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The effect of an inclined landing surface on biomechanical variables during a jumping task

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Abstract

Background—Professional dancers sustain a high number of injuries. Epidemiological studies have suggested that performing on inclined “raked” stages increases the likelihood of injury. However, no studies have examined if biomechanical differences exist between inclined and flat surfaces during functional tasks, such as landing from a jump. Such differences may provide a biomechanical rationale for differences in injury risk for raked stages.

Methods—Eight professional dancers performed drop jumps from a 40 cm platform on flat and inclined surfaces while forces, lower extremity kinematics, and electromyographic activity were collected in a controlled laboratory environment.

Findings—Dancers landed on the laterally inclined surface with significantly higher knee valgus, peak knee flexion, and medial-lateral ground reaction force (GRF) compared to the flat condition. The posterior GRF was higher in the anterior inclined condition compared to the flat condition. In the anterior inclined condition, subjects landed with 1.4° higher knee valgus, 4° more plantarflexion at initial contact, and 3° less dorsiflexion at the end of landing.

Interpretation—Biomechanical variables that have been suggested to contribute to injury in previous studies are increased in the inclined floor conditions. These findings provide a preliminary biomechanical rationale for differences in injury rates found in observational studies of raked stages.

Introduction

The annual incidence rate of injury for dancers in professional dance companies is reported to be as high as 67%–95%.(Solomon et al., 1999, Garrick and Requa, 1993, Bronner et al., 2003) Approximately half of the performers on Broadway and in London’s West End productions have sustained a work-related injury within their current production.(Evans et al., 1996, Evans et al., 1998). Dancers performing in Broadway shows sustained 5.1 injuries per 1000 performances. (Evans et al., 1996, Evans et al., 1998). The high incidence of injury may be more understandable when one considers the workplace challenges: 1) high degree of repetition (doing the identical show repeatedly, sometimes twice daily); 2) high level of physical demands (jumping, lifting, running, etc.) especially in dancers with lack of physical fitness and suboptimal muscle strength (Koutedakis and Jamurtas, 2004, Koutedakis et al., 1997); and 3) environmental risk factors (inclined flooring, heavy costumes, high heeled shoes, etc.).

Environmental risk factors, specifically “raked stages,” have been a central issue in recent negotiations between the producers (Broadway Producers League) and the performers (Actor’s Equity Association) in Broadway theatrical productions. A raked stage is one that inclines downward toward the audience and is present in approximately 20% of Broadway productions. Two studies, one of Broadway productions (n = 318)(Evans et al., 1996) and one of West End productions (n = 269)(Evans et al., 1998), have provided support to the suggestion that raked stages may increase the risk of injury for performers.(Evans et al., 1996, Evans et al., 1998). For dancers, raked stages resulted in a 3-fold increase in injuries for the Broadway productions (Evans et al., 1996) and 2-fold increase in injuries for the West End productions.(Evans et al., 1998) 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. Floor inclination alters kinetic and/or kinematic variables during gait,(Kawamura et al., 1991, Tokuhiro et al., 1985, Gehlsen et al., 1989, Vogt and Banzer, 1999, Sun et al., 1996, McIntosh et al., 2006) static standing,(Wenning and O’Connell, 1999) and during lifting tasks.(Shin and Mirka, 2004, Zhao et al., 1987) Similarly, but less directly applicable, several small laboratory studies have examined the effect of increased heel heights on posture and gait.(Opila-Correia, 1990b, Opila-Correia, 1990a, Nyska et al., 1996, Corrigan et al., 1993, Franklin et al., 1995) Collectively, these studies suggest a plausible biomechanical rationale linking the inclination of the floor surface and changes in applied force and motion of the human body that may lead to increased tissue loading, and ultimately to increased injury risk.

Conceptually, the biomechanical risk from raked stages can be divided into effects that occur through high-load/short duration forces such as jumping, or from low-load/long duration forces, such as occur during asymmetrical prolonged standing posture. One common laboratory model used to determine the effects of high load/short duration forces is landing from a jump from a specified height.(Ford et al., 2003, Decker et al., 2003, Madigan and Pidcoe, 2003, Pappas et al., 2007) This model is ideal for initial exploration of the effect of inclined surfaces to produce injury in performers because: 1) It is a standard model in many studies that will allow comparison to previous evidence (Ford et al., 2003, Decker et al., 2003, Madigan and Pidcoe, 2003, Pappas et al., 2007); 2) It is a valid representation of a common functional task performed on raked stages; 3) It creates high load forces that are 2 to 7 times body weight (Dufek and Bates, 1990, Mizrahi and Susak, 1982) and therefore likely to demonstrate any potential effects of the inclined surface; 4) The most injured areas for both dancers and actors are the knee and ankle (Evans et al., 1996, Evans et al., 1998), which will be most challenged by force with this protocol.

As a preliminary investigation it is possible to use measures of joint angles, muscle activation as measured by electromyography (EMG), and ground reaction force vector (GRF) to determine if significant differences exist between two conditions (e.g., level vs inclined floor). Significant differences in these variables between floor conditions would support a biomechanical rationale for differences that may exist in injury rates relative to floor conditions. Therefore, the purpose of this preliminary study was to determine the effect of an inclined surface (raked stage) on lower extremity biomechanical and electromyographic variables (joint angles, EMG, and GRF) during landing from a 40 cm jump.

Methods

This was a repeated measures experimental study using measures of EMG, kinetic, and kinematic data. The study was conducted at Harkness Dance Center Motion Analysis Laboratory, NYU - Hospital for Joint Diseases, USA. Eight healthy dancers between the ages of 21–40 years were recruited. All participants were performing in Broadway theaters at the time of the study. Exclusion criteria were: obesity (body mass index greater than 30 kg/m^2); a history of injuries and/or diseases that would render unsafe the execution of the protocol; and a history of injuries and/or diseases that could affect the biomechanics of landing such as lower extremity fractures.

Data were obtained from eight dancers, (3 male, 5 female), aged 28.1 (3.2) years, height 167.2 (8.2) cm, and weight 63.5 (15.1) km. Subjects completed the entire protocol (three landings for each one of the five floor conditions) in a single session. All testing was performed between 10AM and 3PM and subjects did not exercise, practice, or perform prior to the testing session. Subjects performed bilateral landings on a force plate from a 40 cm platform as in similar studies (Ford et al., 2003, Decker et al., 2003, Madigan and Pidcoe, 2003, Pappas et al., 2007) that investigated drop landings. Subjects were informed of the study protocol and total time needed for testing. All risks and possible harms as described in the consent form were verbally explained. All subjects completed a medical history questionnaire, signed a consent form approved by the NYU School of Medicine IRB, and were measured for height, weight, foot width and length, and knee width. The skin was prepared and surface electrodes were placed on the medial gastrocnemius, rectus femoris, biceps femoris, medial hamstrings as described elsewhere (Fagenbaum and Darling, 2003) and on the bulk of the vastus medialis and anterior tibialis muscles. These sites of electrode placement are consistent with recent guidelines (Hermens et al., 2000). The reflective markers were placed bilaterally on the second metatarsal, calcaneus, lateral malleolus, mid-fibula, lateral femoral condyle, mid-thigh, anterior superior iliac spine, acromion, lateral humeral epicondyle, distal radioulnar joint. Reflective markers were also placed on the sacrum and the left posterior superior iliac spine (offset) as per the Helen Hayes system (Richards, 2002)

The order of the five different slope conditions was randomized. The subjects were allowed two practice jumps and then performed three bilateral drop jumps from the 40 cm platform. They were instructed to drop directly down off the box and land with both legs on the force plate. Subjects did not receive any instructions on the landing technique to avoid a coaching effect. The effect of the arms was minimized by asking the subjects to keep their arms crossed against their chest.(Rodacki et al., 2002, Decker et al., 2003, Pappas et al., 2007) Trials were repeated when they were judged as non-acceptable (such as when subjects lost their balance or did not land with both feet on the force plate).

In order to replicate the flat and “raked” stages effect it was necessary to construct flooring, (two wedges and one flat surface) which could be attached to the surface of the force plate. 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.

Two primary concerns were addressed regarding the validity of the force data acquired through the wooden flooring:1) All three wooden floors should approximate rigid objects in order to transfer impact force fully to the force plate, and, more importantly in this repeated measures study, all three wooden floors should have similar deformation characteristics when impact force was applied; 2) All three wooden floors should be attached to the force plate in such a manner that no motion at the floor/force plate interface occurs. To insure similar deformation characteristics, the three floors were constructed by a single individual using identical pieces of solid oak and identical construction techniques. To reduce interface motion, the floors were attached on the force plate with the use of temporary adhesive and were tested prior to each trial to determine if any visible, or kinesthetically sensed, motion occurred between the wedge and the force plate during jumping. Tests to determine the equivalence of the ground reaction forces across the wooden floor conditions were performed. A 10.3 kg bag filled with sand was dropped from a height of 91.4 cm three times each onto the bare force plate and onto each of the three wooden floors. This combination of height and mass approximated the peak force values found during the subject trials (2–6 times body weight). The difference in the measured GRF between the different floor conditions was less than 1%, suggesting that the deformation characteristics between floors were essentially similar.

The independent variable was floor inclination. The floor inclination was either flat (0°) or 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; 5) +3.6°, lateral (see Figure 1). The dependent variables were: EMG amplitude of the quadriceps (rectus femoris), hamstrings (biceps femoris and medial hamstrings), anterior tibialis, and gastrocnemius; vertical, medial-lateral, anterior-posterior, and resultant GRF; ankle, knee, hip, and pelvis angles in all three planes. The values of the kinetic, kinematic and EMG variables were calculated at five different points of the landing cycle (initial contact, 30°, 45°, 60°, and peak knee flexion) and were averaged for each subject across the three trials. Although the jumps were bilateral, all reported NEMG and kinematic measurements were analyzed only in reference to the right lower extremity.

All angles were in reference to the local coordinate system except for pelvic angles which were in reference to the laboratory coordinate system. All GRF vectors were transformed to the wedge coordinate system for each condition, such that vertical force was perpendicular to the superior surface of the wooden floor and not to the force plate. The medial-lateral and anterior-posterior GRF were also transformed to be parallel to the wooden floor.

Instrumentation

EMG data was collected with the Noraxon Myosystem 1400 (Noraxon USA, Inc., Scottsdale, AZ, USA). The electrodes were disposable, surface, passive electrodes (blue sensor, Ambu, Inc., Linthicum, MD, USA). The force plate was an OR6-5 AMTI biomechanical platform (AMTI, Watertown, MA, USA). Kinematic data was collected with the use of 8 Eagle cameras (Motion Analysis Corp. Santa Rosa, CA, USA) and reflective markers were placed as per the Helen Hayes system (Richards, 2002, 2003). The software for data collection was the EvaRT 4.0 (Motion Analysis Corp. Santa Rosa, CA, USA). The calculation of the data was performed with the Visual 3D, 3.33 software package (C-Motion Inc, Rockville, MD, USA).

The force platform was time synchronized to the EMG and the motion analysis system. The kinetic and EMG data was sampled at 1200 Hz and the kinematic data was sampled at 240 Hz as appropriate for fast athletic maneuvers (Ford et al., 2003). Before each data collection session the system was calibrated to the manufacturer's recommendations. A reproducibility and accuracy study of a precursor of the system we are using found the error of static measurements to be less than 0.4°, and the within trial variability during functional tasks to be less than 2.58 mm (Vander Linden et al., 1992). The magnitude of the error introduced by the system is negligible for the type of measurements we are interested in this study.

Normalization

The kinetic data collected from the force plate (GRF) was normalized to body weight as in previous studies (Hewett et al., 1996, Hewett et al., 1999). An initial "neutral" standing position was used to create anatomic coordinate system for each subject. EMG normalization was not used because all comparisons were repeated measures and data collection occurred in a single session.

Data analysis

Measurements were analyzed only in reference to the right lower extremity and the mean values of the three trials for each condition were used for all analysis. The kinetic, kinematic, and EMG data of the dependent variables as well as the different levels of the independent variables were entered to a statistical software package (SPSS 13.0, SPSS Inc., Chicago, IL, 60606). The level of significance was set a priori at 0.05. Three separate MANOVA procedures were used to evaluate the effect of floor on kinetic (ankle, knee, hip, and pelvis angles across all three planes), kinematic (GRF across all three planes and the resultant vector), and EMG (across all muscles tested) variables. Univariate tests were performed when the MANOVA was significant to identify the specific variables that reached significance followed by pairwise comparisons on those variables between the flat condition and each one of the incline conditions to identify the comparisons that were significantly different. The Greenhouse-Geisser adjusted values were used for the variables in which sphericity was violated. Cohen's d statistic of effect size was calculated in order to give a more complete picture of the effect of the independent variables on the dependent variables. The effect size is defined as trivial if it is <0.2, small 0.2–0.5, medium 0.5–0.8, and large>0.8 (Portney and Watkins, 2000)

Results

The three separate MANOVAS found that floor had a significant effect on kinematic and kinetic variables (p<0.001) but not on EMG (p=0.199), consequently, no further analysis was performed on the EMG data.

Univariate ANOVAS found that floor had a significant effect on ankle dorsiflexion (p<0.001), knee flexion (p=0.001), and knee valgus (p<0.001) and a significant effect on the anterior-posterior and medial-lateral components of the GRF (p<0.001).

Pairwise comparisons of kinematic variables (inclined conditions vs flat condition) found that ankle dorsiflexion (p=0.007, d=0.66) and knee valgus (p=0.022, d=0.17) were different for the anterior incline condition. Knee flexion and knee valgus were different for the lateral incline condition (p=0.014, d=0.94 and p=0.008, d=0.56 respectively). In the anterior incline condition, subjects landed with an average of 1.4° higher knee valgus, 4° more plantarflexion at initial contact, and 3° less dorsiflexion at the end of landing. In the lateral incline condition subjects exhibited an average of 9° more peak knee flexion and 4° more knee valgus (see Figure 2).

Pairwise comparisons for kinetic variables (inclined conditions vs flat condition) found that the posterior GRF was 10.2% body weight (BW) higher in the anterior incline condition (p=0.001, d=0.51) and 21.1% BW (p<0.001, d=0.96) and 4.7% BW (p=0.007, d=0.23) lower in the posterior and lateral incline conditions, respectively. Pairwise comparisons also found that medial-lateral GRF decreased by 1.3% BW (p=0.005, d=0.3) during the posterior incline condition and increased by 13.4% BW (p<0.001, d=2.54) during the lateral incline condition. The medial-lateral GRF was directed laterally during the medial incline condition and it was significantly higher compared to the flat condition (11.2% BW, p<0.001, d=3.0). The medial-lateral GRF was directed medially for all other conditions (see Figure 3).

Discussion

This study is the first to demonstrate that kinematic and kinetic variables of the lower extremities are significantly altered when dancers land on an inclined floor (similar to those used on Broadway stages) compared to a level floor. These findings provide preliminary and indirect support for a biomechanical rationale for the increased risk of injury during raked stage performances found in some studies.

Although biomechanical differences were found between the flat condition and all four inclined conditions, it appears that the most consistent differences from the flat condition occur when the leg lands on a laterally inclined floor. In this condition the knee flexes an additional 9°, moves into an additional 4° of valgus, and the frontal component of the GRF increases by 13.4% BW directed from lateral to medial (see Figure 3). Similar but opposite results were *not* observed in the joint angles with a medially inclined floor suggesting that unique interactions occur when the incline rises laterally, rather than medially, to the foot. We speculate that these effects are due to the normal interactions linking pronation of the foot to internal rotation, flexion, and valgus of the knee. The large muscle groups of the lower extremity (quadriceps, hamstrings, gastrocnemius) are very effective in controlling motion in the sagittal plane but are not anatomically designed to control motion in the frontal plane. The combination of increased knee valgus angle and frontal plane GRF observed in the lateral incline condition may place unique demands on the lower extremity musculature which may be related to risk of knee injury. (McLean et al., 2004a,Ireland, 1999)

There is some evidence in the literature that increases in the values of kinetic and kinematic variables, as found in this study, are related to increased musculoskeletal injury risk. For example, several research reports have suggested that increased knee valgus may be linked to knee injury.(Hewett et al., 2005, Pflum et al., 2004, Markolf et al., 1995, McLean et al., 2004a, McLean et al., 2004b, Malinzak et al., 2001, Ford et al., 2003, Kernozek et al., 2005, Russell et al., 2006, Pappas et al., 2007) Cadaveric (Kanamori et al., 2000, Markolf et al., 1995, Hollis et al., 1991) and computer simulation (Bendjaballah et al., 1997, McLean et al., 2004a, Pandy and Shelburne, 1997) studies have demonstrated that increased knee valgus angle causes significant increases in anterior cruciate ligament (ACL) stress, with one study (Bendjaballah et al., 1997) suggesting that a 4° increase in knee valgus causes approximately 15% increase in ACL force. Additionally, a prospective biomechanical/epidemiological study showed that female athletes who subsequently suffer knee injury land with 7.6° higher knee valgus compared to female athletes who do not suffer knee injury.(Hewett et al., 2005) Knee valgus has been suggested to be a frequently observed component of the ACL mechanism of injury in athletes.(Olsen et al., 2004, Krosshaug et al., 2007) Due to the lack of similar studies in dance medicine, it is unclear if knee valgus is an important contributor to knee injuries in dancers.

Significant increases of posterior GRF were observed when subjects landed on the anterior incline condition. This finding is consistent with the findings of a recent study that investigated the effect of inclined surfaces on gait (McIntosh et al., 2006). Increased posterior GRF during landing from a jump leads to increases in ACL forces (Pflum et al., 2004, Chappell et al., 2005) possibly due to increased quadriceps muscle force that is necessary to counteract the external flexion moment.(Chappell et al., 2005) Excessive quadriceps forces can lead to complete tears of the anterior cruciate ligament of the knee.(DeMorat et al., 2004) However, significant differences in EMG activity were not observed in the present study.

Limitations

The findings of the current study need to be interpreted with caution due to several limitations. This was a preliminary study with a small sample size attempting to provide relevant objective information regarding whether different conditions in floor inclination may cause biomechanical changes during a drop landing task. The results are applicable only to dancers performing a bilateral landing task and may not adequately represent the various types of performers and functions commonly performed on stage, including unilateral landing tasks. This study did not examine the question of whether raked stages increase injury risk and should not be interpreted in this manner. However, the significant differences found between floor conditions in this study provide a preliminary biomechanical rationale for differences in injury rates found in previous studies and in future studies in which increased injury risk is found. Additionally, the effect of fatigue has not been examined in the present study. Fatigue is associated with changes in joint angles (Pashalis et al., 2007, Pappas et al., 2007) and disturbed position sense (Pashalis et al., 2007) which may increase the likelihood of injury (Liederbach et al., 1994). The subjects in the present study were rested and possibly minimally challenged by the protocol. It is unclear if a fatigue protocol would have altered our findings or if well-trained dancers are less susceptible to injuries when performing on inclined floors.

Future studies are needed to clarify the degree to which raked stages increase risk as well as the relationship between biomechanics and injury 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, Evans et al., 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 is obtained on a relatively large sample of performers who are then observed for long periods of time for occurrence of injury.

If future studies determine that inclined stages clearly increase injury risk and that this increased risk is related to biomechanical variables, then solutions to this problem may be pursued through two different mechanisms. The first is through an ergonomic approach which attempts to modify the environment to fit the worker. For most productions, a raked stage is a planned event, as stages are constructed anew with each production. In these cases, stage floors can be designed and constructed as level floors. The second approach, in cases where a flat stage is not desired or possible, may focus on retraining the performer to improve adaptation to the flooring surface. Biomechanical studies have shown that injury prevention programs can lead to decreases in biomechanical variables that have been linked to lower extremity injury and to injury risk in athletes.(Hewett et al., 1999, Myklebust et al., 2002, Cerulli et al., 2001) Programs that consist of plyometric and proprioception exercises have been shown to be particularly effective in decreasing injury risk.(Hewett et al., 2006) Future studies may investigate if injury prevention programs are effective in reducing lower extremity injuries in dancers who perform on raked stages.

Conclusion

Performers landing on “raked” surfaces, similar to those used in Broadway productions, compared to level surfaces exhibit significantly greater levels of ankle and knee joint angles and significantly greater levels of GRF. These findings may provide a preliminary biomechanical rationale for differences in injury rates found in observational studies of raked stages.

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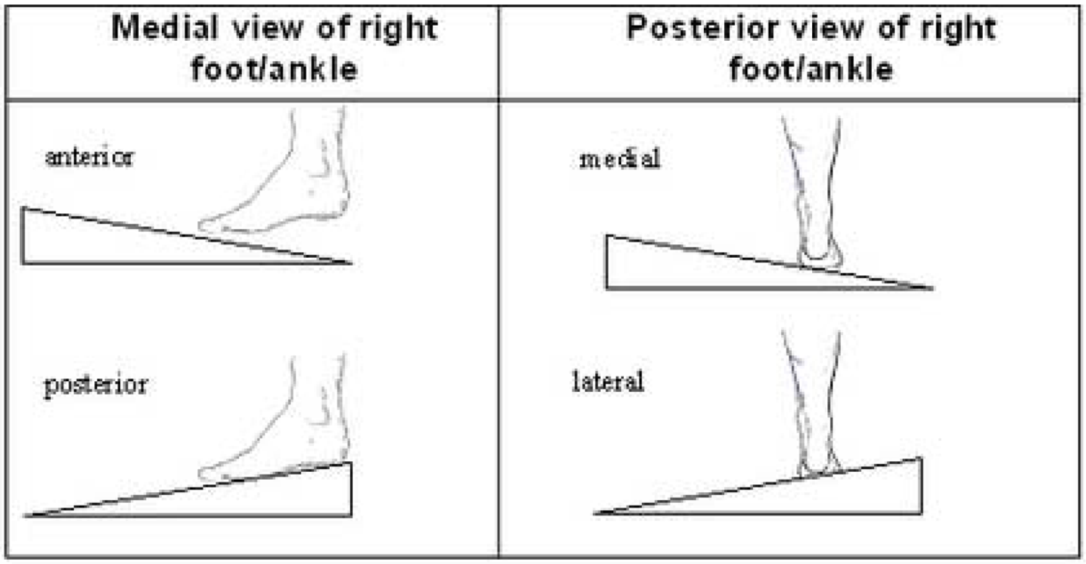

Figure 1.
Experimental set up relative to inclined flooring

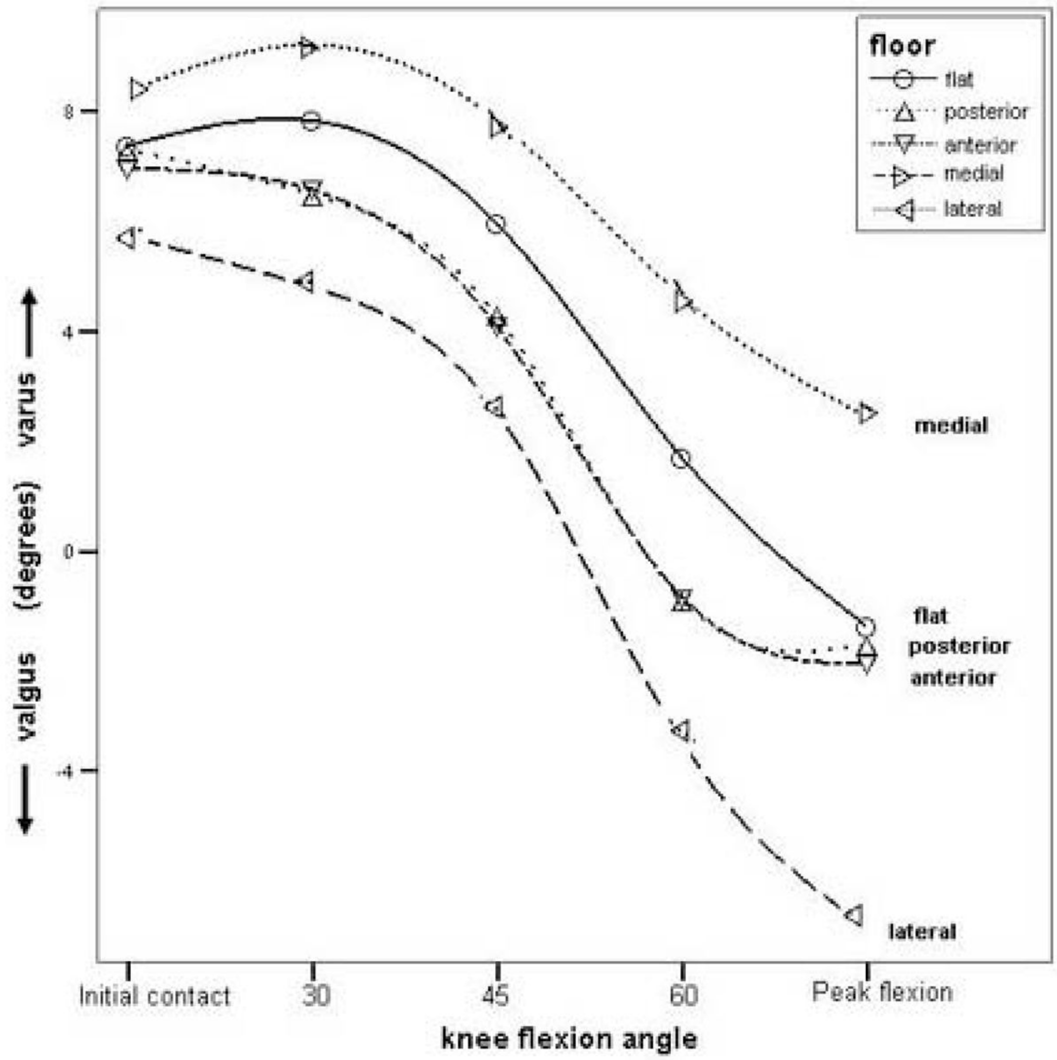

Figure 2.
Coronal plane motion of the knee during landing on level and inclined floors

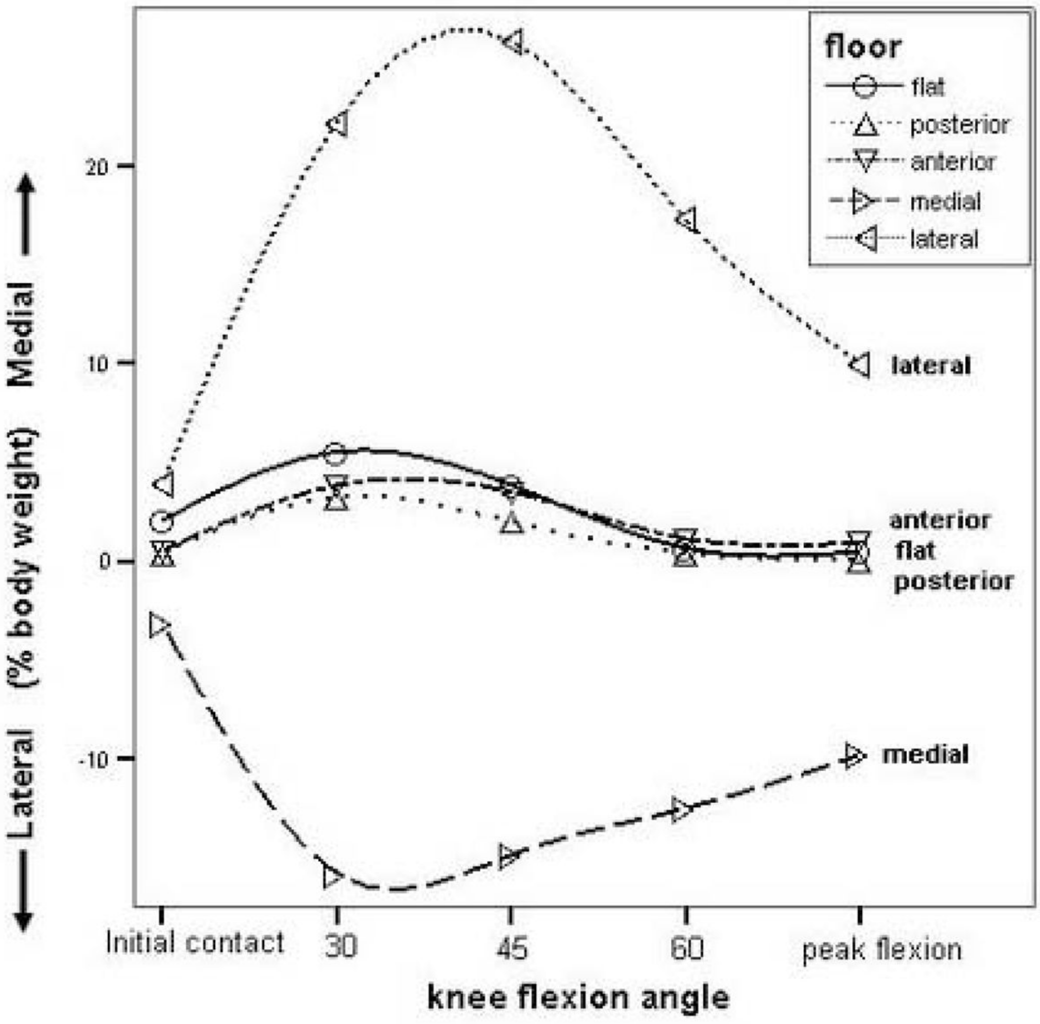

Figure 3.
Medial-Lateral GRF during landing on level and inclined floors