n increase in participation of women in athletics has resulted in an exceedingly high incidence of noncontact ACL injuries.\(^1\)\(^3\) Sports such as soccer, basketball, handball, volleyball, field hockey, and softball have the greatest incidence of female noncontact ACL injuries,\(^4\)\(^6\) particularly in relation to the incidence among male athletes who participate in the same sports.\(^3\)\(^7\) Surprisingly, fewer noncontact ACL injuries have been reported in dancers\(^8\)\(^10\) and cheerleaders,\(^11\) who also perform activities that involve turning, jumping, and landing. Is this because the jumping and landing mechanics of these female athletes are different?

Why are ACL injury rates different for female athletes participating in different sports? Two possible answers are (a) athletes who participate in different sports may use different biomechanical techniques during generation of propulsive force and jump landing, and (b) anticipatory muscle activation may play an important role in stabilizing the knee during performance of stressful maneuvers like jump landing, which may be developed to a greater extent through participation in specific sports. If there are no biomechanical differences among female athletes from various sports, future research should focus on the anticipation factor. If there are differences in jumping kinematics, specific training and coaching techniques might reduce the injury rates of those participating in high-risk sports. Thus, comparison of female athletes who participate in high-risk and low-risk sports may provide important information.

The purpose of this study was to compare the kinematics (joint angles) and kinetics (ground reaction force) of female athletes who participate in sports that present low-risk versus high-risk sports for ACL and nonathletic controls during loading and landing phases of a maximal vertical jump. We operationally defined dancers and cheerleaders as low-risk athletes on the basis of fewer reported knee injuries.\(^3\)\(^8\)\(^11\) The high-risk group consisted of volleyball and soccer players, who have been demonstrated to have greater risk for ACL injury occurrence than other female athletes.\(^3\)\(^5\)\(^12\) We looked for any differences in the manner in which the participants jumped and landed to identify any factors that might contribute to ACL injury risk. Do the demands imposed by a sport reinforce specific jumping mechanics, or are there behaviors that coaches and athletic trainers or therapists can teach athletes to improve the mechanics?

We predicted that there would be biomechanical differences among the groups of high-risk athletes (soccer and volleyball players), low-risk athletes (cheerleaders and dancers), and nonathletes. We hypothesized that the peak vertical ground reaction force (peak VGRF) and knee joint angle would be larger (greater extension) during landing for the high-risk group than the low-risk group and that the group of nonathletes would have the highest peak VGRF and largest landing angles.

**Procedures and Findings**

Fifty-nine healthy female collegiate undergraduates (20 ± 2.3 years of age) volunteered to participate and completed the study. All high-risk and low-risk athletes were recruited from an NCAA Division I athletic program.
and nonathlete participants were recruited from the general student population of the same university. All participants completed a medical questionnaire and an informed consent document approved by the university’s Institutional Review Board. Volunteers who had current or previous lower extremity musculoskeletal injuries were excluded from participation.

Twenty reflective joint markers were attached to both lower extremities for 3-D motion tracking, digitization, and analysis. Following warm-up movements and practice jumps, each participant performed three maximal-effort vertical jumps, taking off and landing on a force plate. Each athlete was asked to imagine a sport-specific situation in which a maximal jump effort is required, which has been shown to improve the intensity of effort. Cheerleaders were instructed to jump in the same manner as during performance of a tuck jump. Dancers were instructed to jump in the same manner as during performance of a highest place jump in second position. Volleyball players were instructed to jump in the same manner as during an attempt to block an opponent’s spike. Soccer players were instructed to jump in the same manner as during performance of a header shot on the goal. Nonathletes were instructed to simply jump as high as possible.

Separate ANOVAs were performed for each dependent variable, which included maximum dorsiflexion, maximum knee flexion, and peak vertical ground reaction force (expressed as a multiple body weight; X BW) for both the loading and landing phases and jump height. The loading phase was defined as maximum lower extremity flexion to take-off (VGRF = 0). The landing phase was defined as initial ground contact to lower extremity extension at the hip and knee (standing upright but not necessarily motionless). Ankle dorsiflexion and knee flexion were measured as change from anatomic standing position (neutral).

As we hypothesized, differences were observed in the kinematics and kinetics of the three groups during loading and landing phases of the jump (Figure 1). Statistically significant differences ($p > 0.05$) were found for five of the seven dependent variables. The high-risk group loaded with significantly smaller dorsiflexion angles (limited ROM) compared to the low-risk and nonathlete groups. The low-risk group landed with significantly greater dorsiflexion than both the high-risk and nonathlete groups (Figure 2). During the loading phase, the high-risk group demonstrated significantly greater knee extension than the low-risk group, and the nonathlete group demonstrated the greatest amount of knee flexion. A different pattern was observed during the landing phase. The nonathlete group landed with greatest amount of knee extension, followed by the high-risk group. The low-risk group demonstrated the greatest amount of knee flexion (Figure 1). The low-risk group landed with the smallest peak VGRF and the high-risk group landed with the greatest peak VGRF (Figure 3).

**Application of Findings**

Females exhibit greater knee extension and lesser ankle dorsiflexion during jump landing than males, as well as other biomechanical differences. Susceptibility to knee injury is increased when the knee is...
in an extended position upon jump landing or during performance of a cutting maneuver. Such kinematic behavior has been observed among female basketball, volleyball, and soccer athletes and nonathletes, but differing behavior has been documented for dancers.

Our finding that high-risk group landed with a more extended knee position (Mean = 42 degrees) is consistent with findings reported by others. We found that low-risk athletes landed with the knee in a more flexed position (Mean = 62 degrees), which is consistent with the finding reported by Hughes et al. for males (Mean = 62 degrees). Our findings for the high-risk and nonathlete groups are also consistent with those of Yu and colleagues, who reported peak VGRF approaching 4X BW and a relative lack of knee flexion at ground contact. Such a stiff landing technique could transmit a greater load to the knee, thereby exposing the ACL to greater risk for disruption.

Orishimo et al. reported similar values for knee flexion and peak VGRF among male and female dancers as those we observed in low-risk athletes. The smaller peak VGRF observed for the low-risk group may be an indicator of a greater ability to attenuate impact loading, which may relate to the lower incidence of knee injuries for dancers and cheerleaders. The low-risk group also demonstrated values for knee flexion, ankle dorsiflexion, and peak VGRF for the loading and landing phases that were more similar to each other than those demonstrated the other groups (Figure 1a).

Might the goal of a specific activity differentially affect the mechanics of jumping and landing? High-risk volleyball and soccer athletes need to get to the location of the ball quickly (for spiking, blocking, or heading), which may not provide sufficient time to increase knee flexion during the loading phase of a jump. The different mechanics for jumping and landing we observed may relate to motor control system adaptations to environmental and task-oriented constraints. Female athletes participating in high-risk sports probably need to create a more rigid kinetic chain to impart force to the ball during blocking and heading, whereas the performance goals of dancers and cheerleaders may be achieved with a less rigid jumping technique. McKeon has suggested that an understanding of self-organization for goal attainment is an important consideration for sport-specific rehabilitation.

The differences we observed in the mechanics of the loading and landing phases of vertical jumping may relate to the specific goal of the jumping task for each sport. We believe that the constraints imposed by sport-specific performance demands influence motor programming, which explains the differing kinematics and kinetics among the three groups.

Participants were encouraged to put forth maximal effort, but psychological factors might have influenced the performance of the jumping task. We did not evaluate the jumping mechanics of athletes who had a history of knee injury. Future longitudinal research might...
document the jumping mechanics of female athletes participating in various sports before injuries occur, which might identify individual athletes who possess elevated injury risk. A future case-control study might compare the jumping mechanics of female athletes with a history of knee injury to uninjured athletes who are matched on the basis of sport, age, competition level, etc.

**Conclusion**

Most jumping, landing, and turning during participation in dance and cheerleading is unplanned and anticipated, which allows the athlete to anticipate required movement patterns. Conversely, many volleyball and soccer movements are reactionary in nature, which cannot be anticipated. The findings of this study suggest that the jumping biomechanics of female athletes differ on the basis of participation in high-risk versus low-risk sports. Reduction of ACL injury risk may be achieved through training that increases hamstring strength and modifies jumping and landing mechanics, but constraints imposed by sport-specific performance demands may influence motor programming in a manner that is manifested by characteristic jumping kinematics and kinetics.

**End Note**

A detailed Methods file for this study can be found at the **IJAITT** website under Extras.

**References**


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