and Knee Flexion Strength



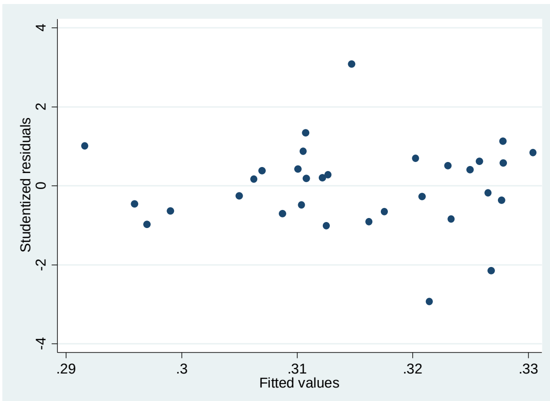
RESIDUAL PLOTS FOR DPSI AND INDEPENDENT STRENGTH VARIABLES IN

MALE DANCERS

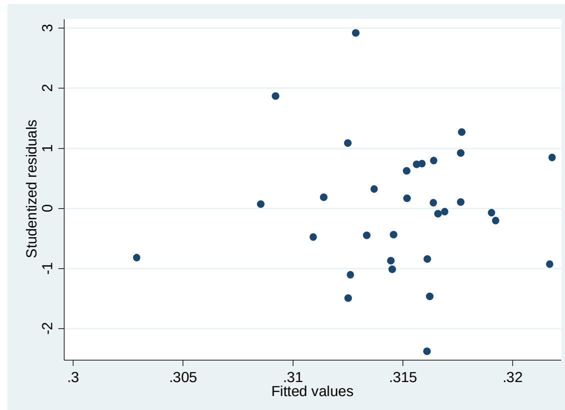
DPSI and Right Trunk Rotation Strength	DPSI and Hip Abduction Strength
	
DPSI and Knee Extension Strength	**DPSI and Knee Flexion Strength**
	

RESIDUAL PLOTS FOR DPSI AND INDEPENDENT STRENGTH VARIABLES IN FEMALE DANCERS

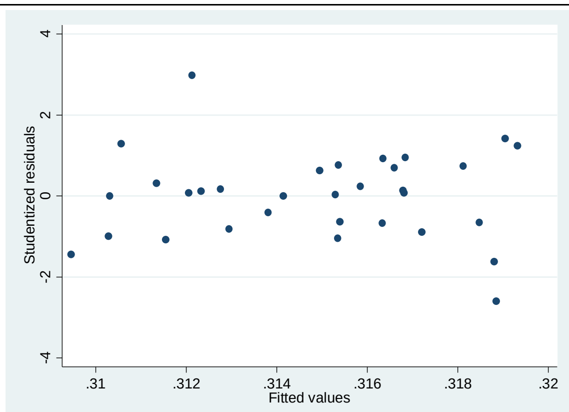
DPSI and Right Trunk Rotation Strength



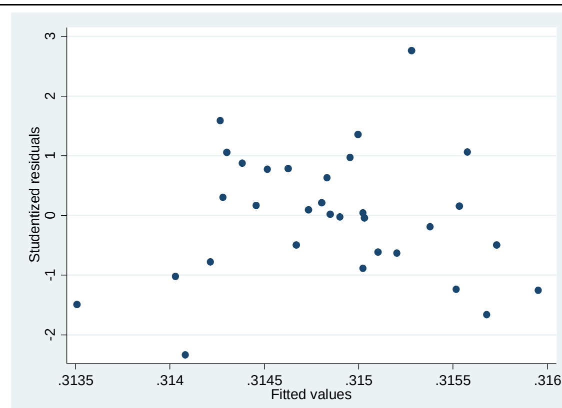
DPSI and Hip Abduction Strength



DPSI and Knee Extension Strength



DPSI and Knee Flexion Strength



C.2 RESIDUAL PLOTS FOR KNEE VALGUS ANGLE AT INITIAL CONTACT AND INDEPENDENT STRENGTH VARAIABLES

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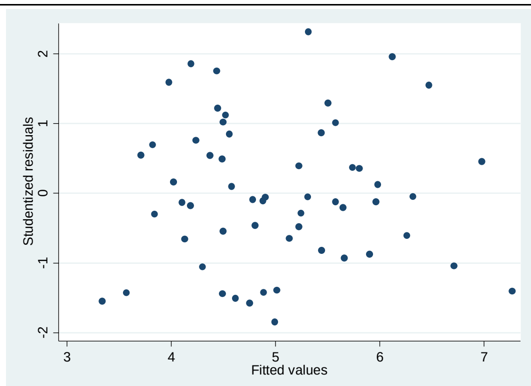
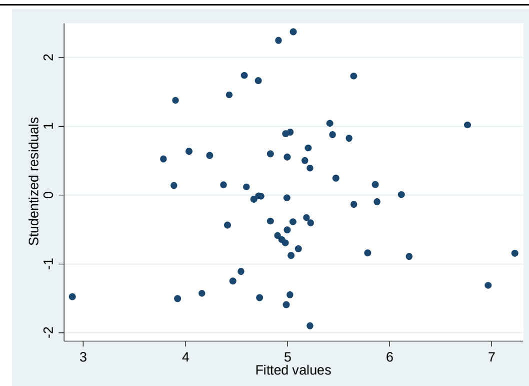
<tr><td>
</td><td>
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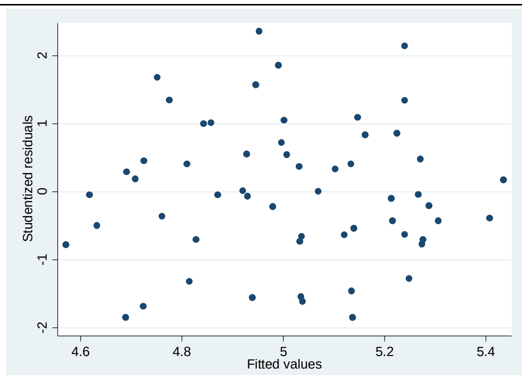
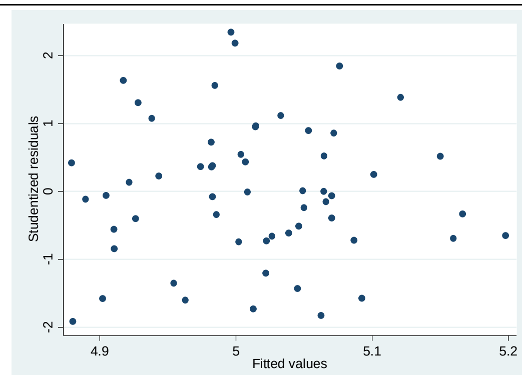
<tr><td>KneeValgus at Initial Contact and Knee Extension Strength</td><td>KneeValgus at Initial Contact and Knee Flexion Strength</td></tr>
<tr><td>
</td><td>
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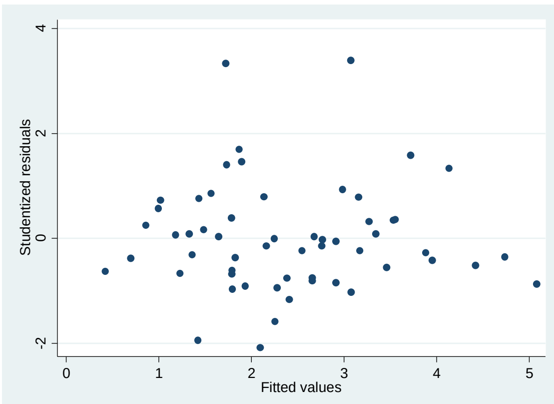
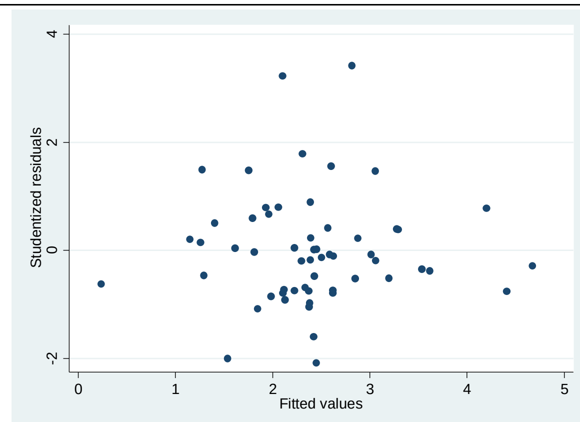
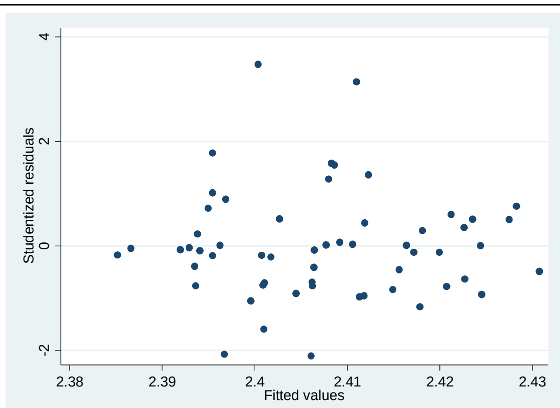
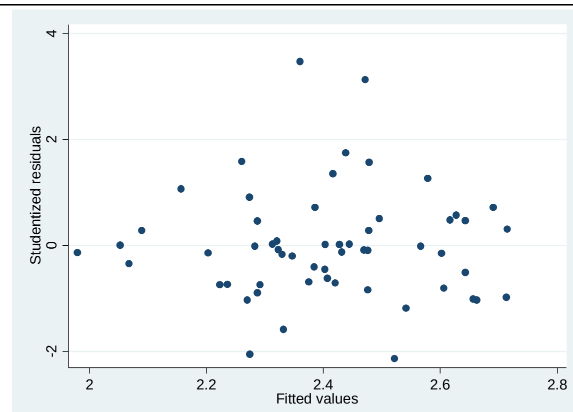
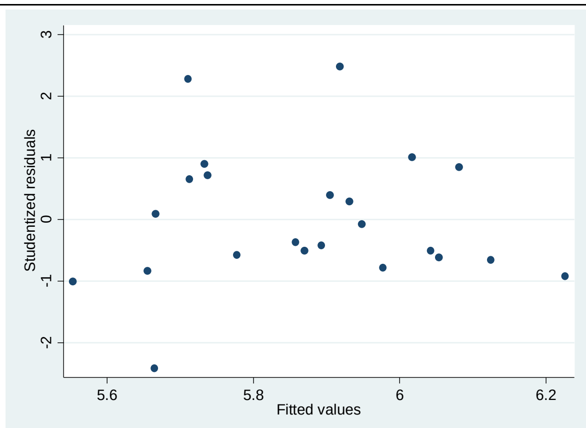
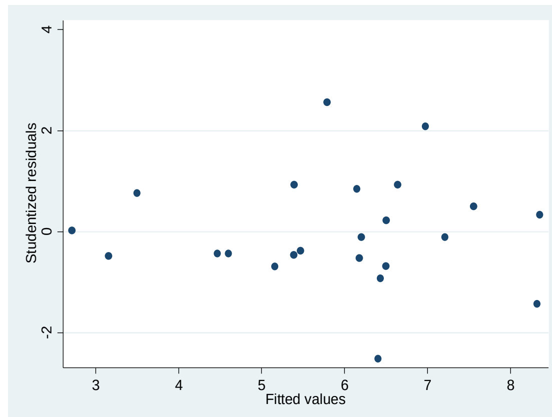
C.3 RESIDUAL PLOTS FOR MAXIMUM KNEE VALGUS ANGLE AND INDEPENDENT STRENGTH VARAIABLES

Maximum Knee Valgus Angle and Hip External Rotation Strength	**Maximum Knee Valgus Angle and Hip Abduction Strength**
	
Maximum Knee Valgus Angle and Knee Extension Strength	**Maximum Knee Valgus Angle and Knee Flexion Strength**
	

RESIDUAL PLOTS FOR MAXIMUM KNEE VALGUS ANGLE AND INDEPENDENT STRENGTH VARAIABLES IN MALE DANCERS

<table>
<tr><td>Maximum Knee Valgus Angle and Hip External Rotation Strength</td><td>Maximum Knee Valgus Angle and Hip Abduction Strength</td></tr>
<tr><td>
</td><td>
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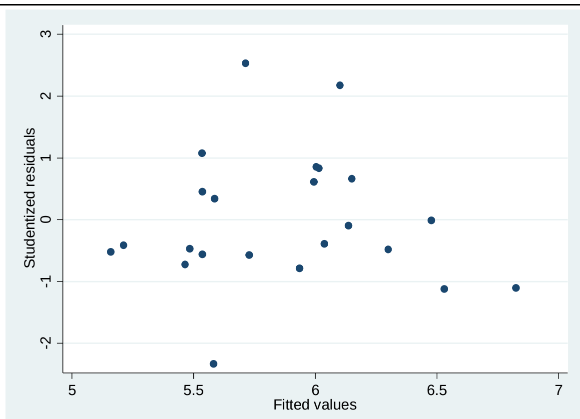
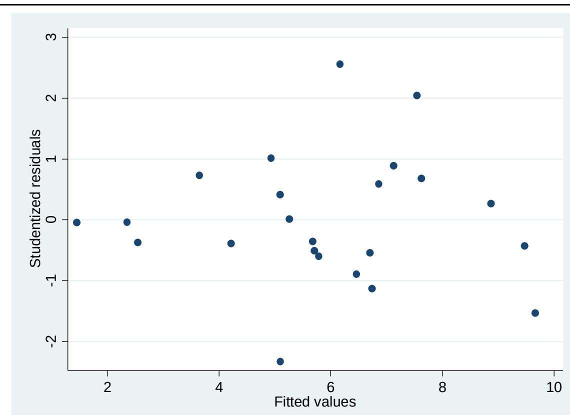
<tr><td>Maximum Knee Valgus Angle and Knee Extension Strength</td><td>Maximum Knee Valgus Angle and Knee Flexion Strength</td></tr>
<tr><td>
</td><td>
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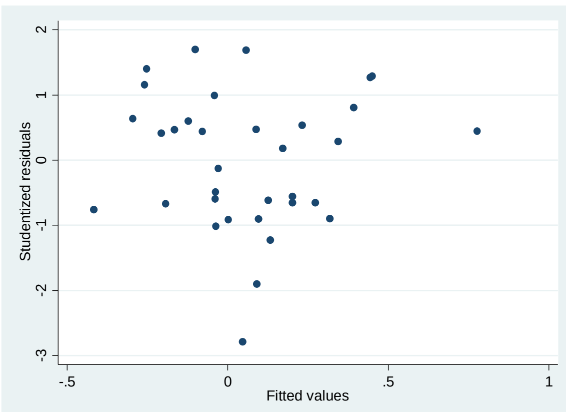
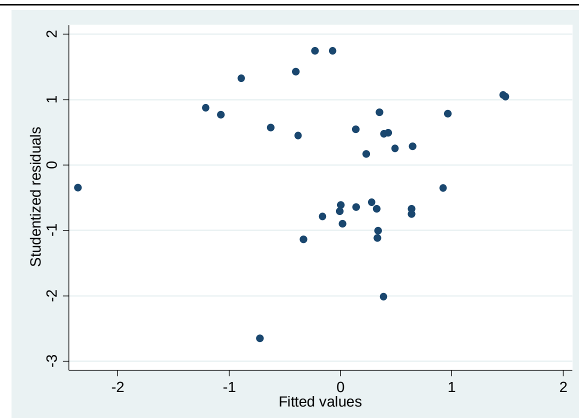
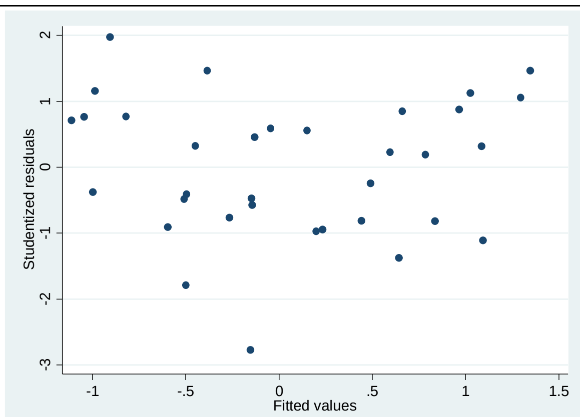
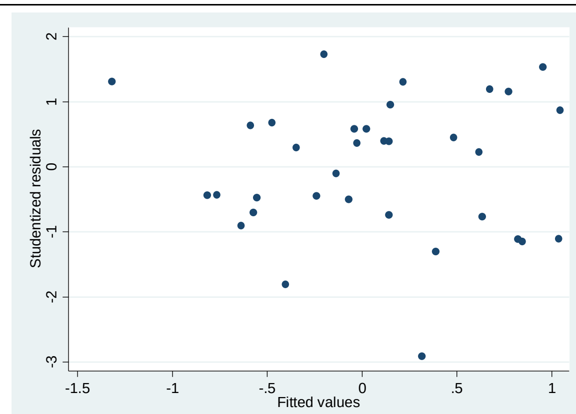
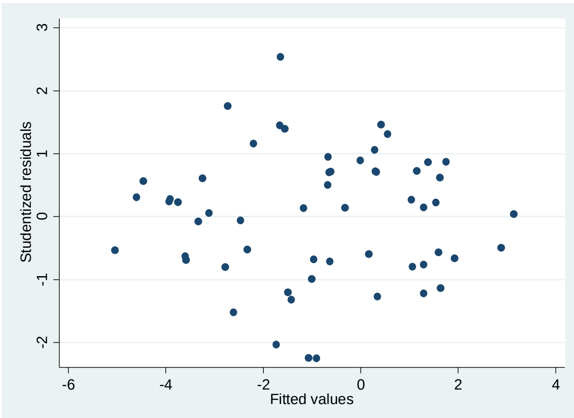
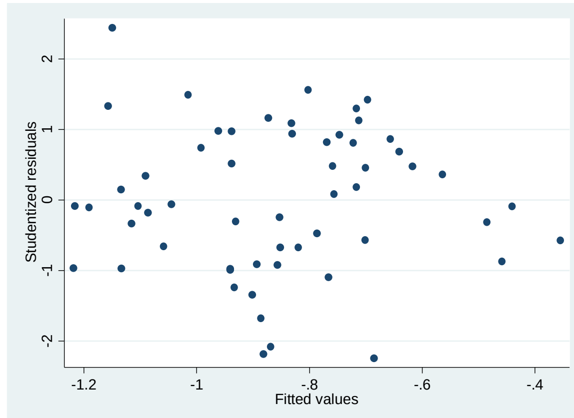
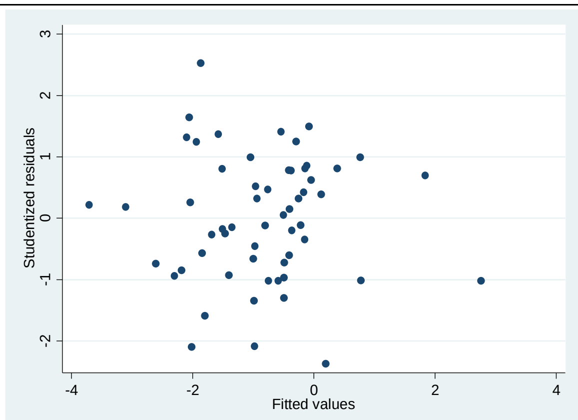
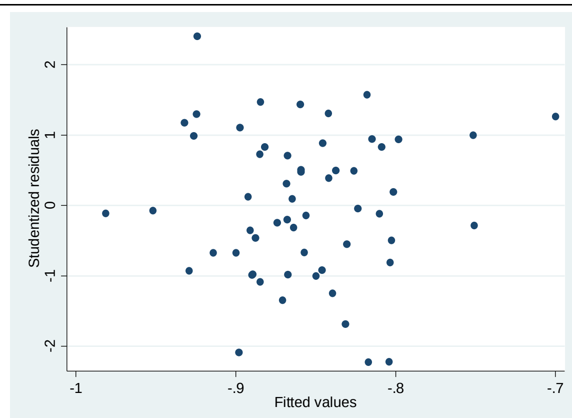
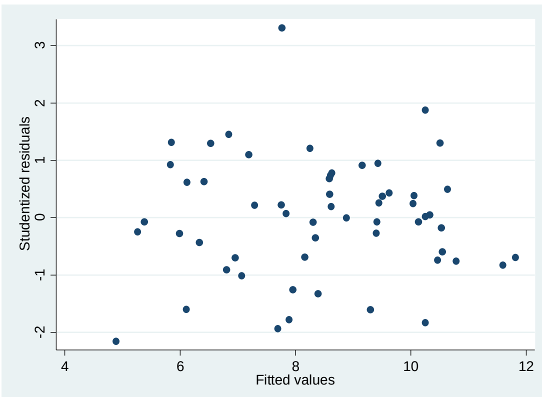
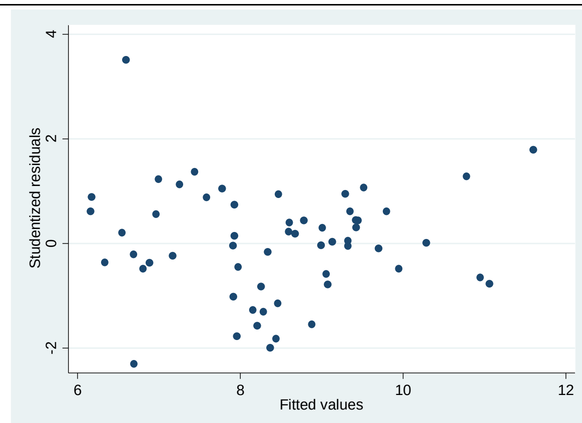
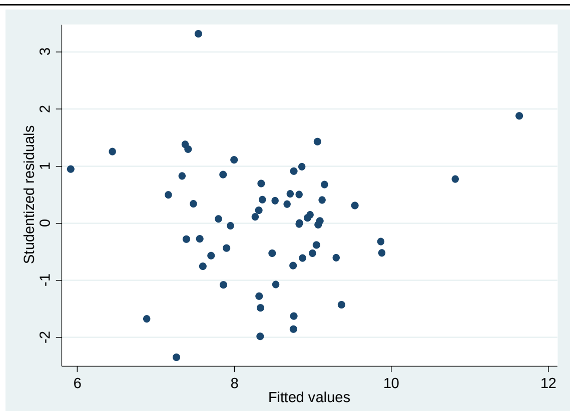
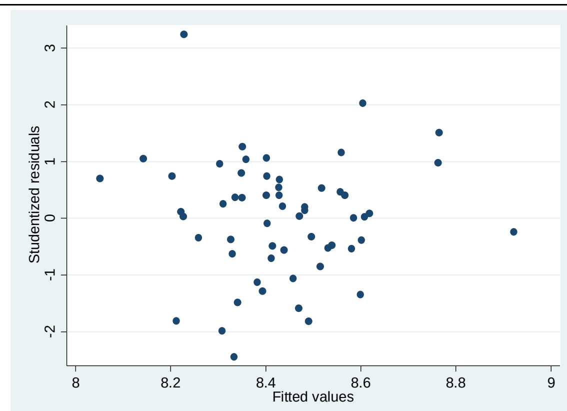
RESIDUAL PLOTS FOR MAXIMUM KNEE VALGUS ANGLE AND INDEPENDENT STRENGTH VARAIABLES IN FEMALE DANCERS

Maximum Knee Valgus Angle and Hip External Rotation Strength	**Maximum Knee Valgus Angle and Hip Abduction Strength**
	
Maximum Knee Valgus Angle and Knee Extension Strength	**Maximum Knee Valgus Angle and Knee Flexion Strength**
	

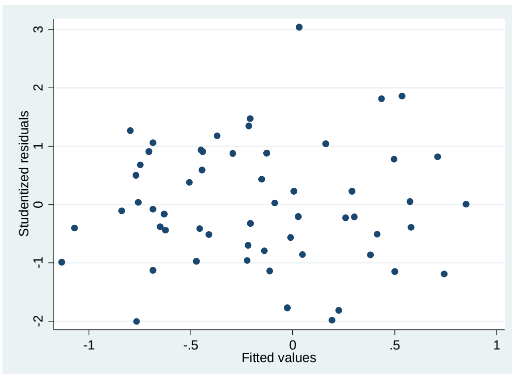
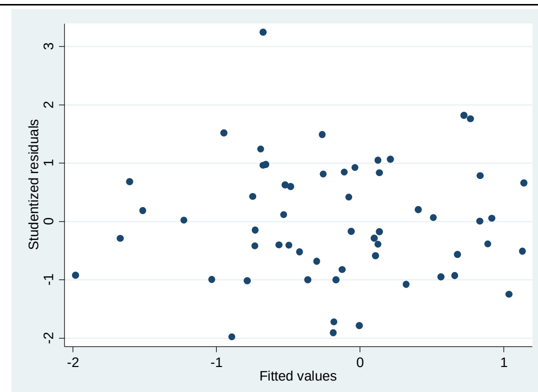
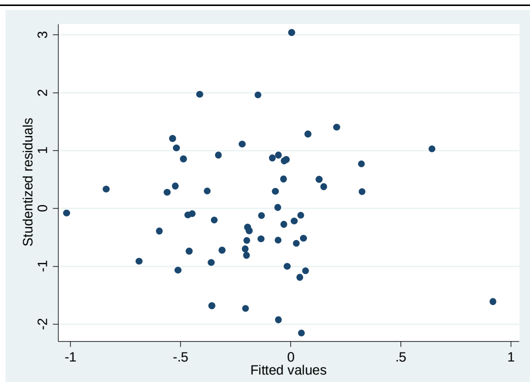
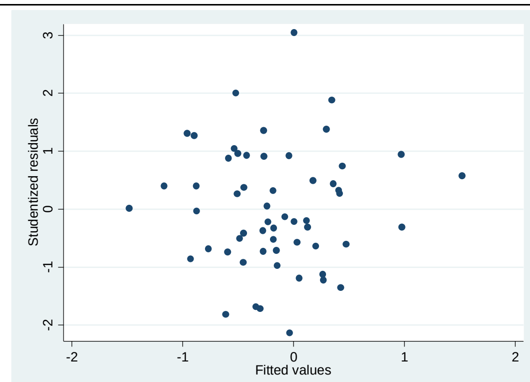
C.5 RESIDUAL PLOTS FOR INVERSION ANGLE AT INITIAL CONTACT AND INDEPENDENT STRENGTH VARAIABLES

Inversion Angle at Initial Contact and Knee Extension Strength	Inversion Angle at Initial Contact and Knee Flexion Strength
	
Inversion Angle at Initial Contact and Ankle Inversion Strength	**Inversion Angle at Initial Contact and Ankle Eversion Strength**
	

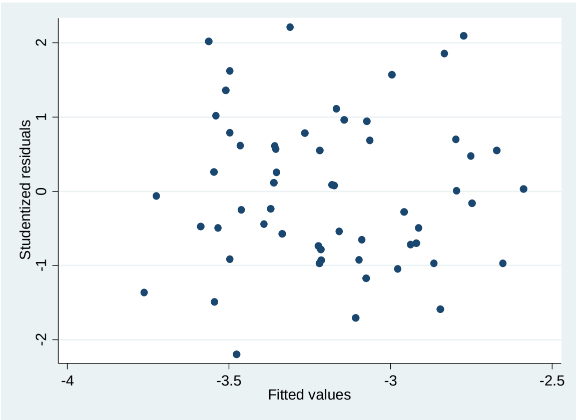
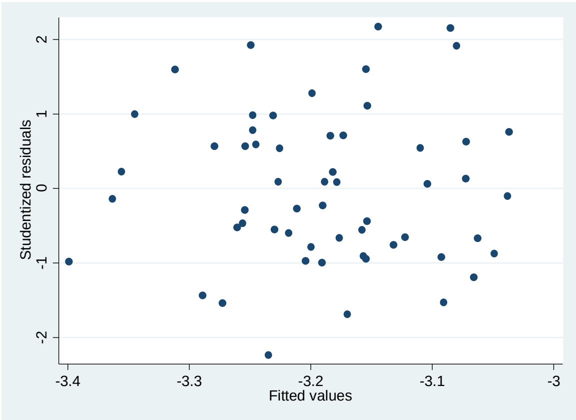
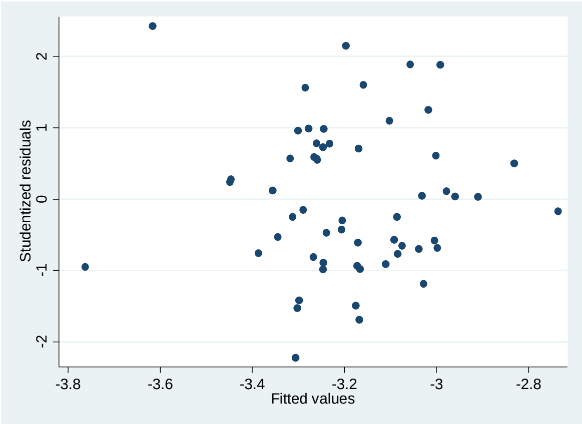
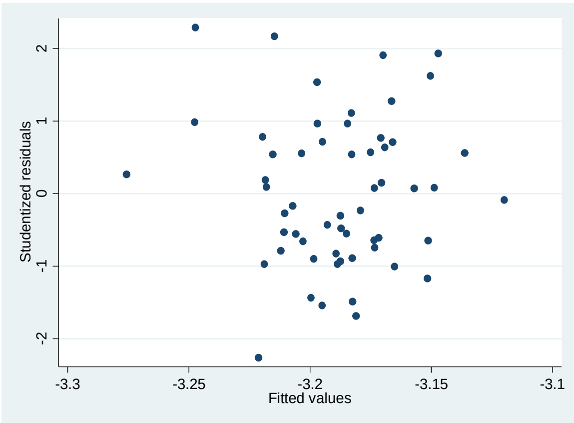
C.6 RESIDUAL PLOTS FOR MAXIMUM INVERSION ANGLE AND INDEPENDENT STRENGTH VARAIABLES

Maximum Inversion Angle and Knee Extension Strength	**Maximum Inversion Angle and Knee Flexion Strength**
	
Maximum Inversion Angle and Ankle Inversion Strength	**Maximum Inversion Angle and Ankle Eversion Strength**
	

C.7 RESIDUAL PLOTS FOR PRONATION ANGLE AT INITIAL CONTACT AND INDEPENDENT STRENGTH VARAIABLES

Pronation Angle at Initial Contact and Knee Extension Strength	**Pronation Angle at Initial Contact and Knee Flexion Strength**
	
Pronation Angle at Initial Contact and Ankle Inversion Strength	**Pronation Angle at Initial Contact and Ankle Eversion Strength**
	

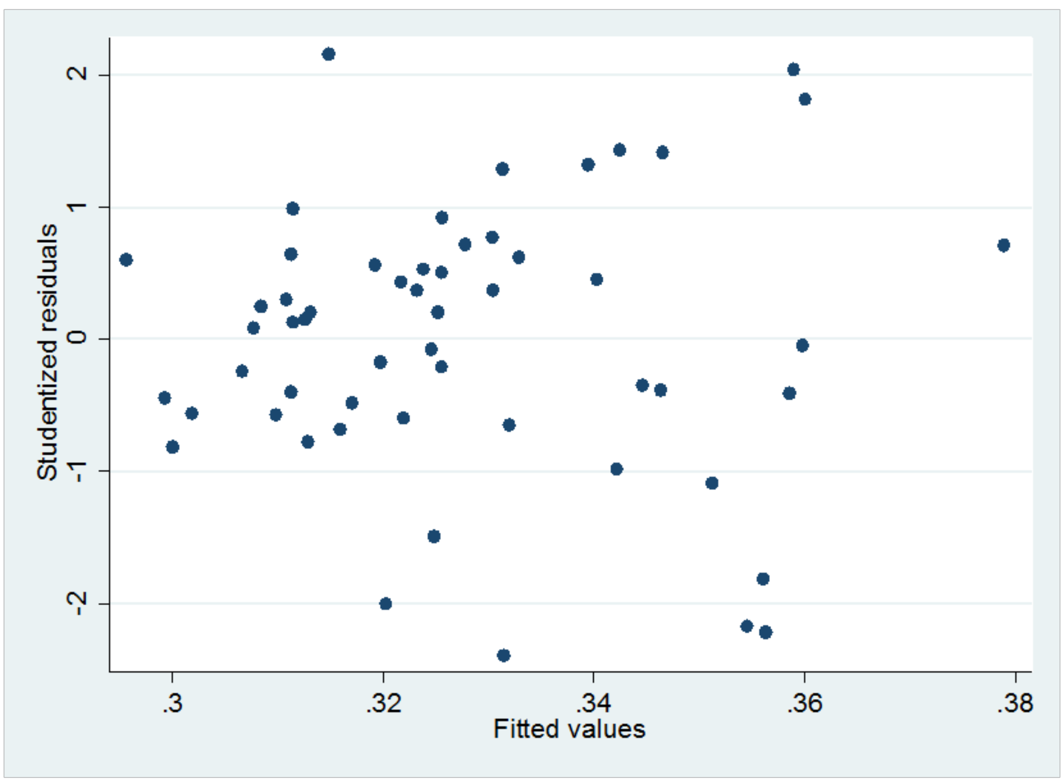
C.8 RESIDUAL PLOTS FOR MAXIMUM PRONATION ANGLE AND INDEPENDENT STRENGTH VARAIABLES

Max Pronation Angle and Knee Extension Strength	Max Prontation Angle and Knee Flexion Strength
	
Maximum Pronation Angle and Ankle Inversion Strength	**Maximum Pronation Angle and Ankle Eversion Strength**
	

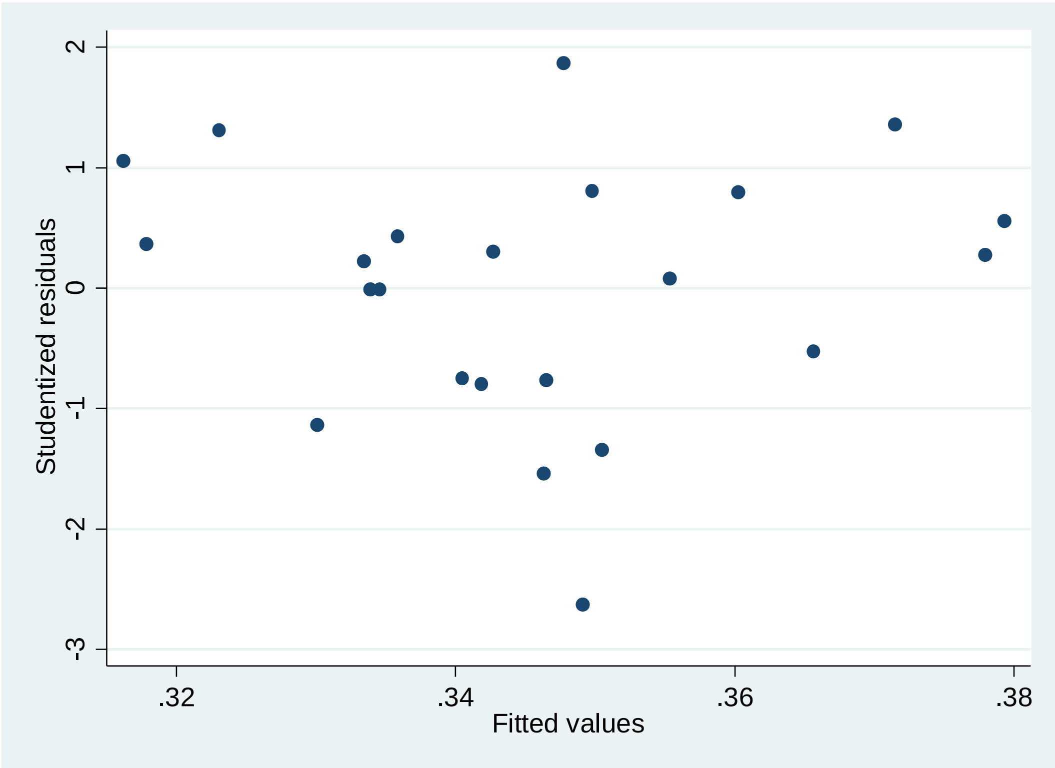
APPENDIX D

SCATTER PLOTS OF THE RESIDUALS AND FITTED VALUES OF THE MULTIPLE LINEAR REGRESSIONS

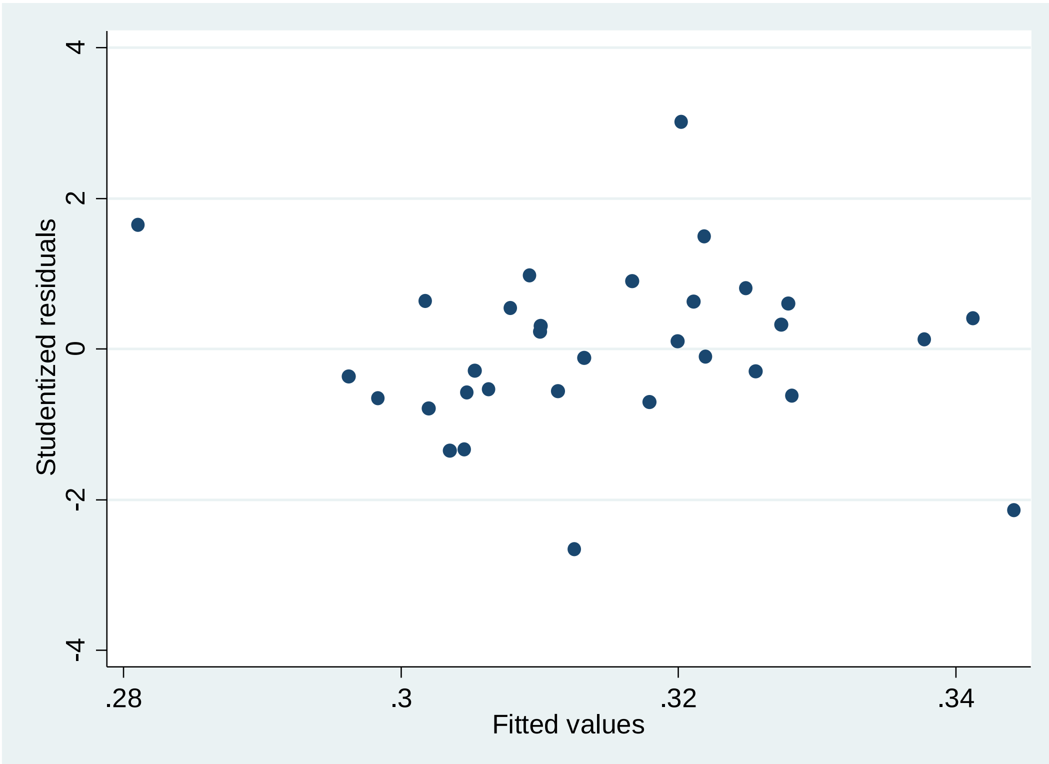
D.1 FINAL MODEL RESIDUAL PLOT FOR DPSI AND INDEPENDENT STRENGTH VARAIABLES



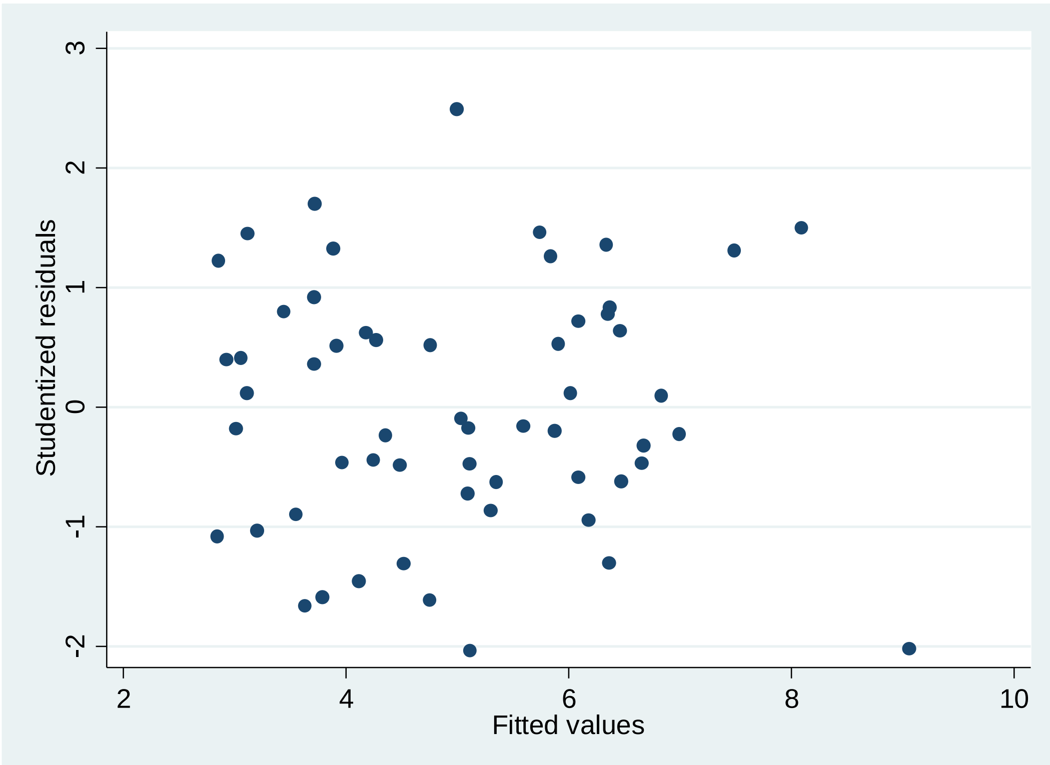
FINAL MODEL RESIDUAL PLOT FOR DPSI AND INDEPENDENT STRENGTH VARAIABLES IN MALE DANCERS



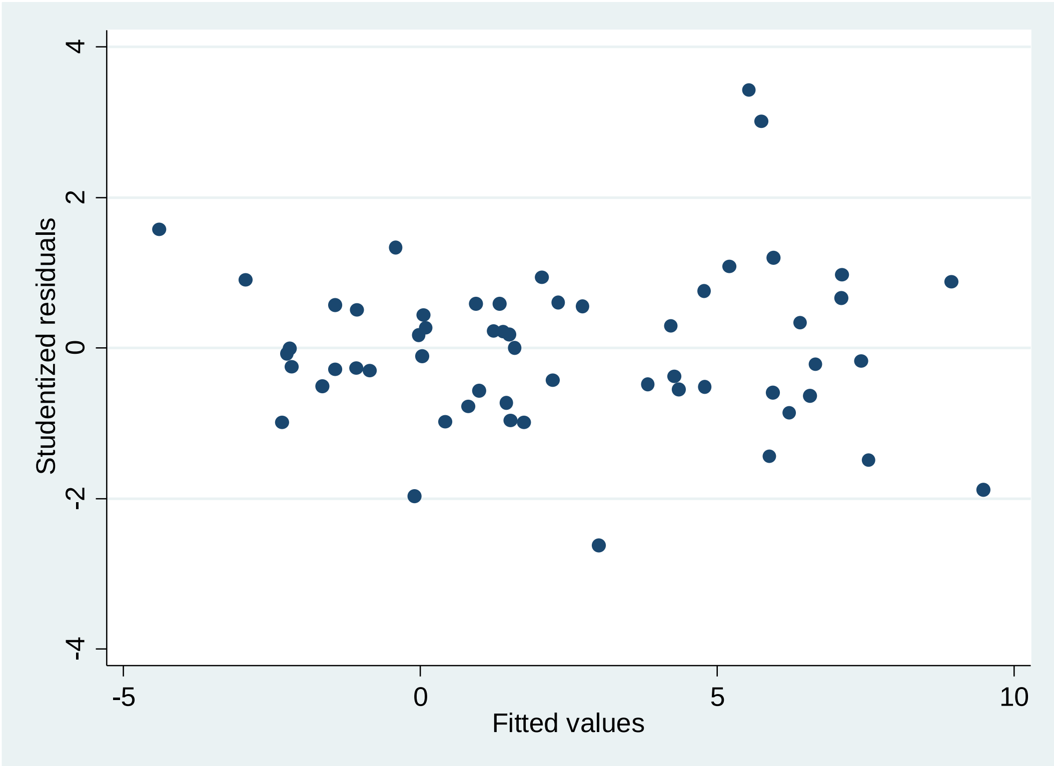
FINAL MODEL RESIDUAL PLOT FOR DPSI AND INDEPENDENT STRENGTH VARAIABLES IN FEMALE DANCERS



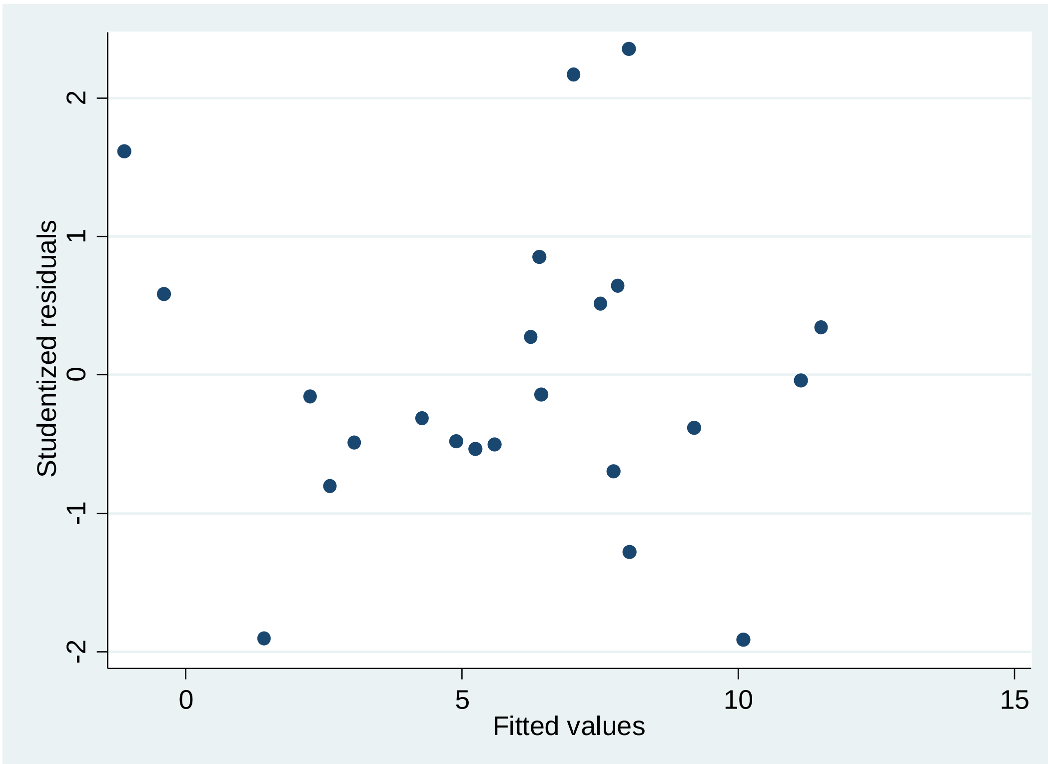
D.2 FINAL MODEL RESIDUAL PLOT FOR KNEE VALGUS ANGLE AT INITIAL CONTACT AND INDEPENDENT STRENGTH VARAIABLES



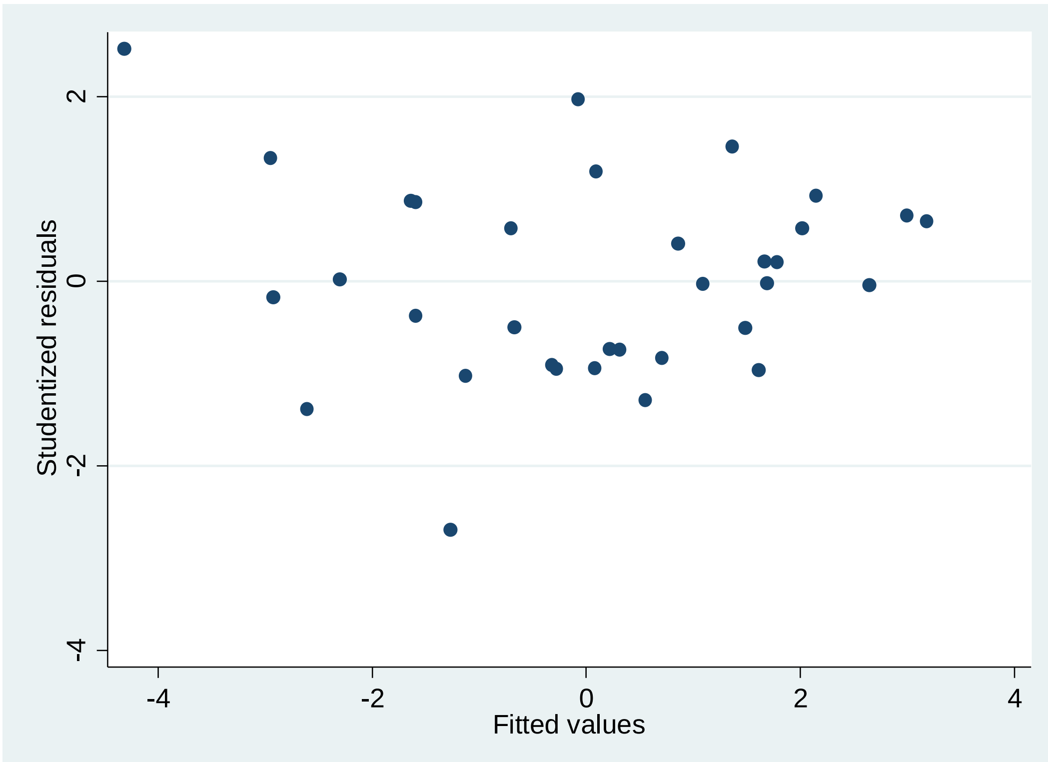
D.3 FINAL MODEL RESIDUAL PLOT FOR MAXIMUM KNEE VALGUS ANGLE AND INDEPENDENT STRENGTH VARAIABLES



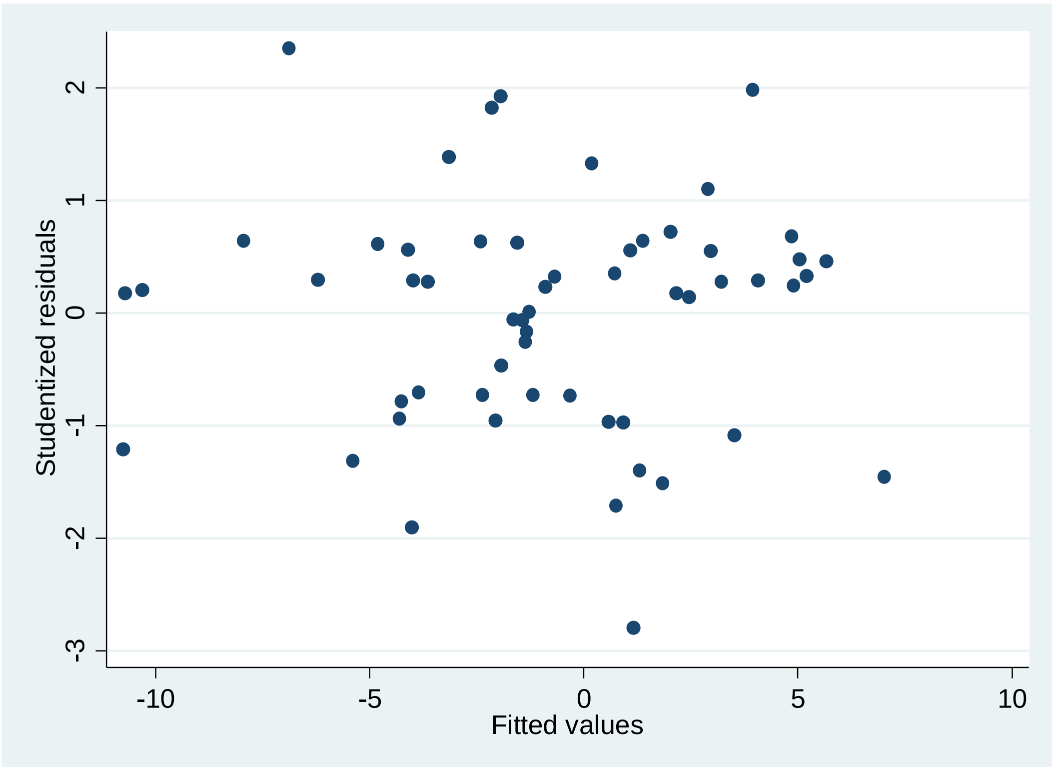
FINAL MODEL RESIDUAL PLOT FOR MAXIMUM KNEE VALGUS ANGLE AND INDEPENDENT STRENGTH VARAIABLES IN MALE DANCERS



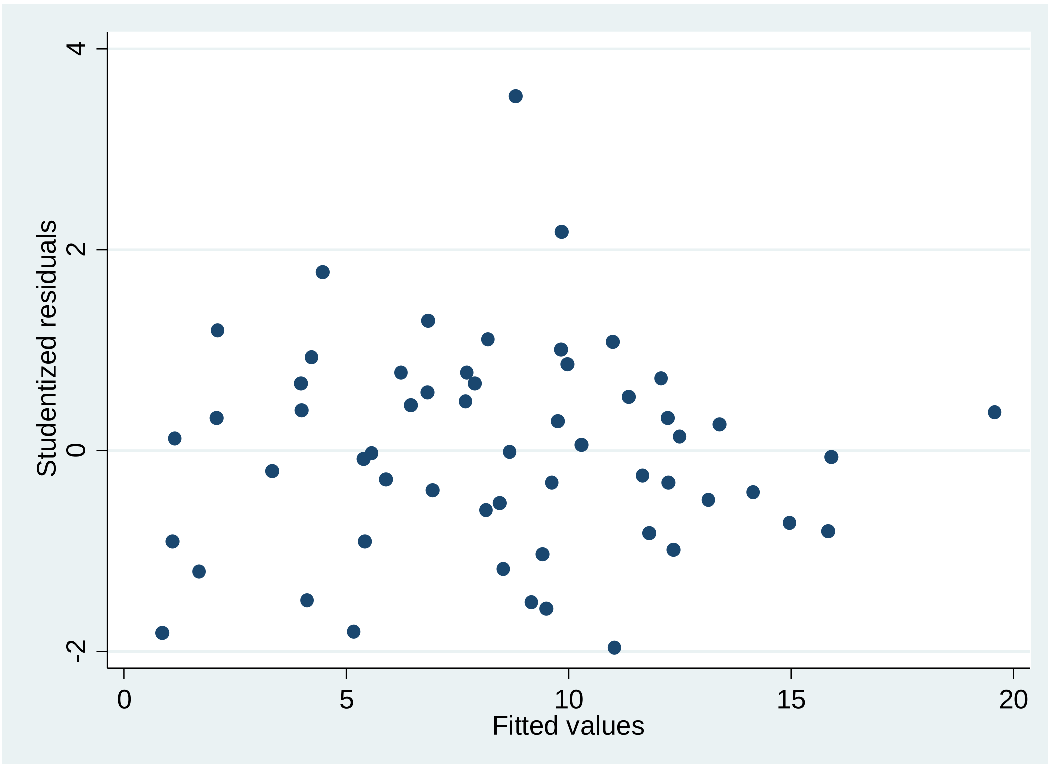
FINAL MODEL RESIDUAL PLOT FOR MAXIMUM KNEE VALGUS ANGLE AND INDEPENDENT STRENGTH VARAIABLES IN FEMALE DANCERS



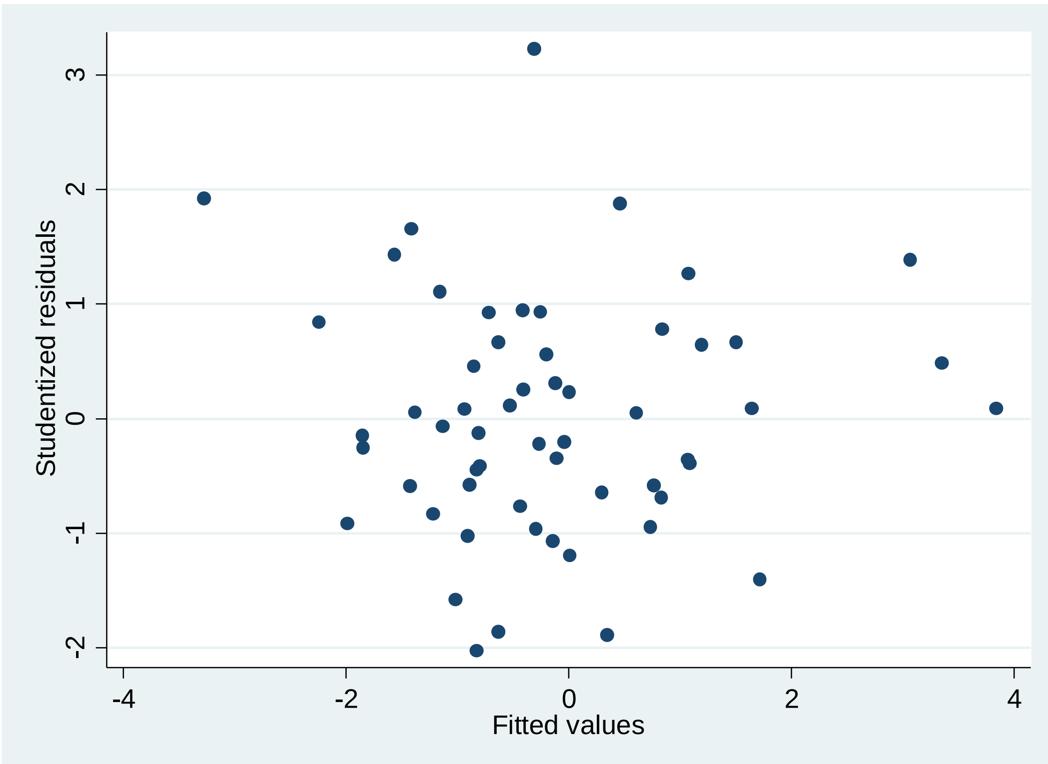
D.5 FINAL MODEL RESIDUAL PLOT FOR INVERSION ANGLE AT INITIAL CONTACT AND INDEPENDENT STRENGTH VARAIABLES



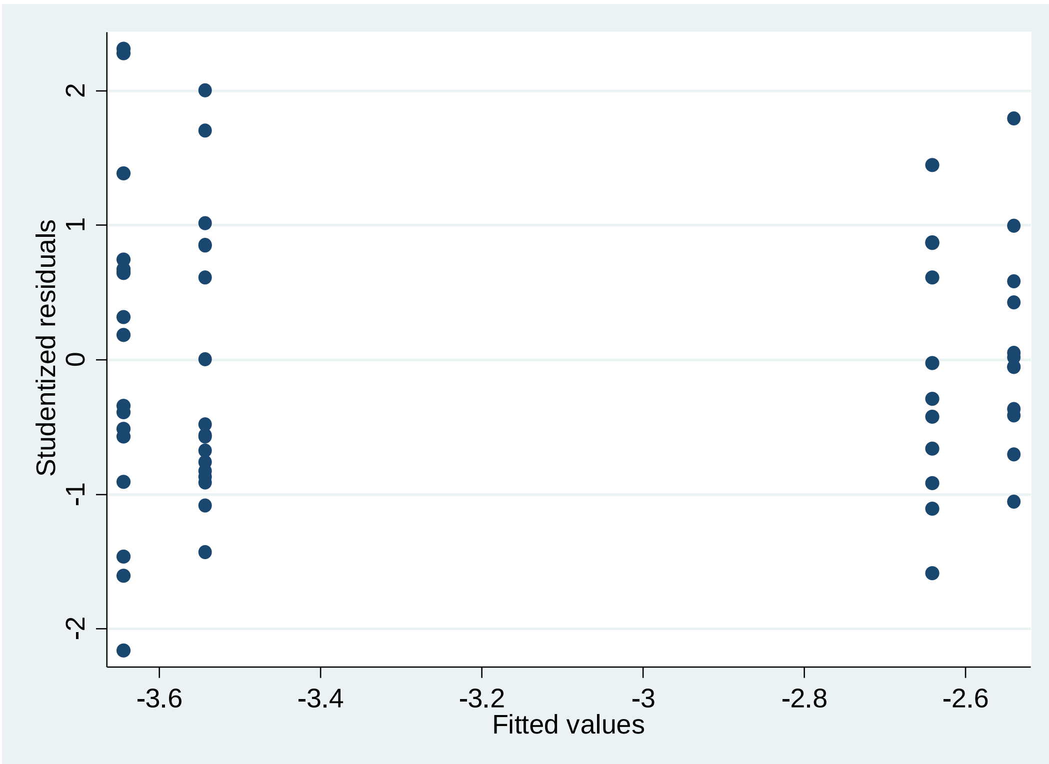
D.6 FINAL MODEL RESIDUAL PLOT FOR MAXIMUM INVERSION ANGLE AND INDEPENDENT STRENGTH VARAIABLES



D.7 FINAL MODEL RESIDUAL PLOT FOR PRONATION ANGLE AT INITIAL CONTACT AND INDEPENDENT STRENGTH VARAIABLES



D.8 FINAL MODEL RESIDUAL PLOT FOR MAXIMUM PRONATION ANGLE AND INDEPENDENT STRENGTH VARAIABLES



APPENDIX E

EFFECT SIZES FOR BETWEEN GROUP COMPARISONS

	All Subjects Effect Size	Female Subjects Effect Size	Male Subjects Effect Size
Body Fat (percentage)	0.60	1.12	0.60
Muscular Strength			
Trunk Extension (NM%BM)	0.53	0.24	0.94
Trunk Flexion (NM%BM)	0.71	0.31	1.66
Right Trunk Rotation (NM%BM)	0.31	0.20	0.90
Left Trunk Rotation (NM%BM)	0.22	0.07	0.60
Hip Abduction (kg%BM)	0.77	0.40†	0.85
Hip Adduction (kg%BM)	0.67	0.30†	0.88
Hip External Rotation (kg%BM)	0.82	0.52	1.39
Hip Internal Rotation (kg%BM)	0.81	0.71	1.19
Knee Extension (NM%BM)	0.37	0.21	0.62
Knee Flexion (NM%BM)	0.73	0.56	1.14
Ankle Inversion (kg%BM)	0.51	0.49	0.21†
Ankle Eversion (kg%BM)	0.42	0.42	0.48
Dynamic Postural Stability			
DPSI	0.04	0.15	0.29
MLSI	0.46	0.50	0.35
APSI	0.17	0.11	0.56
VSI	0.05	0.19	0.33
Initial Contact Angles			
<u>Trunk</u>			
Flexion (°)	0.38	0.04	0.81
Lateral Flexion (°)	0.11†	0.23	0.03
Rotation (°)	0.16	0.11	0.20
<u>Pelvis</u>			
Flexion (°)	0.01†	0.08	≤0.01†
Lateral Flexion (°)	0.55	0.20	1.19

Rotation (°)	0.11†	0.11	0.21†
<u>Hip</u>			
Flexion (°)	0.03	0.00	0.12†
Abduction (°)	0.02	0.02	0.09
Rotation (°)	0.37	0.16	0.57
<u>Knee</u>			
Flexion (°)	0.02	0.34	0.47
Valgus (°)	0.17	0.43	0.15
Rotation (°)	0.00	≤0.01†	0.10
<u>Ankle</u>			
Flexion (°)	0.16†	0.04	0.84
Inversion (°)	0.01	0.38	0.53
Rotation (°)	0.49	0.62	0.26
<u>Foot</u>			
Flexion (°)	0.46	0.72	0.09
Inversion (°)	0.05	0.19	0.37
Rotation (°)	0.10	0.10	0.05†

Maximum Angles			
<u>Trunk</u>			
Flexion (°)	0.29	0.07	0.74
Lateral Flexion (°)	0.02	0.14	0.11
Rotation (°)	0.30	0.36	0.23
<u>Pelvis</u>			
Flexion (°)	0.14†	0.61	0.04†
Lateral Flexion (°)	0.07	0.45	0.65
Rotation (°)	0.21†	0.73	0.26
<u>Hip</u>			
Flexion (°)	0.37	0.58	0.01
Abduction (°)	0.18†	0.34	0.07
Rotation (°)	0.27	0.36	0.51†
<u>Knee</u>			
Flexion (°)	0.01	0.12	0.19
Valgus (°)	0.16†	0.70	0.22
Rotation (°)	0.40	0.43	0.45
<u>Ankle</u>			
Flexion (°)	0.23†	0.30†	0.12†
Inversion (°)	0.13	0.76	0.58
Rotation (°)	0.17†	0.54	0.07
<u>Foot</u>			
Flexion (°)	0.07†	0.14†	0.20

Inversion (°)	0.03	0.28	0.36
Rotation (°)	0.02	0.11	0.27

† non-parametric effect size

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