

The Effects of Floor Incline on Lower Extremity Biomechanics During Unilateral Landing From a Jump in Dancers

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Retrospective studies have suggested that dancers performing on inclined (“raked”) stages have increased injury risk. One study suggests that biomechanical differences exist between flat and inclined surfaces during bilateral landings; however, no studies have examined whether such differences exist during unilateral landings. In addition, little is known regarding potential gender differences in landing mechanics of dancers. Professional dancers ($N = 41$; 14 male, 27 female) performed unilateral drop jumps from a 30 cm platform onto flat and inclined surfaces while extremity joint angles and moments were identified and analyzed. There were significant joint angle and moment effects due to the inclined flooring. Women had significantly decreased peak ankle dorsiflexion and hip adduction moment compared with men. Findings of the current study suggest that unilateral landings on inclined stages create measurable changes in lower extremity biomechanical variables. These findings provide a preliminary biomechanical rationale for differences in injury rates found in observational studies of raked stages.

Keywords: performing arts, risk factor, occupation

Studies suggest that as many as 67–95% of professional dancers are injured each year (Bronner et al., 2003; Garrick & Requa, 1993; Solomon et al., 1999). In Broadway and London’s West End productions approximately 50% of dancers will sustain a work-related injury within their current production (Evans et al., 1996, 1998). The daily repetition of highly specific dance motions, the high level of physical demand, and environmental risk factors, such as high-heeled shoes and inclined flooring (Hagins et al., 2007; Liederbach et al., 2008), may all contribute to the high incidence of dance-related injuries.

The specific environmental risk factor of inclined flooring, known as *raked stages*, has received some study (Evans et al., 1996, 1998; Hagins et al., 2007; Liederbach et al., 2008; Pappas & Hagins, 2008). A raked stage is one that inclines downward toward the audience and is present in approximately 20% of Broadway productions. There is preliminary scientific evidence supporting the risk of

raked stages to performers. Two studies, one of Broadway productions ($N = 318$) (Evans et al., 1996) and one of West End productions ($N = 269$) (Evans et al., 1998), both using a retrospective design with self-reported injury rates, have suggested that raked stages result in a substantial increase in the risk of injury (twofold increase or higher). In addition, a study using a retrospective design and self-report data found that 19% of dancers suggested that better flooring would help reduce injuries (Bowling, 1989). The issue of injury risk relative to floor incline continues to be a point of negotiations between the producers of Broadway productions (Broadway League) and performers (Actor’s Equity Association) with the performers suggesting that stages convey substantial risk while producers suggesting that raked stages convey little, if any, increased risk.

Several studies have suggested that kinetic and kinematic variables of the lower extremities are altered when the foot is on an inclined surface thereby supporting a biomechanical rationale for differences in injury risk between floor conditions. Studies have found that floor inclination alters kinetic and/or kinematic variables during gait (Gehlsen et al., 1989; Kawamura et al., 1991; McIntosh et al., 2006; Sun et al., 1996; Tokuhiko et al., 1985; Vogt & Banzer, 1999), static standing (Wenning & O’Connell, 1999), lifting tasks (Shin & Mirka, 2004; Zhao et al., 1987), and landing tasks (Hagins et al., 2007; Liederbach et al., 2008).

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Landing from a jump from a specified height is a common laboratory model used to examine lower extremity functioning (Decker et al., 2003; Ford et al., 2003; Madigan & Pidcoe, 2003; Pappas et al., 2007a). Landing tasks are a valid activity for examining the effects of raked stages on lower extremity function in dancers given that (1) jumping and landing constitute a common functional task for dancers; (2) large forces of 2–12 times body weight are produced (Dufek & Bates, 1990; Mizrahi & Susak, 1982; Simpson & Kanter, 1997); and (3) the lower extremity is the most commonly injured region for dancers (Evans et al., 1996, 1998; Liederbach, 2000).

Previously, we have shown that dancers landing from a box-drop jump on two feet onto a laterally inclined floor (inclined 3.6°, similar to those used as raked stages on Broadway) exhibit significantly higher knee valgus, peak knee flexion, and medial-lateral ground reaction force (GRF) when compared with the flat floor condition (Hagins et al., 2007). A limitation of the previous work examining the effect of an inclined floor was the use of a bilateral landing model. Using two legs for the landing task may not fully reflect the reality of dance training and function. During training, ballet dancers tend to jump and land on a single limb approximately 50% of the time whereas modern dancers jump and land on a single limb 89% of the time (Liederbach et al., 2006). There is evidence from studies of athletes that landing onto a single leg compared with two legs increases ground reaction force (Pappas et al., 2007a; Yeow et al., 2010) and risk of certain types of injuries (Olsen et al., 2004). Therefore, the primary purpose of the current study was to determine the effect on dancers of an inclined surface (raked stage) on joint angles and joint moments during a single leg landing task from a 30 cm platform.

A secondary issue of interest concerns potential differences in landing mechanics between males and females. Female dancers have a greater incidence of ankle injuries compared with males (Garrick & Requa, 1997; Liederbach, 2007; Solomon et al., 1999). There are multiple potential causative factors for this asymmetry in incidence rate such as differences in training, performance, or shoe wear between male and female dancers. For example, there is evidence that inclined floors have a significant interaction with shoe wear among female dancers on biomechanical variables associated with increased risk of injury (Liederbach et al., 2008). Differences in landing mechanics between genders is a well-studied issue in athletes and results suggest a link between landing patterns in female athletes and some forms of injury (Hewett et al., 2005). However, it is currently unclear whether male and female dancers have different landing mechanics when on the different floor surfaces and whether any potential differences may help explain the asymmetry in lower extremity injury rates. Consequently, the secondary purpose of the current study is to examine the effect of gender and the interaction of gender and floor condition on kinematic and kinetic lower extremity variables during a landing task.

Methods

This was a mixed design experimental study with the repeated-measures independent variable being floor condition, the within-group independent variable being gender and the dependent variables being measures of lower-extremity kinematics and kinetics. Subjects performed three single-leg drop landings from a 30 cm platform for each of five floor conditions. The floor inclination was either flat (0 degrees) or inclined (3.6 degrees). The two levels of inclination combined with the direction of the inclination created five levels of the independent variable as follows: (1) 0°, level (flat); (2) -3.6°, posterior (downhill); (3) +3.6°, anterior (uphill); (4) -3.6°, medial; and (5) +3.6°, lateral (see Figure 1).

Subjects

Fourteen male professional dancers, mean (*SD*) age: 25 (4) yr, height: 178 (6) cm, weight: 72 (5) kg, and 27 female professional dancers, age: 27 (5) yr, height: 167 (6) cm, weight: 57 (6) kg, were recruited from dance companies in the New York City area. Exclusion criteria were as follows: a history of injuries and/or diseases that would render unsafe the execution of the protocol; a history of injuries and/or diseases that could affect the biomechanics of landing such as lower extremity fractures; and obesity (body mass index greater than 30 kg/m²). All subjects completed a medical history questionnaire and signed an informed consent form approved by the New York University Langone Medical Center Hospital for Joint Diseases Institutional Review Board.

Experimental Setup

To replicate the flat and raked stages effect, it was necessary to construct flooring that could be attached to the surface of the force plate. Due to the asymmetrical rectangular dimensions of the force plate it was not possible to simply create one inclined floor and rotate it in four directions, as attachment occurred along the border of the force plate. Consequently, two wedges and one flat surface were created. One wedge was alternated in position to achieve lateral and medial inclines and the other inclined wedge was alternated in position to achieve anterior and posterior inclines. The slope of 3.6° was achieved in both wedges to be equal to the currently allowable maximum raked stage inclination for Broadway productions. Uniformity of construction of the wooden surfaces and concerns regarding equivalence of deformation characteristics across the surfaces were addressed in a previous study (Hagins et al., 2007). Briefly, the three floors were constructed of oak by the same craftsman using identical materials and tests were performed using weights dropped onto the floors to determine equivalence of peak forces measured by the force plate. Difference in peak values between floors was less than ± 1% (Hagins et al., 2007).

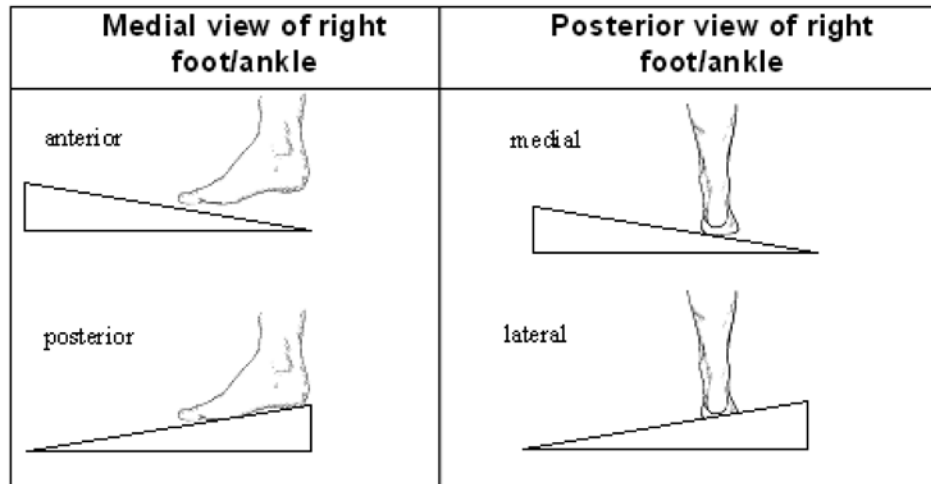


Figure 1 — Direction of inclined surfaces relative to foot landing position.

Drop Landing Task

The order of the drop landing task on the five different slope conditions was randomized. The subjects were allowed two practice jumps and then performed three drop jumps from the 30 cm platform. All subjects brought in and wore their own shoe wear, which was flat (no heel) tennis shoes in all cases. Subjects did not receive any instructions on the landing technique to avoid a coaching effect. However, the effect of the arms was minimized by asking the subjects to keep their arms crossed against their chest (Decker et al., 2003; Pappas et al., 2007a; Rodacki et al., 2002). 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. The right leg was the dominant leg for all subjects. Trials were repeated when they were judged as nonacceptable (such as when subjects lost their balance). Subjects completed the entire protocol in a single session. All testing was performed between 10 AM and 5 PM and subjects did not exercise, practice, or perform on the day of the testing session before being tested.

3D Motion Analysis

Twenty reflective markers were placed bilaterally over the calcaneus, second metatarsal, lateral malleolus, lateral femoral condyle, midshank, midhigh, 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. Kinematic data were collected at 250 Hz using eight Eagle cameras (Motion Analysis Corp., Santa Rosa, CA, USA). The motion data were then filtered with a fourth-order Butterworth low-pass filter with a cutoff frequency of 10 Hz to eliminate any high-frequency noise. Ground reaction forces (GRF) were recorded at 2500 Hz with a multicomponent force plate (AMTI, Watertown, MA, USA).

Data Processing

Landings were defined from initial contact with the force plate to the maximum amount of knee flexion achieved during each trial. Sagittal, transverse and frontal plane joint angles were calculated for the ankle, knee and hip using the motion capture data. Ankle inversion/eversion was defined as rotation of the foot segment in respect to the shank segment in the frontal plane. Joint angles were assessed at the time of peak vertical GRF. All inverse dynamic calculations were performed by using the forces and center of pressure measured at the force plates. Net joint moments were calculated for each joint by standard inverse dynamic techniques using specialized computer software (Visual 3D, C-Motion Inc., Rockville, MD). Peak joints moments were normalized to body mass and refer to the external joint moment in each plane.

According to Winter (1980), total support moment (TSM) is a parameter that represents the total action of the whole leg to support the body and prevent it from collapsing when the leg is loaded during a movement task. The total support moment for each landing was calculated at each data collection point (250 Hz) throughout the length of each trial by adding the sagittal plane moments at the ankle, knee and hip (Winter, 1980; Winter). The maximum value of the total support moment during landing was then determined and the relative contribution of each joint to that maximum value was identified. Mean values of the three trials were then calculated for all measurements within each subject.

Statistical Analysis

The effects of floor and gender were evaluated with eighteen 5×2 univariate tests (5 levels for the floor condition and 2 levels for gender) for lower extremity joint angles at peak GRF and peak moments (3 planes for ankle, knee and hip). An additional four univariate tests for the peak total support moment (TSM) and for the ankle, knee

and hip sagittal plane moments at peak TSM were performed. A Bonferroni correction ($\alpha = 0.004$) was applied to account for the multiple ANOVAs in each category of variables (13 kinetic and 9 kinematic) and decrease the possibility of type I error. *P*-values that were ≤ 0.004 were considered statistically significant while *p*-values > 0.004 and ≤ 0.05 were classified as statistical trends. The Huynh–Feldt test was used when sphericity was violated. Post hoc pairwise comparisons between the reference floor (flat) and the inclined floors were performed for the variables that were identified as having a significant floor effect by the ANOVAs. As the purpose of the post hoc tests is to identify the comparisons between floors that are significant on a variable that has been already identified as having a significant effect of floor by the ANOVA we a priori decided to leave the alpha level at 0.05.

Results

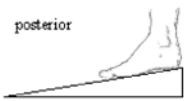
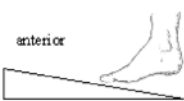

Generally floor incline affected lower limb joint kinematics (Table 1). Ankle dorsiflexion ($p = .001$) and foot abduction ($p = .003$) were affected by floor incline. Post hoc comparisons showed that the posteriorly inclined floor had significantly less (-4.5°) dorsiflexion and foot abduction (-2.5°) than the flat floor while the anteriorly inclined floor had significantly more dorsiflexion ($+5^\circ$) than the flat floor. There was a trend for the effect of floor on knee flexion ($p = .014$) with post hoc comparisons

showing that the anteriorly inclined floor had more knee flexion ($+1.3^\circ$) than the flat floor.

Floor incline affected various lower limb joint kinetics. There was a significant effect on ankle moments in all three planes and for sagittal plane knee moment ($p < .001$). Post hoc tests showed that the posteriorly inclined floor had significantly more ($+24\%$) foot abduction moment and knee flexion moment ($+4\%$) compared with the flat floor but significantly less (-6%) ankle dorsiflexion moment and foot eversion moment (-9%). Post hoc comparisons also showed that the anteriorly-inclined floor had significantly more ($+6\%$) ankle dorsiflexion moment and significantly less (-14%) foot abduction moment than the flat floor. The laterally inclined floor had significantly less foot abduction moment (-19%), foot eversion moment (-20%) and knee flexion moment (-5%) compared with flat floor. Finally, there was a trend for hip flexion moment ($p = .014$) to be affected by floor incline with a post hoc comparison revealing that the laterally inclined floor had significantly less (-14%) peak hip flexion moment compared with the flat floor.

At the time of peak TSM some of the individual joint moment contributions changed with different floor conditions. The anteriorly inclined floor had significantly more (13%) dorsiflexion moment than the flat floor at peak TSM ($p < .001$) while the posteriorly inclined floor had a trend toward less (7%) dorsiflexion moment than the flat floor at peak TSM ($p = .011$). There was a trend for floor incline to affect the hip moment at peak TSM

Table 1 Significant differences between flat floor condition and inclined floor conditions for angles at peak vertical ground reaction force and peak moments

	Posterior	Anterior	Lateral
			
Angles			
Ankle Dorsiflexion*	-4.5°	$+5^\circ$	—
Foot Abduction*	-2.5°	—	—
Knee Flexion†	—	$+1.3^\circ$	—
Peak Moments			
Ankle Dorsiflexion*	-6%	$+6\%$	—
Foot Abduction*	$+24\%$	-14%	-19%
Foot Eversion*	-9%	—	-20%
Hip flexion†	—	—	-14%
Knee flexion*	$+4\%$	—	-5%

*ANOVA statistically significant ($p \leq 0.004$); †ANOVA trend ($p > 0.004$ and $p \leq 0.05$).

Note. Positive (+) value = increased amounts of angular motion in degrees or in percentage of moment in the inclined condition compared with the flat condition. Negative (–) value = decreased amounts of angular motion in degrees or in percentage of moment in the inclined condition compared with the flat condition. Medial floor condition not shown, as no post hoc test showed significant differences between this floor condition and flat floor. All subjects used the right foot for landing.

($p = .04$) as well as a trend for changes in peak TSM ($p = .013$). However, these trends were mainly due to differences between the medially, laterally, and posteriorly inclined floors and were not due to differences between the flat and inclined floor conditions.

There was a limited number of differences between the results for males and females. There was a trend for females to have more hip flexion (8°) than males ($p = .03$). Women had significantly less dorsiflexion moment (18%) than men ($p = .002$) and a trend toward less hip adduction moment (15%) than men ($p = .038$). There was a trend for the effect of gender on the ankle moment at peak TSM ($p = .005$) with females exhibiting 24% less ankle moment than men. However, there was no statistically significant gender by floor interaction for any of the joint moments or kinematics.

Discussion

The primary finding of the current study is that inclined floors (raked stages) have a significant effect on joint angles at peak VGRF and peak moments when compared with flat floors when dancers perform a unilateral drop landing from a 30 cm high platform. The findings should be seen in practical terms as establishing that the currently used inclines for Broadway productions have biomechanical effects on lower extremity angles and moments during landing tasks. Therefore, any suggestion that an incline of this magnitude is too small to cause measurable changes in the movement patterns or tissue stresses of dancers is likely invalid. Importantly, however, this is not identical to establishing that the inclined floors increase risk of injury and this study should not be interpreted as such.

The current study found that moments are significantly decreased in some floor conditions while increased in others (Table 1). Interpretation of these specific findings relative to injury risk is difficult, if not impossible, given the lack of an explanatory theoretical framework and the lack of valid studies demonstrating a link between such changes and injury risk. It is assumed that increases in moment at a joint increase demands on the joint system. These demands are typically managed via increased muscle effort or increased force on passive restraints, which may have immediate deleterious effects if exceeding some threshold value (e.g., acute injury) or delayed effects if they are at some lesser value but repetitive and ongoing (e.g., cumulative trauma). Interestingly, in the current study, the medially inclined floor had no significant effect on joint moments while the laterally-inclined floor significantly reduced several lower extremity moments. The posteriorly and anteriorly inclined floors increased some moments while decreasing others. In a previous study that compared biomechanical variables during unilateral horizontal jump landings on flat versus inclined floors in female dancers when wearing flat versus high-heeled shoes, there was a highly significant increase in joint moments on the medially and posteriorly inclined floor (Liederbach et al., 2008). From

the current study, it appears that unilateral box-drop landings performed in flat-soled shoes on a laterally inclined surface may decrease the demands on the ankle joint while the posteriorly and anteriorly inclined condition may increase or decrease demands on the ankle joint.

The current study extended our original line of investigation that examined bilateral landings (Hagins et al., 2007) to an examination of unilateral landings. Specific and direct comparisons between the two studies are difficult due to differences in the task and methodological approach. Briefly, the previous study examined the effect of flooring on landing from a 40 cm jump at five points during the landing cycle (initial contact, knee flexion angles of 30, 45, 60 degrees, and maximal knee flexion). However, the current study examined the effect of flooring on landing from a 30 cm jump at a single point in the landing cycle (peak VGRF). The original bilateral landing study found significant differences between inclined and flat floors for ankle dorsiflexion and knee valgus angles as well as for the posterior GRF vector. The current study also found significant differences between inclined and flat floors for ankle dorsiflexion angles. However, unlike the original bilateral landing study, the current study did not find significant differences in knee valgus but found significant differences in foot abduction. Nevertheless, the combination of these studies suggests that during either unilateral or bilateral landings of dancers there is an effect of floor incline on joint angles.

It is tempting to view the specific angular and moment findings from the current study as simply the interaction of foot and surface interface. Such a view would suggest for example that the posteriorly inclined slope would have a lower dorsiflexion moment because the direction of the incline facilitates plantar flexion; similarly, the anteriorly inclined slope would have a higher dorsiflexion moment because the direction of the incline facilitates dorsiflexion. Although both of these suggestions are confirmed by the findings of our study, this *prima facie* approach disregards the influence of the rapidly changing positions of mass of multiple superincumbent segments and the impact of feedforward motor planning and does not explain other findings of this study. For example, it is difficult to interpret why the peak abduction and eversion ankle moments are decreased in the laterally inclined condition. A simple foot-surface interface approach would suggest that these values should increase, as is the case when subjects walk with a laterally inclined rearfoot insole (Kakihana et al., 2005). A possible explanation may be that the laterally inclined floor allowed the subtalar joint to have a greater degree of range of motion excursion into pronation allowing a greater period of deceleration and a "softer" landing. Such a response has been found when athletes land on medially inclined surfaces with a "softer" landing technique (Chen, 2009).

There are some cases in which laboratory biomechanical studies have been linked with prospective epidemiological studies to produce convincing evidence that biomechanical factors found in the laboratory are valid

risk factors for injury. For example, female athletes who exhibit high knee valgus moments during landing are at increased risk of suffering an ACL injury (Hewett et al., 2005). Such studies are difficult, time-consuming, and costly, but ultimately, extremely beneficial in understanding the relationship of biomechanical variables to injury risk. Similar studies regarding floor inclination will need to be performed to provide convincing evidence that inclined floors are causative factors in dancers' injuries.

Regarding our secondary question of the effects of gender, the findings demonstrate that women had a trend toward more hip flexion angle than men at peak VGRF, but significantly less peak dorsiflexion moment than men. There was also a trend for women to have less hip adduction moment than men. Female athletes have been shown to demonstrate increased hip adduction moments and knee valgus angles than men in landing tasks (Hewett et al., 2006a; Hewett et al., 2006b; Pappas et al., 2007b). These previously described biomechanical differences have been linked to the increased incidence of ACL injury risk for female athletes. In contrast to female athletes, female dancers do not have increased risk for ACL injury compared with their male counterparts (Liederbach et al., 2008) and the findings of the current project demonstrate that they exhibit similar knee valgus angle and lower hip adduction moment as male dancers, as was also found in our previous work (Orishimo et al., 2009). These findings may explain the low incidence of injury among female dancers. Notably, although the female dancers in this study demonstrated differences in landing mechanics compared with men in some variables, these variables were not those which have been found in previous studies to be linked to increase in injury risk (Hewett et al., 2005, 2006b).

To our knowledge, our previous study (Orishimo et al., 2009) is the only one that has examined gender differences in biomechanical variables in dancers during a single-leg landing task. Unlike the current study, the findings in that study suggested there were no significant differences in landing mechanics relative to gender. As both studies were part of a larger project, 33 of the subjects were used in both of them. Examination of Tables 2 and 3 from the first study (Orishimo et al., 2009) suggest that underlying trends existed in the data moving in the direction of the current study findings for gender differences. Women in the original study had nonsignificant, but higher, hip flexion angles, and ankle and hip sagittal plane moments compared with men, which are congruent with the findings of the current study. We speculate that the increased power obtained from the additional subjects and the additional floor conditions allowed the underlying trends to achieve significance in the current study.

The findings of the current study need to be interpreted with caution due to several limitations. The results are applicable only to dancers performing a single-leg, vertical drop landing task and may not adequately represent the various types of dancers and functions commonly performed on stage. The findings are preliminary and, although generally supportive of the potential for

a biomechanical link between raked stages and injury risk to exist, they do not establish the degree to which, if any, raked stages may increase injury risk. Future studies are needed to clarify the degree to which raked stages increase risk. Observational designs should be prospective and use objectively measured variables such as work loss, costs of medical care, or number and type of injuries documented by medical personnel rather than self-reports of injuries, as in previous studies. (Evans et al., 1996, 1998) A study design which combines objective biomechanical data with observational data, as has been successfully used in the study of ACL injuries (Hewett et al., 2005) may be able to more accurately assess the relationship of biomechanics to any increased injury risk. Such a design would require that biomechanical data are obtained on a relatively large sample of performers who are then observed for long periods of time for occurrence of injury.

Inclined floors (raked stages) have a significant effect on joint angles and moments when compared with flat floors when dancers land onto a single leg from a 30 cm high platform. The findings may be seen in practical terms as establishing that the currently used inclines for Broadway productions have biomechanical effects on the lower extremities. This study did not determine the degree of injury risk associated with inclined floors. Significant gender differences exist during landing with women having less peak ankle dorsiflexion and hip adduction moment than men. There were no floor-by-gender effects on joint angle and moments during landing.

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