

A Comparison of Knee Kinetics between Male and Female Recreational Athletes in Stop-Jump Tasks

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ABSTRACT

We compared the knee kinetics of 10 male and 10 female recreational athletes (aged 19 to 25 years) performing forward, vertical, and backward stop-jump tasks. Three-dimensional videography and force plate data were used to record the subjects' performance of the three stop-jump tasks, and an inverse dynamic procedure was used to estimate the knee joint resultant forces and moments. Women exhibited greater proximal anterior shear force than did men during the landing phase. All subjects exhibited greater proximal tibia anterior shear force during the landing phase of the backward stop-jump task than during the other two stop-jump tasks. Women also exhibited greater knee extension and valgus moments than did men during the landing phase of each stop-jump task. Men exhibited greater proximal tibia anterior shear force than did women during the takeoff phase of vertical and backward stop-jump tasks. These results indicate that female recreational athletes may have altered motor control strategies that result in knee positions in which anterior cruciate ligament injuries may occur. The landing phase was more stressful for the anterior cruciate ligament of both women and men than the takeoff phase in all stop-jump tasks. Technical training for female athletes may need to be focused on reducing the peak proximal tibia anterior shear force in stop-jump tasks. Further studies are needed to determine the factors associated with the increased peak proximal tibia anterior shear force in female recreational athletes.

An ACL tear is a commonly seen knee injury, with an annual incidence rate of 1 per 3000 people for the general population.²² More than 70% of ACL injuries are sports-related.^{17,26} The majority of ACL injuries in sports are caused by noncontact injury mechanisms; that is, there is no direct physical contact between athletes when the injury occurs.^{3,31} Women have a higher ACL injury rate compared with men, especially in basketball, soccer, and volleyball.^{1,7,10,16} Studies have repeatedly shown that the ACL injury rate for women is as much as eight times higher than that for men.^{6,12}

A variety of intrinsic and extrinsic factors have been proposed as contributing to the increased ACL injury rate in women. Intrinsic factors include the small cross-sectional area of the ACL in women; a narrower intercondylar notch,^{9,24,27,28} greater quadriceps angle,²⁷ and greater knee laxity in women than in men^{15,30}; subtalar joint pronation^{19,25}; and hormonal variations.²⁸ Extrinsic factors include level of conditioning, level of muscle strength, and altered motor control strategies.^{8,9,20,21} There has been a concentrated effort over the last decade to investigate the association between intrinsic factors and ACL injuries.

Extrinsic factors, on the other hand, especially the factor of altered motor control strategies and their relevance in the higher ACL injury rate in women, have not been studied as intensively, despite the dynamic nature of ACL injuries. A recent study by Malinzak et al.²⁰ suggested that female recreational athletes have smaller knee flexion angles, greater knee valgus angles, increased quadriceps muscle activation, and decreased hamstring muscle activation during the stance phases of running and cutting tasks when compared with their male counterparts. As previous studies have suggested, small knee flexion angle, greater knee valgus angle, increased quadriceps muscle activation, and decreased hamstring muscle activation tend to increase the strain on the ACL.^{2,4,22,25,29} In

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combination, these studies indicate that, on average, women may have altered motor control strategies that frequently bring them into lower extremity positions in which ACL injuries may occur.

The purpose of this study, which continues the work begun by Malinzak et al.,²⁰ was to compare the knee kinetics of female and male recreational athletes in the three stop-jump tasks of forward jumping, vertical jumping, and backward jumping (Fig. 1). These three stop-jump tasks are frequently performed in basketball, soccer, and volleyball. Boden and Garrett³ recently reported that noncontact ACL injuries frequently occur during these stop-jump tasks. On the basis of the previous study by Malinzak et al.²⁰ on lower extremity kinematics of female and male recreational athletes, we hypothesized that female recreational athletes would have increased proximal tibia anterior shear force, knee extension moment, and knee valgus moment in the three selected stop-jump tasks.

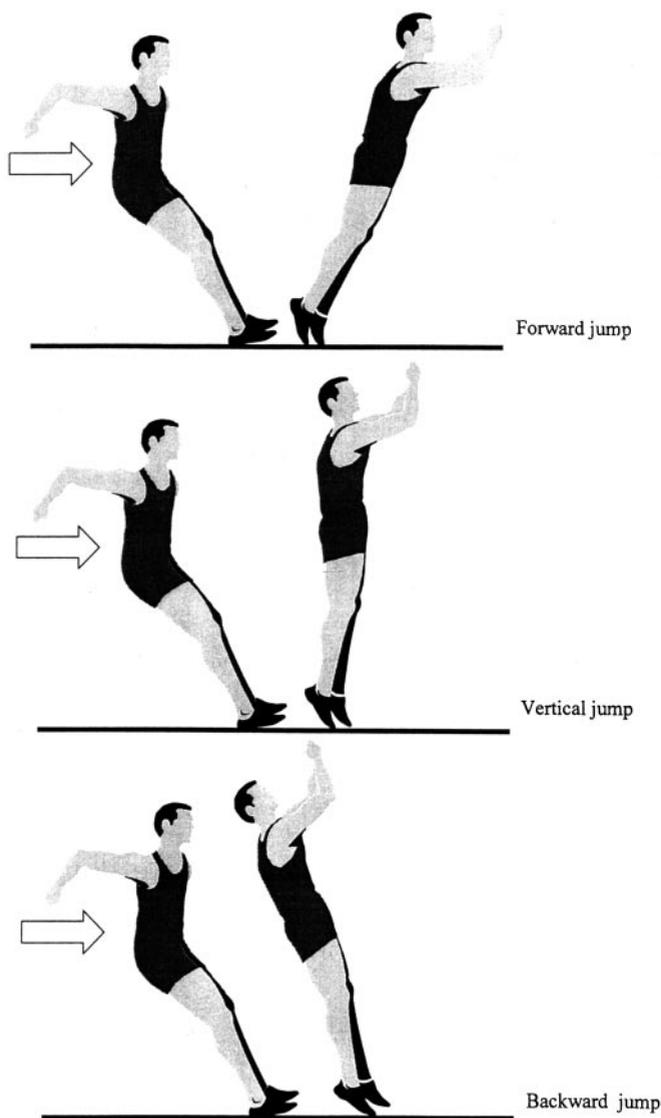


Figure 1. The three stop-jump tasks.

MATERIALS AND METHODS

Subjects

Twenty healthy recreational athletes (10 men and 10 women) were recruited as subjects from the University of North Carolina at Chapel Hill and Duke University. A recreational athlete was defined as a person who competes three times or less per week in sports events that regularly require stop-jump tasks such as basketball, soccer, and volleyball, but does not follow a professionally designed training regimen. The mean age, body mass, and height of the subjects were 23.4 ± 1.1 years, 76.6 ± 9.5 kg, and 1.80 ± 0.04 meters, respectively, for men, and 21.0 ± 1.7 years, 60.0 ± 5.9 kg, and 1.70 ± 0.06 meters, respectively, for women. Subjects with cardiovascular or respiratory disease, knee abnormalities, prior knee injury, or other musculoskeletal injuries that could prevent performance of the stop-jump tasks were excluded. Pregnant women were also excluded. The use of human subjects in this study was approved by the Internal Review Board at the University of North Carolina at Chapel Hill.

Experimental Procedure

Written consent was obtained after the experimental apparatus and movement procedures were reviewed with each subject. Women wore a sports brassiere; both men and women wore spandex pants and their own shoes and socks. Each subject's height, weight, knee widths, and ankle widths were recorded. Subjects were allowed unlimited time to warm up in their own manner, which generally consisted of light stretching. The subjects were also allowed to practice the tasks to be performed until they felt comfortable performing each task. To avoid the coaching effect on the subject's natural performance of the tasks, we gave no instructions regarding jumping techniques.

Thirteen retroreflective markers were attached on the right and left acromioclavicular joints, anterosuperior iliac spines, thighs, lateral condyles, shanks, and lateral malleoli, as well as on the L-4 spinous process. The thigh markers were carefully placed in line with the markers on the lateral condyles and greater trochanters. The shank markers were carefully placed in line with the lateral malleoli and lateral condyles at the point of greatest curvature of the lower legs.

Each stop-jump task consisted of an approach with up to three steps followed by a two-footed landing with each foot landing on a separate force plate and a two-footed takeoff for maximum height. There was no target for landing after the takeoff from the force plates, but the subjects were instructed to obtain maximum height for each jump and to limit horizontal motion. Each subject performed five consecutive trials for each task. The testing order of the three stop-jump tasks for each subject was randomized.

Data Collection

Four video cameras were used to record subjects' performances in each task at a frame rate of 180 frames per

second with a setup for a direct linear transformation procedure. Two Bertec 4060A force plates (Bertec, Worthington, Ohio) were used to collect ground-reaction force and moment data at a sampling rate of 540 samples per second. The video cameras and force plates were time-synchronized using a Peak Motus video analysis system (Peak Performance, Englewood, Colorado). The four video cameras were calibrated with a 25-point calibration frame for a 2.0 meters long by 1.5 meters wide by 2.5 meters high space in which the stop-jump tasks were performed.

Data Reduction

The recorded video images of the retroreflection markers' trajectories were digitized using the Peak Motus video analysis system. The last three trials of each stop-jump task were digitized for each subject from 10 frames before the landing to 10 frames after takeoff. Three-dimensional coordinates of the retroreflection markers were estimated from the digitized two-dimensional trajectories and camera calibration parameters using a MotionSoft Direct Linear Transformation (MSDLT) system (version 4.0, MotionSoft, Chapel Hill, North Carolina). Three-dimensional coordinates of the hip, knee, and ankle joint centers were estimated from the three-dimensional coordinates of the retroreflective markers.¹⁸ The raw three-dimensional coordinates were filtered through a low-pass Butterworth digital filter with estimated optimum cutoff frequency.³² Ground-reaction forces, free moments, and the location of the center of pressure were determined from force-plate data using the MotionSoft Force Plate system version 2.0.

Joint-resultant forces and moments at the knee on the tibia were estimated using an inverse dynamic procedure¹¹ and a MotionSoft Kinetic system version 4.0 with modified Clauser's segment inertia parameters.¹⁴ In this inverse dynamic procedure, the segment angular velocities and accelerations were estimated using Euler parameters.^{5,13} The estimated knee joint-resultant forces and moment vectors were translated to the tibial reference frames and deconstructed into anterior-posterior shear, medial-lateral shear, and axial force components and flexion-extension, valgus-varus, and internal-external rotation moment components.

To allow data analysis, we normalized the estimated joint-resultant forces to the subject's body weight, and the estimated joint-resultant moments were normalized to the product of the subject's body weight and height. The duration from the landing to the takeoff was defined as the stance phase. A full-stance phase was divided into 100 time intervals. Each time interval was normalized as 1% of the full stance phase.

The peak knee joint anterior-posterior shear forces, flexion-extension moments, and valgus-varus moments were identified during the landing and takeoff in each stance phase. The first part of a stance phase from the initial foot contact with the ground to the first local minimum of the vertical ground-reaction force in a stop-jump task is referred to as the landing phase (Fig. 2). The remaining portion of the stance phase was referred to as the takeoff phase (Fig. 2).

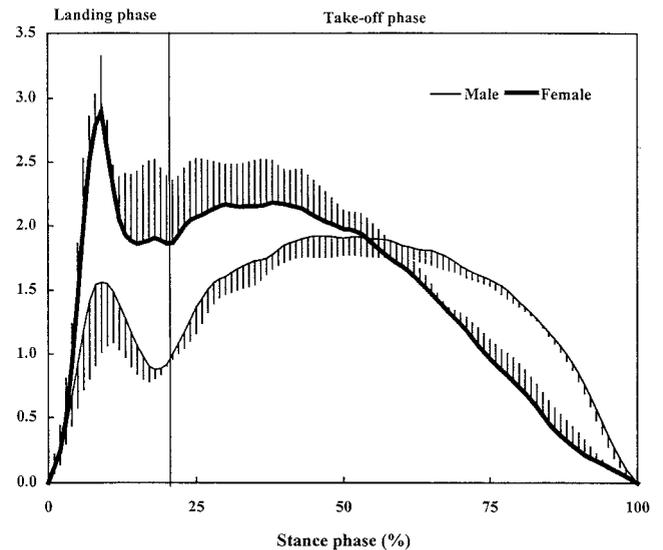


Figure 2. Landing and takeoff phases of a stop-jump task identified from vertical ground-reaction forces.

Data Analysis

The knee joint kinetic measures of the dominant leg were used for data analysis. The dominant leg was defined as the leg used for single-legged jumps. The intrasubject repeatability of knee kinetics during each stop-jump task was evaluated using the coefficient of multiple correlation introduced by Kadaba et al.¹⁸ The coefficient of multiple correlation is a measure of overall waveform similarity of a group of curves. The magnitude of this coefficient is close to one if the waveforms of a group of curves are similar, whereas the magnitude is close to zero if the waveforms of a group of curves are dissimilar.

A two-way analysis of variance with mixed design was conducted for each peak knee joint anterior-posterior shear force, flexion-extension moment, and valgus-varus moment. The independent variables in each analysis were sex and task, with task used as a repeated measure. A 0.05 level of type I error was chosen to indicate statistical significance. Post hoc paired *t*-tests were performed to compare each dependent variable between tasks. Post hoc independent *t*-tests were performed to compare each dependent variable between sexes. The Bonferroni procedure was used to adjust the overall type I error rate.

RESULTS

Intrasubject Repeatability

The magnitudes of the intrasubject coefficients of multiple correlation for the proximal tibia anterior-posterior shear force, knee flexion-extension moment, and knee valgus-varus moment were above 0.90, indicating a good intrasubject repeatability of the general patterns of these variables over time. There was no significant difference in intrasubject coefficients of multiple correlation for these variables between sexes or tasks.

Duration of Stance Phases, Landings, and Takeoffs

The landing phase of a stop-jump task was generally less than 20% of the stance phase (Table 1). There was no significant difference in absolute duration of stance phase, landing, and takeoff between sexes and tasks. There was also no significant difference in the relative duration of landing and takeoff between sexes and tasks.

Peak Proximal Tibia Anterior Shear Force during Landing

There was a significant difference between sexes in peak proximal tibia anterior shear force during the landing phase (Fig. 3). Women exhibited significantly greater proximal tibia anterior shear force than did men, regardless of the jumping task ($P = 0.00$). The task also had significant effects on the proximal tibia anterior shear force during the landing phase in men and women ($P = 0.00$). Subjects exhibited an increased anterior shear force at the knee during the landing phase of jumping backward in comparison with jumping vertically ($P = 0.00$) and forward ($P = 0.00$). Subjects also exhibited an increased anterior shear force at the knee during the landing phase when jumping vertically in comparison with when jumping forward. There was no significant interaction effect between sex and task.

Knee Flexion-Extension Moment during Landing

There was a significant interaction effect ($P = 0.00$) between sex and task on the knee flexion-extension moment at the peak proximal tibia anterior shear force during landing (Fig. 3). Post hoc analysis showed that women exhibited a significantly different knee flexion-extension moment than did men in all three tasks ($P = 0.01$). Women exhibited a knee extension moment at the peak proximal tibia anterior shear force when jumping forward, whereas men exhibited a knee flexion moment. Women exhibited a greater knee extension moment at the peak proximal tibia than did men when jumping vertically ($P = 0.01$). Women exhibited greater knee extension moments when jumping forward and vertically than when jumping backward. Men exhibited similar knee flexion moments when jumping forward and backward, but exhibited an extension moment when jumping vertically. The peak knee extension moment and peak proximal tibia anterior

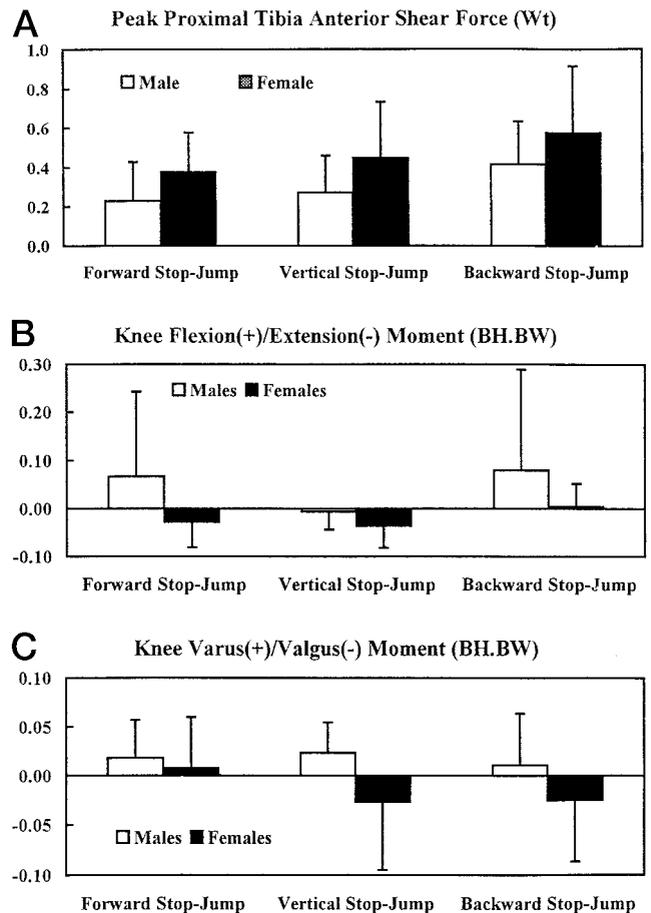


Figure 3. Comparisons of peak proximal tibia anterior shear force (A), knee flexion-extension moment (B), and knee varus-valgus moment (C) during the landing phase of three stop-jump tasks. Results are normalized by body weight (Wt) (peak shear force) or by body height times body weight (BH.BW) (knee flexion-extension moment and varus-valgus moment).

shear force for women occurred essentially at the same time during landing (Fig. 4).

Peak Knee Varus-Valgus Moment during Landing

Sex had a significant effect ($P = 0.01$) on the knee varus-valgus moment at the peak proximal tibia anterior shear

TABLE 1
Mean Absolute and Normalized Duration (Standard Deviations) of Stance, Landing, and Jumping Phases

Task	Sex	Mean absolute duration			Normalized duration	
		Stance (sec)	Landing (sec)	Jumping (sec)	Landing (%)	Jumping (%)
Forward stop-jump	F	0.292 (0.060)	0.045 (0.017)	0.247 (0.058)	15.8 (6.2)	84.2 (6.2)
	M	0.281 (0.066)	0.045 (0.011)	0.236 (0.062)	16.5 (4.7)	83.5 (4.7)
Vertical stop-jump	F	0.279 (0.053)	0.051 (0.019)	0.228 (0.057)	18.9 (7.6)	81.1 (7.6)
	M	0.296 (0.099)	0.055 (0.015)	0.241 (0.097)	19.8 (7.2)	80.2 (7.2)
Backward stop-jump	F	0.314 (0.071)	0.048 (0.017)	0.266 (0.064)	15.6 (5.1)	84.4 (5.1)
	M	0.329 (0.082)	0.057 (0.078)	0.272 (0.017)	18.0 (5.9)	82.0 (5.9)

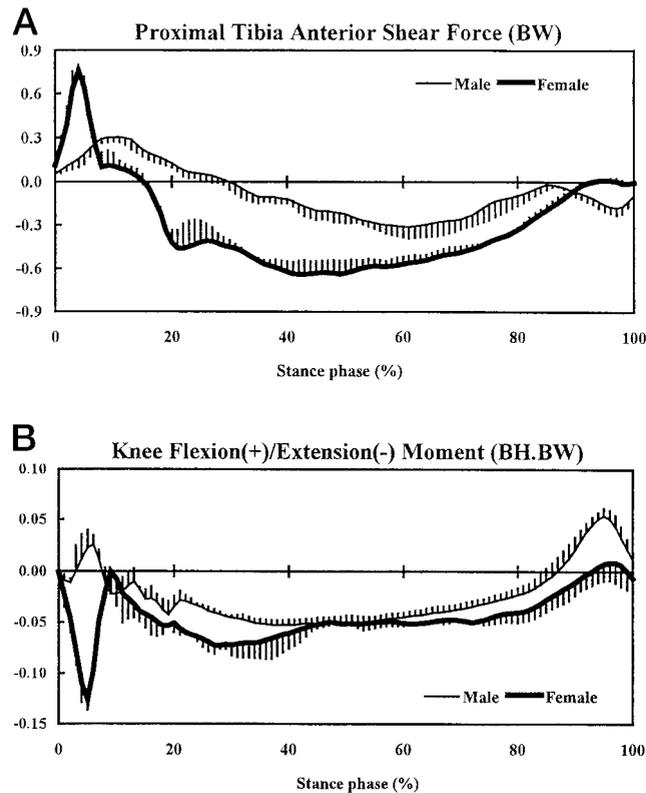


Figure 4. A, the proximal tibia shear force (normalized by body weight [BW]). B, knee flexion-extension moment patterns (normalized by body weight times height [BH.BW]) during a forward stop-jump task.

force during landing (Fig. 3). Women exhibited less knee varus moment at the peak proximal tibia anterior shear force than did men when jumping forward. Women exhibited valgus moments at the peak proximal tibia anterior shear force while men exhibited varus moments when jumping vertically and backward. The knee varus-valgus moment at the peak proximal tibia anterior shear force during the landing was a function of task for women ($P = 0.00$), whereas this knee moment was not significantly affected by task for men.

Peak Proximal Tibia Anterior Shear Force during Takeoff

There was a significant difference in peak proximal tibia anterior shear force during the takeoff with respect to sex ($P = 0.01$) and task ($P = 0.00$) (Fig. 5). The peak proximal tibia anterior shear force during the takeoff increased as the direction of the stop-jump moved from forward to backward ($P = 0.00$). Men exhibited greater anterior shear force at the knee than did women during the takeoff of the vertical and backward stop-jump tasks ($P = 0.01$). There was no significant interaction effect between sex and task on the peak proximal tibia anterior shear force during the takeoff. When compared between the landing and takeoff phases, the peak proximal tibia anterior shear

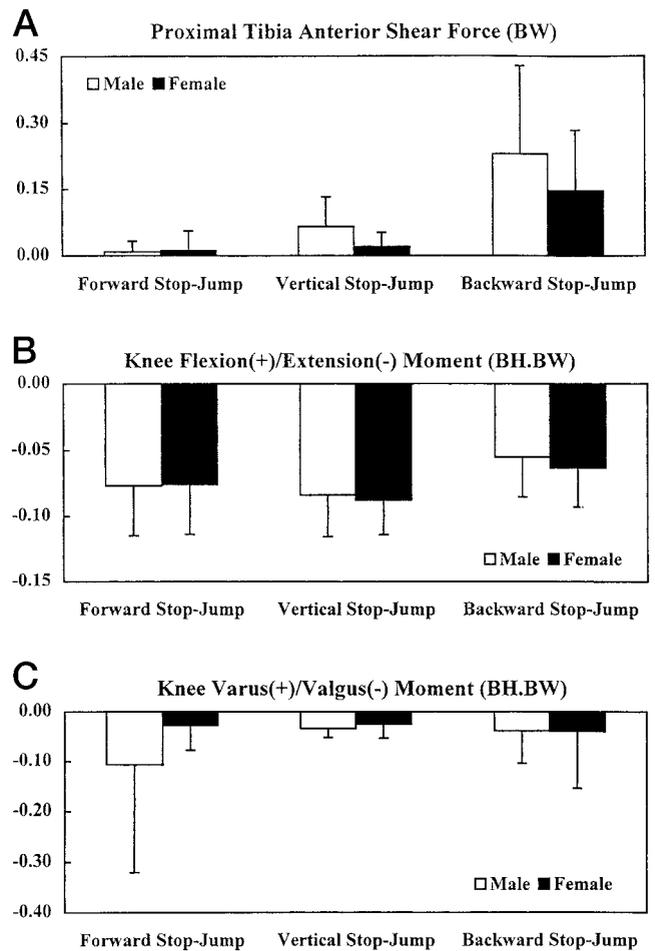


Figure 5. Comparisons of peak proximal tibia anterior shear force (A), knee flexion-extension moment (B), and knee varus-valgus moment (C) during the takeoff phase of three stop-jump tasks. Results are normalized by body weight (BW) (peak shear force) or by body weight times height (BH.BW) (knee flexion-extension moment and varus-valgus moment).

force was significantly greater during the landing than during the takeoff ($P = 0.00$).

Knee Flexion-Extension Moment during Takeoff

There was a significant task effect ($P = 0.00$) on the knee flexion-extension moment at the peak flexion-extension moment during the takeoff (Fig. 5). Both groups exhibited the greater extension moment at the peak proximal tibia anterior shear force during takeoffs of the forward and vertical stop-jump tasks than during the takeoff of the backward stop-jump task ($P = 0.00$), but no difference in this moment between the forward and vertical stop-jump tasks. There was no significant sex effect on the knee extension moment at the peak proximal tibia anterior shear force during the takeoff between the forward and vertical stop-jump tasks. There was no significant interaction effect between sex and task on the knee flexion-

extension moment at the peak proximal tibia anterior shear force during the takeoff.

Knee Varus-Valgus Moment during Takeoff

The knee varus-valgus moment at the peak proximal tibia anterior shear force during the takeoff was not significantly different between sexes or between tasks (Fig. 5). There was no significant interaction effect between sex and task on the knee varus-valgus moment at the peak proximal tibia anterior shear force during the takeoff.

DISCUSSION

The results of this study provide significant information on the possible risk factors of noncontact ACL injuries, especially for female recreational athletes. The proximal tibia anterior shear force is an important contributor to anterior tibial translation that may result in excessive strain on the ACL. Such strain is the direct cause of ACL tears. The results of this study support our hypothesis that female recreational athletes have increased proximal tibia anterior shear force compared with male recreational athletes during the landing phase in stop-jump tasks. This result indicates that female recreational athletes may have altered lower extremity motion patterns that tend to increase the proximal tibia anterior shear force during selected athletic tasks.

The increased proximal tibia anterior shear force in female recreational athletes during landings is likely due to 1) an increased quadriceps muscle force,^{15,20,23} 2) a decreased hamstring muscle force,^{20,23} 3) a decreased knee flexion angle,²⁰ or 4) a combination of all three. As our results show, female recreational athletes exhibited a greater peak proximal tibia anterior shear force and a greater peak knee extension moment than did their male counterparts. Our results also show that the peak proximal tibia anterior shear force and knee extension moment were time-synchronized for women. To a certain degree, the increased knee extension moment indicates an increased quadriceps-to-hamstring muscle force ratio. These results combined indicate that the increased peak proximal tibia anterior shear force in women was more likely due to the combination of at least the first two factors mentioned.

Our results further show that female recreational athletes had valgus moments at the knee, whereas their male counterparts had varus moments at the knee during the landing phases of vertical and backward jumps. These results are consistent with the findings of Malinzak et al.²⁰ that female recreational athletes had increased valgus knee angles compared with their male counterparts in selected athletic tasks. Bendjaballah et al.² showed that a valgus or varus moment applied to the tibia significantly increases the strain on the ACL. However, our results further showed that there was essentially no difference in the magnitude of the knee varus-valgus moment between the sexes. This indicates that female knee valgus-varus moment may not be responsible for the sex difference in

the ACL strain of recreational athletes during stop-jump tasks.

The results of this study show that the peak proximal tibia anterior shear force during the landing phase of each stop-jump task is greater than that during the takeoff phase. Also, the peak proximal tibia anterior shear force during the backward stop-jump task is greater than that during the vertical and forward stop-jump tasks. This indicates that noncontact ACL injuries may be more likely to occur during the landing phase than during the takeoff phase of each stop-jump task. Furthermore, it seems that noncontact ACL injuries are more likely to occur during the backward stop-jump task than during the vertical and forward stop-jump tasks.

Neuromuscular motor control is likely to be an important factor affecting lower extremity kinetics during athletic tasks. As the results of this study show, female recreational athletes tended to have a knee extension moment during landing, whereas their male counterparts tended to have a knee flexion moment. As discussed before, the knee flexion-extension moment calculated in this study represents the resultant knee flexion-extension effect of the quadriceps and hamstring muscle groups. The increased knee extension moment of the female recreational athletes observed in this study was consistent with the increased quadriceps muscle activation and decreased hamstring muscle activation of female recreational athletes observed by Malinzak et al.²⁰ These results combined suggest that male and female recreational athletes may have different neuromuscular control strategies, at least in selected athletic tasks. Differences in neuromuscular motor control strategies between male and female recreational athletes may result in increased strain on the ACL for female athletes compared with male athletes. On the basis of the results of this study, we believe that technical training for female athletes may need to include aspects that would assist in altering quadriceps and hamstring muscle contraction patterns to reduce knee extension moments during landing.

The peak joint-resultant forces and moments, especially those during the landing phase, might have been underestimated in this study because of the relatively low sampling rate of the video cameras. The peak joint-resultant forces and moments during the landing phase are mainly due to the impact between the subject and the ground. The peak ground-reaction forces in these impact situations consist of signals with very high frequencies. Although a sample rate of 540 samples per second was used to sample the ground-reaction force signals, the sample rate of the video cameras was limited to 180 frames per second. The actual sampling rate was reduced to 180 samples per second when force plate and videographic data were integrated to estimate joint-resultant forces and moments. This low sampling rate relative to the frequency of the ground-reaction force signals might have resulted in sampling errors in the estimated joint-resultant forces and moments. However, this error in the estimated joint-resultant forces and moments should be considered as random error across subjects and should not have significant effects on the results of this study.

The variation in the approach speed is another limitation of this study. The experimental protocol allowed for a two- or three-step approach that began with the subject in an upright position. The approach was not adjusted for stride length, and approach speed was not restricted. Subjects were instructed to perform the tasks at self-selected speeds with a certain degree of variation that might affect the magnitudes of estimated joint-resultant forces and moments. However, we believe that the women in this study, on average, had a lower approach speed than the men. We believe that the female subjects would have even greater peak proximal tibia anterior shear forces if they had the same approach speed as male subjects.

Fatigue might also affect the results of this study. Fatigue is a possibility because subjects were instructed to perform multiple trials of each task with their maximum efforts. However, the order of tasks performed in this study was randomized for each subject, which should have protected our results from the fatigue effects.

The results of this study provide a basis for future studies on the prevention of ACL injuries. Although kinetics studies are currently the most accurate method of determining joint load, the kinetic data from this study consist only of knee joint-resultant forces and moments and may not actually represent ACL strain. More sophisticated kinetic models of the knee are needed to estimate the strain on the ACL. Other topics requiring further study are the effects of anatomic and physiologic factors on ACL strain in athletic tasks and the kinetics of male and female elite athletes performing stop-jump tasks. Adolescent populations, fatigued subjects, subjects with ACL deficiency, and subjects with repaired ACL injuries should also be studied. Our study provides evidence that the stop-jump tasks commonly performed in high-risk sports could represent a different mechanism of injury for recreational female athletes.

In conclusion, there are significant differences in the kinetics of male and female recreational athletes during the landing phase of stop-jump tasks. Women exhibited greater proximal tibia anterior shear forces, knee extension moments, and knee valgus moments compared with men. The peak proximal tibia anterior shear force is apparently associated with quadriceps muscle contraction. These differences in the kinetics of the stop-jump tasks likely place increased strain on the ACL of female subjects compared with that in male subjects and represent a potential risk factor for noncontact ACL injuries. Modifying training techniques for the stop-jump tasks may aid in the prevention of noncontact ACL injuries in women.

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