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Are Jumping Asymmetries Associated with Prospective Injury Risk in Pre-Professional Ballet?

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Abstract

Background: Pre-professional ballet dancers are exposed primarily to injury risk in the lower extremities with most injuries occurring during jumping and landing activities. Inter-limb asymmetry during jumping and landing activities has been associated with injury risk in adolescent athletes but this has not been examined in dancers.

Purpose: To investigate associations between interlimb asymmetry in double-leg (DL-CMJ) and single leg (SLJ), countermovement jump performance and prospective injury risk in pre-professional adolescent ballet dancers.

Study Design: Cohort-Study.

Methods: Pre-professional adolescent ballet dancers (n=255) performed 3 DL-CMJ's and 3 SLJ's on force plates during of annual profiling. Absolute and directional (separate values for left and right dominance) asymmetries in a range of DL-CMJ kinetic variables and in SLJ height were calculated. Each variable was dichotomised as "high" or "normal" asymmetry according to whether % asymmetry was > or ≤ mean + 0.5 SD, based on the present sample. Risk ratios (RR) and 95% confidence intervals (95% CI) were calculated based on injury incidence in the subsequent academic year.

Results: Of 242 dancers, 128 injuries were observed in the subsequent academic year. In the full sample, two absolute, six left limb dominant and one right limb dominant kinetic asymmetries across eccentric, concentric and landing phases of the DL-CMJ, and left limb dominant jump height asymmetry in the SLJ were associated with a significant (p=<0.001) increase in injury risk (RR= between 1.48 and 1.71, 95% CI = 1.01 to 2.48). Separating by sex, eccentric DL-CMJ asymmetries were not significant in boys, while in girls RR's for eccentric asymmetries increased and SLJ height was not significant.

Conclusions: Higher asymmetries in specific DL-CMJ kinetic variables and in SLJ height were associated with an elevated risk of injury in elite pre-professional ballet dancers with some specific sex differences. Associations were mainly identified for high left limb dominant asymmetry in the take-off phase suggesting that risk may be specific to a relative right limb deficit.

Clinical Relevance: This study provides detailed and thorough initial research investigating associations between jumping asymmetry and prospective injury risk in pre-professional ballet dancers. This may lead to the introduction of more proactive injury reduction strategies in the future. This research also highlights that jump-land asymmetry-risk analyses should not only consider absolute values, but also left and right limb dominant asymmetries separately as associations are missed if directional asymmetries are not considered.

Key Words: Injuries, Jumping, Limb asymmetry, Dance, Risk Factors, Biomechanics, Knee Injury, Ankle Injury, Foot Injury

What is already known on the topic: Pre-professional adolescent ballet dancers face significant exposure to injury in the lower extremities and jumping and landing during dance is the most common mechanism of injury. Associations between SLJ height asymmetry and injury risk have been reported in team sports.

What this study adds: High (relative to population norms), jump-land double leg CMJ and single leg jump height asymmetries, predominantly left dominance (right limb deficits) are associated with prospective injury risk in pre-professional ballet dancers. In addition, using internal descriptive statistics to classify asymmetry and analysis of directional asymmetries may provide a useful method to investigate interactions between asymmetry and injury.

Introduction

Professional ballet is extremely physical and technically demanding. [41] Technical ballet training and performances involve slow controlled movements at a lower intensity with bursts of intermittent higher intensity exercise such as jumping.[25] Dancers train at vocational schools as pre-professionals from as young as 9 years old, training between 20 and 30 hours per week. [5,6,10,45] These high training volumes expose pre-professional dancers to injury risk[12] with the majority of injuries in the lower extremities occurring during jumping and landing activities.[1,31] Injuries influence dancers' ability to train, and therefore achieve their professional ambitions, and may have other longer-term musculoskeletal consequences.[38] Reducing injury incidence is, therefore, a primary goal for practitioners working with pre- and professional ballet dancers.

During ballet performances, professional dancers can complete up to 14 jumps per minute involving high levels of technical mastery.[42] Pre-professional dancers complete a large volume of jump training to be able to reach the standards of the senior level.[19] Balletic jumps demand large levels of force production during jump take-off and attenuating large ground reaction forces during the landing. The technical and aesthetic demands of ballet may lead dancers to favour specific limbs to maximise aesthetic quality. Consistent preference of one limb during training and performance may expose dancers to increased stress on the dominant limb or lead to a relative weakness on the contralateral limb. Limb imbalance has been quantified as a % asymmetry, a factor that has been associated with injury risk in studies in other sports.[11,36] However, associations between jump-landing asymmetries and injury risk have not been reported in dancers. Moreover, there is a paucity of research available that associates any physical qualities with prospective injury risk for pre-professional ballet dancers[29].

In high-performance settings the double-legged countermovement jump (DL-CMJ), performed on dual force platforms is a common means to assess strength qualities or "neuromuscular performance" and to simultaneously evaluate interlimb asymmetries.[8] across eccentric (downward), concentric (upward) and landing phases.[8] However, in settings without force platforms, asymmetries in single leg jump (SLJ) height are a more accessible means to quantify interlimb asymmetry due to the range of cheaper equipment that can reliably collect these data.[21,44] It is unclear whether DL-CMJ kinetic asymmetries and SLJ height asymmetries have similar associations with prospective risk or not, as these asymmetries often do not align.[7,39] To the researchers knowledge both assessments have not been concurrently examined in the same study.

The purpose of this study was therefore to investigate prospective injury risk associations between interlimb percentage asymmetries (% ILA) across a comprehensive range of kinetic variables during a DL-CMJ and jump height during a SLJ, in pre-professional adolescent ballet dancers.

Methods

Participants

A total of 255 participants took part in jump testing as part of their annual screening protocol and informed written consent was obtained for use of the data in the present analysis from the participants and parents. Ethical approval was obtained from the ethics board at St. Mary's University, Twickenham in accordance with the declaration of Helsinki. All participants were pre-professional, and all trained at the same ballet school (The Royal Ballet School, London, UK). Participants were informed data would be used for research and disseminated in order to improve dancer health. The dancer's training schedule corresponded with a normal British academic school year and the specific training demands were defined by the participants' gender and year group (see Table 1). Participants were excluded from the study if they had a current lower limb injury at the time of jump testing or if they left the school during the academic year following the initial screening. All data were removed for excluded participants.

Year Group (age)	Sex	N	Approx Training Hours Per Week*
Year 7 (11-12)	Male	19	18.8
	Female	26	18.8
Year 8 (12-13)	Male	12	20.7
	Female	14	20
Year 9 (13-14)	Male	10	21.1
	Female	18	21.1
Year 10 (14-15)	Male	14	21.5
	Female	16	21.5
Year 11 (15-16)	Male	12	21.3
	Female	13	21.3
Year 12 (16-17)	Male	19	23
	Female	21	23
Year 13 (17-18)	Male	17	26
	Female	13	26
Year 14 (18-19)	Male	11	29.3
	Female	7	29.3
	Total		
All participants	Male Female	114 128	Average approximate training hours (22.7)
*Approximate training hours calculated by using the annual weekly timetable template. Hours likely to vary depending on performance/rehearsal.			

Table 1- Participant characteristics

Data collection

The present analysis pertains to jump assessments performed during the first week of two consecutive academic years (09/2018, 09/2019) and injury data collected during the whole proceeding school year until the final days of the academic term (07/2019 and 07/2020, respectively). The majority of the participant data (195 of 242) that forms the analysis were from the 2018-19 year as the only data included from the 2019-20 school year were obtained for dancers that were new to the school and had not participated in the previous year's analysis. Six chartered physiotherapists collected injury data which consisted of: Participant information, injury diagnosis, injury location, injury mechanism, days restricted from full dance practice, days fully off dance practice.

Injuries occurring in the corresponding school year following the jump testing that affected the lower back and pelvis and any structures inferior to this were included in the analysis. An injured dancer was only included once in the analysis regardless of the number of additional injuries. A minimum "moderate" threshold, defined as 'any anatomic tissue level impairment that resulted in full time loss or a restriction from activity for seven or more days'[9] was used to define injury. Dancers who had only injuries below this threshold were therefore categorised as "non-injured". The number of days of restricted activity or time lost from activity was taken from the first date the dancer reported the injury with the physiotherapist until the therapist removed all restrictions from full class. Therefore, a dancer that sustained a minor injury (less than seven days of activity restriction) was included in the study but classified as non-injured.

All participants performed three bilateral countermovement jumps with five seconds pause between each repetition. Jumps were performed on FD4000 (VALD performance™) and PASCO force plates (PASCO, Roseville, California) with one force plate per leg. Data were acquired via VALD performance ForceDecks software (Brisbane, Queensland) with a sample rate of 1000 HZ. Prior to measurement, a standardised jump warm up was performed, consisting of three warm up DL-CMJ followed by three SL jumps. Participants were instructed to 'jump as high as possible' with their hands on their hips and to land on the force plates (Figure 1.). The process was then repeated for left and right leg for the SLJ's, with three jumps performed on the left leg followed by three on the right leg.

<u>**Figure 1. Countermovement Jump**</u>

A) **B)** **C)**

- **A)** Participants moved from a standing position into a bent knee position as part of the countermovement section of the jump.
- **B)** Participants then jumped as high as possible
- **C)** Participants then landing with each foot on each plate. Hands were maintained on hips throughout.

Data analysis

Raw force-time data were exported, and kinetic asymmetries analysed using Python (3.10.01, Python, Beavertown, USA). Descriptions of the kinetic variables can be found in Appendix 1. Asymmetries for all kinetic variables were calculated using the bilateral strength asymmetry (BSA) score.[20]

BSA Formula

$$\frac{(Stronger\ Limb - Weaker\ Limb)}{Stronger\ Limb} \times 100$$

For all variables, the higher value of the two limbs was used as the “stronger limb”. Absolute asymmetries ignore in the direction of asymmetry. Directional asymmetries use the same calculation as absolute but direction (i.e. dominance) is also expressed. The analysis was performed on a variable-by-variable basis – such that “dominance” was defined for each variable not for the individual. An example of this calculation can be seen in Appendix 2.

Asymmetries were defined as High or Normal according to whether the value was ≥ than the variable´s mean + 0.5 standard deviation (SD):

High Asymmetry

$$\geq Mean\ Asymmetry\ \% \ + (0.5 * SD))$$

Normal Asymmetry

$$\leq Mean\ Asymmetry\ \% \ + (0.5 * SD))$$

Statistical Analysis

Due to the lack of previous research in this area an exploratory analysis[27] was performed on all kinetic variables for absolute and directional asymmetries for males and females. To do this, all participants left limb dominant, right limb dominant and absolute asymmetry % value for each DL-CMJ variable and for SLJ height was individually dichotomised as high or normal. After this, risk ratios were calculated to describe the probability of injury for those with high relative to normal asymmetries. A significant association between asymmetry and risk was indicated by risk ratio confidence intervals (95% CI) that do not cross 1.

Results

Participant Characteristics

The final analysis included 242 participants, of which, 128 suffered at least one injury during the study. All data collected from the 13 participants that withdrew from the study were removed from the analysis. Participant characteristics can be found in Table 1. Descriptive injury data are displayed in Table 2.

Table 2- Descriptive Injury Data From the First Injury Event For Each Injured Participant

Total number of injuries	128
Mean Time from Jump Testing to Injury	125.6 ± 88.6 days
Median Time from Jump Testing to Injury	121 days
Left Sided Injury	54
Right Sided Injury	58
Bilateral Injury	13
Central Injury[1]	3
Tenogenic	22
Athrogenic	51
Myogenic	29
Osteogenic	26
[1]Central injury represents one that occurred either side of the spine/sternum.	

Asymmetry and prospective risk

In the DL-CMJ, the majority of participants displayed dominance on the right limb in eccentric, concentric phase variables and SLJ height as well as left limb dominance in landing phase variables. Contingency tables displaying the number of dancers with high and low asymmetry across each variable and each limb can be seen in Appendix 3. Variables for which high asymmetry was significantly associated with increased injury risk (all p<0.001) were left limb dominant eccentric peak force (RR= 1.44, 95% CI = 1.02 to 2.05), eccentric rate of force development (RFD), (RR=1.6, 95% CI=1.15 to 2.23), ; concentric impulse (RR= 1.58, 95% CI = 1.16 to 2.15,),) (RR=1.6, 95% CI = 1.12 to 2.16,), concentric impulse 100ms (RR=1.69, 95% CI= 1.21 to 2.37,) and concentric impulse part 2 (RR=1.71, 95% CI= 1.17 to 2.48). Absolute asymmetries were significantly associated with increased injury risk in concentric peak force (RR=1.28, 95% CI= 1.01 to 1.62), landing RFD 40ms (RR= 1.29, 95% CI = 1.02 to 1.64) and landing impulse 40ms (RR=1.31, 95%=1.03 to 1.66). Right limb dominant asymmetry in landing impulse 40ms (RR=1.40, 95% CI=1.02 to 1.91) also demonstrated significant associations with injury risk. In addition, having left limb dominant (right limb deficit) asymmetry in SLJ height was significantly associated with injury risk (RR=1.48, 95% CI = 1.01 to 2.03). Of the variables measured, two absolute, six left limb dominant and one right limb dominant asymmetry was associated with a significant increase in prospective injury risk. The distribution of individuals' values across significant kinetic variables is shown in Figure 2 and a full list of the distribution can be seen in Appendix 3. A full list of risk ratios and confidence intervals values associated with high asymmetries and lower limb injury can be found in Table 3.

When participants were split by sex there was a difference in the variables that displayed significant relationships with prospective injury risk. For male dancers (Table 4) left limb dominant eccentric minimum force (RR=1.57, 95% CI=1.06 to 2.32), concentric impulse

100ms (RR=1.9, 95% CI= 1.19 to 3.04), concentric impulse part 1 (RR=1.57, 95% CI=1.03-2.39), concentric peak force (RR=1.71, 95% CI=1.16 to 2.53), concentric impulse (RR=1.9, 95% CI= 1.19 to 3.04) and left limb SLJ asymmetry (RR=1.81, 95% CI = 1.18-2.76) showed significant associations with injury risk. No absolute or right limb dominant asymmetries shared this association for male dancers. For female dancers (Table 5) left limb dominant eccentric peak force (RR=1.72, 95% CI = 1.05 to 2.84), eccentric RFD (RR =1.72, 95% CI= 1.04 to 2.82), concentric impulse 100ms (RR = 1.69, 95% CI =1.04-2.84), concentric impulse part 1 (RR = 1.8, 95% CI = 1.09 to 2.97), concentric impulse part 2 (RR = 1.78, 95% CI = 1.11 to 2.86) were all significantly associated with injury risk alongside absolute asymmetry during landing RFD 40ms (RR = 1.47, 95% CI= 1.05 to 2.08), concentric impulse 100ms (RR = 1.44, 95% to CI=1.03 to 2.77) and concentric impulse part 1 (RR=1.44, 95% CI = 1.02-2.03).

Figure 2. Participant Distribution Across Significant Kinetic Variables

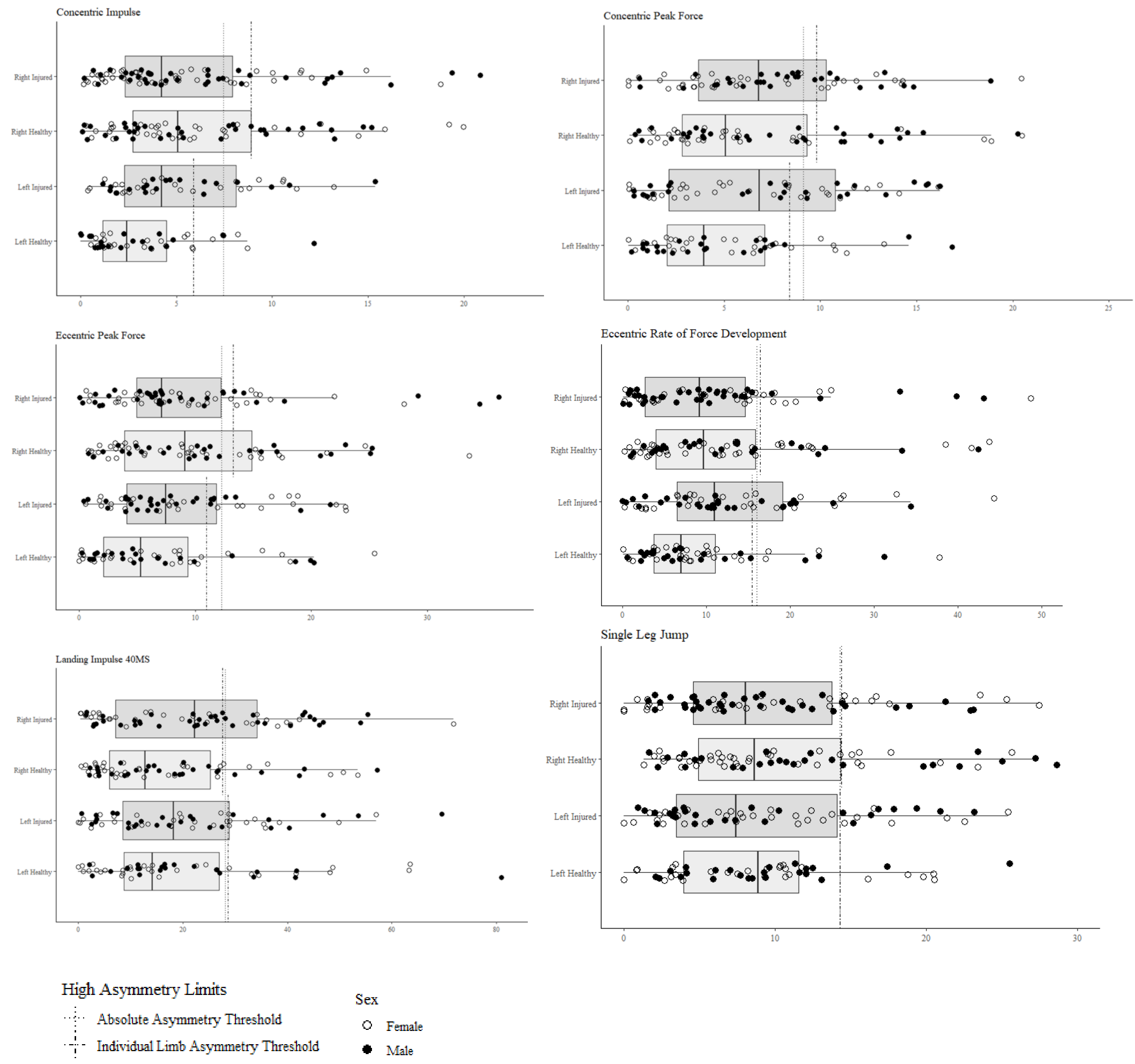

Table 3-Full List of Kinetic Variable Asymmetries and Risk Ratio's

	ABSOLUTE	**LEFT**	**RIGHT**
DOUBLE LEG COUNTERMOVEMENT JUMP			
DOWNWARD ("*ECCENTRIC*") PHASE			
ECC MINIMUM FORCE	0.98 (0.72-1.34)	1.23 (0.82-1.87) n = 129	0.88 (0.59-1.32) n =113
ECC YIELDING RFD	0.87 (0.65-1.16)	0.78 (0.51-1.20) n = 112	0.85 (0.56-1.29) n = 130
ECC DECELERATION RFD	1.00 (0.14-0.77)	1.10 (0.79-1.55) n = 113	0.89 (0.58-1.36) n = 129
ECC RFD	1.12 (0.85-1.47)	**1.60 (1.15-2.23) n = 107**	0.84 (0.55-1.30) n = 135
ECC DECEL IMPULSE	0.85 (0.62-1.15)	0.93 (0.61-1.42) n = 108	0.81 (0.52-1.26) n = 134
ECC PEAK FORCE	1.01 (0.77-1.33)	**1.45 (1.02-2.05) n = 107**	0.78 (0.52-1.18) n = 135
FORCE @ 0 VELOCITY	1.01 (0.77-1.32)	1.36 (0.96-1.93) n = 108	0.76 (0.50-1.15) n =134
UPWARD ("*CONCENTRIC*") PHASE			
CON IMPULSE 100 ms	1.21 (0.94-1.55)	**1.69 (1.20-2.37) n = 105**	0.89 (0.60-1.30) n = 137
CON IMPULSE PART 1	1.17 (0.9-1.51)	**1.65 (1.19-2.28) n = 108**	0.91 (0.61-1.35) n = 134
CON IMPULSE PART 2	1.09 (0.84-1.42)	1.71 (1.17-2.48) n = 90	0.91 (0.65-1.31) n = 152
CON PEAK FORCE	**1.28 (1.01-1.62)**	**1.60 (1.18-2.16) n = 107**	1.15 (0.80-1.64) n = 135
FORCE @ CON PEAK POWER	1.07 (0.82-1.40)	1.42 (0.98-2.07) n = 100	0.80 (0.55-1.18) n = 142
CON IMPULSE	1.14 (0.88-1.48)	**1.58 (1.16-2.15) n = 98**	1.00 (0.68-1.48) n = 144
LANDING PHASE			
LANDING IMPULSE 40 ms	**1.31 (1.03-1.67)**	1.12 (0.77-1.64) n = 113	**1.40 (1.02-1.91) n = 129**
LANDING RFD 40 ms	**1.29 (1.02-1.64)**	1.21 (0.84-1.73) n= 116	1.35 (0.98-1.85) n = 126
AVERAGE LANDING RFD	1.12 (0.87-1.46)	1.23 (0.90-1.70) n = 115	1.08 (0.73-1.59) n = 127
LANDING PEAK FORCE	1.88 (0.83-1.42)	1.25 (0.88-1.79) n = 121	0.95 (0.63-1.42) n = 121
LANDING IMPULSE	1.09 (0.84-1.42)	0.93 (0.60-1.45) n = 112	1.27 (0.93-1.73) n = 130
SINGLE LEG COUNTERMOVEMENT JUMP			
JUMP HEIGHT	1.20 (0.94-1.54)	**1.48 (1.08-2.03) n = 111**	1.01 (0.69-1.46) n = 131
ECC=Eccentric; CON=Concentric; RFD=Rate of force development			

Table 4-Full List of Kinetic Variable Asymmetries and Risk Ratio’s - Male Dancers.

	ABSOLUTE	**LEFT**	**RIGHT**
DOUBLE LEG COUNTERMOVEMENT JUMP			
DOWNWARD (“*ECCENTRIC*”) PHASE			
ECC MINIMUM FORCE	1.21 (0.87-1.68)	**1.57 (1.06-2.32)**	1.04 (0.64-1.69)
ECC YIELDING RFD	0.92 (0.62-1.36)	0.86 (0.52-1.43)	0.87 (0.46-1.66)
ECC DECELERATION RFD	0.97 (0.68-1.38)	0.96 (0.6-1.54)	0.96 (0.56-1.65)
ECC RFD	1.09 (0.75-1.58)	1.5 (0.96-2.35)	0.75 (0.38-1.48)
ECC DECEL IMPULSE	0.93 (0.62-1.38)	0.71 (0.36-1.4)	0.83 (0.45-1.5)
ECC PEAK FORCE	0.85 (0.55-1.29)	1.24 (0.76-2.03)	0.71 (0.39-1.29)
FORCE @ 0 VELOCITY	0.88 (0.59-1.32)	1.21 (0.74-1.97)	0.72 (0.4-1.32)
UPWARD (“*CONCENTRIC*”) PHASE			
CON IMPULSE 100 ms	1.05 (0.73-1.51)	**1.9 (1.19-3.04)**	0.95 (0.58-1.54)
CON IMPULSE PART 1	0.93 (0.62-1.38)	**1.57 (1.03-2.39)**	0.78 (0.45-1.37)
CON IMPULSE PART 2	1.2 (0.85-1.68)	1.59 (0.85-2.96)	1.06 (0.7-1.58
CON PEAK FORCE	1.17 (0.85-1.62)	**1.71 (1.16-2.53)**	0.96 (0.57-1.6)
FORCE @ CON PEAK POWER	1.02 (0.7-1.48)	1.45 (0.8-2.64)	0.88 (0.55-1.42)
CON IMPULSE	1.05 (0.73-1.51)	**1.9 (1.19-3.04)**	0.95 (0.58-1.54)
LANDING PHASE			
LANDING IMPULSE 40 ms	1.28 (0.93-1.75)	1.05 (0.6-1.84)	1.44 (0.98-2.13)
LANDING RFD 40 ms	1.13 (0.82-1.55)	0.97 (0.56-1.67)	1.2 (0.8-1.79)
AVERAGE LANDING RFD	1.07 (0.76-1.52)	1.09 (0.70-1.69)	1.08 (0.64-1.8)
LANDING PEAK FORCE	1.04 (0.73-1.49)	1.12 (0.67-1.87)	0.97 (0.59-1.6)
LANDING IMPULSE	1.03 (0.72-1.46)	1 (0.5-2.01)	1.08 (0.73-1.58)
SINGLE LEG COUNTERMOVEMENT JUMP			
JUMP HEIGHT	1.12 (0.8-1.58)	**1.81 (1.18-2.76)**	0.75 (0.43-1.29)

ECC=Eccentric; CON=Concentric; RFD=Rate of force development

Table 5-Full List of Kinetic Variable Asymmetries and Risk Ratio's - Female Dancers.

	ABSOLUTE	**LEFT**	**RIGHT**
DOUBLE LEG COUNTERMOVEMENT JUMP			
DOWNWARD ("*ECCENTRIC*") PHASE			
ECC MINIMUM FORCE	0.56 (0.26-1.2)	0.6 (0.18-1.99) n = 70	0.63 (0.28-1.44) n = 58
ECC YIELDING RFD	0.84 (0.55-1.27)	0.69 (0.34-1.4) n = 62	0.83 (0.5-1.44) n = 66
ECC DECELERATION RFD	1.02 (0.68-1.53)	1.26 (0.78-2.04) n = 59	0.83 (0.43-1.58) n = 69
ECC RFD	1.16 (0.79-1.71)	**1.72 (1.05-2.82) n = 55**	0.94 (0.53-1.66) n = 73
ECC DECEL IMPULSE	0.77 (0.48-1.24)	1.26 (0.70-2.25) n = 55	0.79 (0.41-1.51) n = 73
ECC PEAK FORCE	1.19 (0.83-1.73)	**1.72 (1.04-2.84) n = 56**	0.86 (0.48-1.53) n = 72
FORCE @ 0 VELOCITY	1.15 (0.79-1.66)	1.56 (0.94-2.59) n = 58	0.8 (0.44-1.43) n =70
UPWARD ("*CONCENTRIC*") PHASE			
CON IMPULSE 100 ms	**1.44 (1.02-2.03)**	**1.69 (1.03-2.77) n = 56**	1.04 (0.61-1.78) n = 72
CON IMPULSE PART 1	**1.44 (1.02-2.03)**	**1.8 (1.09-2.97) n = 56**	1.04 (0.59-1.82) n = 72
CON IMPULSE PART 2	1.02 (0.69-1.5)	**1.78 (1.11-2.86) n = 50**	0.8 (0.44-1.45) n = 78
CON PEAK FORCE	1.38 (0.97-1.96)	1.48 (0.93-2.37) n = 57	1.37 (0.83-2.25) n = 71
FORCE @ CON PEAK POWER	1.15 (0.79-1.66)	1.4 (0.87-2.26) n = 57	0.76 (0.41-1.4) n = 71
CON IMPULSE	1.24 (0.86-1.79)	1.36 (0.89-2.08) = 54	1.06 (0.56-1.99) n = 74
LANDING PHASE			
LANDING IMPULSE 40 ms	1.34 (0.94-1.91)	1.19 (0.71-1.98) n = 65	1.31 (0.78-2.19) n = 63
LANDING RFD 40 ms	**1.47 (1.05-2.08)**	1.43 (0.9-2.28) n= 68	1.52 (0.91-2.54) n = 60
AVERAGE LANDING RFD	1.16 (0.79-1.71)	1.38 (0.87-2.19) n 61	1.07 (0.59-1.94) n = 1.84
LANDING PEAK FORCE	1.12 (0.74-1.69)	1.38 (0.85-2.25) n = 66	0.89 (0.46-1.75) n = 62
LANDING IMPULSE	1.16 (0.79-1.69)	0.88 (0.50-1.57) n = 64	1.5 (0.9-2.49) n = 64
SINGLE LEG COUNTERMOVEMENT JUMP			
JUMP HEIGHT	1.29 (0.9-1.84)	1.23 (0.76-1.99) n = 60	1.39 (0.82-2.36) n = 68
ECC=Eccentric; CON=Concentric; RFD=Rate of force development			

Discussion

This study determined associations between interlimb asymmetry in a comprehensive range of DL-CMJ kinetic variables and in SLJ jump height, with prospective injury risk in pre-professional ballet dancers aged 11-19. In the full mixed sample of both sex's high asymmetry in specific DL-CMJ kinetic variables derived from the three phases of jump and in SLJ height during annual profiling, were associated up to a 69% higher risk of injury during the subsequent 9-month school year. The comprehensive kinetic analysis of the DL-CMJ asymmetries in relation to injury risk,[3,9] allowed the identification of specific asymmetry risk associations not previously identified. Notably, 7 significant associations were found using directional asymmetry analysis, with six of these occurring only with high left limb dominant asymmetry (i.e. a greater right limb deficit) - eccentric peak force, eccentric RFD, concentric impulse, concentric impulse 100 ms, concentric impulse part 2 and SL jump height. In contrast, landing impulse 40ms with right limb dominance was significantly associated with injury risk. Importantly, despite the larger sample size in the absolute asymmetry risk analysis, only 2 variables were significantly associated with injury risk – concentric peak force and landing impulse 40ms. The significant associations observed were principally driven by the high probability of injury in students with high asymmetry, for example in specific variables over 2 in 3 of those with elevated asymmetry were injured. In contrast, just under 1 in 2 of those classified as having normal asymmetry were also injured. This is reflected by the substantially higher specificity was than sensitivity of the significant variables (0.78-0.91 and 0.31 to 0.50, respectively). As such, this aligns with the complex and multifactorial nature of injury risk and demonstrates that having low asymmetry in specific variables does not determine injury risk. However, the high specificity demonstrates that jump-land asymmetries represent a potentially modifiable risk factor to screen for and address as part of risk reduction strategies, at least in the present population.

Limb Asymmetry and Ballet

To the authors knowledge, this is the first study to examine associations between asymmetries in DL-CMJ kinetics or SLJ height and prospective injury risk in dance. The elevated risk associated with higher left limb dominant asymmetry during the take-off phase and right limb during landing could be related to the nature of balletic activity. Kimmerle et al.,[23] highlighted a preference for dancers to use their right leg in powerful activities such as turning and jumping, aligning with other evidence suggesting a right bias in ballet training [2,16,35]. Traditionally young dancers begin to learn at the barre with their left leg as the "supporting" leg and their right leg as the "gesture" leg.[2] This may lead to interlimb differences in motor proficiency. However, two studies investigated the *grande jete* jump in pre-professional dancers and found no significant differences in jump height between take-off leg.[14,43] Despite this, Wyon et al.,[43] did identify greater right limb knee flexion during the take-off and landing phases and Golomer et al.,[15] observed a significant relationship between right limb muscle mass and jump height which was not observed contralaterally. These findings correspond with the present population in which dancers were right limb dominant in the majority of variables.

Injury risk may be heightened by the design of practice and performances directly or indirectly favouring the best aesthetic to be produced by the majority of dancers, rather than the minority. For instance, Baker et al.,[2] observed that the majority of exercises during ballet classes for both beginner and advanced level dancers, were taught favouring the use of or more frequent use of the right side. This type of practice forces left limb dominant dancers to use their weaker (right) leg as the lead leg, thereby increasing the relative demands of these activities on the limb, which in turn may drive the greater injury risk observed in dancers with large magnitudes of left dominance (relative right sided deficit). Similarly, in a prospective study in mixed team-sport youth athletes (n=81), Fort-Vanmeerhaeghe et al.,[11] found a significantly higher ($p<0.001$) SLJ height asymmetry in injured than non-injured athletes and suggested that the less dominant limb might have lower ‘tolerance capacity’ increasing the likelihood of exceeding that tolerance and becoming injured. In the present study however, injury incidence in the dancers was similar across limbs (Table 2), challenging a simple explanation with respect to dominance and risk of injury.

Managing the symmetry of dance practice and performance by implementing more left limb dominant training might help to mitigate some of the asymmetries that are present in pre professional ballet dancers[35] and better suit those who are more dominant on their left limb. Shaw et al.,[37] validated the use of an accelerometery algorithm to monitor ballet specific jump height and frequency. This type of approach could be used to monitor the demand placed upon each individual limb to provide an insight into the relative balance of training and potentially modify accordingly. Where this is not possible targeted conditioning of the less dominant limb might provide an alternative solution.

Direction Specific Findings

One of the strengths of this analysis was the size of the present sample, which enabled the use of internal descriptive data routinely collected by the school as representative of the population and enabling further exploration into directional asymmetry sub-analysis. The finding that injury risk was associated with a relative deficit in the dominant limb aligns with a study in elite youth footballers which observed a significant association between lower right but not left limb dominant vertical ground reaction forces in the SLJ and prospective injury risk[33] (the majority of players were right footed). Absolute SLJ peak force asymmetries also displayed significant relationships ($p<0.001$) with injury risk.

Asymmetry-risk studies have generally considered absolute magnitude, but not direction of asymmetry.[11,36] An exception being Malaver et al.,[30] who examined army cadets and medial tibia stress syndrome risk as an outcome, this studies findings broadly align with theirs in that a left limb dominant (eccentric deceleration RFD) asymmetry identified in a pre-participation DL-CMJ assessment was associated with prospective risk, while right limb asymmetry was not. Similarly, this study found a significant association between left limb eccentric RFD asymmetry and injury risk, but this association was not evident for absolute or right limb asymmetry.

These direction-specific findings may have implications for the analysis and interpretation of asymmetry-risk data in other cohorts, providing greater evidence of injury risk not identified by only examining associations with absolute asymmetry – the most commonly used approach to asymmetry analysis.

Sex Differences

There were some potentially important gender differences in the asymmetry – risk associations observed in the results of this study. In comparison to the full sample, when examining in the girls alone, RR´s associated with eccentric, and to a lesser extent landing asymmetries increased. However, specific concentric variables (concentric peak force and concentric part 2) and SLJ height asymmetry became non-significant. In contrast, in the boys alone, RR's for associations between DL-CMJ concentric asymmetries and risk were similar or greater than in the whole sample, while associations with eccentric and landing asymmetries became non-significant.

Previous evidence suggests sex differences in jumping asymmetries may influence injury risk. For instance, concentric peak force asymmetry was associated with injury risk in boys but not girls appear to align with a recent study from Koźlenia et al.,[26]. They found that injury risk was associated with asymmetry in DL-CMJ "peak force" in a sample of active young adult males but not females – peak force typically occurs in the upward phase and therefore equal in most cases to concentric peak force in the present study. In contrast, this study found SLJ height asymmetry was only associated with significantly elevated risk in boys, while, Fort-Vanmeerhaeghe et al., [11] reported that in both young male and female athletes, SLJ height asymmetries were significantly higher in those that became injured. Interestingly, however the difference in mean % asymmetry between injured and uninjured group was larger in males (uninjured: 9.7 % injured 17.1%) than in females (uninjured: 7.7% injured: 12.8%).

There are well established sex differences in drop jump landing biomechanics and associations to anterior cruciate ligament (ACL) injury risk [17,34] in female athletes. These injuries are however uncommon in female ballet dancers[10,31] (0 incidence in the present study) and therefore the relevance of this to a pre-professional ballet cohort is questionable. Nonetheless, it is interesting that asymmetry in downward phase "eccentric" variables related to rapid deceleration of body mass and early landing impact were more robustly associated with risk of (principally overuse) injuries in the female dancers. For example, despite the large loss of sample size in the analysis (from n= 107 to n = 56), RR's for eccentric peak force on the with a dominant left limb rose from 1.45 to 1.72 in female dancers. Whether sex differences in jump biomechanics or neuromuscular and musculotendinous qualities related to deceleration and force attenuation could explain some of the findings within the present study should be examined in further research.

In understanding and interpreting these findings the substantially different nature of activities performed by males and female dancers within the balletic training and performance context should also be considered. For instance, female dancers traditionally perform much more work "en pointe" (in a fully plantarflexed position), whereas male dancers traditionally perform more intensive jumping activities.[1,31] This difference affects injury mechanisms within male and female dancers. Female dancers are more likely to get overuse foot and ankle injuries while male dancers suffer more severe traumatic injuries related to jumping and landing[1,31]a pattern replicated in this study (15 of the 80 female dancers suffering from a traumatic injury in comparison to 25 of the 70 male dancers).

Inherent to the sub-analysis separating boys and girls there was a substantial loss of statistical power, and sample size may not have been adequate for such an analysis resulting in a type II error. In particular, when separating left and right limb dominant asymmetry students to determine associations with direction of asymmetry. For instance, in female's significant associations between eccentric RFD asymmetry on the dominant left side were observed with 10 of the 14 dancers (71%) with high asymmetry becoming injured. In male dancers, despite 9 of the 12 dancers (75%) with high asymmetry in the same variable becoming injured, risk ratios for the association were not significant due to the lower overall numbers and as such reduced sensitivity (Appendix 3). As such, noted sex differences should not be over interpreted and further research with larger samples are needed to confirm the apparent differences.

Implications for Dance Clinicians

In addition to the DL-CMJ kinetic asymmetries, higher left SLJ height asymmetry was associated with prospective injury risk, although not significant in females. This is useful from a practical perspective as it can be measured using a variety of lower cost devices [21,44] and therefore can be obtained by practitioners working within less well funded dance or other sporting institutions without access to force platforms. Given the present and prior evidence,[11,33,36] in these environments, SLJ height asymmetry assessment might be considered a prudent screening practice, at least in young athletes. Future studies should also examine SLJ kinetic asymmetries as well as height asymmetries, to determine if asymmetries in other aspects of neuromuscular performance are more strongly associated with risk.

Overall, this study's analysis indicates that DL-CMJ kinetic asymmetries may be more strongly associated with risk than SLJ height asymmetry; specifically, the early upward phase variables (con impulse 100 or con impulse part 1) - the only variables to be significant for both sexes. Furthermore, this detailed kinetic analysis identifies asymmetries in specific neuromuscular characteristics and phases within the jump-land movement cycle, insights which may inform more targeted corrective programming. The finding that elevated asymmetry in specific DL-CMJ variables in a phase were associated with risk (i.e. eccentric RFD and peak force), while other variables in the same phase (eccentric deceleration impulse, force @ 0 velocity) were not, also supports the value of a comprehensive kinetic analysis of DL-CMJ data to allow the identification of the variables and characteristics they represent that are most strongly associated with the outcome of interest (i.e. injury risk).[4,8,40]

Critique of analysis techniques

This study used a greater than moderate severity threshold classification to define injury, an approach chosen so that only injuries affecting participation in dance practice or require more substantial or lengthy rehabilitation were included. Due to the wide range of intensities and skills required during ballet practice, participation in light rehearsal is possible even when a dancer is suffering a significant injury. Conversely, performing higher intensity activities such as large pirouettes and jumps can be impossible even with a relatively minor injury. For this reason, injury definitions commonly applied in studies of prospective risk in athletic populations may be inappropriate for the present population.[22] Therefore, while this severity threshold classification does not align with other epidemiological studies in ballet dancers,[13,28] it was considered the most relevant from a practical perspective within the current population. The inclusion of all lower intensity injuries that may have limited full participation in dance practice would have substantially increased the number of dancers defined as injured (to 143) and made the analysis less meaningful.

An asymmetry threshold of ≥Mean Asymmetry % +(0.5*SD) was used to classify elevated asymmetry, while being an arbitrary cut point, is a statistically derived threshold based on the characteristics of the sample and specific to each variable , rather than the pre-defined asymmetry thresholds of 10 or 15% often employed in risk studies.[18,24,32] ≥Mean Asymmetry % +(0.75*SD) and % + (1*SD) cut points (data not shown) were also studied with both showing inferior performance considering RR's and CI's, and contingencies, suggesting that at least in the present population such a cut point is appropriate. The results suggest cut points for high asymmetry determined using simple descriptive statistics applied to the cohort data are also associated with a meaningful clinical outcome and therefore useful in classifying risk. This is particularly pertinent to pre-professional ballet for whom there is little normative data or prospective research available, and while this approach has also been demonstrated in army cadets[30] , further research in other athletic groups is warranted to establish if this approach can be more widely applied across populations. This approach may however be limited to scenarios where the practitioner has access to a large enough pool of athletes to calculate a representative mean and standard deviation.

Limitations

This study provides some rationale for the use of jump-based asymmetry screening assessments at the start of pre-professional ballet dancers annual training cycle. However due to the exploratory nature of this investigation this should be considered the first step in investigating potential links between jumping asymmetry and injury in pre-professional ballet dancers. Due to the considerable number of comparisons made in this trial there is an increased chance of type 1 error in these findings. However, this study does provide detailed evidence for future research within this population, which was previously lacking.

If these prospective findings can be replicated there is also a lack of clarity on how these factors respond longitudinally and interact with injury. Various dynamic factors such as maturation levels, energy intake, specific loading and fatigue may have influenced neuromuscular performance and asymmetries prior to the injury occurrence since the mean time between test and injury was 125.6 days (Table 2). Further analysis investigating how asymmetries respond longitudinally and during dynamic dance activity is warranted. In addition, the generalizability of these findings to other groups is unclear due to the highly specialised training and characteristics of the present population. The association between jump-land kinetic asymmetries and injury risk in other groups of youth athletes or dancers should be investigated in future studies using an internal, variable-specific, statistical cut-point approach.

Conclusions

Asymmetry values-based on population and variable specific cut points in specific kinetic asymmetries in the DL-CMJ, and SLJ height asymmetries, were associated with an elevated risk of injury in pre-professional ballet dancers. Most of these associations were observed in left limb dominant but not right limb dominant nor absolute jumping asymmetries. This indicates the importance of investigating not only absolute but also and left limb dominant and right limb dominant asymmetries as associations would have been missed if directional asymmetries were not evaluated. Sex differences were also observed with these associations. For female dancers DL-CMJ eccentric and landing asymmetries were more strongly associated with risk while DL-CMJ concentric asymmetry and SLJ height associations were attenuated, whilst the opposite was the case for male dancers. This study builds on previous research describing the dominance of the right side in ballet practice and performance and provides a starting point for further detailed investigations of links between jumping asymmetry and prospective injury risk within this population. Should these links be further established this may provide rationale for the diversification of ballet practice and the provision of unilateral supplementary training. While neuromuscular asymmetries are only one component in the complex and multifactorial injury risk picture, this study provides useful insights into a potentially modifiable risk factor that can be screened for in various settings and might be addressed with appropriate training modifications.

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