Received: 21 February 2018 | Revised: 7 September 2018 | Accepted: 18 September 2018

DOI: 10.1111/sms.13309

ORIGINAL ARTICLE

WILEY

Comparison of lower limb stiffness between male and female dancers and athletes during drop jump landings

Rachel E. Ward[1] | **Alycia Fong Yan**[2] | **Karl F. Orishimo**[3] | **Ian J. Kremenic**[3] | **Marshall Hagins**[4,5] | **Marijeanne Liederbach**[5] | **Claire E. Hiller**[2] | **Evangelos Pappas**[2]

[1]School of Medical Sciences, UNSW Sydney, Sydney, New South Wales, Australia

[2]Faculty of Health Sciences, The University of Sydney, Sydney, New South Wales, Australia

[3]Nicholas Institute for Sports Medicine and Athletic Trauma, Lenox Hill Hospital, New York, New York

[4]Division of Physical Therapy, Long Island University, Brooklyn, New York

[5]Harkness Center for Dance Injuries, NYU Langone Orthopedic Hospital, New York, New York

Correspondence
Rachel E. Ward, School of Medical Sciences, UNSW Sydney, Sydney, NSW, Australia.
Email: rachel.ward@unsw.edu.au

Funding information
Jacob and Valeria Langeloth Foundation

Repetition of jumps in dance and sport training poses a potential injury risk; however, non-contact landing injuries are more common in athletes than dancers. This study aimed to compare the lower limb stiffness characteristics of dancers and athletes during drop landings to investigate possible mechanisms of impact-related injuries. Kinematics and kinetics were recorded as 39 elite modern and ballet dancers (19 men and 20 women) and 40 college-level team sport athletes (20 men and 20 women) performed single-legged drop landings from a 30-cm platform. Vertical leg stiffness and joint stiffness of the hip, knee, and ankle were calculated using a spring-mass model. Stiffness data, joint kinematics, and moments were compared with a group-by-sex 2-way analysis of variance. Multiple linear regression was used to assess the relative contribution of hip and knee and ankle joint stiffness to variance in overall vertical leg stiffness for dancers and athletes. Dancers had lower leg ($P < 0.001$), knee joint ($P = 0.034$), and ankle joint stiffness ($P = 0.043$) than athletes. This was facilitated by lower knee joint moments ($P = 0.012$) and greater knee ($P = 0.029$) and ankle joint ($P = 0.048$) range of motion in dancers. Males had 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. Male and female dancers demonstrated reduced lower limb stiffness compared to athletes, indicating a more pliable landing technique. Dance training techniques could potentially inform approaches to injury prevention in athletes.

KEYWORDS
injury prevention, landing, training

1 | INTRODUCTION

Jumps are an important feature of many dance styles, creating a sense of flight and weightlessness of the dancer. In many dance styles, jumps are practiced and performed in repetition, with more than 200 jumps performed in a typical class.[1] Although there may be differences between dance styles in the time spent jumping, there does not appear to be a difference in time spent jumping between males and females.[2,3] The repetition of jumps in dance and sport training enables the development of strength, stamina, and correct technique, but also poses a potential injury risk.[4] Injury may occur either from repetitive malalignment of the lower limb segments which overloads restraining mechanisms or from landing impact.[4] Jump landing has often been linked with non-contact anterior cruciate ligament (ACL) injuries in active populations.[5-9]

Although jumps are a commonly performed element within dance and many sports, research indicates that dancers have a lower overall incidence of ACL injury (0.009 ACL injuries per 1000 exposures) compared with team sport athletes (0.07-0.31 ACL injuries per 1000 exposures).[10] Female athletes have a higher incidence of ACL injuries than male athletes[11,12]; however, a similar sex difference is not evident for ACL injuries among dancers.[10]

Landing impact can be assessed using measures of mechanical stiffness. Mechanical stiffness refers to the body's ability to resist deformation against an applied force under the assumption that the body acts as a spring and has uniform stiffness properties (k).[13] The term "leg stiffness" is used for measures of resistance to change in overall leg length after application of internal or external forces.[13,14] Rather than applying a uniform stiffness property (k) to the whole lower limb, leg stiffness can be regulated by modulating stiffness at individual joints.[14] Joint stiffness can be controlled by altering the joint range of motion (ROM) and the associated muscle activity. For example, impact during running has been shown to be attenuated through altering knee and ankle joint stiffness by changing the footfall technique[15] from a heel strike to a forefoot strike.[16] There are two factors that mainly determine stiffness during landing from a jump: the external force and the ROM.

Leg stiffness has been shown to be an important indicator for injury risk in sport, with bilateral differences in leg stiffness prior to a season increasing the likelihood of developing a non-contact lower limb injury.[17] Joint stiffness has been linked with impact-related injury, however, the optimal joint stiffness is still unknown. Increased lower limb joint stiffness has been associated with bony injuries, such as stress fracture risk in runners,[18-20] while reduced joint stiffness has been linked with soft tissue injuries.[21]

A review of the literature has shown there are differences in relative leg stiffness between males and females during jump landings[22]; however, it is unknown whether there are sex differences in leg stiffness or joint stiffness due to differences in training at the elite level. For elite athletes and dancers, specific movement patterns are trained over a long period of time, usually many years, resulting in development of preferred movement strategies. In most jump landings, a forefoot strike is common; however, the technique of "rolling through the foot" is unique to dance.[2,10,23] The dance aesthetic typically requires a controlled landing with a toe strike followed by the ball of the foot and a delayed controlled lowering of the heel and sequential flexion of the lower limb joints.[10,24] This has the aesthetic effect of a quiet and smooth landing.[2,10,25] The strong emphasis placed on the unique aesthetic requirements of dance may lead to the development of distinct lower limb stiffness properties in highly trained dancers.

The primary aim of this study was to measure and compare vertical leg stiffness, and sagittal plane hip, knee, and ankle joint stiffness for male and female dancers and athletes during single-leg drop jump landings for non-dance-specific landings. A secondary aim was to compare sagittal plane joint moments and ROM between these groups. We hypothesized that dancers will exhibit lower stiffness than athletes; however, it is currently unknown whether dancers will apply their dance-specific jump landing technique to other landing types.

2 | MATERIALS AND METHODS

Data from this project focusing on sex and training differences as they relate to the biomechanical risk of lower extremity injury[26] and the effects of fatigue[27] have been previously published. This paper will focus on lower extremity stiffness. An a priori power analysis for the main variable of knee valgus angle determined that with 20 participants per group, we achieve 80% power for an α level of 0.05 and a moderate effect size (partial eta squared = 0.13).

2.1 | Participants

Forty dancers (20 M and 20 F) and 40 team sport athletes (20 M and 20 F) were recruited to participate in this study at the Motion Capture Laboratory of the Harkness Center for Dance Injuries, NYU Langone Orthopedic Hospital. Due to technical issues, data from one male dancer were incomplete for the purpose of calculating joint stiffness.

All participants completed a medical history questionnaire and signed an informed consent form approved by the local institutional review board. Demographic information including height, weight, and age at the time of testing is displayed in Table 1. All dancers were currently active in a professional ballet or modern dance company, and all athletes were currently competing at the collegiate level (Division I-III) in jumping and/or cutting sports (ie, basketball, volleyball, soccer, lacrosse, rugby). Additionally, for inclusion, all participants had no history of surgery to the lower extremities, no current lower extremity injuries, and no lower extremity injuries within the previous year.

2.2 | Drop landings

Participants performed three single-leg drop landings from a 30-cm platform onto a force plate. Each participant wore their own personal athletic shoes for the testing, and all landings were performed on the dominant leg which was defined as the leg that would be used to kick a ball for maximal distance. As illustrated in Figure 1, participants were required to cross their arms over their chest and begin each trial in single-limb stance on the dominant leg. They then dropped off the platform and landed on the force plate using the same leg.

TABLE 1 Participant demographic data (mean ± SD)

	Dancers		Athletes		2-way ANOVA effects		
	Female (n = 20)	Male (n = 19)	Female (n = 20)	Male (n = 20)	Interaction	Group	Sex
Age (y)[a]	25.53 ± 5.39	26.83 ± 6.060	20.70 ± 1.81	22.60 ± 4.35	NS ($P = 0.780$)	Dancers > athletes ($P < 0.001$)	NS ($P = 0.134$)
Age began training (y)[c]	6.05 ± 2.91	14.16 ± 4.93	8.90 ± 3.71	10.00 ± 4.32	Females dancers < all others ($P < 0.001$)	NA	NA
Height (m)[a,b]	1.71 ± 0.07	1.83 ± 0.07	1.77 ± 0.08	1.86 ± 0.08	NS ($P = 0.384$)	Athletes > dancers ($P = 0.011$)	Males > females ($P < 0.001$)
Mass (kg)[a,b]	56.81 ± 5.98	72.81 ± 9.05	67.50 ± 8.38	78.95 ± 13.54	NS ($P = 0.298$)	Athletes > dancers ($P < 0.001$)	Males > females ($P < 0.001$)
BMI (kg/m^2)[a,b]	19.49 ± 1.53	21.76 ± 1.96	21.66 ± 2.63	22.76 ± 3.48	NS ($P = 0.338$)	Athletes > dancers ($P = 0.001$)	Males > females ($P = 0.005$)

NS, not significant; NA, not applicable.
[a]Group effect.
[b]Sex effect.
[c]Group × sex interaction.

2.3 | 3D motion analysis

Twenty reflective markers were placed bilaterally over the calcaneus, second metatarsal, lateral malleolus, lateral femoral condyle, mid-shank, mid-thigh, anterior superior iliac spine, acromion, lateral humeral epicondyle, and distal radius. Two additional markers were placed on the sacrum and the left posterior superior iliac spine as per the Helen Hayes system.[28] Marker positions were collected at 250 Hz using eight Eagle cameras (Motion Analysis Corp., Santa Rosa, CA, USA). The motion data were then filtered with a 4th-order Butterworth low-pass filter with a cutoff frequency of 10 Hz in order to eliminate any high-frequency noise. Ground reaction forces (GRFs) were recorded at 2500 Hz with a multi-component force plate (AMTI; Watertown, MA, USA).

Landings were defined as the period of time from initial contact with the force plate to the point in time at which peak knee flexion was achieved during each trial. Sagittal plane joint angles were calculated for the ankle, knee, and hip using the motion capture data. Net joint moments were calculated for each joint by standard inverse dynamic techniques using specialized computer software (Visual 3D; C-Motion Inc, Rockville, MD, USA). All joint moments were reported as external moments and normalized to body mass.

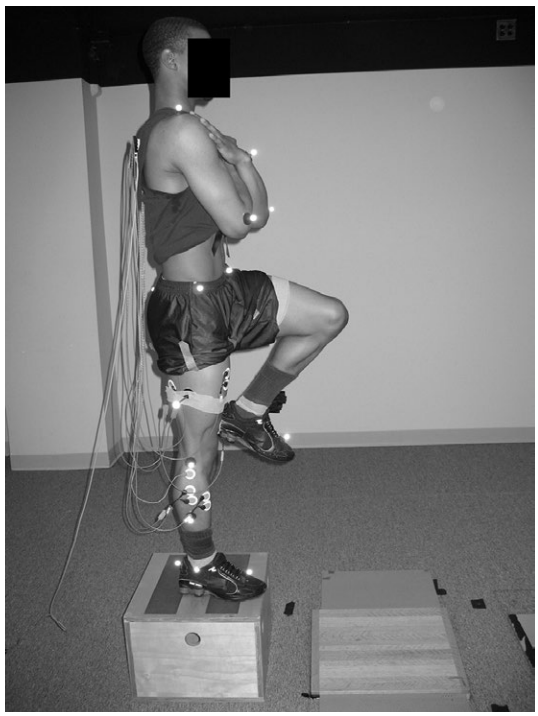

FIGURE 1 Laboratory setup for 30-cm drop landings. Participants crossed their arms over their chest and started each trial in a single-limb stance on the dominant leg. They then dropped off the platform and landed on the force plate using the dominant leg

2.4 | Stiffness calculations

A spring-mass model was used to calculate vertical leg stiffness (K_{leg}) and joint stiffness (K_{joint}) of the hip, knee, and ankle, as described in previous studies.[29,30] K_{leg} was calculated using the following formula:

$$K_{leg} = \text{peak } GRF_{vertical} / \Delta L_{COM}$$

where peak $GRF_{vertical}$ is the maximum vertical ground reaction force and ΔL_{COM} is the vertical displacement of the center of mass (COM) from the initial contact position to peak GRF. COM was calculated in Visual3D based on the position and inertial properties of each body segment using the whole-body biomechanical model. GRF data were normalized to body weight (BW), and COM displacement was normalized to height and also reported in absolute terms. K_{leg} was normalized to body weight and height. K_{joint} was calculated using the following formula:

$$K_{joint} = \Delta M_{joint} / \Delta \Theta_{joint}$$

where ΔM_{joint} is the change in joint moment between initial ground contact and the instant of peak joint moment and $\Delta \Theta_{joint}$ is the angular displacement of the joint between initial ground contact and peak joint moment.

2.5 | Statistical analysis

Two-way between-group analyses of variance (ANOVAs) were performed to assess the effect of group (dancers vs athletes) and sex (males vs female) on all demographic data. Two-way between-group ANOVAs were performed to investigate the effects of group (dancers vs athletes) and sex (males vs females) on stiffness, COM kinematics, GRF, joint kinematics, joint kinetics, and landing time during drop landings. Specific primary data included in the analyses were vertical leg stiffness and hip, knee, and ankle joint stiffness. Secondary variables included COM vertical displacement and peak GRF; hip, knee, and ankle flexion at initial contact; hip, knee, and ankle flexion angle at peak moment; hip, knee, and ankle ROM from initial contact to peak joint moment; hip, knee, and ankle peak moment and change in moment from initial contact to peak joint moment.

A stepwise multiple linear regression was used to examine the contributions of hip, knee, and ankle joint stiffness to variance in vertical leg stiffness for each training and sex group: female dancers; male dancers; female athletes; and male athletes. The standardized beta (β) statistic was reported to provide a measure of the percentage of variance of vertical leg stiffness accounted for by each independent variable included in the regression model. Alpha was set at 0.05 for the regression analyses. Given the sequential joint flexion of the hip, knee, and ankle typically demonstrated on jump landings,[31] the timing of peak joint moments for the lower limb joints may not necessarily align with the instant of peak GRF. This may have implications for these parameters being used as predictors of vertical leg stiffness.

Time-series data were calculated for COM vertical displacement and vertical GRF, as well as joint angles and moments for the hip, knee, and ankle. These were presented for the landing cycle (ie, from initial contact to peak knee flexion in 1% increments). Data were averaged for each group: female dancers; male dancers; female athletes; and male athletes. IBM SPSS Statistics for Windows, version 24 (IBM Corp., Armonk, NY, USA), was used for all statistical analyses.

3 | RESULTS

Dancers were older than athletes, but males and females were of similar age across both training groups. Female dancers started their training at a younger age (6 years) than all other groups (8-14 years). Athletes had greater height, mass, and body mass index (BMI) than dancers. Males had greater height, mass, and BMI than females (Table 1).

For all stiffness, kinematic, and kinetic variables, the two-way ANOVAs revealed no interaction effect for group and sex, only main effects (Tables 2-5). Time-series graphs for the kinematic and kinetic variables, presented as a percentage of landing cycle, are provided as Supporting Information.

3.1 | Group effects

Dancers had lower vertical leg, knee joint, and ankle joint stiffness than athletes. Additionally, dancers had greater absolute COM vertical displacement, greater COM vertical displacement per height, and lower peak GRF per body weight than athletes. Dancers also had increased landing time compared to athletes, taking an additional 28 milliseconds to land (Table 2). Group effects at the hip joint included increased hip moment change and peak for athletes compared to dancers, while there were no differences in flexion ROM or hip joint stiffness between dancers and athletes (Table 3). At the knee joint, in addition to decreased knee joint stiffness, dancers had higher flexion ROM and lower change and peak in joint moment compared to athletes (Table 4). In addition to decreased ankle joint stiffness, dancers also exhibited increased initial plantar flexion angle and increased ankle ROM compared to athletes. There was no difference in ankle moment change or peak between dancers and athletes (Table 5).

3.2 | Sex effects

Males had greater vertical leg stiffness compared to females, this occurred with lower COM vertical displacement

TABLE 2 Vertical leg stiffness, center of mass (COM) displacement, ground reaction force (GRF) during drop landings (mean ± SD), and 2-way ANOVA effects of group (dancer vs athlete) and sex (male vs female)

	Dancers		Athletes		2-way ANOVA effects		
	Female (n = 20)	Male (n = 19)	Female (n = 20)	Male (n = 20)	Interaction	Group	Sex
Vertical leg stiffness[a,b] (body weight/height)	73.24 ± 20.23	92.13 ± 24.63	98.71 ± 28.33	129.03 ± 36.71	NS ($P = 0.371$)	Athletes > dancers ($P < 0.001$)	Males > females ($P < 0.001$)
COM vertical displacement/ height IC to peak GRF[a,b]	0.057 ± 0.008	0.050 ± 0.008	0.047 ± 0.008	0.041 ± 0.007	NS ($P = 0.763$)	Dancers > athletes ($P < 0.001$)	Females > males ($P = 0.001$)
COM vertical displacement IC to peak GRF (m)[a]	0.097 ± 0.015	0.091 ± 0.015	0.082 ± 0.015	0.076 ± 0.014	NS ($P = 0.975$)	Dancers > athletes ($P < 0.001$)	NS ($P = 0.062$)
Peak GRF[a,b] (body weight)	3.93 ± 0.84	4.42 ± 0.62	4.41 ± 0.56	5.00 ± 0.99	NS ($P = 0.746$)	Athletes > dancers ($P = 0.003$)	Males > females ($P = 0.003$)
Landing time[a] (s)	0.210 ± 0.042	0.194 ± 0.025	0.175 ± 0.044	0.173 ± 0.033	NS ($P = 0.399$)	Dancers > athletes ($P = 0.001$)	NS ($P = 0.303$)

NS, not significant; IC, initial contact.
[a]Group effect.
[b]Sex effect.

TABLE 3 Hip joint stiffness, kinematic and kinetic data during drop landings (mean ± SD), and 2-way ANOVA effects of group (dancer vs athlete) and sex (male vs female)

	Dancers		Athletes		2-way ANOVA effects		
	Female (n = 20)	Male (n = 19)	Female (n = 20)	Male (n = 20)	Interaction	Group	Sex
Hip joint stiffness (Nm/kg/ degree)	3.57 + 7.10	4.32 + 4.83	3.66 ± 7.10	9.46 ± 20.40	NS ($P = 0.325$)	NS ($P = 0.308$)	NS ($P = 0.203$)
Hip flexion at IC[b] (degrees)	13.41 ± 8.14	5.89 ± 9.49	12.60 ± 9.56	6.36 ± 8.25	NS ($P = 0.748$)	NS ($P = 0.934$)	Females > males ($P = 0.001$)
Hip flexion at peak moment[b] (degrees)	16.41 ± 8.47	7.61 ± 9.56	15.20 ± 9.20	8.02 ± 8.38	NS ($P = 0.688$)	NS ($P = 0.839$)	Females > males ($P < 0.001$)
Hip flexion ROM IC to peak moment[b] (degrees)	3.00 ± 2.52	1.73 ± 2.20	2.59 ± 2.01	1.65 ± 1.51	NS ($P = 0.726$)	NS ($P = 0.611$)	Females > males ($P = 0.021$)
Hip moment change IC to peak moment[a,b](Nm/kg)	3.33 ± 1.34	4.28 ± 1.46	4.25 ± 1.46	4.87 ± 1.48	NS ($P = 0.609$)	Athletes > dancers ($P = 0.022$)	Males > females ($P = 0.018$)
Hip moment peak[a,b] (Nm/kg)	2.81 ± 1.07	3.92 ± 1.34	3.57 ± 1.20	4.52 ± 1.42	NS ($P = 0.777$)	Athletes > dancers ($P = 0.020$)	Males > females ($P = 0.001$)

NS, not significant; ROM, range of motion; IC, initial contact.
[a]Group effect.
[b]Sex effect.

TABLE 4 Knee joint stiffness, kinematic and kinetic data during drop landings (mean ± SD), and 2-way ANOVA effects of group (dancer vs athlete) and sex (male vs female)

	Dancers		Athletes		2-way ANOVA effects		
	Female (n = 20)	Male (n = 19)	Female (n = 20)	Male (n = 20)	Interaction	Group	Sex
Knee joint stiffness (Nm/kg/degree)	0.085 ± 0.030	0.117 ± 0.073	0.123 ± 0.070	0.138 ± 0.067	NS ($P = 0.561$)	Athletes > dancers ($P = 0.034$)	NS ($P = 0.079$)
Knee flexion at IC (degree)	10.65 ± 4.13	10.03 ± 5.88	13.14 ± 4.90	11.36 ± 5.41	NS ($P = 0.615$)	NS ($P = 0.101$)	NS ($P = 0.300$)
Knee flexion at peak moment (degree)	39.92 ± 9.03	39.07 ± 9.85	39.11 ± 6.97	35.12 ± 8.95	NS ($P = 0.429$)	NS ($P = 0.231$)	NS ($P = 0.223$)
Knee flexion ROM IC to peak moment (degrees)	28.51 ± 9.62	28.61 ± 11.55	26.00 ± 7.01	23.28 ± 6.38	NS ($P = 0.482$)	Dancers > athletes ($P = 0.029$)	NS ($P = 0.522$)
Knee moment change IC to peak moment (Nm/kg)	2.26 ± 0.59	2.60 ± 0.71	2.72 ± 0.63	2.86 ± 0.58	NS ($P = 0.480$)	Athletes > dancers ($P = 0.012$)	NS ($P = 0.095$)
Knee moment peak (Nm/kg)	2.51 ± 0.53	2.70 ± 0.55	2.94 ± 0.55	2.94 ± 0.53	NS ($P = 0.419$)	Athletes > dancers ($P = 0.008$)	NS ($P = 0.404$)

NS, not significant; ROM, range of motion; IC, initial contact.
[a]Group effect.
[b]Sex effect.

TABLE 5 Ankle joint stiffness, kinematic and kinetic data during drop landings (mean ± SD), and 2-way ANOVA effects of group (dancer vs athlete) and sex (male vs female)

	Dancers		Athletes		2-way ANOVA effects		
	Female (n = 20)	Male (n = 19)	Female (n = 20)	Male (n = 20)	Interaction	Group	Sex
Ankle joint stiffness[a,b] (Nm/kg/degree)	0.061 ± 0.025	0.079 ± 0.032	0.064 ± 0.034	0.113 ± 0.061	NS ($P = 0.098$)	Athletes > dancers ($P = 0.043$)	Male > female ($P < 0.001$)
Ankle plantar flexion at IC[a,b] (degrees)	24.60 ± 3.23	19.96 ± 4.214	20.56 ± 5.56	17.34 ± 4.58	NS ($P = 0.480$)	Dancers > athletes ($P = 0.001$)	Female > male ($P < 0.001$)
Ankle dorsiflexion at peak moment (degrees)	8.87 ± 8.84	8.51 ± 8.29	11.31 ± 4.89	5.24 ± 5.96	NS ($P = 0.081$)	NS ($P = 0.801$)	NS ($P = 0.050$)
Ankle ROM IC to peak moment[a,b] (degrees)	33.47 ± 9.68	28.46 ± 8.91	31.87 ± 6.77	22.59 ± 7.34	NS ($P = 0.253$)	Dancers > athletes ($P = 0.048$)	Female > male ($P < 0.001$)
Ankle moment change IC to peak moment[b] (Nm/kg)	1.70 ± 0.33	1.88 ± 0.30	1.78 ± 0.28	1.91 ± 0.32	NS ($P = 0.737$)	NS ($P = 0.404$)	Male > female ($P = 0.020$)
Ankle moment peak[b] (Nm/kg)	1.90 ± 0.27	2.05 ± 0.29	1.98 ± 0.21	2.11 ± 0.31	NS ($P = 0.813$)	NS ($P = 0.244$)	Male > female ($P = 0.022$)

NS, not significant; ROM, range of motion; IC, initial contact.
[a]Group effect.
[b]Sex effect.

per height and greater peak GRF per body weight in males compared to females. However, when expressed in absolute terms, the COM vertical displacement was not significantly different between the sexes (Table 2). Even though there were no sex differences in hip joint stiffness, males landed with decreased initial hip flexion, decreased hip flexion range, and increased change and peak in hip moment (Table 3). There were no sex differences in knee joint stiffness, knee flexion, or knee joint moment. Males had greater ankle joint stiffness compared to females, with decreased initial plantar flexion angle, decreased ankle ROM, and greater change and peak in ankle moment compared to females (Table 5).

3.3 | Hip, knee, and ankle contribution to vertical leg stiffness

The stepwise multiple linear regression revealed that for all groups except female dancers, the variance in vertical leg stiffness was explained primarily by knee joint stiffness. For athletes, knee joint stiffness was the only statistically significant independent variable included in the model, accounting for 52.9% ($\beta = 0.529$, $P = 0.016$) and 60.0% ($\beta = 0.600$, $P = 0.005$) of the variance in vertical leg stiffness for female and males athletes, respectively. For male dancers, knee joint stiffness accounted for less of the variance in vertical leg stiffness, 43.1% ($\beta = 0.431$, $P = 0.026$), but was still the only contributing variable. For female dancers, neither hip, knee, nor ankle joint stiffness were included in the regression model, so none of these variables contributed significantly to the variance in vertical leg stiffness (Table 6). Timing of peak joint moments occurred at different times throughout the landing phase for different joints. Mean timing of peak joint moment occurred at 23.3%, 46.8%, and 48.1% of landing for the hip, knee, and ankle joints, respectively, compared to 26.5% of the landing phase for peak vertical GRF.

4 | DISCUSSION

Overall, our hypothesis was supported as total lower extremity stiffness was significantly lower in dancers compared to athletes. Significant differences in joint stiffness were found between dancers and athletes at the knee and ankle. These findings suggest an effect of dance training on landing technique. The significantly reduced vertical leg stiffness displayed by the dancers compared to athletes can be attributed to the greater vertical displacement of the COM in conjunction with a lower GRF during landing. The decreased vertical stiffness demonstrated by the dancers was also associated with a significantly longer landing time in this group; however, there was no sex difference in landing time. It appears that the dance training technique which emphasizes quiet and smooth landings[2,10,25] was transferred to a non-dance-specific drop landing task.

To our knowledge, this is the first study to compare stiffness characteristics of dancers and athletes during drop landings. Ambegaonkar et al[32] examined stiffness in dancers and athletes during drop jumps (ie, rebounding from landing to perform another jump), rather than drop landings (ie, stopping on landing). However, in contrast to our results, they found that dancers had greater leg stiffness than athletes. It is possible that this difference may be due to the dancers having a feedforward motor planning mechanism[33] which altered stiffness in anticipation of what was to come next. Additionally, the different results may be due to our inclusion of athletes from a variety of sports while the previous study only included basketball players, and their participants performed double-leg versus single-leg jumps from a 45-cm box vs a 30-cm box.

Our data indicate that differences in kinematics and kinetics at the knee and ankle predominantly contributed to differences in overall vertical leg stiffness between dancers and athletes. Dancers displayed significantly reduced knee joint stiffness compared to the athletes, with this being attributed to a larger range of knee joint motion and lower knee joint moments compared to athletes. Data from previous publications from this project[26,27] compared frontal plane landing kinematics for the same cohort of dancers and athletes. Unlike the sagittal plane data presented in the current study, in the previous studies, female athletes demonstrated increased frontal plane knee joint range on landing compared to female dancers. This increased valgus range may place female athletes at greater risk of ACL injury. Therefore, collectively, data from this series of papers on landing biomechanics indicate that in the case of females, dancers demonstrate increased knee flexion and decreased knee valgus on landing compared to female athletes, a landing pattern that may contribute to their lower incidence of ACL injuries.

The significantly lower ankle joint stiffness found in dancers appears to be due to differences in joint angles rather than moments. The ankle joint moments during landing was similar between dancers and athletes; however, greater plantar flexion at initial contact resulted in an increased overall ankle joint ROM, thereby contributing to the lower joint stiffness displayed by the dancers. In dance, the instruction to “roll through the feet” on landing is implemented from very early in training. Such instruction encourages initial floor contact to occur with the tips of the toes with a fully plantar-flexed ankle, followed by controlled lowering through the foot finishing with smooth and controlled heel contact. Young dance students are also often instructed to “keep your heels down” when connecting with the floor during jump landings. Additionally, the requirement of achieving a maximal *demi-plié* (knee flexion while keeping the feet flat on the floor) is also one of the first fundamental techniques taught.

TABLE 6 Stepwise multiple linear regression of contribution of hip, knee, and ankle joint stiffness to variance in normalized vertical leg stiffness (body weight/height)

	Dancers				Athletes			
	Female (n = 20)		Male (n = 19)		Female (n = 20)		Male (n = 20)	
	No variables entered into regression model		R^2 = 0.239; P = 0.019		R^2 = 0.280; P = 0.016		R^2 = 0.360; P = 0.005	
	β	P	β	P	β	P	β	P
Hip joint stiffness	—	—	—	—	—	—	—	—
Knee joint stiffness[a]	—	—	0.531	0.019	0.529	0.016	0.600	0.005
Ankle joint stiffness	—	—	—	—	—	—	—	—

β, standardized beta coefficient; —, non-significant contribution to variance in vertical leg stiffness, variable excluded from regression model.
[a]Significant contribution to variance in vertical leg stiffness, variable included in regression model.

This combination of instructions therefore has the effect of increasing ankle ROM, peak ankle dorsiflexion, and knee flexion angles (ie, producing a deeper *demi-plié*) during landing. It is clear from this study that even in a task that is not dance-specific, dancers were able to apply their training to the drop landing task, utilizing a greater proportion of their available ankle and knee joint ROM while controlling the eccentric load with a lower knee joint moment. The resulting reduction in ankle and knee joint stiffness therefore reduced overall vertical leg stiffness.

When comparing males and females, the greater vertical leg stiffness demonstrated by males was consistent with previous studies.[29,34,35] Our finding that increased leg stiffness in males was due to increased vertical GRF and decreased COM vertical displacement was in agreement with Márquez et al[34] and Hughes and Watkins.[29] In terms of specific joint stiffness, we found that males had higher ankle joint stiffness compared to females, but similar knee and hip joint stiffness. Our data indicate that the higher ankle joint stiffness is due to a reduced range of ankle joint motion during landing as well as higher moments compared to females. In contrast to our study, Hughes and Watkins[29] reported significantly lower knee joint stiffness in females compared to males, with the knee being the only lower limb joint analyzed in the study. Although we did not find sex differences in hip joint stiffness, there were differences in hip joint moments and flexion range. Despite our findings of some sex differences in landing variables, a review by Bruton et al[22] of sex differences in the kinematics of landing, and a more recent study in basketball and floorball athletes,[36] provides little support for the presence of sex-specific kinematic patterns for landing tasks. Data for sagittal hip, knee, and ankle joint angles show sex differences in only a minority of studies and contrasting results between studies make it difficult to compare our kinematic data with previous research.

In relation to links between lower limb stiffness and injury, there are no prospective studies that directly correlate stiffness and injury. However, review of retrospective studies suggests that too much stiffness may be associated with bony injuries and too little stiffness may result in soft tissue injuries.[14] Many studies have focused on the link between jump landing mechanics and ACL injury; increased knee valgus ROM has been linked to ACL injury.[2,5,6,8,27,37] It has also been well established that increased valgus motion on landing is more common in female than male athletes,[2,6,36,38,39] thereby resulting in a higher incidence of ACL injuries in females. Our previously published data on frontal plane landing kinematics and kinetics[26,27] support these findings. With respect to sagittal plane joint mechanics, studies have indicated that sagittal factors are also related to ACL injury mechanisms[2,5,8,9,37,40]; however, in this case, landings with a low knee flexion ROM and increased vertical GRF, that is, a more stiff landing, have been suggested to cause increased loading of the knee and therefore an increased risk of ACL injury.[9,40,41] Hewett et al[40] described a quadriceps dominance theory for ACL injuries in which a low knee flexion angle at landing, and higher activation of the quadriceps muscles to stiffen and stabilize the knee joint, may result in excessive anterior translation of the tibia and strain on the ACL. In light of such previous research, our finding of dancers having decreased sagittal knee joint moments, increased knee flexion range, and associated reduced knee joint stiffness during landing suggests that dancers may exhibit a safer landing technique compared to athletes in relation to ACL injury, supporting prior study conclusions.[2,27]

Various studies have investigated the effectiveness of injury prevention programs in reducing ACL injury in athletes, with a recent review by Lopez et al,[42] indicating that such programs resulted in increased peak hip flexion, increased knee flexion, and decreased peak knee moment during landing. The majority of these studies included activities that prioritized soft landings by increasing knee flexion through implementation of plyometrics and jump landing tasks.[42] Interestingly, our study found that for all groups except female dancers, knee joint stiffness was the only lower limb stiffness variable that made a significant unique contribution to variance in overall vertical leg stiffness, with the proportion of this contribution being higher in both male and female athletes compared to dancers. This result suggests that athletes rely on their knee joint to moderate their overall vertical stiffness rather than the hip or ankle. It should be noted, however, that the mean timing of peak knee joint moment occurred after the mean timing of peak vertical GRF (ie, 46.8% of the landing phase for the knee moment compared to 26.5% for the GRF). Since the timing of peak knee joint moment and peak GRF influences the calculation of knee joint stiffness and vertical leg stiffness, respectively, this discrepancy in timings may have implications for the validity of knee joint stiffness as a predictor of vertical leg stiffness.

Our finding that male and female elite-level dancers already exhibit a softer landing mechanism at the knee joint and for overall vertical stiffness, together with previous research showing dancers to have a much lower overall incidence of ACL injuries compared to team sport athletes,[10] suggests that adoption of similar training approaches to those used in dance may be beneficial in reduction in lower limb injury within sporting populations.[2,27]

4.1 | Limitations

Several limitations need to be acknowledged and taken into consideration during interpreting the findings. This was a cross-sectional study; thus, dance training alone may not account for the entirety of the group differences. We focused on sagittal plane stiffness while injuries such as ACL tears have a triplanar contribution. Finally, we did not include trunk stiffness which may add additional insight into the difference between groups and sexes.

5 | PERSPECTIVES

Male and female dancers displayed lower vertical leg stiffness, which is a softer landing technique, than athletes. This was facilitated by reduced knee and ankle joint stiffness, which occurred via lower knee joint moments, and higher knee and ankle joint ROM. This finding supports our previous work which suggests that dancers may use a safer landing technique than athletes in relation to existing theories of mechanisms of lower limb injuries, particularly with respect to ACL injuries. A notable finding of this study was that without the imposition of any time constraints due to particular performance requirements, dancers took longer to land than athletes. This extra time may contribute to facilitation of the dancers' softer landing. The study revealed that elite dancers applied a softer, less stiff, landing technique even when performing non-dance-specific movements, and athletes used a stiffer technique even without the time pressures they are often exposed to during competition. This finding therefore suggests that athletes could potentially be trained to adopt some of the landing techniques used by dancers, particularly for application in sporting situations where a quick landing time is not necessarily a priority. Since knee joint stiffness was the only joint found to contribute significantly to overall variance in vertical leg stiffness in athletes, a focus on modification on knee joint mechanics during landing may prove beneficial for athletes. The training approaches used during the development of dance technique could therefore potentially offer some insight and application into approaches to injury prevention in elite and recreational sporting populations.

ACKNOWLEDGEMENTS

The authors thank the Jacob and Valeria Langeloth Foundation for its support of this work. They also thank Emily Junck, MD, and Megan Richardson, MS, ATC, DiplAc, LAc of the Motion Capture Laboratory at the Harkness Center for Dance Injuries, NYU Langone Health, for their major assistance with data collection. This study was selected for presentation at the 2016 annual conference of the International Association for Dance Medicine and Science.

CONFLICT OF INTEREST

The authors declare no conflict of interest for this study.

ORCID

Rachel E. Ward http://orcid.org/0000-0001-5643-5650
Ian J. Kremenic http://orcid.org/0000-0002-1426-1020

REFERENCES

1. Liederbach M, Richardson M, Rodriguez M, Compagno J, Dilgen FE, Rose DJ. Jump exposures in the dance training environment: a measure of ergonomic demand. *J Athl Train*. 2006;41(S85).
2. Orishimo KF, Kremenic IJ, Pappas E, Hagins M, Liederbach M. Comparison of landing biomechanics between male and female professional dancers. *Am J Sports Med*. 2009;37(11):2187-2193.

3. Wyon MA, Twitchett E, Angioi M, Clarke F, Metsios G, Koutedakis Y. Time motion and video analysis of classical ballet and contemporary dance performance. *Int J Sports Med*. 2011;32(11):851-855.
4. Aerts I, Cumps E, Verhagen E, Verschueren J, Meeusen R. A systematic review of different jump-landing variables in relation to injuries. *J Sports Med Phys Fitness*. 2013;53(5):509-519.
5. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med*. 2010;38(11):2218-2225.
6. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007;35(3):359-367.
7. Leppanen M, Pasanen K, Kujala UM, et al. Stiff landings are associated with increased ACL injury risk in young female basketball and floorball players. *Am J Sports Med*. 2017;45(2):386-393.
8. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med*. 2004;32(4):1002-1012.
9. Shimokochi Y, Shultz SJ. Mechanisms of noncontact anterior cruciate ligament injury. *J Athl Train*. 2008;43(4):396-408.
10. Liederbach M, Dilgen FE, Rose DJ. Incidence of anterior cruciate ligament injuries among elite ballet and modern dancers: a 5-year prospective study. *Am J Sports Med*. 2008;36(9):1779-1788.
11. Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. *Am J Sports Med*. 2005;33(4):524-530.
12. Arendt EA, Agel J, Dick R. Anterior cruciate ligament injury patterns among collegiate men and women. *J Athl Train*. 1999;34(2):86-92.
13. Serpell BG, Ball NB, Scarvell JM, Smith PN. A review of models of vertical, leg, and knee stiffness in adults for running, jumping or hopping tasks. *J Sports Sci*. 2012;30(13):1347-1363.
14. Butler RJ, Crowell 3rd HP, Davis IM. Lower extremity stiffness: implications for performance and injury. *Clin Biomech (Bristol, Avon)*. 2003;18(6):511-517.
15. Hamill J, Moses M, Seay J. Lower extremity joint stiffness in runners with low back pain. *Res Sports Med*. 2009;17(4):260-273.
16. Gruber AH, Silvernail JF, Brueggemann P, Rohr E, Hamill J. Footfall patterns during barefoot running on harder and softer surfaces. *Footwear Science*. 2013;5(1):39-44.
17. Pruyn EC, Watsford ML, Murphy AJ, et al. Relationship between leg stiffness and lower body injuries in professional Australian football. *J Sports Sci*. 2012;30(1):71-78.
18. Milner CE, Hamill J, Davis I. Are knee mechanics during early stance related to tibial stress fracture in runners? *Clin Biomech*. 2007;22(6):697-703.
19. Williams 3rd DS, Davis IM, Scholz JP, Hamill J, Buchanan TS. High-arched runners exhibit increased leg stiffness compared to low-arched runners. *Gait Posture*. 2004;19(3):263-269.
20. Williams 3rd DS, McClay IS, Hamill J. Arch structure and injury patterns in runners. *Clin Biomech*. 2001;16(4):341-347.
21. Granata KP, Padua DA, Wilson SE. Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. *J Electromyogr Kinesiol*. 2002;12(2):127-135.
22. Bruton MR, O'Dwyer N, Adams R. Sex differences in the kinematics and neuromuscular control of landing: biological, environmental and sociocultural factors. *J Electromyogr Kinesiol*. 2013;23(4):747-758.
23. Walter HL, Docherty CL, Schrader J. Ground reaction forces in ballet dancers landing in flat shoes versus pointe shoes. *J Dance Med Sci*. 2011;15(2):61-64.
24. Fong Yan A, Hiller C, Sinclair PJ, Smith RM. Kinematic analysis of sautés in barefoot and shod conditions. *J Dance Med Sci*. 2014;18(4):149-158.
25. Franklin E. *Floors and Soft Landings. Dance Imagery for Technique and Performance*. Champaign, IL: Human Kinetics; 1996:187.
26. Orishimo KF, Liederbach M, Kremenic IJ, Hagins M, Pappas E. Comparison of landing biomechanics between male and female dancers and athletes, part 1: influence of sex on risk of anterior cruciate ligament injury. *Am J Sports Med*. 2014;42(5):1082-1088.
27. Liederbach M, Kremenic IJ, Orishimo KF, Pappas E, Hagins M. Comparison of landing biomechanics between male and female dancers and athletes, part 2: influence of fatigue and implications for anterior cruciate ligament injury. *Am J Sports Med*. 2014;42(5):1089-1095.
28. Davis RB, Õunpuu S, Tyburski D, Gage JR. A gait analysis data collection and reduction technique. *Hum Mov Sci*. 1991;10(5):575-587.
29. Hughes G, Watkins J. Lower limb coordination and stiffness during landing from volleyball block jumps. *Res Sports Med*. 2008;16(2):138-154.
30. Lyle MA, Valero-Cuevas FJ, Gregor RJ, Powers CM. Control of dynamic foot-ground interactions in male and female soccer athletes: females exhibit reduced dexterity and higher limb stiffness during landing. *J Biomech*. 2014;47(2):512-517.
31. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Richard SteadmanJ. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech*. 2003;18(7):662-669.
32. Ambegaonkar JP, Shultz SJ, Perrin DH, Schmitz RJ, Ackerman TA, Schulz MR. Lower body stiffness and muscle activity differences between female dancers and basketball players during drop jumps. *Sports Health*. 2011;3(1):89-96.
33. Mouchnino L, Aurenty R, Massion J, Pedotti A. Coordination between equilibrium and head-trunk orientation during leg movement: a new strategy build up by training. *J Neurophysiol*. 1992;67(6):1587-1598.
34. Marquez G, Alegre LM, Jaen D, Martin-Casado L, Aguado X. Sex differences in kinetic and neuromuscular control during jumping and landing. *J Musculoskelet Neuronal Interact*. 2017;17(1):409-416.
35. Wang IL, Wang SY, Wang LI. Sex differences in lower extremity stiffness and kinematics alterations during double-legged drop landings with changes in drop height. *Sports Biomech*. 2015;14(4):404-412.
36. Leppanen M, Pasanen K, Kulmala JP, et al. Knee control and jump-landing technique in young basketball and floorball players. *Int J Sports Med*. 2016;37(4):334-338.
37. Walden M, Krosshaug T, Bjorneboe J, Andersen TE, Faul O, Hagglund M. Three distinct mechanisms predominate in noncontact anterior cruciate ligament injuries in male professional football players: a systematic video analysis of 39 cases. *Br J Sports Med*. 2015;49(22):1452-1460.

38. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc*. 2003;35(10):1745-1750.
39. Kernozek TW, Torry MR, Van Hoof H, Cowley H, Tanner S. Gender differences in frontal and sagittal plane biomechanics during drop landings. *Med Sci Sports Exerc*. 2005;37(6):1003-1012; discussion 1013.
40. Hewett TE, Ford KR, Hoogenboom BJ, Myer GD. Understanding and preventing ACL injuries: current biomechanical and epidemiologic considerations – update 2010. *N Am J Sports Phys Ther*. 2010;5(4):234-251.
41. Boden BP, Dean GS, Feagin Jr JA, Garrett Jr WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23(6):573-578.
42. Lopes T, Simic M, Myer GD, Ford KR, Hewett TE, Pappas E. The effects of injury prevention programs on the biomechanics of landing tasks: a systematic review with meta-analysis. *Am J Sports Med*. 2017;46(6):1492-1499.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Ward RE, Fong Yan A, Orishimo KF, et al. Comparison of lower limb stiffness between male and female dancers and athletes during drop jump landings. *Scand J Med Sci Sports*. 2019;29:71–81. https://doi.org/10.1111/sms.13309