LANDING BIOMECHANICS IN CLASSICAL BALLET

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ABSTRACT

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Objective: The primary aim of this study was to investigate interseason variability in the knee frontal plane projection angle (FPPA) at the impact phase of a single-leg drop-jump test in female and male professional ballet dancers. The secondary aim was to explore the effect of leg dominance and ankle dorsiflexion mobility on the FPPA.

Methods: Twenty-six professional ballet dancers (females *n*=14, males *n*=12) performed single-leg vertical drop jump tests at the beginning of the 2019-2022 seasons. FPPA was measured from the most profound knee angle of the impact phase of the single-leg drop jump. Self-determined leg dominance and a knee-to-wall test were used to measure other variables.

Results: Mean values for the knee FPPA varied from 0.3° to 3.1° in the right and from 1.2° to 2.6° in the left leg in female ballet dancers during the three study years. In male ballet dancers, the corresponding values were from 1.3° to 3.1° on the right and -3.9° to -3.1° on the left leg. There was a statistical difference in the FPPA of the left leg between females and males ($p<0.01$).

No intra-individual differences in FPPA were observed between the three study years. Also, no statistical difference was found in the change of FPPA values between males and females in the study years. When comparing dominant and non-dominant legs, there were no statistically significant differences in the FPPA between the legs and the study years. A correlation between increased knee valgus and decreased ankle ROM was found in this study in the dominant leg (-0.356) and in the non-dominant leg (-0.379) ($p<0.01$).

Conclusion: To our knowledge, this is the first study on the interseason variability of landing biomechanics in professional ballet dancers, showing no statistically significant differences between study years. This study indicated minor differences between female and male dancers' knee valgus position during the impact phase of a drop jump, and in knee control between dominant and non-dominant legs. The effect of ankle dorsiflexion mobility on knee control was confirmed with professional ballet dancers. This study provides more profound information on female and male dancers' biomechanics, which has not been investigated widely.

Keywords: Biomechanics, ballet, knee

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1 INTRODUCTION

Classical ballet is an aesthetic art form in which dancers perform precise movements in the music, expressing stories and feelings through the movement. Classical ballet has created formalized movements and positions designed to enable dancers to move lightly, gracefully and effortlessly.

Sports science research among professional ballet dancers has increased over the past 30 years, but the progress in this field has been slow because of ballet traditions and reluctance to utilize training principles from sports. Studies show ballet dancers' lack of physical condition, such as aerobic fitness and strength, and the potential risk for injuries. Ballet dancers are prone to overuse injuries because of the repetitive nature of training and prolonged training hours. Jumping is essential to ballet training and performances; dancers are exposed to jumping daily.

Landing biomechanics' relation to injury risk is investigated in sports science. Non-contact knee injuries are typical in female athletes, and one risk factor can be increased knee valgus angle. Female team sport athletes seem to have significantly higher knee valgus ankles compared to male athletes. Such a disparency has not been identified between female and male dancers. This could be reasoned by the basic ballet training, which relies on traditional ballet classes, similar for both females and males. Also, the nature of training is highly focused on neuromuscular training, in which controlling the alignment has a significant role.

The first part of this thesis is a literature review presenting previous sports and dance science findings related to dancers' physiological demands, biomechanical characteristics of jumping and landing, and their association with injury risk. Studies with professional ballet dancers are primarily used, but other dance genres and different levels of expertise may be used if there is a lack of studies with professional ballet dancers. To avoid confusion, the term "ballet dancer" refers to professional ballet dancers only, and the term "dancer" includes pre-professional level ballet dancers and dancers from other dance genres, such as contemporary dancers. Notably, female dancers were the main participants in these studies, and only a few studies included male dancers. Ballet companies use a ranking system to categorize dancers by skill level and determine their roles in classical ballet performances. Typically, four categories exist: principals, soloists, artists and corps de ballet. Names may vary between the companies, but this review uses this division.

The second part of this thesis is a research article examining a drop jump test on professional ballet dancers. The study's primary interest is knee control at the impact phase of the drop jump. The research aims to look at the interseason variability between three consecutive seasons. It also aims to investigate the differences between females and males and see the differences between dominant and non-dominant legs. Lastly, the effect of ankle dorsiflexion mobility on knee control is investigated.

2 PHYSIOLOGICAL DEMANDS OF CLASSIC BALLET

In ballet, many physical abilities are needed, such as endurance, strength, appropriate body composition and high joint mobility (Koutedakis et al. 2005). The extreme mobility and the control of the joints at the end of the range of motion are challenges for a dancer's physique, e.g. in complex jumps or high leg lifts (Deighan 2005).

The scheduled weekly dance and rehearsal hours in a large professional ballet company have been reported to vary throughout the season, from 19 to over 40 hours a week (Shaw et al. 2023). Another study reported that female ballet dancers training more than 30 hours weekly, including scheduled dance hours and additional training (Escobar Alvarez et al., 2020). However, the mean exercise intensity of professional female dancers remains relatively low, and only short rest periods are observed during the working day (Twitchett et al. 2010a).

2.1 Aerobic condition

Classical ballet is typically described as an intermittent type of exercise. Only one study by Twitchett et al. (2010a) has investigated the training volume and intensity closer, showing that mean exercise intensity stays relatively low (<4 MET) during the working day for most female ballet dancers. However, there are significant differences between rankings in the workload and the percentages spent in different intensities. The soloist had a significantly greater workload (4 MET) than the other groups, principals (3 MET), artists and corps de ballet (both <3 MET). Principal dancers and soloists trained significantly more in high and moderate intensities (5-15%) compared to artists and corps de ballet dancers (<5%) ($p<0.05$). The highest intensities ballet dancers reached were 11.2 MET ± 3.32 for principal dancers, 11.3 MET ± 4.02 for soloists, 9.7 MET ± 3.16 for artists, and 10.1 MET ± 3.83 for corps de ballet dancers. Also, the resting time varied between categories, with corps de ballet having the greatest work-to-rest ratio. They spent more time resting (<1.5 MET) than working throughout the day. It is crucial to note that this study was conducted only with female ballet dancers, and no corresponding information is available for male dancers.

Ballet dancers' aerobic capacity has been reported in several early studies. A review paper reveals that in different studies, female ballet dancers' VO2 max averages have been between 40.9 to 53 $mL \cdot kg^{-1} \cdot min^{-1}$, and male dancers between 43.8 to 59.3 $mL \cdot kg^{-1} \cdot min^{-1}$ (Twitchett et al. 2009). This wide variety of results indicates that ballet training does not create cardiovascular adaptations to training. Ballet class generates only low-aerobic workloads, but the rehearsals have higher intensities depending on the choreography (Rodrigues-Krause et al. 2014).

2.2 Strength, power and jumping

The jumping ability has been identified as one of the best predictors of dance performance. Dancers who could jump higher were able to implement a greater range of skills to fulfil the aesthetic components of dance (Angioi et al. 2009). Compared to other dance genres, higher jumping volume is observed in ballet (Wyon et al. 2011). Naturally, male dancers achieve a greater vertical jump height. One study reported significant differences between company rankings; averages for females were from 33.0 (principals) to 39.2 cm (artists), and from 50.5 cm (principals) to 56.0 cm (artists) in males ($p<0.01$) (Wyon et al. 2006). Another study reported lower values for female ballet dancers, with averages between rankings being from 26.1 cm (corps de ballet) to 33.7 cm (soloists) (Escobar Alvarez et al. 2020). Soloists seemed to have significantly greater vertical jump height for both females (39.2 ± 5.74 cm) and males (55.3 ± 4.99 cm) ($p <0.05$) (Wyon et al. 2006).

Jumping in ballet differs from jumping in general. Ballet dancers' hips are externally rotated in all ballet movements, and they attempt to maintain upright positions in their torso and pelvis during jumping (Imura & Iino 2017). When comparing jump height in ballet-specific jumps and typical CMJ, dancers jumped significantly less while jumping in ballet style (Imura & Iino 2017).

A study by Escobar Alvarez and colleagues (2020) examined female ballet dancers' force-velocity relationship. They found that all dancers, despite the ranking, were velocity-oriented and showed a lack of force production. Researchers suggest that a high or low force deficit may negatively affect dancers' jumping ability and, therefore, the quality of their performance.

2.3 Joint range of motion

Ballet dancers need an extreme range of motion, mainly in the hip and ankle joints, for the positions required in ballet. Most ballet training happens in the "turnout" position, which means the maximum external rotation of the hip and the whole lower extremity. Ballet dancers' bony morphology measures from the hip show that they fall within normal values but differentiate from athletes. The study by Mayes et al. (2017) looking for bony differences between ballet dancers and age-matched athletes found that dancers had higher neck-shaft angles (dancers 134.6° ± 4.6°/ athletes 130.8° ± 4.7°, p=0.002), lower acetabular version angles (13.5° ± 4.7°/ 17.1° ± 4.7°, p=0.003), lower superior alpha angles (38.9° ± 6.9° / 46.7° ± 10.6°, p<0.001), similar anterior alpha angles (43.6° ± 8.1° / 46° ± 7°, p=0.2), and similar lateral centre edge angles (28.8° ± 4.6° / 30.8° ± 4.5°, p=0.07) compared to athletes. All of these are beneficial for the hip joint in producing greater movements. Also, some abnormal morphology was detected in dancers: 3% acetabular dysplasia (athletes 0%), 15% borderline dysplasia (6%), 24% cam morphology (33%), 24% coxa valga (6%), and 21% acetabular retroversion (18%).

However, "turnout" is a combination of whole lower limb mobility. Together with the hip, there is a contribution from knee rotation, tibial torsion, and ankle and foot mobility (Grossman et al. 2008; Quanbeck et al. 2017). An early study by Grossman (2008) found 16°-60° tibial torsion values in dancers, suggesting that it contributes a large portion of turnout together with the hip. Values were measured from MRI images. Later on, Quanbeck and colleagues (2017) measured turnout with motion capture and showed significant rotational movement (mean 20° / side) in dancers' knee joints. It could be concluded that there is a substantial individual anatomical variation in ballet dancers' turnout.

Professional ballet dancers have a higher prevalence of hypermobility than the general population, which seems advantageous for achieving the aesthetics needed in ballet. Phan and colleagues (2020) looked for the prevalence of lower extremity hypermobility and patterns in pre-professional and professional dancers. Generalized and lower-limb-specific hypermobility was prevalent in dancers; 44% of the dancers had their right leg, and 40% had their left leg hypermobile. Subtalar pronation, hip abduction, and external rotation were seen more in professional dancers with significant bilateral differences.

3 INJURIES IN BALLET DANCERS

Even though injury surveillance among dancers has increased over the years, reporting injuries in dance is still inconsistent. Most recent systematic reviews (Armstrong & Relph 2018; Kennny et al. 2018; Vassallo et al. 2019) noted that still comprehensive, high-quality studies are missing at all levels of ballet and dance. Injury definition varies between self-reported, medical-seeking, and time-loss injuries in different studies. That makes systematic reviews and meta-analyses, as well as concluding and, after all, building prevention strategies, difficult.

3.1 Prevalence

The systematic review shows that the injury occurrence with professional ballet dancers is 1.06 with males and 1.46 injuries with females / 1000 dance hours. 64% of females' injuries were overuse injuries, while male dancers had 50% overuse injuries (Smith et al. 2015). A recent prospective study describing medical attention and time-loss injuries in a professional ballet company over a 5-year follow-up period found similar time-loss incidence rates (Mattiussi et al. 2021b). The incidence of medical attention injuries was 3.9 with females and 3.1 with males / 1000 dance hours. Rates for time-loss injuries were 1.2 and 1.1 / 1000 dance hours for females and males, respectively. Some variety was found between rankings when comparing categories. Soloists and principals were more prone to both medical attention and time-loss injuries than other categories.

Most injured body parts in all dance genres and levels are ankle, knee, hip and back (Vassallo et al. 2019). Lower extremity injuries cover 66-91% of all injuries in ballet dancers. A few studies have provided more specific information about the injuries, but the systematic review found lumbosacral pain, painful snapping hip and patellofemoral pain to be the most prevalent diagnosis (Smith et al. 2015).

The actual number of injuries may be underreported among dancers. A study completed with professional ballet and contemporary dancers found that 15% of injured dancers did not report their injuries to employers and/or medical staff due to the expectations that pain is a normal part of dance, not wanting to stop dancing or not wanting to appear unreliable (Jacobs et al. 2017). Dancers may also modify their training due to the pain and injury to hide the underlying injury (Kenny et al. 2018).

3.2 Risk factors

One systematic review aimed at identifying risk factors for injuries in professional ballet dancers was found (Biernacki et al. 2018). However, this was only looking for female ballet dancers. The review indicated poor lumbopelvic movement control, inappropriate transversus abdominis contraction, decreased lower-extremity strength, and poor aerobic fitness were risk factors for lower-extremity injury. This is supported by the finding of Vera et al. (2020) which indicated that ballet dancers committed to additional strength and conditioning training had reduced injury rates.

Other findings with professional dancers suggested fatigue as one risk factor for injuries. Lin et al. (2016) suggested that long working hours might lead to fatigue and impaired movement control in lower limbs, causing a risk of dance injury. Another study found that injuries happened most often late in the day and season, also suggesting an effect of fatigue (Liederbach et al. 2008). Arnwine and Powell (2020) found sex differences in landing GRFs and suggested that could potentially explain divergent injury rates in female and male ballet dancers.

The relatively recent systematic review by Kenny et al. (2018) examined pre-professional ballet dancers' risk factors. Previous injury and insufficient psychological coping skills were the most significant risks for injuries. Also, anthropometric variables (low body mass index (BMI), low adiposity (percentage of body fat), and increased thigh circumference and inadequate aerobic capacity had an association with injury occurrence. From the biomechanical variables, lower extremity alignment (sacrum inclination angle) correlated with lumbosacral pain and jump landing technique, such as higher GRF and impulse for patellar tendinopathy. One study found an association between increased ankle joint ROM and patellofemoral pain in dancers (Steinberg et al. 2012).

According to a few studies, vertical jump height and power are not associated with pre-professional dancers' injuries (Ambegaonkar et al. 2018; Twitchett et al. 2010b). However, horizontal jump distance predicted lower extremity injuries (Ambegaonkar et al.

2018). The single-leg hop norm was determined as a percentage of hop distance to one's height (SLH norm, % height). Injured dancers had a significantly lower single-leg hop norm (85.2 % ± 11.2) than non-injured dancers (76.8 % ± 8.4) (p=0.009). The study could not find significant differences in vertical jump height or power between the injured and non-injured dancers.

The systematic review and meta-analysis by Armstong and Relph (2018) examined the screening tools that might predict dancers' injuries, including all dance levels and genres. They found some evidence that dance-specific movements could potentially predict injuries. In particular, compensated turnout and forced turnout seemed to have some association with injuries. Only some positive association was found in evaluating hypermobility, strength, and power.

4 LANDING BIOMECHANICS

Jumps are essential to ballet training; dancers are exposed to jumps daily. A typical ballet class has been reported to consist of about 200 jumps (Liederbach et al. 2006). In addition, ballet dancers have rehearsals throughout the working day, during which the number of jumps varies depending on their choreography and role.

As mentioned earlier, ballet dancers' jumping actions differ from natural jumping. All movements are executed in the "turnout" position, which means external rotation of the hip and the whole lower extremity. Ballet dancers try to maintain an upright position of their torso and pelvis throughout the jumps (Imura & Iino 2017). This may alter the biomechanics and, therefore, needs closer investigation.

A recent systematic review of ballet dancers' jumping biomechanics found 29 articles investigating kinematics and/or kinetics of take-off (7 articles) and landings (23 articles) on dancers especially (Mattiussi et al. 2021a). However, only nine of them were conducted among professional ballet dancers. Also, it is noticeable that most of the data collected from dancers is presenting female dancers (Mattiussi et al. 2021a).

4.1 Kinematics

Kinematic measures researched among dancers were lower limb joint angles and excursions, and velocities. Measured values of peak joint angles in landing vary greatly and are poorly reported among professional dancers. In ballet-specific jumps, reported peak joint angles are in the ankle -5.7-27.5°, in the knee 15-83°, and in the hip 7.9-59.7°; in non-specific jumps in the ankle 25.2-60.5°, in the knee 54-79.8° and in the hip 29.1-62.8° (Mattiussi et al. 2021a). Pre-professional dancers displayed greater sagittal plane joint excursion during the landings compared to non-dancers (Harwood et al. 2018).

The study by Orishimo and colleagues (2014) showed that female dancers landed with significantly lower knee valgus angle, hip adduction moment and trunk side flexion than female team sports athletes. Orishimo and colleagues (2009) found that dancers' years of training affected the peak hip adduction angle during landing. Dancers who began training younger could limit hip adduction during landing.

4.2 Kinetics

From kinetic measures, ground reaction force is the most reported variable. Some studies also report joint moments, power, stiffness, and loading rates.

Ground reaction force (GRF) has been researched among ballet dancers on landings in both ballet-specific jumps and "normal" jumps. Relative peak landing vertical GRF values are between 1.4 and 9.6 times body weight in ballet-specific jumps (Mattiussi et al. 2021a). The highest values are measured during the biggest ballet jumps called "grand jeté", in which a dancer splits in the air and lands on a single leg. No difference was found in GRF between limbs on ballet-specific single leg landings when comparing dancers' perception of their leg preference (Mertz & Docherty 2012).

Studies in ground reaction forces (GRF) during landing have found that dancers show lower GRF compared to athletes (Ward et al. 2019), and female dancers have lower GRF compared to male dancers (Arnwine & Powell 2020). The latter study investigated professional and pre-professional ballet dancers in landing tasks and found that during single-leg landing, male dancers had smaller peak vertical GRFs ($p<0.01$), greater time-to-peak GRF ($p=0.03$), and smaller loading rates ($p<0.01$) than female dancers. No differences were observed in vertical impulse during single-leg landing or in any variables during double-leg landing (Arnwine & Powell 2020).

The study by Ward and colleagues (2019) revealed professional modern and ballet dancers had significantly lower leg ($p<0.001$), knee joint ($p=0.034$), and ankle joint stiffness ($p=0.043$) compared to athletes. This occurred through the greater range of motion (ROM) in the knee ($p=0.029$) and ankle joints ($p=0.048$), and lower knee joint moments ($p=0.012$). The findings are in line with the research among athletes, showing that restrictions in ankle dorsiflexion contribute to a stiff landing with less flexion at the ankle and knee in male athletes (Dowling et al. 2018). Also, dancers showed greater vertical displacement of the centre of mass (COM) and longer landing time compared to athletes (Ward et al. 2019).

Female and male dancers diverged in the stiffness measurements, with males having higher leg ($p< 0.001$) and ankle joint stiffness ($p<0.001$) than females. This occurred through lower ankle range of motion ($p < 0.001$) and greater ankle moment ($p=0.022$) compared to females. (Ward et al. 2019.)

4.3 Knee valgus position in landing

Knee valgus position has been linked to increased knee injury risk in athletes (Larwa et al. 2021). The difference between females' and males' landing biomechanics is present in team sports, with female athletes showing more significant knee valgus than male counterparts (Cronström et al. 2020; Jenkins et al. 2017). In sports, female athletes have more non-contact knee injuries than male athletes, especially anterior cruciate ligament (ACL) injuries. In dancers, no clear difference in knee injuries between females and males has been reported (Orishimo et al. 2014).

Previous studies among dancers (Orishimo et al. 2014, Orishimo et al. 2009, Ward et al. 2019) could not find a difference between female and male dancers' knee control on landings. These studies used professional ballet and contemporary dancers and found similar lower extremity kinematics and kinetics in both females and males. Two studies (Orishimo et al. 2014 & Ward et al. 2019) compared dancers to athletes and found that all dancers landed similarly to male athletes.

A recent systematic review found that limited ankle dorsiflexion mobility is linked to dynamic knee valgus (Lima et al. 2020). Several studies suggest that biomechanical variables such as sagittal plane joint excursion, low knee valgus values, high ankle dorsiflexion mobility and low ground reaction force values contribute to softer landing and reduce the risk of knee injuries (Orishimo et al. 2014).

5 AIM OF THE STUDY

This master's thesis aimed to provide information on professional ballet dancers' landing biomechanics. The previous findings in this literature review show the limited data available from professional ballet dancers and the need to investigate this topic.

The existing data collected as a part of the FinBallet study at the Finnish National Ballet provided data for this study. Prospective study design enabled the comparison of dancers' biomechanics between seasons. No previous studies on interseason variability were found. However, ballet dancers' training and work remain similar from season to season, so it is hypothesized that no significant differences occur.

Differences between female and male dancers' biomechanics and comparison based on leg preference have been poorly investigated earlier. Significant differences in sports between males and females have been suggested to lead to specific injuries. This study will provide more profound information about the possible differences between female and male dancers and leg preference, offering a base for further research looking for injuries.

The second part describes the study *"Interseason variability of a single-leg drop jump test in professional ballet dancers."* The study was interested in observing knee control during the impact phase of a drop jump test. Frontal plane knee projection angle (FPPA) was used as a variable to measure knee alignment.

The primary research question of the study:

1) Is there inter-season variability of frontal plane projection angle (FPPA) between three consecutive seasons in professional ballet dancers?

Secondary research questions of the study:

2) Is there a difference between female and male dancers' FPPA values?
3) How does self-perceived leg dominance affect knee control?
4) Is there a correlation between ankle dorsiflexion mobility and FPPA values?

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7 INTERSEASON VARIABILITY OF A SINGLE LEG DROP JUMP TEST IN PROFESSIONAL BALLET DANCERS

INTRODUCTION

Jumping and landing are essential parts of ballet training and performance, and the jumping ability has been identified as one of the best predictors of dance performance. Dancers jumping higher are able to implement a greater range of skills to fulfil the aesthetic components of dance (Angioi et al. 2009). Compared to other dance genres, higher jumping rates are observed in ballet (Wyon et al. 2011). Therefore, it is unsurprising that jumping and landing have also often been involved in injury situations in professional ballet dancers (Mattiussi et al. 2021).

Knee valgus position has been linked to increased knee injury risk in athletes (Larwa et al. 2021). In sports, the sex difference is present in landing biomechanics, with female athletes showing increased knee valgus compared to their male counterparts (Cronström et al. 2020; Jenkins et al. 2017). However, recent studies including professional ballet dancers (Orishimo et al. 2014 & Ward et al. 2019) did not find similar sex differences in dancers' single-leg landings. Both female and male dancers landing kinetics and kinematics seemed identical to male athletes; female dancers show significantly lower knee valgus angles than female team sports athletes (Orishimo et al. 2014). Previous evidence also shows that reduced ankle dorsiflexion range of motion can be linked with more significant dynamic knee valgus angles (Lima et al. 2018). However, to our knowledge, this has not yet been studied in dancers.

Ballet training in all skill levels relies on traditional ballet classes. In ballet terms, "supporting leg" and "working leg" determine which leg the exercises are executed. The supporting leg refers to the leg in which the dancer stands while the working leg executes movements in the air. Even if ballet training aims to train both sides equally, all exercises are typically first executed using the left leg as a supporting leg. That has been suggested leading to lateral bias (Golomer et al. 2009). However, the effect of leg dominance in landing biomechanics has been scantly studied in ballet dancers. Few existing studies measured ground reaction forces and postural control based on self-perceived leg dominance and found no bilateral difference between dominant and non-dominant legs in pre-professional ballet dancers (Clarke et al. 2020; Mertz & Docherty 2012). It is considerable that there is a notable gap in the literature representing biomechanical data mainly from female professional ballet dancers (Mattiussi et al. 2021). To our knowledge, no studies have examined the interseason variability in professional ballet dancers' landing biomechanics.

Our primary aim was to investigate interseason variability in the knee frontal plane projection angle (FPPA) at the impact phase of single-leg drop-jump landing in female and male professional ballet dancers. The secondary aim was to explore the effect of leg dominance and ankle dorsiflexion mobility on the FPPA.

Previous literature has examined dancers' landing biomechanics from controlled landings. This study wanted to examine the impact phase of the drop landing, in which the motor control differs from controlled landings.

MATERIALS AND METHODS

This study is part of a larger 5-year prospective cohort study investigating the epidemiology of injuries in female and male professional ballet dancers (FinBallet Study). The study's data collection was launched in 2017, and the data have been collected by 1) a pre-season questionnaire, 2) pre-season test sessions, and 3) injury reports collected by the in-house healthcare team at the Finnish National Ballet.

The inclusion criteria of the present study included attending pre-season testing sessions in three consecutive seasons (2019–2022) and being free from injury. Dancers were considered to be injury-free if they did not report injuries in the pre-season questionnaire and could fully participate in testing.

The study protocol was approved by the Ethics Committee of the Hospital District of Helsinki and Uusimaa (HUS 1766/2017), and all participants provided written informed consent for participation in the study. Participation in the study was voluntary, and participants were informed about their right to withdraw from the study at any point.

Participants

Twenty-six professional ballet dancers (females: *n*=14, males: *n*=12) were selected for this study. The participants represented a wide range of ages and years of experience as professional dancers, with males having slightly greater mean age and experience (Table 1).

TABLE 1. Baseline characteristics.

	Age	Height	Body mass	Years as professional
Females (*n*=14)	27.6 ± 6.1 yrs (range 18-40 yrs)	164.7 ± 3.1 cm (range 160-172 cm)	50.4 ± 3.6 kg (range 43-58 kg)	9.2 ± 5.5 yrs (range 0-20 yrs)
Males (*n*=12)	30.0 ± 5.5 yrs (range 19-41 yrs)	181.1 ± 4.1 cm (range 174-189 cm)	74.8 ± 6.3 kg (range 63-86 kg)	11.4 ± 5.4 yrs (range 0-21 yrs)

Note: cm=centimeters; kg=kilograms; yrs=years

Testing procedures

The pre-season testing sessions were conducted at the Finnish National Ballet, Helsinki, Finland, in July–September 2019, 2020 and 2021. Each dancer completed a pre-season questionnaire about their injury history and dance experience. Standing height (centimeters), body mass (kilograms), and self-perceived leg dominance were recorded. The dominant leg was determined as the supporting leg in ballet movements (i.e., leg that dancers reported to prefer when they balance and turn).

Single-leg vertical drop jump

In the single-leg vertical drop jump, dancers stood on a 10-cm box in a unilateral stance, dropped off the box on the same weight-bearing leg, and performed a maximal vertical jump on the same leg (Pasanen et al. 2015). Dancers were instructed to jump as high as possible and attempt to touch the ceiling at an unobtainable height, reaching with both hands and landing unilaterally. A trial was invalid when the dancer jumped instead of dropping off the box, touched the contralateral leg to the floor, reached with only one hand, or clearly lost balance during the test. All participants performed the tests barefoot to eliminate the effect of the shoe type. For each testing session, dancers performed three valid trials on each leg. The mean value of three trials per leg per testing session was used for the analyses.

Each trial was recorded with a digital video camera (Zoom, Q4, USA) positioned on a tripod at a distance of 5 m. A single investigator analyzed all video footage using Kinovea software version 0.9.5. (Charmant & co 2021). From the first impact phase, knee flexion was visually assessed based on the lowest point of pelvis height.

For the video analysis, four markers (left and right anterior superior iliac spine (ASIS) and left and right tuberositas tibiae) were placed on the participants by the researcher or experienced assistant.

The frontal plane projection angle (FPPA) was measured from the most profound knee angle of the impact phase after the drop (Figure 1). FPPA was calculated as the intersection of a line crossing the ankle joint centre and knee joint centre and the line created by the markers on the ASIS and the knee joint centre. Neutral alignment was considered 0°; positive values represented valgus alignment, and negative values represented varus alignment.

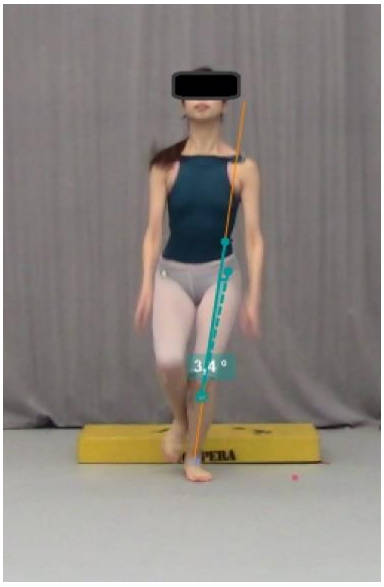


FIGURE 1. The frontal plane projection angle was measured from the most profound knee angle.

Ankle dorsiflexion

Ankle dorsiflexion was measured with the "knee to the wall"-test (Konor et al. 2012), where each leg was measured separately. A participant placed a foot on the measurer and bent the knee to touch the wall, keeping the heel on the ground and the pelvis towards the wall throughout the movement (Figure 2). The longest distance between the tip of the big toe and the wall was recorded.

FIGURE 2. Knee to wall -test to measure ankle dorsiflexion mobility.

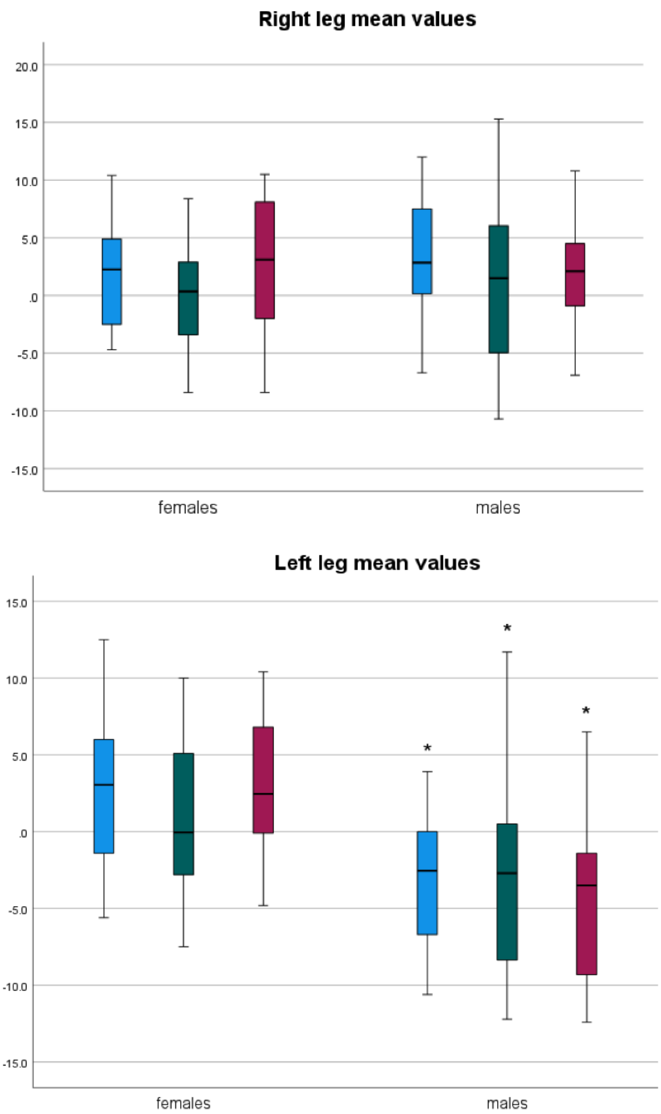
Statistical methods

First, normal distribution was tested with the Kolmogorov-Smirnow test. Descriptive statistics were analyzed using repeated ANOVA measures to test differences between legs, study years and sexes. Lastly, the Pearson correlation was used to assess the association between FPPA and ankle dorsiflexion in dominant and non-dominant legs separately. The level of significance in all the tests was set $p < 0.05$. Statistical analyses were performed using IBM SPSS statistical software (version 28.0.1.1).

RESULTS

Interseason variability

Mean values for FPPA in females were right 2.2°, left 2.6°; right 0.3°, left 1.2°; right 3.1°, left 2.5° (study years 1-3, respectively) and in males, right 3.1°, left -3.4°; right 1.3°, left -3.1°; right 1.8°, left -3.9° (study years 1-3, respectively) (Figure 3). There was a statistically significant difference in FPPA on the left leg between females and males when comparing all study years together (p=0.009).



**statistically significant difference*

FIGURE 3. Mean values for right and left FPPA in female and male participants between study years (blue=1st study year, green=2nd study year, red=3rd study year).

No intra-individual differences in FPPA were observed between the three study years in the right or left leg (right leg: p=0.07, p=0.14, p=0.60; left leg: p=0.63, p=0.89, p=0.60, 1st to 2nd year, 2nd to 3rd year, 1st to 3rd year, respectively). Also, no statistical difference was found in the change of FPPA values between males and females in the study years right leg (p=0.99, p=0.11, p=0.14) or left leg (p=0.75, p=0.10, p=0.36, 1st to 2nd year, 2nd to 3rd year, 1st to 3rd year, respectively).

Leg dominance

Most participants (n=19) reported the left being their dominant leg, and only six favoured the right as the supporting leg. Leg dominance data was missing from one participant. There was no difference in leg dominance between female (left 10/right 3) and male dancers (left 9/right 3) (p=0.91).

The mean values for females in the dominant leg were 1.4°, 0.9° and 2.0° and for the non-dominant leg 3.8°, 0.6° and 3.8° (study years 1-3, respectively). For males, the values for the dominant leg were -1.2°, -1.7° and -2.7°, and for the non-dominant leg, 1.2°, 0.0° and 0.5° (study years 1-3, respectively).

When comparing dominant and non-dominant legs, there were no statistically significant differences in the FPPA between the legs and the study years (p=0.10, p=0.63, p=0.10, study years 1-3 respectively) (Figure 4).

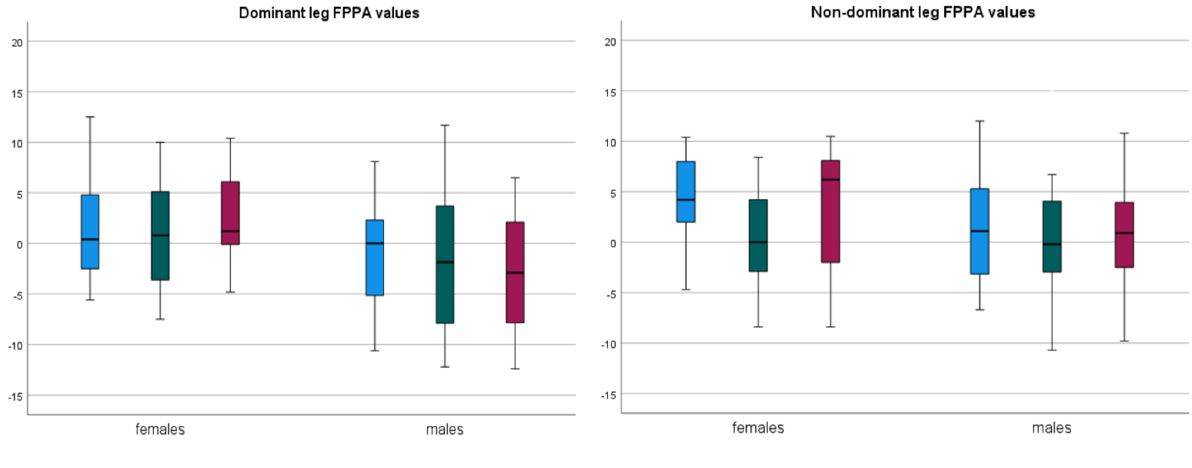


FIGURE 4. Mean values for dominant and non-dominant leg FPPA in female and male participants between study years (blue=1st study year, green=2nd study year, red=3rd study year).

Ankle dorsiflexion

Mean values for ankle dorsiflexion were slightly greater for males, but no difference was found between dominant and non-dominant legs in females or males (Table 2).

TABLE 2. The mean values of ankle dorsiflexion for male and female ballet dancers.

		Study year 1	Study year 2	Study year 3
Females	Dominant leg ("supporting leg")	12.9 ± 2.43 cm	13.1 ± 2.79 cm	12.4 ± 2.64 cm
	Non-dominant leg ("working leg")	12.9 ± 2.21 cm	13.0 ± 2.74 cm	11.8 ± 2.56 cm
Males	Dominant leg ("supporting leg")	15.3 ± 1.49 cm	15.4 ± 1.44 cm	14.0 ± 2.05 cm
	Non-dominant leg ("working leg")	15.2 ± 2.21 cm	15.2 ± 3.01 cm	13.4 ± 2.28 cm

Note: cm=centimetres

A statistically significant correlation between increased knee valgus and decreased ankle dorsiflexion values was found in both dominant -0.356 (p=0.002) and non-dominant legs -0.379 (p<0.001) (Figure 5).

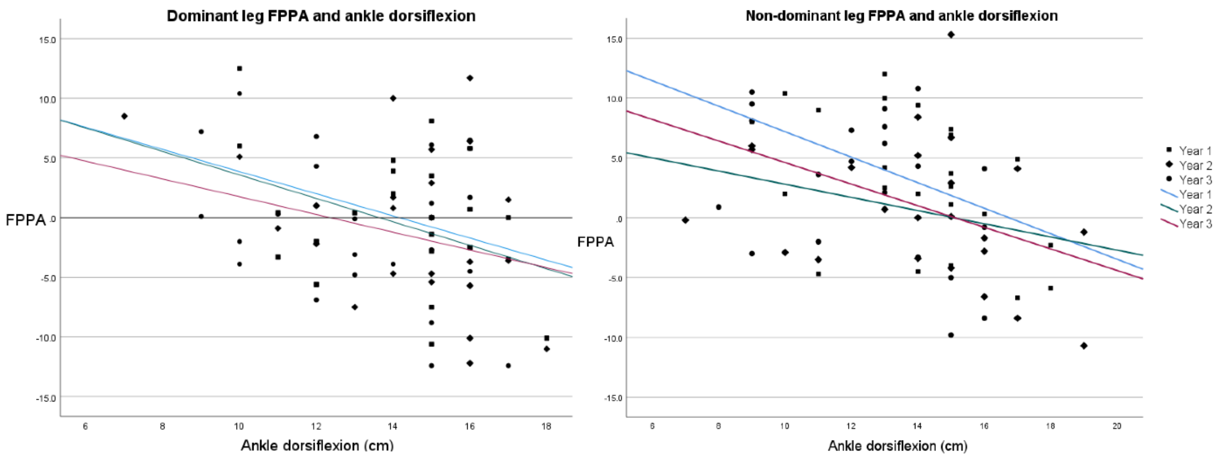


FIGURE 5. Correlation between increased FPPA values and decreased ankle dorsiflexion mobility values.

DISCUSSION

This study was set to examine the interseason variability of frontal plane knee control in professional ballet dancers. No statistically significant variability was found between the three study years. We found a statistically relevant difference between females and males in the left leg knee control, but a similar difference was not observed in the right leg. No significant differences in the control were found when adjusting the data based on self-perceived leg dominance. It is noteworthy that landing biomechanics was evaluated from the impact phase of the drop jump, not the controlled landing most previous studies have examined. This study confirmed the correlation between increased knee valgus position and limited ankle dorsiflexion mobility in the professional dancer population.

To our knowledge, this is the first study on the interseason variability of landing biomechanics in professional ballet dancers. The differences between seasons were minor and not statistically significant. Basic ballet training remains similar for all the dancers throughout their education and professional careers, so this result was expected. Participants in this study presented a wide range of ages and experiences as professional ballet dancers, indicating that movement control remains steady throughout their careers.

This study found no statistically significant differences between dominant and non-dominant leg variables, either in knee valgus or ankle range of motion. This could be reasoned by the fact that both legs are trained in every ballet class. One previous study examined the ground reaction forces on landings in dominant and non-dominant legs and found no difference between limbs (Mertz & Docherty 2012). Another study looking for postural control in landing biomechanics found no bilateral difference based on leg preference (Clarke et al. 2020). It seems that dancers' self-perceived leg dominance is not connected with altered alignment control.

Bias towards the left leg, being the "supporting leg", was noticeable among participants in this study. Typically, in ballet class, that is the leg in which all the exercises are executed first, which could affect the leg preference (Golomer et al. 2009). Therefore, it was expected that some difference was found between legs, but surprisingly only in male dancers. This finding contradicts previous studies where dancers were mainly biased towards the right leg (McMahon et al. 2021; Wyon et al. 2013). However, the definition of the dominant and non-dominant leg can be debatable, and there is no clear consensus on how to define that in dance. In this study, dominance was based on the participants' subjective feeling of a "better supporting leg", which the dancer relies on balancing and turning movements. Some of our participants reported that for turning, they do not mind which limb they use, the rotational direction is more relevant.

Decreased ankle dorsiflexion range has been linked to more significant knee valgus angles (Lima et al. 2018). Similar to these previous findings, we found correlations between limited ankle dorsiflexion and positive knee FPPA values (knee valgus). However, our sample size is small to testify that ankle mobility would be the sole cause for weaker lower limb alignment. This finding should be confirmed with a larger group of dancers.

The measured frontal plane projection angle values were small in this study, indicating that participants have steady knee control. Knee valgus values were low in female and male ballet dancers in both dominant and non-dominant legs. Therefore, previous findings about minor sex differences in dancers' landing biomechanics were confirmed by this study (Orishimo et al. 2016 & Ward et al. 2019).

Jumping in ballet differs from jumping in general. Ballet dancers' hips are externally rotated in all ballet movements, and they attempt to maintain upright positions in their torso and pelvis during jumping (Imura & Iino 2017). Ballet dancers perform all the ballet exercises in a "turnout" position where the whole lower limb is rotated externally. External rotation of the lower limb has contributions from the hip, knee and ankle joint movements, as well as the anatomical variations of the hip and tibial torsion angles (Grossman et al. 2008; Quanbeck et al. 2017). Landing biomechanics in this study were analyzed in a neutral lower limb position. Several participants had difficulty keeping their feet aligned in a neutral (parallel) position while landing and taking off. This could potentially affect the result. If participants were guided to keep their feet strictly in parallel, the knee valgus values could have increased.

Strengths of the study

One of the biggest strengths of this study is having an almost equal number of male and female participants. This study provides more profound information on the similarities in female and male dancers' biomechanics.

Another remarkable strength of this study is the large scale of participants' expertise (0-21 years as professionals) and a wide range of ages (19-41 years). Also, the participants consist of international dancers with several nationalities and ethnical backgrounds.

The pre-season measurements were conducted at the same time point every year by the same research assistants, and one researcher evaluated the primary variable from the videos. All these minimized the variability between measurements and increased the reliability of results.

Limitations of the study

There are several limitations in this study concerning the tests and methods used. These tests were planned as field tests to screen dancers quickly with low costs and not time-consuming in studio settings. Therefore, only one camera was used, and only one plane was measured. Motion analysis could provide more detailed and precise data in the laboratory setting. Simple and cost-effective measurement for ankle ROM was used in the studio.

The sample size of this study is too small to draw general conclusions on landing biomechanics. More research is needed to confirm similar findings in different ballet companies.

This study is biomechanical research that does not consider the relation to participants' physical performance levels. We did not validate dancers' jump height, making it hard to evaluate whether they performed maximal jumps during the test. This study could be replicated by examining the correlation between landing biomechanics and physical performance level.

CONCLUSION

To our knowledge, this is the first study on the interseason variability of landing biomechanics in professional ballet dancers, showing no statistically significant differences between study years. This study indicated minor differences between female and male dancers' knee valgus position during the impact phase of a drop jump and in knee control between dominant and non-dominant legs. The effect of ankle dorsiflexion mobility on knee control was confirmed with professional ballet dancers. This study provides more profound information on female and male dancers' biomechanics, which has not been investigated widely.

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