Spring 2019

Fascia Thickness and Mechanical Demand at the Ankle Joint during Dance Jumps in Classically Trained Ballet Dancers

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By

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Accepted in Partial Completion
of the Requirements for the Degree
Master of Science

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Master's Thesis

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Date: 24 May, 2019

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A Thesis

Presented to

The Faculty of

Western Washington University

In Partial Fulfilment

Of the Requirements for the Degree

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May 2019

Abstract

Ballet is an athletic activity that combines aesthetics and artistry with power and skill. One of the most athletic aspects of dance is observed during jumps. Many jumps in ballet involve takeoff from a single leg, but differ in propulsion direction. To assess differences in mechanical demand, two single leg jumps commonly trained in ballet were compared; a saut de chat (SDC) and a temp levé from a step (SLSJ). Fifteen female classically trained dancers with similar number of years of training (13.9 ± 5.0 years) were instrumented with lower body reflective markers and performed each jump three times on a force plate. The marker position data and ground reaction forces (GRF) were captured synchronously at 250 hz and 100 hz, respectively, using a Vicon motion capture system. Peak vertical GRF, average rate of force development (RFD), peak ankle moment and peak ankle power were measured and averaged across trials. Paired t-tests were used to determine differences between the SDC and the SLSJ. When compared to the SLSJ, the SDC displayed significantly higher peak vertical GRF ($p = .003$), RFD ($p = .002$), and peak ankle moment and power ($p < .001$). Analysis of effect size for these differences revealed a large effect size for all variables (Cohen's $d > .80$). In conclusion, results of this study indicate the mechanical demand of different dance jumps is diverse, which has implications for performance enhancement, injury prevention, and rehabilitation.

Acknowledgements

First, I would like to thank the faculty of the kinesiology department for their support and guidance on this project. I would also like to thank my research assistants: Carolyn Barbee, Haliegh White, Paul Sage, Jordan Orr, and Jelena Bojic, without whose help I would not have been able to complete this research. Additionally, Susan Haines of the dance department at WWU was integral to this project, consulting on dance terms and jumps, providing a standardized barre warm up routine, distributing recruitment materials to students in the dance program, and featuring in videos used during collection for demonstration purposes. Finally, I must thank my friends and family for their continuous support these past two years as I pursued my degree.

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Introduction

Ballet is a unique form of dance that requires a high level of athleticism while maintaining a specific visual aesthetic.[1,2] The artistic requirements of classical ballet dictate physical training and performance.[2] Unlike other forms of physical activity, performance of athletic acts such as jumps in ballet primarily serve to achieve the desired aesthetic rather than maximal performance. One of the most athletic aspects of ballet can be observed during jumping movements.[3] These movements place a high mechanical demand for rapid muscular effort on the lower extremity and are associated with injuries at the ankle joint.[4-12] Due to the prevalence of impact injuries,[4,8] a majority of previous research in the discipline of ballet has focused on the landing phase of the jump.[13-16] However, common injuries such as Achilles tendinopathy and Achilles tendon rupture are associated with the take-off phase of the jump.[11,12] While altered kinematics have been observed during the take-off phase of jump in dancers with Achilles tendiopathy,[17] no research has examined the kinetic demands at the ankle joint during the take-off phase of different ballet jumps in healthy dancers.

Many jumps specific to ballet involve rapid take-off from a single leg and place a high mechanical demand on the tendons and muscles around the ankle joint. Two of the most frequently performed jump types that have similar take-off strategies but differ in the landing technique are a jeté and a temps levé.[3,18] A jeté is a jump that takes off from single foot and lands on the other. The saut de chat (SDC) is a specific jeté in which a dancer takes off, jumps with high vertical and horizontal propulsive effort, performs the splits mid-air and lands on the opposite foot.[19] A temps levé is a jump type in which the dancer takes off and lands on the same foot. A common type of temps levé jump requires the dancers to take a single step forward and then take-off with propulsion mainly in the vertical direction (single leg step jump: SLSJ).[3]

From a mechanical perspective, single leg jumps such as SDC which involve a combined vertical and horizontal propulsion would place substantially greater propulsive demands on the lower extremity and the ankle joint compared to jumps such as SLSJ that primarily involve vertical direction propulsion. The mechanical demand on the lower extremity during jumping movements can be determined by examining peak vertical ground reaction forces (GRF) and the rate of force development (RFD).[20] Similarly, peak net joint moments and powers can be used to quantify the mechanical demand about the ankle specifically.[21-26] To date, no research has examined the differences in mechanical demand at the ankle joint during take-off phase of different ballet jumps. Determining these differences may provide insights for training progression,[19,27] injury risk,[6-11] and rehabilitation for dancers with Achilles tendinopathy.[10,28]

The purpose of this study therefore was to examine differences in the mechanical demand on the lower extremity and about the ankle joint in classically trained ballet dancers during two common dance jumps (SDC and SLSJ) that take-off from a single foot. We hypothesize that mechanical demand on the lower extremity and about the ankle joint is greater for the SDC compared to the SLSJ.

Methods

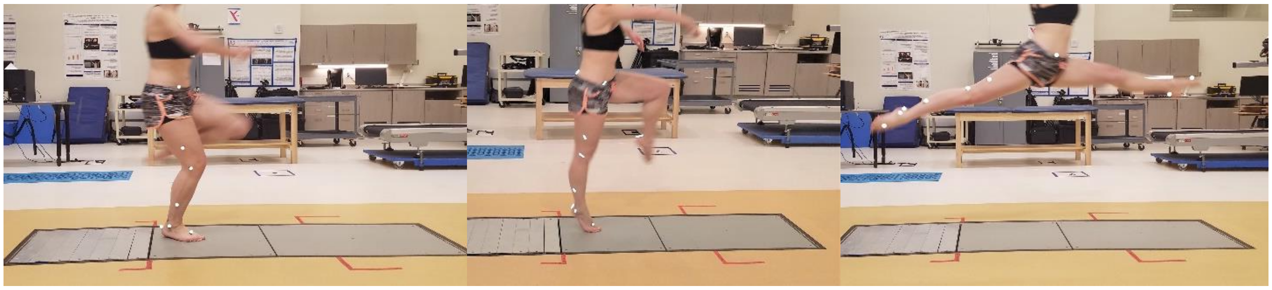
Participants: Fifteen female classically trained ballet dancers (age: 20.7 ± 2.7 years; height: 1.6 ± 0.1 m; mass: 56.4 ± 3.98 kg; training: 13.9 ± 5.0 years) participated in the study. The inclusion criteria included: no current injury, no major prior injury or surgery, no previous Achilles tendon (AT) tendinopathy, and >3 years training in classical ballet at the advanced level.[29,30] All participants signed a written informed consent prior to participation. The University Institutional Review Board approved the study.

Data collection: Participants completed a single testing session lasting approximately one hour. The session began with 10 minutes of standardized ballet barre warm-up exercises followed by measurement of anthropometric characteristics such as body mass, height, leg length, inter-anterior superior iliac spine horizontal distance, as well as knee and ankle widths. Participants wore tight fitting spandex clothes and 16 reflective markers were placed bilaterally on participants' feet, legs, thigh, and around the pelvis according to Vicon Plug-in-Gait lower body model guidelines (Centennial, Colorado, USA). Three-dimensional lower extremity marker position data were collected using a 10-camera Vicon motion capture system (Vantage V8, Centennial, Colorado, USA) at 250 Hz.[31-33] GRF and moment data were collected using two AMTI in-ground force plates (Advanced Mechanical Technology Inc.,Waterton, MA, USA) sampling at 1000 Hz.[30]

Each participant performed the two different jump conditions: SDC and SLSJ [3,18,19] with their preferred take-off leg in a random order. Preceding each jump condition, participants were shown a video of the jump and then they performed three familiarization jumps on the force plate. The participants then performed three successive jumping trials for each jump condition.[13] Marker position and GRF data were captured synchronously using the Vicon Nexus software

(Vicon Nexus version 2.6, Centennial, Colorado, USA). During the jumps, the dancers were encouraged to give maximal effort. The jump conditions were separated by a 1-minute rest period.[34,35] SDC with lower body marker placement is shown in Figure 1.

Figure 1. SDC and lower body marker placement.



Data analysis: Duration of the take-off phase of the jump was defined from the instant of the dancer stepping on the forceplate (i.e., when vertical GRF exceeded 20 N) [36,37] to becoming airborne (i.e. when vertical GRF was 0 N). All dependent variables were identified during the take-off phase of the jump. The GRF data were normalized to body mass and then the peak values were identified for the vertical component of GRF for each trial. The mean rate of force development (RFD) was computed as the slope of the change in GRF from minimum to peak and the corresponding change in time. Using marker position data, a rigid 7-segment linked lower extremity model was created via the Vicon dynamic Plug-in Gait pipeline. Markers placed on the lower body segments were used to create rotational matrices for calculating cardan segment and joint angles. A flexion/extension, abduction/adduction, internal/external rotation sequence was used. Segment masses, centers of mass locations, and moments of inertia were estimated using anthropometric measurements and Dempster's equations were used to calculate joint moments. The angular and center of mass velocities and accelerations of each segment were calculated using finite difference equations. An inverse dynamics approach was then used to determine sagittal plane net joint moments and forces at the ankle joint via the dynamic Plug-in Gait pipeline in Vicon Nexus.[38] For each trial, peak moment and power values were identified for the take-off phase and then normalized to body mass. For all variables, the data were averaged across the three trials for each condition.

Statistical analysis: For each variable, paired t-tests were used to determine differences between the SDC and SLSJ conditions. The alpha level was set at 0.05. The effect sizes were calculated as Cohen's d. Small, medium, and large effect sizes correspond to Cohen's d values of 0.20, 0.50, and 0.80, respectively.[39] All statistical analysis was performed using the SPSS software version 25 (Chicago, IL, USA, 2011).

Results

For one participant, we were not able to obtain maker position data due to a technical error. Therefore, peak ankle moment and peak ankle power were reported for 14 participants whereas peak vertical GRF and average RFD were reported for 15 participants. All dependent variables were significantly higher during the SDC than during the SLSJ ($p>0.05$; Table 1). The mean difference between conditions for all variables was large (Cohen's *d* > 0.80; Table 1), with the difference between peak ankle power showing the largest effect size (Cohen's *d* = 2.290). Additionally, all dancers showed very similar jump profiles for vertical GRF, ankle moment, and ankle power during the propulsive phase of the jump. Representative data for vertical force, ankle moment, and ankle power during take-off are presented in Figures 2-4.

Table 1. Kinetic variables for the take-off phase of SDC and SLSJ

	Saut de Chat	Single leg Step Jump	t-value	*p*	*Cohen's d*
Peak Vertical Force (N/kg)	23.2 ± 2.7	21.2 ± 2.3	t_{14}=3.53	.003*	.914
Mean RFD (N/kg/s)	103.3 ± 35.6	74.4 ± 17.8	t_{14}=3.83	.002*	.987
Peak Ankle Moment (Nm/kg)	3.03 ± 0.40	2.61 ± 0.38	t_{13}=4.68	<.001*	1.238
Peak Ankle Power (W/kg)	20.7 ± 4.7	15.6 ± 3.5	t_{13}=8.53	<.001*	2.290

* denotes significant difference ($p<0.05$)

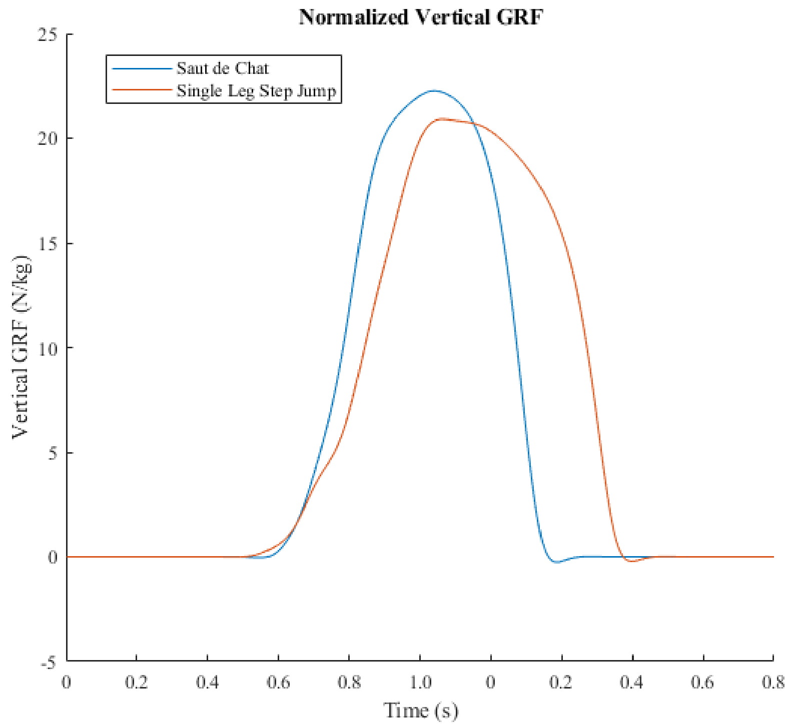


Figure 2. Showing GRF during the take-off phase in the vertical direction for both jumps.

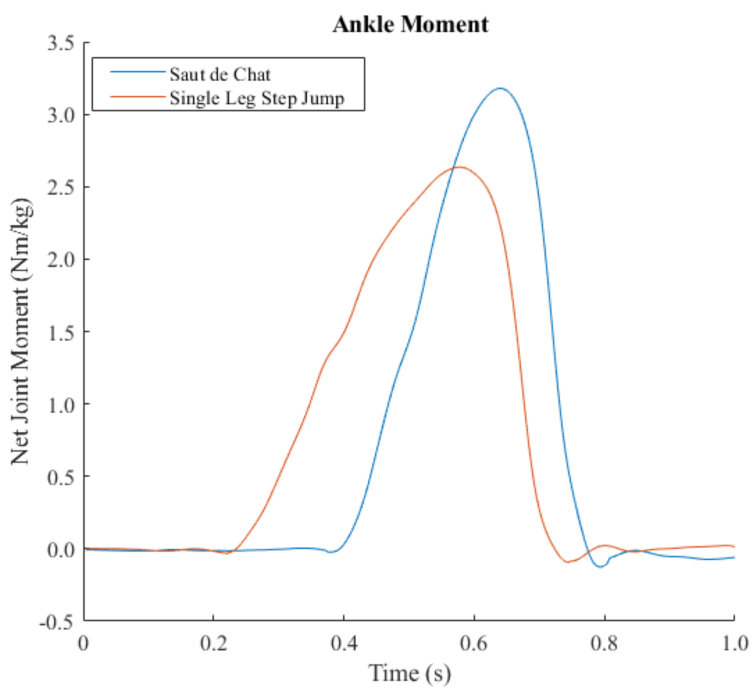


Figure 3. Showing net ankle moment during take-off phase of both jumps.

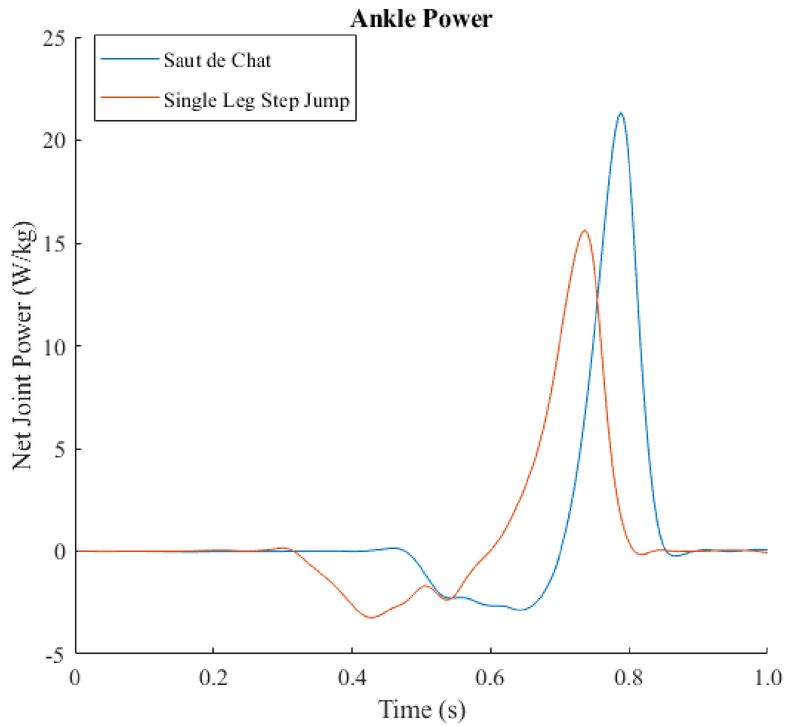


Figure 4. Showing power at the ankle joint during the take-off phase of each jump.

Discussion

The results of this study support our hypothesis. The lower extremity mechanical demand during the take-off phase was greater for the SDC jump, which showed greater peak vertical GRF and RFD, when compared to the SLSJ. The effect sizes of the difference in the jump conditions for both RFD and peak vertical GRF were large, indicating that the difference in lower extremity demand between the two jumps is meaningful. Similarly the mechanical demand, specifically at the ankle joint, was greater for the SDC when compared to the SLSJ as indicated by greater peak net joint moment and positive power. The effect size for peak ankle moment and power were also very large. This indicates meaningful differences in mechanical demand at the ankle joint between these two jumps. All variables showed the same trend, indicating that the SDC elicits a greater mechanical demand when compared to the SLSJ.

These net joint moment and power data imply that a high demand is placed on the AT during jumping movements in ballet specifically during the take-off phase. During the entire take-off phase, the net ankle moment was plantarflexor (figure 3) and, simultaneously, the net ankle power was predominately positive (figure 4). The ankle moment, which accelerates the body upward and forward,[21] differs in magnitude depending on the direction of the jump.[26] The concurrence of plantarflexor moments and positive power suggest that the plantarflexors would be acting concentrically.[40] Because primary plantarflexors are gastrocnemius and soleus, the concentric actions of these muscles would pull on and increase tension on the AT, thereby transferring the moment and power to the ground needed for the jump take-off.[21,24] This concentric plantarflexor action places tensile stresses on the AT. Based on the repetitive nature of dance movements, these stresses may contribute to the high prevalence of development of overuse injury at the ankle and Achilles tendinopathies associated with the takeoff phase of jumps.[5,7,8,17]

Further analysis of the moment and power data reveals that the rate of increase in power was more rapid and the magnitude of the extensor moment were greater during the SDC than SLSJ. The SDC requires both vertical and horizontal movement, and a substantial flight time is required to achieve the mid-air splits and horizontal movement required of that specific jump.[3,18,19] In contrast, the SLSJ is primarily a vertical jump.[3,18] When comparing jumps with movements in either vertical or horizontal directions, peak ankle moments and powers are often larger and occur later during vertical jumps than horizontal jumps.[26] The combination of vertical and horizontal movement required by the SDC results in even greater peak ankle moment and more rapid power increase than the vertical only jump. Therefore, the moment and power is greater during the SDC due the need for both forward and upward propulsion,[21] as opposed to just vertical propulsion as in the SLSJ. This rapid increase in tension on the musculature and tendons at the ankle joint places a high stress on the AT during the take-off phase of the jump. These data indicate that the tension and the rate of increase in tension on the AT would be greater for SDC compared to the SLSJ, and may further elucidate the mechanisms behind the high prevalence of Achilles tendinopathies in ballet dancers.

Although there is limited research on ballet jumps, the data collected in the current study is similar to data collected by Jarvis and Kulig.[19] During the SDC leap take-off, Jarvis and Kulig found high vertical GRF (approximately 3 bodyweights) and a large ankle plantarflexor moment (3.25 Nm/kg).[19] These data are slightly higher than the measured vertical GRF and moment in this study (2.36 bodyweights; 3.03 Nm/kg), likely due to differences in jump approach. Additionally, Jarvis and Kulig found that the overall contribution of the ankle joint was greater during the take-off phase of the jump compared to during jump landings.[19] This indicates that the take-off phase is particularly taxing to the ankle joint, and often results in overuse injury.[11,12]

Differences in demand between these jumps may be explained by how they are used in practice and performance. The SDC is trained as a more powerful jump compared to jumps such as the SLSJ.[3] Additionally, the aesthetic demand of each jump may actually temper a "maximal effort" jump by determining the optimal jump execution based on the timing of the musical cue or the intended effect of the jump.[2] This implies that the demand at the ankle joint for different jumps may be indicative of the desired outcome which for the SDC is a larger, more powerful jump. These considerations may also determine how often a jump is practiced and to what degree of effort. The repetitive nature of ballet training,[7,8] combined with the need to meet a certain aesthetic requirement,[2] increases the risk of overuse injury and Achilles tendinopathies.[1,4,6] By determining the differences in mechanical demand at the ankle joint during the take-off phase of different jumps, the risk of injury due to overuse may be lessened.

Since the SDC places a greater mechanical demand on the ankle joint than the SLSJ, these two specific types of jump can be used progressively in training. This could prove beneficial for both beginner students and advanced students. Intensive ballet training often begins at a young age, and high demand movements that are introduced too early can impact the development of injuries.[41,42] Even in advanced training, by ensuring that lower demand jumps (such as the SLSJ) are performed adequately before training higher demand jumps (such as the SDC) the development of overuse type injuries may be mitigated.[43,44] This strategy could be applied at the beginning of the ballet season after the dancers have taken time off to ensure high demand jumps are not performed when the dancer may be in a slightly deconditioned state.[45] Similarly, this type of progression could be used in rehabilitation for ballet dancers with AT rupture[46] or chronic injuries. In fact, demand of the lower power SLSJ could be further reduced by limiting jump height until correct mechanics are observed, then increasing jump height of this jump, and then moving on to higher demand jumps. This would hopefully reduce the possibility of re-injury during rehabilitation by ensuring proper, progressive training of the tendon.

Some limitations to the current study include the testing of ballet jumps in isolation, as well as the modification to the jump approach. In ballet training and performance, jumps are never performed as a single movement, but are a part of a choreographed set of movements. Additionally, the SDC typically has a running approach,[19] as opposed to a single step approach. By controlling the approach strategy, we were able to reduce the variability in our data. In fact, with a running approach, the differences in GRF and net moment and power at the ankle between the SDC and SLSJ would have been even greater. However, by isolating the jumps the values measured in this study may not be indicative of true peak values achieved during ballet practice and performance. Another limitation to this study is that all jumps were tested with bare feet as opposed to ballet shoes. This aspect of the study was also intended to control for possible variability due to differences in shoe stiffness.[4,6,13]

Future studies should investigate the mechanical demand of other ballet jumps so a comprehensive progression based on mechanical demand at the ankle joint can be determined and applied to training and rehabilitation programs. Additionally, the effects of upper extremity kinematics on ballet jumps, specifically during the take-off phase, should be observed. Upper extremity kinematics often determine the aesthetic quality of the movement in ballet.[47] Therefore, upper extremity movement may play a large role in total take-off strategy, and may alter the demand at the ankle for specific jumps depending on the desired aesthetic.

In conclusion, the mechanical demand at the ankle joint is significantly greater for the SDC than the SLSJ. The results of the current study can be used to begin a compendium of ballet jumps organized by mechanical demand at the ankle. This has implications for injury prevention as well as potential for developing effective training and rehabilitation progressions for the classically trained ballet dancer.

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Review of Pertinent Literature

Introduction

Dance is a unique form of athletic training that combines power, endurance, flexibility and aesthetics.[1] A professional dancer is, in many ways, the same as any elite athlete; striving for optimal performance. Though there are many forms of dance, classical ballet is possibly the most unique since training must adhere to historical requirements of the art.[1] Flexibility and power in athletic training are not often emphasized together,[2-5] but in dance, a high level of both are required to execute difficult jumps that appear effortless.[1] The artistic requirements of classical ballet define the physical training and affect the definition of optimal performance. In other fields of athletic performance, height and distance are the most common goals, whereas in dance the primary objective is aesthetic appeal.[6]

The structural and physiological adaptations that occur due to dance training demonstrate how dancers develop different skills than athletes trained to a similar level in other fields. These specialized adaptations relate to the age a dancer begins professional training and specific adaptations that occur during adolescence,[7] as well as the extreme emphasis placed on flexibility training.[8] In a professional ballet, barre work incorporates long, slow, dynamic stretching as part of the daily routine, and can last for several hours. This type of stretching may affect the dancer's body and abilities through stimulation of connective tissues such as fascia.[8]

Fascia is a vast, multi-faceted, system of connective tissues that is continuous through all parts of the body.[9] Very little is known about fascia and, to date, it has mostly been studied during dissection. What has been discovered through observations of dissected fascia is that it contributes to the transmission of force in muscles.[9,10,11,12,13] The role of fascia in living, moving muscles and limbs is unknown, but the known contributions to muscle force elicit intriguing questions about the role of fascia in active force production. Just like muscles, fascia responds to training, and is continually remodeled in order to be mechanically adapted for its roles in developing and growing muscles.[14]

Tendons are one aspect of the fascial system, connecting bones to muscles and to the intra-muscular fascia. They are one of the most accessible ways to study fascia in action. The Achilles tendon (AT) in particular is often studied in relation to jump forces.[15,16] Rate of force development (RFD) is used as a measure of explosive strength, which is integral to dance performance. Several factors can affect RFD, including training,[2,3] muscle activation patterns,[4] lean muscle mass,[5] and, in females, hormones related to the menstrual cycle.[17] Menstrual cycle phase affects strength, force, and power in female athletes.[17] In order to study power in female dancers, it is necessary to compare data collected from subjects at the same stage in the cycle. Even considering all these factors, measured differences in RFD are not fully explained.[4,5] It is evident that dance training stimulates fascia in unique ways and this allows research to look at the potential effect fascia thickness could have on rate of force development.

Physiological and Structural Adaptations in Dancers

Classically trained ballet dancers, through a unique training mode that adheres rigidly to traditional practices and aesthetic requirements, show some intriguing trends in physiological adaptations. Research indicates that daily class barre work may not maintain high VO_2 and elevated heart rates long enough to cause adaptation.[1] However, during performance and soloist-role practice, heart rate, blood lactate and oxygen consumption approach maximal levels indicating high intensities and demand on both aerobic and anaerobic systems.[18] Schantz and Åstrand noted that the artistic requirements of dance movements may actually inhibit reaching maximal levels in performance.[18] Optimal performance in dance takes into account choreography and musical cues, which may not demand maximum jump height at all times. Even when maximal jump height is desired, the height is tempered by the necessary aesthetic of the overall movement. Training still focuses on increasing the power of these jumps, and therefore adaptations can be observed.[6]

Several structural adaptations are unique to dancers. Dancers have stronger isometric quadriceps strength (at peak force: approximately 450 Newtons) and greater lean thigh volume (2,076-3,214 cm^3) than active controls (approximately 325 Newtons; 1,631-2,391 cm^3).[6] Based on these measurements, higher and more forceful jumps were expected from the dancers, but no significant difference in jump height or force between groups was demonstrated. Dancers in this study did have significantly lower EMG recruitment of the rectus femoris muscle ($p < 0.01$), which could indicate different muscle recruitment patterns that may be attributed to training.[6] Another study found a trend in dancers towards more rapid as well as greater overall hamstrings activation both pre- and post- landing when compared to basketball players, indicating that female dancers may have lower extremity neuromechanics that develop differently from those of other athletes that jump.[19] These differences raise questions as to why the same jump forces can appear with lower muscle activation. One possible answer may be due to training-induced adaptations in the elastic components of the musculotendinous tissue, allowing dancers to derive more energy from elastic components.[6] Altered musculotendinous tissues indicate that classical dance training has sport-specific adaptations.

In addition to the changes elicited by training, classical dance training also shows altered patterns of detraining. Within most athletic fields, there is usually a rapid detraining effect; often only a few weeks.[20,21] Some studies, however, report an unexpected lack of detraining effects in dancers following weeks of rest. When dancers were tested at the end of their performance season and again after a six-week break, an increase in flexibility (15%), leg strength (16%), VO_2 max (10%), and peak anaerobic power (14%) were observed.[22] Though this study was not directly compared to other athletes, these inconsistencies in measured detraining effects between other athletes and dancers indicate different adaptation mechanisms.

Adaptations to Training as an Adolescent

Dance training usually begins at a very young age, with professional-trajectory classes commencing as early as age eight,[7] and sport specific adaptations can be observed. In dance, there is a marked decrease in femoral torsion depending on the intensity of training,[23] as well as an increase in bone mineral content depending on hours of training between the ages of ten and twelve.[24] These beginning years are integral to the development of the classical dancer.

A high level of physical activity at an early age in any sport has an effect on the development of muscles and other aspects of physical fitness. Several studies on the effects of athletic training at a young age have found that younger muscle and tendons have unique abilities to adapt due to hormonal influences. In a study on adolescent females, researchers found that training elicited an adaptation in the growth hormone-insulin-like growth factor system, resulting in a hormonally expressed anabolic state.[25] This system of growth hormones and mediators modulates growth in many tissues, and is especially active in adolescents. The observed adaptations suggest the possibility that the combination of circulating levels of insulin-like growth factor (IGF-I) and its binding proteins in young girls before puberty optimizes muscle growth and fitness.[26] This anabolic state supports rapid adaptations to muscles and tendons based on the type of training.

Some studies on adolescent athletes found imbalances between muscle and tendon adaptations. A year-long study comparing young athletes with controls found that athletic training caused fluctuations in muscle strength. These variations in measured muscle strength at each three-month interval were not accompanied by adaptive responses in the tendon, consequently placing higher amounts of strain on the tendon as the muscle developed.[27] In a longitudinal two year study, Messerman, et al. found that the tendon shows greater morphological changes than the muscle in response to strain placed on the tendons as muscles develop from mid to late adolescence (ages 16-18).[28] In both studies the imbalance between muscle and tendon adaptation indicates a greater potential for injury.

These studies focused on adaptations to the patellar tendon but other tendons in the lower limb are similarly stressed since they are also load bearing.[29] Training causes adolescent athletes to have tendon thicknesses similar to thicknesses measured in adults.[30] Achilles and patellar tendon measurements using ultrasonography reveal that, at maximal thickness, adolescent athletes have average Achilles tendon (AT) thicknesses of 5.6 ± 0.7 mm for males and 5.3 ± 0.7 mm for females. Average adult AT thickness ranges from 4-6 mm. The patellar tendon (PT) showed a similar trend, 3.7 ± 0.5 mm for male adolescent athletes and 3.4 ± 0.5 mm for female adolescent athletes. Adult PT thicknesses average 3.0-4.2 mm.[29] While these types of adaptations may not be limited to training as an adolescent, adaptations to muscles and tendons occur faster during this developmental stage.

Achilles Tendon Adaptations to Training

The AT, like most tissues involved in the movement of the human body, is often studied to ascertain potential effects of training and injury on lower limb movement.[15,16] Several studies record differences in AT properties such as thickness, length, and fiber properties among individuals involved in a range of athletic activities including running, jumping, kayaking (as a non-load bearing control) and traditional Nigerian dance.[15,27,31] Jumping athletes had 17.8% greater AT stiffness and 24.4% greater Young's modulus (tensile elasticity) in their jump leg compared to lead leg.[15] Even between dominant and non-dominant legs, there is a long term effect of loading patterns on the mechanical and morphological properties of the AT.[32] In a brief review, Kannus et al. state that the effects of physical training may alter the properties of tendons such that they are larger, stronger and more resistant to injury.[33]

Certain training adaptations to the AT, such as thickness and cross-sectional area (CSA), take much longer to appear than typical muscle adaptation. While early precursors, like stiffness and internal components, can be measured in the tendon after a few months of training,[21] physical adaptations can take years. Most studies performed over a time span of less than a year did not see measurable differences in AT thickness or CSA.[21, 33,34] These studies indicate the effect of long term training on tendon adaptation.

Comparisons between various athletic activities show that trained athletes have adaptations to their AT that are not present in controls.[29] Ultrasound has often been used to non-invasively study tendons. It is a generally well accepted method for measuring tendon thickness,[31] cross sectional area, length, and injuries.[11,35] Standard reference measurement of the AT is at 2 cm proximal to the calcaneal insertion,[37,38,39] but some studies also use AT maximal thickness.[29]

The AT broadens and flattens as it descends to its insertion on the calcaneus, and has a maximal thickness of 4-6.7 mm in an untrained person, though thickness may increase in athletes due to training.[35] In a longitudinal, three-year study, athletes ages 18-25 had higher AT thickness than controls both at the beginning and at the end of the study ($p < 0.001$). Measured AT thicknesses at 2 cm proximal to the calcaneus were 5.1 cm for athletes and 4.6 cm for controls. At the maximum AT thickness, 5.8 cm and 4.8 cm were measured, respectively.[29] There was no significant change over the course of the study within groups, indicating that tendon thickness adaptations to training mostly occur at a younger age. Other studies found that athletes had significantly thicker AT (5.43mm) than untrained subjects (5.08mm),[36] as well as larger Achilles CSA.[11]

Since classical dance training and performance includes jumping, there are adaptations to a dancer's AT. Some aspects of the AT have been researched in dance, such as stiffness[19] and potential for tendinopathy/overuse injury,[40] but the effects of classical ballet training on AT thickness has not been studied to date. The unique adaptations to a dancer's muscles and tendons, combined with training-induced adaptations in the elastic components of the musculotendinous tissue,[6] imply that adaptations may occur in other less well researched tissues throughout the body. Adaptation to the AT in dancers is particularly intriguing because tendons are a part of the complex system of connective tissue called fascia.

Fascia Function

The study of fascia, and how fascial connections can affect human movement, is a relatively new area in exercise science research. Early understanding of the term fascia was limited, and was used only to describe some connective tissues observed in and around muscles. Fascia is not a simple structure but a vast, multi-faceted system that connects all parts of the body with many distinct structures that vary in function.[9] Huijing and Langevin proposed that the definition of fascia include the structures of the dense connective tissue (ie tendons), the areolar connective tissue, the superficial fascia, the deep fascia, the inter-muscular septa, the interosseal membrane, the periost, the neurovascular tract, the epimysium, the intra- and extra-muscular aponeuroses, the perimysium, and the endomysium.[41] More recently the fascia nomenclature committee has defined fascia as a three-dimensional continuum of soft, collagen- containing, loose and dense fibrous connective tissues that permeate the body.[42] The vastness and complexity of this system make it necessary to consider fascia's connective role to other systems.

While fascia research has recently increased at a near exponential rate,[41] understanding of the various functions of the tissue are still elusive. Some functions have been clearly identified through experimentation using rats, as well as through dissection. During anatomical dissections in medical training fascia has historically been less emphasized and is often discarded.[9] Observations of fascia in dissection have shown that cutting the fascia releases up to 50% of the normal pressure generated by muscle contraction and decreases force produced by muscle.[43] Additionally, measured passive forces decrease as normal connective tissues are removed.[44] One of the most important implications of fascia analysis through dissection is the fascial contribution to the contractile force of muscle. By removing fascia from any of the surrounding tissues the full effect of the fascia system is altered, and a clear understanding of function is limited.

The importance of fascia and its function is most clearly demonstrated in the living, moving body due to the fundamental differences in studying structure versus function. Study of structure, while it does give some insight into function, does not allow for complete understanding of how fascia works. To better understand this, study of the fascial system in living, moving limbs is gaining popularity.[45]

Fascial Training

With ever-growing knowledge about fascia, new aspects of the tissue are being studied. One of these areas is fascial training. Current views on fascial training suggest that long, slow dynamic stretch is optimal for stimulating the fascial tissue for regeneration and restoration.[8] Fascial stimulation is further defined as a dynamic muscular loading pattern in which the muscle is briefly activated in its lengthened position. This allows for the most comprehensive stimulation of fascial tissues and specifically targets renewal of the fascial net. The constant strain of daily training on specific facial areas causes matrix remodeling activity so that the tissue architecture can better meet demand.[8] Much like muscle hypertrophy, when repeated stress is placed on the fascia the tissue is damaged. The resulting mechanical microtrauma requires repair, causing rebuilding, strengthening, and growth of the fascia.[36] This is clearly observed in tendons.

Classical dance training focuses on flexibility and aesthetics; daily barre work emphasizes this type of long, slow, dynamic stretch.[8] Dancers selectively develop different flexibility characteristics than other athletes,[1] which is unsurprising as extreme flexibility in movement is one of the most distinctive aspects of classical dance training. Additionally, dancers are uniquely trained for "gentleness" in movement. The more the fascial spring effect is utilized, the quieter and gentler movement will be.[8] This implies that classical dance training enhances fascial effectiveness. A dancer's unique training regimen, with an emphasis on flexibility through slow, dynamic movement, combined with a focus on anaerobic training for power, provides an opportunity to study the fascial contribution to force.

Fascia and Force

That fascia contributes to force production is well accepted.[10,42,46] Exactly how this occurs is still being researched. When myofascial tissues are removed, measured contraction forces of the muscle fibers are diminished.[44] This implies the integral contribution of fascia to total force production. Early experimentation with fascia indicated that muscle fibers should not be considered independent functional units. Huijing et al. showed that force translates between synergist muscles,[47] as well as through the continuous endomysial fascia of the muscle.[10] This was contrary to previously held convictions that force was only transmitted to the muscle through the myotendinous junction. The implications of these early studies show that the tendon is able to transmit force to both the muscle fibers and the fascia layers within the muscle. Similarly, a study where force was measured at progressive levels of dissection again confirmed that there are other paths by which force can be transmitted than simply at the muscle-tendon junction.[44]

The focus changed from passive force enhancement when Schleip, Klingler, and Lehmann-Horn discovered that fascia might actively contribute to muscle contraction and force transmission through smooth muscle-like contractions.[48] More recently, Yucesoy, Baan, and Huijing, showed that contracted agonist muscles may transmit force directly to their antagonist muscles through intra-muscular fascial connections.[12] These studies have added to the understanding of fascia, but relative isolation of a muscle cannot give true results of the actual force that can be achieved in living, working muscle. The most accessible way to study fascia in the moving human body is through thickened areas at the ends of the intra-muscular fascia continuum.[49]

The dense connective tissue aspect of fascia includes tendons which are predominantly aligned Type I collagen fibers specialized for force transmission.[9] The literature indicates that fascial tissues throughout the body are completely interconnected,[42,50,51] therefore the behavior of the tendon under different conditions can allow a small insight into the potential function of the deep fascia layers. Since research has demonstrated that fascia is able to contribute to the contraction force of muscle, measuring rate of force development may elucidate the fascial contribution to jump forces.

Rate of Force Development

The rate of force development (RFD) is the minimal amount of time it takes to produce maximal force. RFD is typically used as an index of explosive strength,[52] and in assessing vertical jump performance.[53] There are many factors that influence force development, such as training,[2,3] muscle activation patterns,[4] lean muscle mass,[5] and differences between sexes. One common way RFD is measured is through jumping movements.[3,53]

There are clearly measured gains in force production and RFD based on training. Resistance training has long been considered an effective method for increasing contractile RFD.[54] Aagaard et al. reported a 17–26% increase in contractile RFD after 14 weeks of resistance training in male subjects without previous experience in resistance training.[4] Plyometric training also results in an increase in RFD during jump performance. An experimental group of conditioned male basketball players who performed drop jump training for six weeks significantly improved their RFD as measured in the knee from 1.5 s to 1.25 s when compared to controls.[3] Ballistic training also increased RFD in male volleyball players, increasing their RFD by 47% pre-test (approx. 7,500 $N \cdot s^{-1}$) to post-test (approx. 10,500 $N \cdot s^{-1}$).[55] How dance training may influence RFD has not been previously studied.

Training affects both the strength of the tissues involved in RFD and the neural drive efficiency, leading to more rapid muscle activations for desired movements. Muscle activation rate is considered one of the main factors in determining RFD, but measured differences in RFD cannot be explained fully by neural drive variations.[53] Lower-limb lean muscle mass may impact RFD as well. Bell et al. observed differences in lean muscle mass between limbs, measured with DXA, that can account for approximately 20% of measured force production asymmetry. Even incorporating lean mass differences, the factors contributing to RFD are not fully elucidated.[5] Knowing that fascia is integral to force transmission in the muscle,[10,43,46] it follows that fascia may also play a role in active force development and contribute to RFD.

Differences between the sexes also influence RFD. There are many dissimilarities between male and female athletes. Though most studies do not compare them, it is a necessary consideration when observing power and RFD. Comparing male and female beach volleyball players, Riggs and Shepard observed that, during a squat jump, the mean maximal RFD for males (7.76 ± 1.92 kN/s) was significantly higher than females (5.10 ± 1.47 kN/s), but did not find a significant difference during a counter-movement jump.[2] Using a reactive strength index to measure explosive strength in Division I athletes, Suchomel et al. found that, in an unloaded counter-movement jump, men produced an RFD of 5,338.9±1,818.9 $N \cdot s^{-1}$ and women produced 3,760.2±1,470.2 $N \cdot s^{-1}$.[56] These differences can be partially explained by obvious sex differences in average size and musculature, but hormones also play a role in the athletic variation between men and women, and even within female subjects.

Effects of Menstrual Cycle on Athletic Training

One main consideration when measuring power when jumping in female athletes is the menstrual cycle. Research supports the hypothesis that menstrual cycle phase has an effect on strength, force, and power in female athletes. This difference is due to differing levels of circulating hormones such as luteinizing hormone, follicle-stimulating hormone, and progesterone throughout the course of the cycle.[17] The two main phases of the cycle are the follicular phase (FP), which precedes ovulation, and the luteal phase (LP), which follows ovulation. The FP is associated with higher levels of androstenedione and testosterone, with these hormones typically reaching peak prior to, or at the time of, ovulation.[57]

Identifying the phases of the menstrual cycle that are relevant to exercise and force production is complicated. Some use blood analysis to track hormone levels,[58] while others take daily temperature readings to identify time of ovulation.[59] In various studies, the cycle is separated into as many as five phases,[60] though using two is more common.[58] One study differentiates menstrual cycle phases by late follicular and late luteal phase, with adjustments for individual variations in cycle length.[61] Still another study based their distinction on time points during the two main phases of the menstrual cycle, early FP and mid LP, when the largest contrast of hormones is measured.[62] The variety of methods utilized in this area of research does not clearly define a standard procedure for testing power based on phase timing within the menstrual cycle.

There is also disagreement in the literature about whether or not oral contraceptives affect physical performance. Some studies have found an enhancement of sustained aerobic performance in the luteal phase when subjects have a non-altered cycle, whereas those that used oral contraceptives showed no aerobic performance difference at different phases of the cycle.[63,64] In a study using high intensity exercise and blood lactate as a marker for intensity, no difference in blood lactate level was found between subjects with non-altered menstruation and those using oral contraceptives.[65] The incongruity in findings, coupled with vastly diverse test protocols and differences in defining the relevant phases of the menstrual cycle, adds to the complexity of studying female subjects.

Recently, studies have begun to focus on using cycle phases as a basis for strength training programming. Sung et al. found a significant increase in maximum isometric force during the FP training over LP training,[61] and Štefanovský et al. found better anaerobic performance in the luteal phase. This could be a result of larger phosphocreatine and adenosine triphosphate stores which can have a positive effect on high intensity performance.[66] Training based on cycle is relatively new, and the research focus is mainly on aerobic versus anaerobic differences, as opposed to focusing on phase training specifically for rate of force development.

Additionally, female sex hormones affect the healing process when recovering from athletic injury. To assess the effects of estrogen on Achilles tendon rupture in a physically active subject, Fryhofer et al. compared AT rupture healing in treadmill trained male, female and ovariectomized (OVX) female mice. At three weeks post injury, non-OVX female mice showed greater recovery in passive ankle ROM and stiffness as well as having more organized tissue regeneration in the tendon than male and OVX female mice when compared to pre-injury values.[67] This indicates a role of female sex hormones in the early recovery process, and continues to highlight the many differences between male and female athletes.

Hormones and athletics have a symbiotic relationship, each affecting the other in various ways.[17,58-61,66,68,69] The effects of dance training on female hormones is clearly demonstrated by frequent occurrence of late menarcheal onset and amenorrhea.[68, 69] The historical aesthetic focus of professional ballet almost demands a specific body type, especially for females. In order to achieve this ideal, many female dancers utilize unhealthy methods to maintain low body weight.[68] Volume of training is used to keep energy expenditure high,[69] and eating disorders are common among the ballet community.[68] These factors often result in amenorrhea: less than 3 menstrual cycles a year. The potential for amenorrhea in dance subjects further complicates research of female ballet dancers.

Ballet Dancers as Athletes

Ballet dancers are not often considered for study in the exercise science field, though some studies have focused on dance and athletic performance. Perhaps one of the most athletic aspects of ballet is jumping. Jumping movements place high demand on the lower extremity in dance, both in takeoff and landing. There are five basic types of jumps that are commonly observed in research. These jumps are defined by how the dancer takes off and lands.[70,71] The term sauté can refer to any type of jump in dance, but is commonly used to describe a jump from two feet landing on both feet. A jeté is a jump from one foot landing on the other, whereas a temps levé is a jump from one foot landing on the same foot.[70] Other common jump types are the assemblé (jump from one foot landing on two) and sissone (jump from two feet landing on one).[71] Typically trained as a part of daily rehearsals, these types of jumps are performed frequently by ballet dancers. The repetitive nature of this type of training places high demand on the lower extremity in dance, both in jump takeoff and landing.

The potential for injury in dance has long been observed.[72-74] Due to the repetitive nature of dance training, there is a propensity for overuse injury[75,76] specifically in the lower limb.[72,77] Overuse type of injuries such as tendonitis are often associated with the take-off phase of the jump, as opposed to jump landings.[73] Injury trends in classical ballet reveal that over half (54%) of injuries commonly reported in a professional ballet company occur at the ankle/foot. The percentage of ankle injury in female ballet dancers is even higher when they are considered separately from male ballet dancers (females: 62%).[76] Of these, two thirds of the injuries are related to overuse, with Achilles tendinopathies as the second most common injury; the most common injuries were ankle sprains.[76] Several environmental factors contribute to the development of tendinopathies in dancers. The type, speed and, repetition of movements, as well as footwear and ground surface can all increase the load on the body during movement and cause chronic tendon disorders.[73] All of these factors are often less than ideal during ballet training. High power jumps are performed repetitively on hard surfaces in pointe shoes which do not adequately support the foot or ankle for impact or propulsion.[1,72] Approximately one third of ballet dancers deal with some form of Achilles tendonitis during their career.[74] The Achilles tendon (AT) is particularly susceptible to overload in dance due to high demand placed on the ankle during most dance movements.[78]

Overall, ankle injuries due to overuse are still the most common injury in dancers.[75] Continued training with the tendon in a weakened condition will lead to additional and potentially more severe injury,[72] and ballet dancers often continue training despite pain.[76] Acute AT rupture, while more common in male dancers due to higher loading, is prevalent in all dancers and can occur when the tendon is placed under high load in either jump landing or jump takeoff.[79] However, tendon rupture is most common when a tendon is lengthened under load, as is common in push-off activities such as jumps.[80] This type of injury is typically repaired surgically, but often dancers will continue to experience pain.[81] The high incidence of injury at the ankle joint in ballet is concerning for the longevity of dance careers. While most research in the field of dance injury is focused on the landing phase of the jump,[82-85] the propulsive phase clearly contributes to overuse injury.[73]

Landing forces in dance jumps have been relatively well studied.[82-85] Simpson & Kanter observed that, as jump distance increases, both axial and shear forces in the ankle, knee, and quadriceps increase, along with greater ground reaction forces and joint flexion on landing.[84,85] Patellofemoral forces also increase with jump distance.[86] These indicate the increased risk of joint wear and injury as jump distances increase. Ground reaction forces (GRF) in the ankle have also been studied, comparing differences when landing en pointe versus rolling through the full foot. Chockley found a significant increase in GRF when landing en point.[82] Following ankle injury, changes in ankle joint angles and increased muscle activation for stabilization during jump landings were observed.[83] Dance jump takeoff kinematics have been studied in dancers with Achilles tendinopathy: pain or injury to the Achilles tendon.[78] Kulig et al. found that injured dancers had greater hip adduction and more knee internal rotation. These are considered to be compensatory mechanisms since no difference in foot and ankle kinematics was observed, even though the injury is in the ankle.[78]

To understand the total mechanical demand on the lower extremity during jumping movements, it is imperative to consider the take-off phase in addition to the landing phase. While there is a propulsive contribution from all joints in the lower limb during jump, the ankle may be the most important. Power transfer occurs during the second half of the propulsive phase,[87] and the ankle moment accelerates the body upward and forward.[88] Peak power of the ankle is higher than that of the knee and hip during jump takeoff in drop jumps,[89] and timing of ankle moment and power has been linked to jump performance.[89,90] When comparing vertical and horizontal jumps, peak ankle moments and powers are larger and occur later during vertical jumps than horizontal jumps.[92] Additionally, ankle moments and powers vary more than knee and hip moments and powers depending on the direction of the jump.[92] This observation is of particular interest when considering dance jumps due to the vast variety of jumps that require individual mastery in ballet. When observing a specific dance jump, the saut de chat, Jarvis and Kulig found high vertical GRF (approximately 3 bodyweights) and a large ankle plantarflexor moment (3.25 Nm/kg) during take-off.[93] Additionally, Jarvis and Kulig found that the overall contribution of the ankle joint was greater during the take-off phase of the jump compared to during jump landings.[93] This indicates that the take-off phase is particularly taxing to the ankle joint, and often results in overuse injury.[79,80] Specifically, the high demand at the ankle during the take-off phase increases the potential for tendinopathy and injury in ballet dancers.

Jump performance in classical ballet is integral to the sport. Not only must jumps be executed perfectly in time with musical cues, but each jump requires a very specific form.[94] On a fundamental level, dancers strive to achieve optimal performance and avoid career ending injury. The incidence of ankle injury in ballet training is high,[72-76] and is often related to the performance of jumping movements. While there is a deficit of research in the field of dance specific jumps, dance jump landings are more commonly studied to assess injury risk.[82-85] The take-off phase, which often results in overuse injury at the ankle and tendon rupture due to the loading demand,[79,80,93] is not well studied. Determining the mechanical demand of different types of jumps may provide insight to the injury risk and training potential of different movements.

Summary

Dance training elicits several structural and physiological changes that are unique to the field, with dancers developing different skills than athletes in other fields who are trained to a similar level. Traditional barre work exemplifies the long, slow dynamic stretch protocol recommended for fascial stimulation, causing adaptation and regeneration. As part of the fascial system, the Achilles tendon is impacted by dance training, and powerful jumps that are timed with the music are an integral part of dance performance. Since tendons are specialized for force transmission, the contributions of fascia to active force can be measured through jump performance. Due to the specific adaptations caused by dance training, lean muscle mass differences, tendon thickness, and hormone fluctuations may have a large impact on jump performance. Because dance training is extremely repetitive, there is a high incidence of injury, specifically in the lower extremity and at the ankle joint. When considering the overall demand of highly athletic movements such as jumping, the take-off phase contributes more to overuse type of injuries, especially of the AT. Determining the mechanical demand at the ankle joint by observing joint moment and powers during the take-off phase may provide insight into the mechanisms of injury of the lower extremity, specifically at the ankle joint. The purpose of the proposed study is to determine the relationship between RFD as a measure of power in dancers and fascia thickness as measured at the Achilles tendon. Additionally, this study aims to determine the differences in mechanical demand at the ankle joint through motion analysis, vertical ground reaction forces, and joint moment and power during the take-off phase of specific ballet jumps.

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Appendix A: Journal of Dance Medicine and Science Guidelines

Journal of Dance Medicine and Science

Journal guidelines to authors:

http://c.ymcdn.com/sites/www.iadms.org/resource/resmgr/imported/info/JDMS_Guidelines_for_Authors.pdf

Citation example provided by Journal of Dance Medicine and Science website:

Burrows HJ. Fatigue infraction of the middle of the tibia in ballet dancers. J Bone Joint Surg. 1956;38B(1):83-94

Appendix B: Fascia Thickness

Additional data collected as a part of this thesis project included Achilles tendon measurement, and several other jumps. Subjects with normal menstruation were asked to come for testing during the luteal phase of the menstrual cycle, approximately two weeks after the start of their most recent cycle. There is potentially an increase in anaerobic performance in this phase,[1] and this controls for the variation in hormones throughout the menstrual cycle.

There are many factors that contribute to the specific adaptations seen in dancers.[2] For professional dancers, the age of training onset is often very young.[3] Hormone levels related to growth and maturation cause development and adaptation to the muscles, bones, and tendons.[4,5] Research suggests that tendon hypertrophy occurs at this stage, since athletes that begin training at a young age have Achilles tendon thicknesses similar to adults.[6] The flexibility focus of a dance training regimen also causes unique adaptations to the dancer's body and abilities. Specifically, the long slow dynamic type of stretch exemplified by daily barre work affects the fascia.[7]

Fascia is a vast, multi-faceted, system of connective tissues that connects all parts of the body.[8] Very little is known about fascia and, to date, it has mostly been studied through dissection. What has been discovered through observations of dissected fascia is that it contributes to the transmission of force in muscles.[8-11] The role of fascia in living, moving muscles and limbs is unknown, but the known contributions to muscle force elicit intriguing questions about the role of fascia in force production. Just like muscles, fascia responds to training, and is continually remodeled in order to be mechanically adapted for its roles in developing and growing muscles.[12] Tendons are one aspect of the fascial system, connecting bones to muscles and to the intra-muscular fascia. Dance training likely has an effect on tendon adaptations due to loading patterns. Tendons are specialized for force transmission and are one of the most accessible ways to study fascia in action.[8]

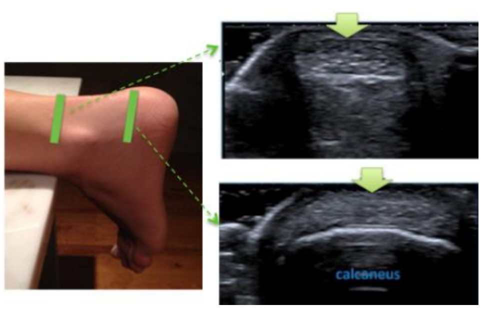
Jump performance in dance is very important. Not only must jumps be executed perfectly in time with musical cues, but each jump requires a very specific form.[13] Jump takeoff is affected by several factors including the rate of force development, as well as moments and powers at the ankle joint. Rate of force development (RFD) is often used to assess jump performance and explosive strength.[14] Training,[15-18] muscle activation patterns,[19] and differences between the sexes affect measured RFD.[20] Dance training includes high power jumps,[2] potentially making dance another style of training that enhances jump performance. To date, the effect of classical dance training on RFD has not been studied.

Differences in measured RFD between male and female athletes are to be expected, but a major contributor is female hormones. Research supports the hypothesis that menstrual cycle phase has an effect on strength, force, and power in the female athlete due to differing levels of circulating hormones.[21] These hormones, such as luteinizing hormone, follicle-stimulating hormone, and progesterone fluctuate throughout the menstrual cycle and have an effect on athletic performance in both aerobic and anaerobic performance. These hormones potentially enhance sustained aerobic capacity,[22,23] and increase anaerobic performance in the luteal phase (LP).[66] The effects of dance training on female hormones is clearly demonstrated by frequent occurrence of late menarcheal onset and amenorrhea.[24,25] The historical aesthetic focus of professional ballet almost demands a specific body type, especially for females. In order to achieve this ideal, many female dancers utilize unhealthy methods to maintain low body weight.[24] Volume of training is used to keep energy expenditure high,[25] and eating disorders are common among the ballet community.[24] Addressing the influence of menstrual cycle phase when researching power output enhances the ability to compare subjects and understand trends in the data. The potential for amenorrhea in dance subjects further complicates studying athletic attributes of the female ballet dancer.[26]

To date, no study has investigated the potential contribution of fascial thickness to the rate of force development in a healthy, uninjured dancer. Additionally, the effects of classical dance training on aspects of fitness parameters such as rate of force development and tendon adaptation has not been studied.

Methods: Each subject's Achilles tendon (AT) thickness was measured by ultrasound.[27] ATs were investigated in a prone position with feet hanging over the examination table and ankle passively dorsi-flexed to a neutral position. Ultrasound measurements of Achilles tendon thickness (transverse diameter) were measured at maximum mid-portion value (AT max) with strict orthogonal placement of the transducer on the AT.[6,27-30] Based on guidelines provided by the European Society of Musculoskeletal Radiology on normal ultrasound findings in the compartments of the ankle, the size of the Achilles tendon should be evaluated on the transverse plane, as the longitudinal axis may overestimate the tendon thickness because of its oblique course.[31] Figure 1 shows the normal Achilles Tendon in the transverse plane with transducer position.[31]

Figure 1.



All measured jumps included: A standard countermovement jump, a counter movement jump in turned out position, a saut de chat which is a jete type jump, and bilateral single leg jumps including a standard single leg countermovement jump, a single leg countermovement jump in turned out position and a single leg countermovement jump from a step approach. A Balanced Latin Square Randomization was used to determine the order of the jumps. The saut de chat (SCD), single leg countermovement jump (SLCMJ), single leg countermovement jump from a turned out position (SLCMJ-TOP), and the single leg jump from a step (SL-Step) from the preferred take off leg were used for analysis.

Data Analysis. Fascia thickness was analyzed using BodyMetrix^{TM} ultrasound equipment. A one-way ANOVA assuming equal variance was used to determine the differences between RFD in the four jumps from the preferred takeoff leg. Correlational analysis of the relationship between fascia thickness and RFD was determined using Excel software (Microsoft, Redmond WA).

Results

The single factor ANOVA with the alpha level set at 0.05 showed a significant difference in RFD between jump conditions ($p<0.001$). Subsequent t-tests revealed that all jump conditions were significantly different from each other ($p< 0.05$) except for the SLCMJ and SLCMJ-TOP ($p=0.87$; Figure 1). Correlational analysis revealed no significant correlation between AT thickness and average RFD in any of the tested jump conditions ($r = -0.11$ to -0.18). Table 1 shows mean and standard deviation of analyzed variables.

Table 1. Mean and SD of RFD for the four jump conditions and AT thickness of the preferred take-off leg.

	Mean	Standard Deviation
RFD – SDC (N/s)	5770.71	1757.18
RFD – SLCMJ (N/s)	2525.38	1018.08
RFD – SLCMJ-TOP (N/s)	2501.90	985.67
RFD – SL-Step (N/s)	4170.68	911.43
AT thickness preferred (mm)	5.0	0.46

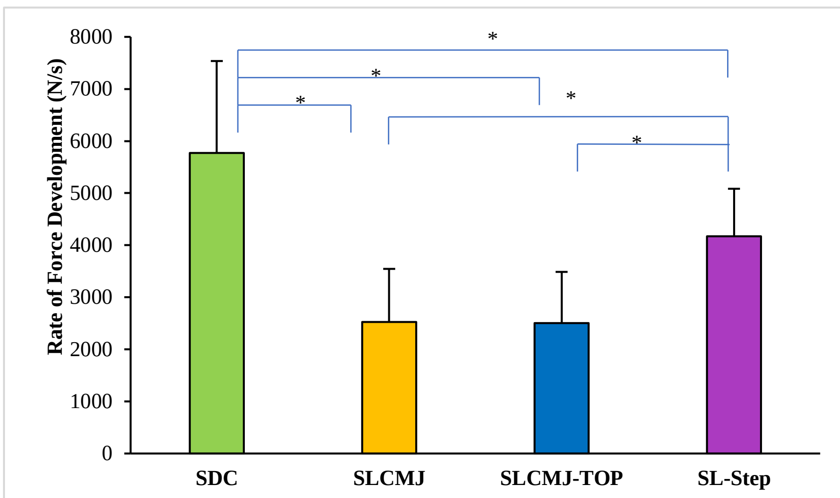


Figure 1. Average RFD between conditions: Saut de chat (SDC), single leg countermovement jump (SLCMJ), single leg countermovement jump in turned out position (SLCMJ-TOP), and single leg step jump (SL-Step). *$p < 0.05$.

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Appendix C: Raw Data

Descriptive, Achilles tendon thickness measurements:

Subject	Age (years)	Height (m)	Mass (kg)	Years of Training	AT thickness (mm) (preferred)	AT thickness (mm) (other)
1	22	1.59	57.5	18	4.5	5.0
2	18	1.525	50.3	14	5.3	4.3
3	20	1.67	56.1	10	5.3	5.1
4	19	1.57	58.5	9	4.4	4.3
5	22	1.64	57.5	17	5.1	5.2
6	22	1.55	50.1	13	4.2	5.0
7	23	1.53	56	20	4.6	5.0
8	21	1.66	59.6	8	5.4	5.9
9	28	1.58	50.7	22	5.2	5.2
10	18	1.59	54.3	9	5.5	5.5
11	21	1.68	65.3	5	4.5	4.5
12	18	1.52	55.4	15	5.2	5.6
13	21	1.625	58.2	17	5.8	6.0
14	18	1.69	57.8	19	4.8	4.3
15	19	1.62	58.7	12	5.2	4.0
Average	20.7	1.6	56.4	13.9	5.0	5.0
Standard Deviation	2.7	0.1	3.98	5.0	0.46	0.61

Non-normalized rate of force development of the four analyzed jump conditions (from preferred takeoff leg).

Subject	RFD-C1 (N/s)	RFD-C2 (N/s)	RFD-C3 (N/s)	RFD-C4 (N/s)
1	4110.38	2910.81	3056.76	3504.14
2	5551.49	2851.42	2653.48	4639.71
3	4177.82	1037.06	1589.83	3636.99
4	5761.44	2096.81	2289.79	4640.84
5	4805.57	3044.07	2869.07	4670.43
6	9370.47	3467.95	3615.93	4411.54
7	4450.14	2180.55	2189.55	3651.41
8	5646.60	4270.37	4831.99	5454.43
9	8195.60	2004.68	832.59	5477.89
10	2989.07	621.623	1760.35	1813.65
11	6591.01	1839.04	1581.29	4248.59
12	5475.57	3862.69	3320.21	4155.31
13	8387.37	1655.69	1742.24	3300.81
14	4856.92	2756.64	2743.16	4379.81
15	6191.20	3281.25	2452.29	4574.79
Average	5770.71	2525.38	2501.90	4170.68
Standard Deviation	1757.18	1018.08	985.67	911.43

Subject	Condition	Trial	Time: max unweight (s)	Fz: max unweight (N)	Time: peak Fz	Fz: peak	Mean RFD (N/s)	Peak Moment (Nm/kg)	Peak Power (W/kg)
1	1	1	1.296	20.51	1.582	1231.54	4234.39	2.256	19.26
1	1	2	1.367	22.15	1.655	1201.10	4093.59	2.483	22.24
1	1	3	1.643	20.29	1.938	1201.23	4003.17	2.475	23.12
1	4	1	1.107	22.46	1.432	1147.02	3460.18	2.355	17.56
1	4	2	1.03	21.87	1.342	1136.71	3573.18	2.262	16.68
1	4	3	1.271	22.19	1.588	1125.05	3479.06	2.218	14.07
2	1	1	1.000	20.46	1.21	1198.28	5608.67	3.148	15.99
2	1	2	0.963	21.44	1.179	1175.64	5343.55	3.068	15.9
2	1	3	0.832	22.59	1.031	1157.34	5702.28	2.909	11.96
2	4	1	0.343	21.57	0.601	1231.35	4689.10	2.974	14.25
2	4	2	0.967	20.67	1.233	1176.08	4343.64	2.846	13.42
2	4	3	0.771	22.49	1.012	1200.11	4886.40	2.829	12.63
3	1	1	0.765	20.16	1.04	1232.62	4408.96	3.259	24.57
3	1	2	0.777	20.37	1.063	1282.38	4412.62	3.28	28.51
3	1	3	0.576	21.12	0.885	1168.09	3711.88	3.111	24.31
3	4	1	0.649	21.53	1.035	1170.68	2977.07	3.126	20.28
3	4	2	0.792	21.79	1.109	1355.11	4206.06	3.588	22.33
3	4	3	0.895	21.86	1.241	1311.70	3727.85	3.721	25.73
4	1	1	0.37	20.03	0.621	1331.07	5223.29	3.251	24.24
4	1	2	0.673	22.26	0.918	1401.74	5630.53	3.492	29.52
4	1	3	0.405	21.95	0.631	1475.25	6430.50	3.463	28.72
4	4	1	0.576	20.60	0.829	1336.75	5202.18		
4	4	2	0.514	21.67	0.784	1282.08	4668.19	2.601	18.6
4	4	3	0.529	21.41	0.832	1249.21	4052.14		
5	1	1	0.978	21.66	1.255	1269.78	4505.84	3.14	21.63
5	1	2	0.827	21.42	1.073	1260.44	5036.65	3.092	18.92
5	1	3	0.733	22.92	0.993	1290.21	4874.20	3.152	21.14
5	4	1	0.816	20.82	1.082	1330.60	4924.00	2.893	16.09
5	4	2	0.588	20.79	0.881	1334.78	4484.60	2.965	17.45
5	4	3	0.597	20.67	0.882	1332.44	4602.70	2.86	16.29
6	1	1	0.99	20.38	1.153	1523.12	9219.27	3.785	23.17
6	1	2	0.976	24.28	1.118	1499.87	10391.46	3.741	22.05
6	1	3	0.957	23.67	1.125	1451.79	8500.68	3.563	21.93
6	4	1	0.921	21.56	1.181	1213.03	4582.57	2.679	15.64
6	4	2	0.885	21.78	1.14	1197.34	4610.02	2.654	14.36
6	4	3	1.058	21.83	1.331	1125.30	4042.01	2.526	14.43

7	1	1	0.794	21.10	1.034	1162.46	4755.67	2.591	17.66
7	1	2	0.783	20.22	1.038	1135.42	4373.34	2.468	15.22
7	1	3	0.981	22.50	1.242	1124.29	4221.42	2.496	15.63
7	4	1	0.863	20.78	1.139	1099.80	3909.50	2.096	13.57
7	4	2	0.819	21.21	1.068	963.06	3782.54	1.845	9.483
7	4	3	0.836	20.96	1.154	1058.34	3262.20	2.133	12.09
8	1	1	0.898	21.61	1.178	1233.92	4329.70	3.142	20.33
8	1	2	0.932	22.60	1.158	1220.16	5298.94	3.044	20.51
8	1	3	0.676	20.12	0.854	1321.51	7311.17	3.043	21.03
8	4	1	1.025	22.03	1.232	1171.77	5554.26		
8	4	2	0.811	22.20	0.986	1134.44	6355.66		
8	4	3	1.129	21.00	1.37	1094.26	4453.37		
9	1	1	0.995	21.04	1.168	1342.97	7641.23	3.423	21.8
9	1	2	0.999	22.11	1.17	1467.44	8452.20	3.757	22.68
9	1	3	0.954	22.74	1.108	1330.72	8493.37	3.413	18.97
9	4	1	1.08	20.04	1.34	1191.64	4506.15		
9	4	2	1.264	20.39	1.483	1311.54	5895.66		
9	4	3	0.902	20.34	1.113	1293.06	6031.86	3.043	14.94
10	1	1	1.393	21.71	1.721	1071.69	3201.15	2.77	25.93
10	1	2	0.877	21.10	1.23	1074.30	2983.58	2.584	17.98
10	1	3	0.91	20.30	1.269	1019.21	2782.47	2.531	19.99
10	4	1	0.852	20.28	1.354	927.40	1807.01		
10	4	2	0.965	20.39	1.525	918.58	1603.92	2.245	14.97
10	4	3	0.972	20.27	1.416	921.59	2030.01	2.126	13.74
11	1	1	1.31	21.17	1.533	1428.94	6312.87	2.797	18.31
11	1	2	1.282	20.00	1.485	1535.74	7466.68	3.179	21.33
11	1	3	1.21	22.13	1.448	1448.58	5993.48	2.933	17.76
11	4	1	1.239	20.69	1.574	1234.31	3622.74	2.199	15.5
11	4	2	1.121	21.84	1.407	1348.06	4637.15	2.634	15.61
11	4	3	1.264	21.43	1.561	1353.73	4485.87	2.782	16.3
12	1	1	0.827	20.84	1.035	1323.03	6260.56	2.898	16.18
12	1	2	0.702	20.07	0.92	1232.38	5561.06	2.758	16.33
12	1	3	0.623	20.29	0.859	1107.09	4605.09	2.419	14.51
12	4	1	0.876	20.35	1.163	1098.24	3755.73	2.185	10.7
12	4	2	0.688	20.13	0.932	1157.78	4662.52	2.343	12.59
12	4	3	0.272	21.34	0.538	1098.02	4047.68	2.229	10.25
13	1	1	0.893	20.90	1.053	1449.86	8930.96	3.168	18.7
13	1	2	0.893	22.29	1.06	1500.91	8854.00	3.244	21.01
13	1	3	0.834	21.18	1.027	1444.97	7377.16	3.201	16.32
13	4	1	0.696	20.98	1.002	1128.48	3619.28	2.533	12.74

13	4	2	0.802	20.84	1.132	1097.67	3263.14	2.501	14.98
13	4	3	0.916	20.31	1.257	1050.14	3020.01	2.422	13.49
14	1	1	0.814	20.76	1.077	1336.44	5002.58	2.755	14.33
14	1	2	0.878	20.95	1.157	1260.83	4444.02	2.596	16.37
14	1	3	0.932	20.94	1.184	1312.23	5124.15	2.803	15.11
14	4	1	0.856	20.19	1.147	1351.08	4573.52	2.685	13.61
14	4	2	0.618	21.17	0.909	1263.18	4268.09	2.591	11.67
14	4	3	0.869	21.83	1.158	1263.91	4297.83	2.516	12.38
15	1	1	0.821	20.57	1.034	1621.25	7514.95	3.42	31.47
15	1	2	0.734	20.59	0.99	1406.66	5414.31	3.296	29.41
15	1	3	1.253	20.80	1.509	1465.75	5644.32	3.297	30.48
15	4	1	0.735	20.22	1.034	1251.69	4118.61	2.666	22.76
15	4	2	0.837	20.82	1.101	1358.62	5067.45	2.85	24.07
15	4	3	0.835	22.11	1.099	1220.22	4538.30	2.531	20.3

Note: Red color indicates data for ankle moment and power that were unable to be analyzed due to technical error.

Appendix D: Statistical Analysis

Descriptive Statistics

	Mean	Std. Deviation	N
AT Thickness (mm)	5.0000	.46752	15
Mean RFD- SDC (N/s)	5770.7100	1757.18058	15
Mean RFD- SLCMJ_Step (N/s)	4170.6890	911.43511	15
Peak Ankle Moment SDC (Nm/kg)	3.0376	.38116	15
Peak Ankle Moment SLCMJ_Step (Nm/kg)	2.6125	.38135	14
Peak Ankle Power SDC (W/kg)	20.7229	4.55286	15
Peak Ankle Power SLCMJ_Step (W/kg)	15.6426	3.53508	14
Peak Norm Fz SDC (N/kg)	23.2131	2.74528	15
Peak Norm Fz SLCMJ_Step (N/kg)	21.1940	2.31953	15

Paired Samples Test

		Paired Differences							
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Pair 1	Mean RFD- SDC (N/s) - Mean RFD- SLCMJ_Step (N/s)	1600.02100	1566.19185	404.38900	732.69286	2467.34914	3.957	14	.001
Pair 2	Peak Ankle Moment SDC (Nm/kg) - Peak Ankle Moment SLCMJ_Step (Nm/kg)	.42237	.33743	.09018	.22754	.61719	4.684	13	.000
Pair 3	Peak Ankle Power SDC (W/kg) - Peak Ankle Power SLCMJ_Step (W/kg)	5.08743	2.23145	.59638	3.79903	6.37583	8.531	13	.000
Pair 4	Peak Norm Fz SDC (N/kg) - Peak Norm Fz SLCMJ_Step (N/kg)	2.01911	2.21855	.57283	.79052	3.24770	3.525	14	.003
Pair 5	Peak Fz SDC (N) - Peak Fz SLCMJ_Step (N)	113.65069	122.49633	31.62842	45.81449	181.48690	3.593	14	.003

T-Test

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	Mean RFD- SDC (N/s)	5770.7100	15	1757.18058	453.70208
	Mean RFD- SLCMJ_Step (N/s)	4170.6890	15	911.43511	235.33153
Pair 2	Peak Ankle Moment SDC (Nm/kg)	3.0349	14	.39539	.10567
	Peak Ankle Moment SLCMJ_Step (Nm/kg)	2.6125	14	.38135	.10192
Pair 3	Peak Ankle Power SDC (W/kg)	20.7300	14	4.72464	1.26271
	Peak Ankle Power SLCMJ_Step (W/kg)	15.6426	14	3.53508	.94479
Pair 4	Peak Norm Fz SDC (N/kg)	23.2131	15	2.74528	.70883
	Peak Norm Fz SLCMJ_Step (N/kg)	21.1940	15	2.31953	.59890
Pair 5	Peak Fz SDC (N)	1305.1161	15	139.21273	35.94457
	Peak Fz SLCMJ_Step (N)	1191.4654	15	117.06462	30.22596

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	Mean RFD- SDC (N/s) & Mean RFD- SLCMJ_Step (N/s)	15	.458	.086
Pair 2	Peak Ankle Moment SDC (Nm/kg) & Peak Ankle Moment SLCMJ_Step (Nm/kg)	14	.623	.017
Pair 3	Peak Ankle Power SDC (W/kg) & Peak Ankle Power SLCMJ_Step (W/kg)	14	.893	.000
Pair 4	Peak Norm Fz SDC (N/kg) & Peak Norm Fz SLCMJ_Step (N/kg)	15	.628	.012
Pair 5	Peak Fz SDC (N) & Peak Fz SLCMJ_Step (N)	15	.555	.032