Sex Differences in Ground Reaction Force Profiles of Ballet Dancers During Single- and Double-Leg Landing Tasks

Rachael A. Arnwine, MS, and Douglas W. Powell, PhD

Proofs to: dwpowell@memphis.edu

Abstract

It is well known that sex differences exist in landing biomechanics in athletes, and these differences are purported to underlie a prevalence of traumatic knee injuries in females compared to males. However, it remains unknown if these differences also apply to artistic athletes such as dancers. The purpose of this study was to investigate sex differences in ground reaction forces (GRFs) between male and female dancers during single- and double-leg dance-specific landing movements. Fourteen pre-professional and professional ballet dancers (seven female and seven male) performed grand jeté (single-leg landing) and sauté (double-leg landing) jumps onto two force platforms. Visual3D was used to calculate the resulting GRF time-series, and MATLAB to select discrete variables of interest including peak vertical GRF, loading rate, landing duration, and vertical impulse. Paired t-tests were used to compare mean GRF variables between male and female dancers. 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. These results indicate that sex differences in landing GRFs are most evident in single-leg landing and may underlie divergent injury rates in male and female dancers. Further investigation of relevant lower extremity biomechanics during single- and double-leg landing in male and female dancers should be conducted to identify the mechanisms underlying these distinct GRF profiles.

In ballet, dancers place significant focus on specific jumping tasks of various intensities, including petite allegro (small, quick jumps), grand allegro (large, quick jumps), and grand jetés (large ballet leaps), with often more than 200 jumps being performed in a typical technique class.[1] Each jumping task results in a landing task, which must be completed with pre-determined landing biomechanics, including a toe strike followed by the ball of the foot and finally the heel (calcaneus). These landing mechanics are unique to dancers and place substantial load magnitude (more than four times body weight) on the lower extremities. Further, the number of repetitions completed during each training session produces a significant loading volume, which means that proper landing biomechanics are necessary for dancers to avoid musculoskeletal injury.[1]

Female athletes have a greater rate of lower extremity injury than male athletes[2-5]; for example, female athletes experience anterior cruciate ligament injuries at a rate two to six times more often than male athletes.[2] However, research findings pertaining to sex differences in lower extremity injury rates in dancers are inconsistent. Nilsson et al.[6] reported that female compared to male dancers have a greater rate of lower extremity injury, similar to findings in team sport athletes. Conversely, Liederbach et al.[7] found no difference in lower extremity injury rates between female and male dancers. Though no consensus exists regarding sex differences in injury rates among dancers, it is known that these injuries are often the result of the magnitude and volume of forces applied to the dancer's musculoskeletal system during landings.

Many factors may influence the development of musculoskeletal injury during a landing task, but ground reaction force (GRF) characteristics are of particular interest. Ground reaction forces represent the magnitude and direction of forces applied to the dancer by the ground upon impact. Further, GRFs reflect the biomechanics used by the dancer to absorb these impact forces. Previous research has investigated landing biomechanics in dancers with emphasis on the lower extremity joint biomechanics involved[8-12]; however, few studies have

Rachael A. Arnwine, MS, and Douglas W. Powell, PhD, School of Health Studies, University of Memphis, Memphis, Tennessee, USA.

Correspondence: Douglas W. Powell, PhD, Exercise Neuroscience Research Lab, School of Health Studies, University of Memphis, Memphis, Tennessee 38152, USA; dwpowell@memphis.edu.

https://doi.org/10.12678/1089-313X.24.3.113

directly investigated GRF profiles in male compared to female dancers. One study[13] reported peak vertical GRFs in dancers compared to non-dancers but did not distinguish sexes in either group. Moreover, that study involved a vertical drop landing rather than a dance-specific movement such as a grand jeté or sauté. The vertical drop landing is not an ecologically valid representation of loads applied to the skeletal system during dance training or performance, which limits its application to injury mechanisms in dancers.

Therefore, the purpose of this study was to determine if differences in GRF profiles exist between male and female dancers during dance-specific single- and double-leg landing tasks. It was hypothesized that female dancers would have 1. smaller peak vertical ground reaction force magnitudes, 2. greater vertical loading rates, and 3. smaller vertical impulses compared to male dancers. Further, it was hypothesized that sex differences would be greater in single- than in double-leg landings.

Materials and Methods

Participants

Fourteen professional and pre-professional ballet dancers (seven female and seven male) between the ages of 18 and 35 years participated in this study. Professional dancers were defined as those who have been hired by a professional dance company to train and perform, and pre-professional dancers were defined as students currently training to become professional dancers. Participants were excluded from this study if they had a history of musculoskeletal injury within the 6 months preceding data collection or if they currently had a neuromuscular condition that impaired dance performance. The study was approved by the University of Memphis Institutional Review Board, and all participants provided written informed consent prior to participation.

Experimental Protocol

Each participant completed a single testing session, which included screening, anthropometric measurements, and biomechanical testing. Screening addressed each participant's eligibility by confirming current level of dance training, no injury in the previous 6 months, and appropriate age (18 to 35 years). Measurements included height, mass, and dominant limb. Participants then performed a ballet-specific warm up composed of a series of pliés, tendus, relevés, and small sautés. Following warm up, participants performed landing movements in their own standard ballet shoes.

Data were collected using two force platforms (1,200 Hz, AMTI, Watertown, Massachusetts, USA) embedded in the floor. Each participant performed eight trials in each of two dance-specific landing conditions: a grand jeté (single-leg landing) and a sauté from first position (double-leg landing). A successful grand jeté trial was characterized by the dancer completing the single-leg landing task with the foot of interest landing on a single force platform while maintaining a stable posture. A successful sauté trial was characterized by the participant maintaining stable posture while performing the double-leg landing task with each foot on an independent force platform. Both jumps were landed with the hip and lower extremity in external rotation, the fundamental technique of ballet. These two specific movements were selected as they represent a skill set with which all ballet dancers are familiar and that is commonly trained even in elite professional dancers.

Data Reduction

Three-dimensional GRF data were analyzed for a period of 350 ms following initial contact. This timing was selected as it represents the period over which load attenuation occurs during most landing movements. Initial contact was defined as the point at which the vertical GRF exceeded a threshold of 20 N and remained above 20 N for a period of at least 25 ms. Visual3D (C-Motion Inc., Bethesda, Maryland, USA) was used to filter 3D GRF data using a low-pass, fourth-order zero-lag Butterworth filter with a cutoff frequency of 50 Hz. Custom software (MATLAB©, MathWorks, Inc., Natick, Massachusetts, USA) was used to calculate discrete data, including peak vertical GRF, time-to-peak

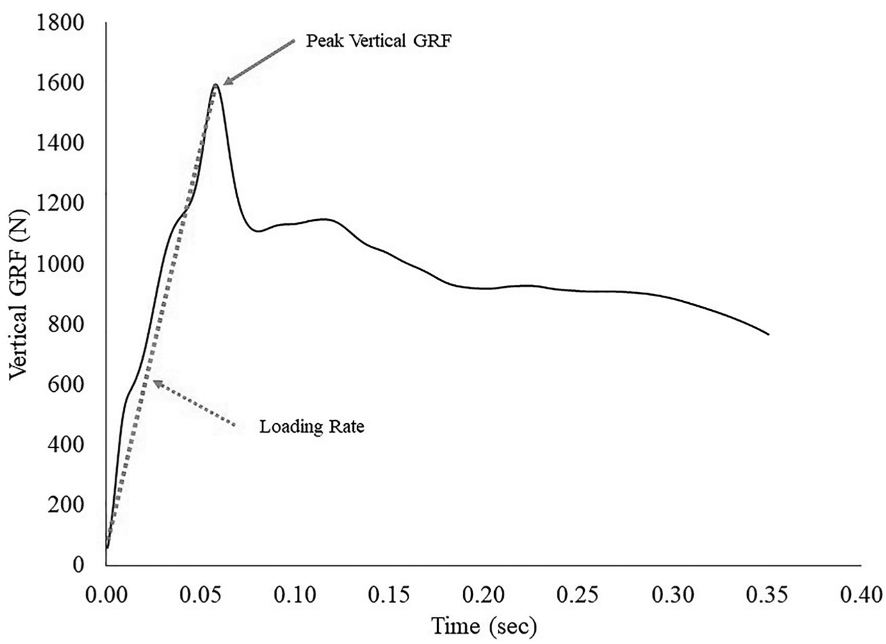

Figure 1 A vertical GRF signal tracing from one representative subject. The peak vertical GRF was defined as the maximum vertical GRF signal following initial contact. Loading rate was defined by the slope of the vertical GRF signal from initial contact to peak vertical GRF.

vertical GRF, loading rate, and vertical impulse for each landing condition. Peak vertical GRF was defined as the maximum value of the vertical GRF during the landing task, while time-to-peak vertical GRF was calculated as the duration of the period between initial contact and peak vertical GRF. Loading rate was calculated as the slope of the vertical GRF curve from initial contact to peak vertical GRF, and vertical impulse as the vertical GRF during the landing movement integrated with respect to time using trapezoidal integration. All GRF data were normalized to body mass to allow for comparison between groups (Fig. 1).

Statistical Analysis

Independent samples t-tests were used to compare dependent variables of male and female ballet dancers in single and double-leg landing tasks. Due to multiple comparisons per dependent variable (single- and double-leg landing), the p-value was adjusted using a Holm-Bonferroni technique. Cohen's d estimates of effect size were also calculated to compare mean values between male and female ballet dancers.[14] All statistical analyses were conducted using GraphicPad Software (GraphPad Software, Inc., La Jolla, California, USA).

Results

Participant anthropometric measurements are presented in Table 1. Female and male participants were similar in age ($p = 0.110$), height ($p = 0.054$), and BMI ($p = 0.525$). Not surprisingly, female participants had less mass than their male counterparts ($p = 0.039$).

Single-Leg Landing Task

During the single-leg landing task peak vertical GRF values (Table 2) were smaller in male compared to female dancers ($p = 0.002$, $d = 1.85$). Moreover, male dancers reached peak vertical GRF later in the landing phase than female dancers ($p = 0.030$, $d = 1.11$). No differences were observed in vertical impulse values; however, a large effect size was observed, suggesting a meaningful difference may exist ($p = 0.055$, $d = 0.92$). Loading rates were smaller in males than in females ($p = 0.001$, $d = 2.20$).

Double-Leg Landing Task

During the double-leg landing task, no differences in peak vertical GRF values (Table 2) were observed between male and female dancers ($p = 0.380$, $d = 0.17$). Further, no differences were observed in the time-to-peak vertical GRF ($p = 0.473$, $d = 0.04$). Vertical impulse values were similar between males and females ($p = 0.434$, $d = 0.09$), and no differences in loading rates were observed ($p = 0.266$, $d = 0.34$).

Discussion

The purpose of the current study was to compare vertical GRF profiles of male and female ballet dancers when landing jumps. The findings demonstrate that male and female dancers exhibit distinct vertical GRF profiles during single- but not double-leg landings. Specifically, during the grand jeté (single-leg landing), male dancers had smaller peak vertical GRF values, loading rates, and vertical impulses. Further, male dancers reached peak vertical GRF later in the landing phase than female dancers. During the sauté (double-leg landing), no differences were observed in the GRF profiles of male and female dancers.

Male and female athletes have been found to adopt unique biomechanical strategies during a landing task. In team sport athletes, males experience smaller peak vertical GRFs,[15] smaller

Table 1 Anthropometric Measures of Female and Male Ballet Dancers

Group	Professional	Pre-Professional	Age (years)	Stature (cm)	Mass (kg)	BMI
Females	3	4	23.4 ± 4.7	165.0 ± 5.3	61.0 ± 5.6	22.4 ± 2.1
Males	4	3	27.4 ± 4.4	173.4 ± 9.7	69.7 ± 8.9	23.2 ± 2.4
P-value			0.110	0.054	0.039*	0.525
Cohen's d			0.89	1.07*	1.17*	0.34

*Statistically significant comparisons and large effects.

Table 2 Vertical GRF Variables in Female Compared to Male Ballet Dancers During Single- (SL) and Double-Leg (DL) Landing Tasks

	Peak Vertical GRF (N/kg)		Time-to-Peak Vertical GRF (s)		Vertical Impulse (N/kg/s)		Loading Rate (N/kg/s)	
Group	SL	DL	SL	DL	SL	DL	SL	DL
Male	2.8 ± 0.8	1.6 ± 0.4	0.091 ± 0.051	0.100 ± 0.035	0.49 ± 0.09	0.29 ± 0.06	49.9 ± 15.6	18.5 ± 9.0
Female	3.8 ± 0.1	1.5 ± 0.3	0.050 ± 0.006	0.101 ± 0.008	0.56 ± 0.03	0.29 ± 0.03	78.2 ± 9.3	16.1 ± 4.7
P-value	0.002*	0.380	0.030*	0.473	0.055	0.434	0.001*	0.266
Cohen's d	1.85*	0.17	1.11*	0.04	0.92*	0.09	2.20*	0.34

*Statistically significant differences and large effect sizes.

joint range of motion in the sagittal and frontal planes,[16] smaller peak knee and ankle joint powers,[4] and smaller energy absorption than their female counterparts.[4] Further, male athletes exhibit less reliance on ankle musculature during load attenuation.[17] These differences in landing biomechanics likely underlie the distinctive injury rates in male compared to female athletes. However, it has been suggested that these sex differences in landing biomechanics may not be present in dancers due to their focus on movement patterns during training.[13]

Though dancers place great emphasis on the aesthetics of the grand jeté and sauté, sex differences persist in landing biomechanics. Ward et al.[12] reported significantly greater vertical GRF and vertical stiffness values as well as smaller center of mass displacement values in males. Further, male dancers had greater peak ankle and hip joint moments and smaller ankle and hip joint ranges of motion compared to female dancers. The greater ranges of motion observed in female dancers, specifically at the knee, may increase concomitant motion in accessory planes of motion, including the frontal and transverse planes, placing greater stress on the anterior cruciate ligament for stability.[18]

The observed differences in landing GRF profiles suggest that female dancers experience a greater volume of loading than male dancers during a standardized training session that includes single-limb landing tasks. This greater loading volume may increase the risk of lower limb injury in female dancers. In response to greater loading volumes, dance instructors should consider modifying training programs to periodize load volumes in female dancers. They might also beneficially develop knowledge pertaining to physical performance as well as signs and symptoms of over-reaching to avoid over-training their dance athletes. In addition, these findings may suggest a need to quantify daily bone load in professional dancers using inertial measurement units to optimize training stimulus, similar to what is done with professional sports athletes.

Although this study presents novel findings with regard to sex differences in landing biomechanics, the authors acknowledge a number of limitations. One is the small sample size, which may negatively affect statistical comparisons as well as the generalizability of these findings (although post-hoc power analysis demonstrated moderate to strong observed powers [0.49 to 0.99] for single-leg landing comparisons, thereby supporting the statistical findings). Another limitation of this study is the focus solely on vertical GRFs, as only forces in the vertical direction are considered. As a result of this limited focus, the anteroposterior and mediolateral forces have not been assessed, although the single-leg landing task does contain a forward movement onto the supporting limb. However, large forces are required to create musculoskeletal injury, and the largest forces applied to the skeletal system during a landing task are in the vertical direction. An alternative analysis might be to compute the GRF vector magnitude, although a disproportionate majority of the GRF vector magnitude would be comprised of the vertical component of the GRF.

A third limitation of the current study is that jump height was not controlled for or measured during these tasks. Differences in jump height no doubt existed, contributing to the observed differences in vertical GRFs. It is known that male athletes (sport or artistic) produce greater maximal jump heights than female athletes,[19] so it is reasonable to assume that our male dancers would have greater jump heights. Therefore, the energy that would need to be dissipated would be greater in males than in females, resulting in greater vertical GRFs and loading rates, which is counter to the findings of this study. Further, given that the participants were products of professional or pre-professional dance training, it is reasonable to expect that inter-trial jump heights were very consistent for each participant.

Conclusions

The findings of this study demonstrate significant and meaningful differences in the vertical GRF profiles of male and female ballet dancers during a single-leg landing task. The application of these greater force magnitudes at greater rates may underlie distinctive injury patterns experienced by male and female dancers. Greater peak vertical GRFs and loading rates are suggested mechanisms underlying tibial stress fractures in runners and other athletes who experience repetitive loading, which definitely could also apply to professional and pre-professional dance populations.

References

1. Liederbach M, Richardson M, Rodriguez M, et al. Jump exposures in the dance training environment: a measure of ergonomic demands. J Athl Train. 2006;41(2 suppl):85.
2. 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 Apr;33(4):524-30.
3. Arendt EA, Agel J, Dick R. Anterior cruciate ligament injury patterns among collegiate men and women. J Athl Train. 1999 Apr;34(2):86-92.
4. Decker MJ, Torry MR, Wyland DJ, et al. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. Clin Biomech (Bristol, Avon). 2003 Aug;18(7):662-9.
5. Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes: Part 1, mechanisms and risk factors. Am J Sports Med. 2006 Feb;34(2):299-311.
6. Nilsson C, Leanderson J, Wykman A, Strender LE. The injury panorama in a Swedish professional ballet company. Knee Surg Sports Traumatol Arthrosc. 2001 Jul;9(4):242-6.
7. 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 Sep;36(9):1779-88.
8. Ambegaonkar JP, Caswell SV, Cortes N. Lower extremity horizontal work, but not vertical power, predicts balance performance in female collegiate dancers. J Dance Med Sci. 2018 Jun;22(2):75-80.
9. Hendry D, Campbell A, Ng L, et al. The difference in lower limb landing

kinematics between adolescent dancers and non-dancers. J Dance Med Sci. 2019 Jun;23(2):72-9.
10. Liederbach M, Kremenic IJ, Orishimo KF, et al. 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 May;42(5):1089-95.
11. Orishimo KF, Liederbach M, Kremenic IJ, et al. 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):1082-8.
12. 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 Jan;29(1):71-81.
13. Orishimo KF, Kremenic IJ, Pappas E, et al. Comparison of landing biomechanics between male and female professional dancers. Am J Sports Med. 2009 Nov;37(11):2187-93.
14. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. Front Psychol. 2013 Nov 26;4:863.
15. Seymore KD, Fain AC, Lobb NJ, Brown TN. Sex and limb impact biomechanics associated with risk of injury during drop landing with body borne load. PLoS One. 2019 Feb 6;14(2):e0211129.
16. Kernozek TW, Torry MR, VAN Hoof H, et al. Gender differences in frontal and sagittal plane biomechanics during drop landings. Med Sci Sports Exerc. 2005 Jun;37(6):1003-12; discussion 1013.
17. Weinhandl JT, Irmischer BS, Sievert ZA. Sex differences in unilateral landing mechanics from absolute and relative heights. Knee. 2015 Sep;22(4):298-303.
18. Neumann DA. *Kinesiology of the Musculoskeletal System: Foundations of Rehabilitation.* St. Louis, Missouri: Mosby, 2010.
19. Smith RE, Paquette MR, Harry JR, et al. Footwear and sex differences in performance and joint kinetics during maximal vertical jumping. J Strength Cond Res. 2020 Jun;34(6):1634-42.