Winner of the 2004 O'Donoghue Award

Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes

A Prospective Study

Timothy E. Hewett,*†‡ PhD, Gregory D. Myer,† MS, Kevin R. Ford,† MS, Robert S. Heidt, Jr,§ MD, Angelo J. Colosimo,‡ MD, Scott G. McLean,|| PhD, Antonie J. van den Bogert,|| PhD, Mark V. Paterno,† MS, PT, and Paul Succop,¶ PhD

From the †Cincinnati Children's Hospital Research Foundation, Sports Medicine Biodynamics Center, Division of Molecular Cardiovascular Biology, Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio, the ‡University of Cincinnati, College of Medicine, Department of Orthopaedic Surgery, Sports Medicine, Cincinnati, Ohio, the §Wellington Orthopaedic and Sports Medicine Center, Cincinnati, Ohio, the ||Department of Biomedical Engineering and Orthopaedic Research Center, Cleveland Clinic Foundation, Cleveland, Ohio, and the ¶Department of Environmental Health, University of Cincinnati, Cincinnati, Ohio

Background: Female athletes participating in high-risk sports suffer anterior cruciate ligament injury at a 4- to 6-fold greater rate than do male athletes.

Hypothesis: Prescreened female athletes with subsequent anterior cruciate ligament injury will demonstrate decreased neuromuscular control and increased valgus joint loading, predicting anterior cruciate ligament injury risk.

Study Design: Cohort study; Level of evidence, 2.

Methods: There were 205 female athletes in the high-risk sports of soccer, basketball, and volleyball prospectively measured for neuromuscular control using 3-dimensional kinematics (joint angles) and joint loads using kinetics (joint moments) during a jump-landing task. Analysis of variance as well as linear and logistic regression were used to isolate predictors of risk in athletes who subsequently ruptured the anterior cruciate ligament.

Results: Nine athletes had a confirmed anterior cruciate ligament rupture; these 9 had significantly different knee posture and loading compared to the 196 who did not have anterior cruciate ligament rupture. Knee abduction angle ($P < .05$) at landing was 8° greater in anterior cruciate ligament–injured than in uninjured athletes. Anterior cruciate ligament–injured athletes had a 2.5 times greater knee abduction moment ($P < .001$) and 20% higher ground reaction force ($P < .05$), whereas stance time was 16% shorter; hence, increased motion, force, and moments occurred more quickly. Knee abduction moment predicted anterior cruciate ligament injury status with 73% specificity and 78% sensitivity; dynamic valgus measures showed a predictive r^2 of 0.88.

Conclusion: Knee motion and knee loading during a landing task are predictors of anterior cruciate ligament injury risk in female athletes.

Clinical Relevance: Female athletes with increased dynamic valgus and high abduction loads are at increased risk of anterior cruciate ligament injury. The methods developed may be used to monitor neuromuscular control of the knee joint and may help develop simpler measures of neuromuscular control that can be used to direct female athletes to more effective, targeted interventions.

Keywords: neuromuscular control; dynamic valgus; knee joint load; anterior cruciate ligament (ACL) injury; injury prevention; gender differences

*Address correspondence to Timothy E. Hewett, PhD, Cincinnati Children's Hospital Medical Center, 3333 Burnet Avenue, MLC 10001, Cincinnati, OH 45229 (e-mail: tim.hewett@chmcc.org).

No potential conflict of interest declared.

The American Journal of Sports Medicine, Vol. 33, No. 4
DOI: 10.1177/0363546504269591

Female adolescents who participate in pivoting and jumping sports suffer ACL injuries at a 4- to 6-fold greater rate than do male adolescents participating in the same sports. Since the passage of Title IX of the Educational Assistance Act, male participation at the high school level has increased less than 3% (from 3.7 to 3.8 million), whereas female participation has increased more than 9-fold, roughly doubling every 10 years (from 0.3 to 2.8 million).[33] This geometric growth in participation has led to an alarming increase in the number of ACL injuries in female athletes. An estimated 38 000 ACL injuries occur in girls' and women's athletics in the United States annually,[41] at an estimated cost per injury of approximately $17 000.[22] At a national level, surgery and rehabilitation costs associated with female ACL injuries total approximately $646 million annually.

Most ACL injuries in female athletes occur during a noncontact episode, typically during deceleration, lateral pivoting, or landing tasks that are often associated with high external knee joint loads.[4,6] Although high knee load tasks occur during sports in both genders, why these tasks result in such a greater incidence of ACL injury in females has remained unclear. However, there appear to be 3 major etiologic contributions to the gender disparity observed in ACL injury rates, namely, anatomical, hormonal, and neuromuscular.[18] A number of studies of ACL injury risk factors have focused on anthropometric/anatomical measures, such as thigh length,[5] height, and femoral notch width.[36] Although these factors may contribute to ACL injury risk, they are in essence nonmodifiable by nature. Hormonal factors, particularly those linked to the follicular and ovulatory phases of the menstrual cycle, have also been linked to ACL injury risk.[2,37,44] However, the precise means by which they may contribute to ACL injury risk and, again, the extent to which these contributions can be modified remain unclear. There is increasing evidence in the literature suggesting that poor or abnormal neuromuscular control of the lower limb biomechanics, and in particular the knee joint during the execution of potential hazardous sporting movements, is a primary contributor to the female ACL injury mechanism.[18,21,26,30] Specifically, dynamic joint stabilization is achieved via a combination of active muscle force and passive ligament restraints. The ACL may experience potentially hazardous 3-dimensional (3D) forces during landing and twisting sports movements if the musculature that controls the knee joint does not sufficiently dissipate the associated torques and forces. Understanding the way neuromuscular control factors may manifest in terms of ACL injury is crucial, as it offers the greatest potential for interventional development and application in high–injury risk populations such as female athletes.[15]

Neuromuscular training studies have been conducted previously in an attempt to reduce ACL injury risk. A prospective study of male soccer players, for example, showed a significant effect of balance board exercises on ACL injury rates.[7] Technique and phase-oriented neuromuscular training corrected jump and landing techniques and significantly reduced abduction moments at the knee[22] and decreased ACL injuries in a female intervention group to a rate similar to that of males.[19] The incidence of ACL injury in women's handball was reduced with training designed to improve neuromuscular knee control during cutting and landing.[32] The above prospective studies demonstrate that neuromuscular training has the potential to decrease ACL injury rates in female athletes. However, the efficacy and efficiency of neuromuscular training protocols could be improved considerably if they could be designed specifically for predetermined high-risk athletes, with defined neuromuscular control deficits at appropriate age and developmental levels.

A successful method for screening and identifying athletes at increased risk of ACL injury is currently not available. Dynamic neuromuscular control parameters are rarely measured in athletes before participation, with measurements typically limited to static measures of joint stability.[38] If lower limb neuromuscular control parameters linked directly to ACL injury could be identified, more effective screening regimens could therefore be implemented to identify those athletes who are at increased risk. These data would also afford the development of more effective neuromuscular training regimens that could effectively reduce current sports-related ACL injury rates, particularly in females.

We collected lower limb biomechanical data in female athletes during the execution of sports movements and followed them prospectively to determine those who suffered noncontact ACL injury. Our hypothesis was that females who went on to ACL injury would demonstrate consistent neuromuscular control differences that manifest in their lower limb biomechanics during jump-landing tasks. We further hypothesized that these biomechanical measures could be used to predict ACL injury risk with high sensitivity and specificity.

MATERIALS AND METHODS

Subjects

This investigation was a prospective controlled cohort study. There were 205 female adolescent soccer, basketball, and volleyball players who were prospectively screened via 3D biomechanical analyses before their seasons. Nine ACL injuries (7 during soccer and 2 during basketball play) occurred in 205 screened female athletes. Ruptures of the ACL were confirmed by arthroscopic surgery (8) or MRI (1). The subjects who did not suffer an ACL knee injury were classified in this study as uninjured. The ACL-injured population was similar in age (15.8 ± 1.0 vs 16.1 ± 1.7 years; $P = .63$), height (167.7 ± 6.8 cm vs 164.1 ± 6.0 cm; $P = .08$), and weight (61.5 ± 8.3 kg vs 59.1 ± 8.1 kg; $P = .39$) to uninjured controls.

Informed written consent was obtained from all subjects and their parents and approved by the Cincinnati Children's Hospital Medical Center Institutional Review Board. After the informed consent was obtained, height, weight, and dominant leg were recorded. The dominant leg was determined for each subject by asking which leg she would use to kick a ball with as far as possible. Anthropometric measures were recorded during the laboratory evaluation.

Test Protocol

Knee joint flexion-extension and adduction-abduction were quantified for each subject over a series of drop vertical jump (DVJ) trials. The DVJ (Figure 1) consisted of the subject starting on top of a box (31 cm in height) with her feet positioned 35 cm apart (distance measured between toe markers).[12] Subjects were instructed to drop directly down off the box and immediately perform a maximum vertical jump, raising both arms as if they were jumping for a basketball rebound. The DVJ has been shown to demonstrate high within-session reliability with intraclass correlation coefficients of greater than 0.93.[11] Three successful trials were recorded for each subject, with the requirement for success being that the impact phase of the movement occurred on 2 precisely located force platforms (AMTI, Boston, Mass), within the field of view of a high-speed motion analysis system (Motion Analysis Corp, Santa Rosa, Calif). The motion analysis system consisted of 8 high-speed (240-Hz) digital cameras (Eagle cameras, Motion Analysis Corp) connected through an Ethernet hub to the data collection computer (Dell Computer Corp, Los Angeles, Calif). The 2 force platforms collected ground reaction force (GRF) data at 1200 Hz and were time synchronized with the motion analysis data. They were embedded into the floor and positioned 8 cm apart so that each foot would contact a different platform during the maneuver. The first contact on the platforms (ie, the drop from the box) was used for analysis.

Kinematic and Kinetic Analyses

Before testing, each subject was instrumented with 25 retro-reflective markers secured to specific anatomical locations (Figure 2). A stationary trial was first taken with each subject in a neutral (standing) position to align her with the global laboratory coordinate system. Each subject's local joint coordinates were aligned to her standing position to control for intersubject variation in anatomical alignment (ie, zero-position valgus alignment) during the static trial. The medial knee and ankle markers were then removed before the execution of movement trials. Raw marker coordinates were recorded with EvaRT software (version 3.21, Motion Analysis Corp) and transformed into global 3D coordinates via the direct linear transformation method[1] and subsequently tracked using EvaRT. Marker trajectories were filtered through a low-pass Butterworth digital filter at a cutoff frequency of 9 Hz and subsequently submitted to custom software (Kintrak, version 6.2, Motion Analysis Corp) to quantify knee flexion-extension and adduction-abduction demonstrated during each trial.[16] The data convention was such that knee flexion and adduction were denoted as positive (see Figure 3). Vertical GRF was used to identify the time at initial contact with the ground (IC) and at toe-off from the jump (TO). Knee flexion-extension and abduction-adduction angles at IC and the maximum abduction and flexion angles demonstrated during the stance phase (IC-TO) were subsequently recorded for each trial.

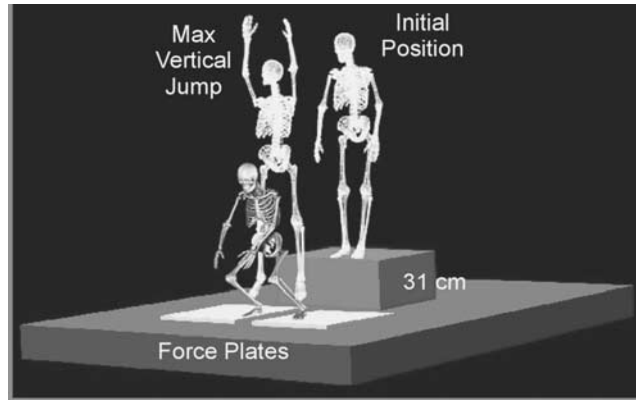

Figure 1. Biomechanical illustration of drop vertical jump procedure.

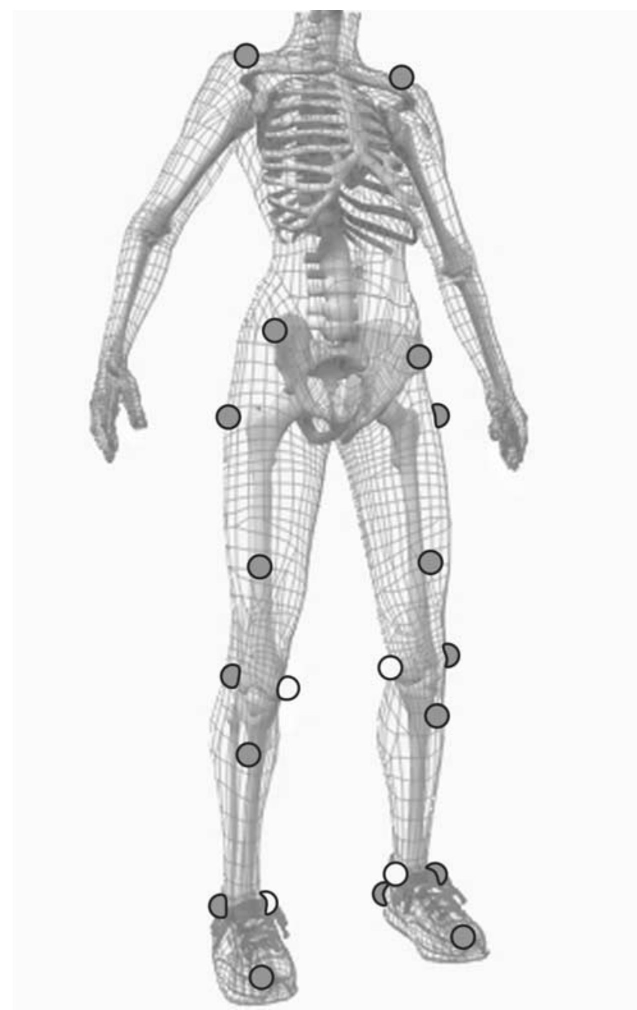

Figure 2. Marker locations and lower extremity joint-naming convention. External marker locations were used to generate lower limb 3-dimensional joint kinematic and kinetic data.

Inverse dynamics analyses were used to calculate knee and hip joint abduction-adduction and flexion-extension

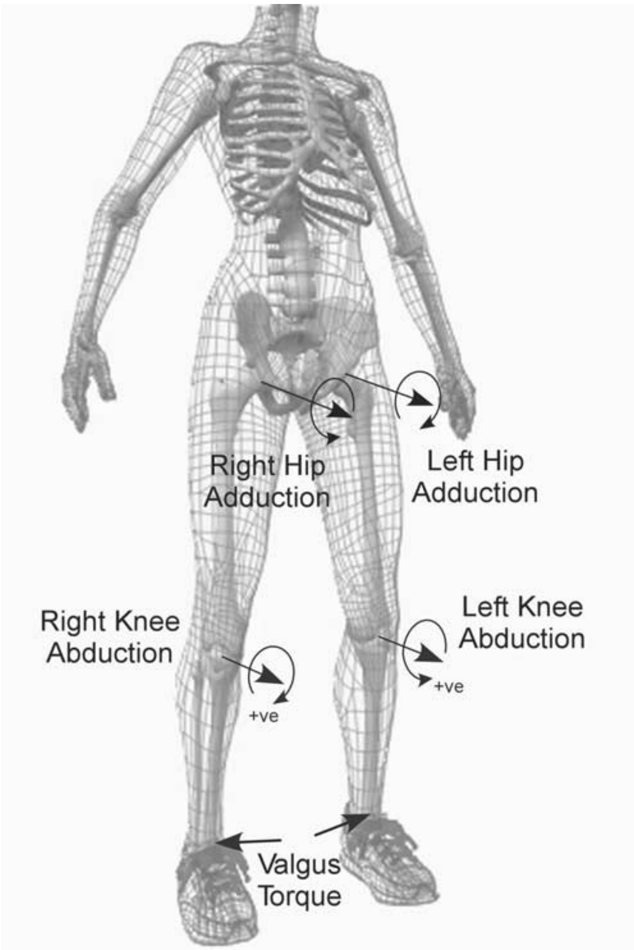

Figure 3. Lower extremity joint motion and moments naming conventions used to define lower limb 3-dimensional joint kinematic and kinetic data obtained from individual movement trials. Text refers to both joint angles and moments. The kinematic model was assigned 8 internal rotational degrees of freedom: 3 at the hip, 3 at the knee, and 2 at the ankle. Joint moments were calculated about these axes.

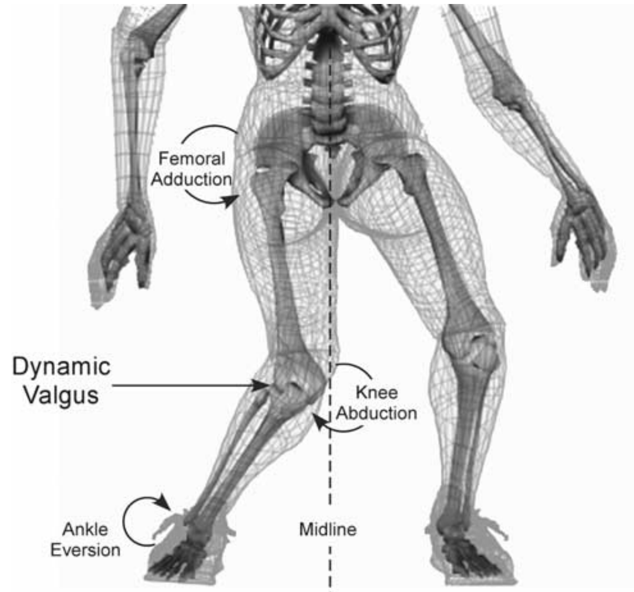

Figure 4. Dynamic valgus was defined as the position or motion, measured in 3 dimensions, of the distal femur toward and distal tibia away from the midline of the body. Dynamic valgus may have included the indicated motions and moments.

moments from the motion and force data.[43] The force data were filtered through a low-pass Butterworth digital filter at a cutoff frequency (50 Hz). By convention, hip and knee adduction and flexion moments were denoted as positive (see Figure 3). External moments are described in this article; for example, an external knee abduction load will tend to abduct the knee (direct the distal tibia away from the midline of the body), and an external knee flexion load will tend to flex the knee (Figure 4). The peak knee abduction and hip adduction moments and peak knee and hip flexion moments during the landing phase for each knee joint were recorded for each trial.[8]

Injury Surveillance

Participants were enrolled in this study during the summer of 2002 and 2003 and the fall of 2002, and they were followed through 2 fall (soccer) and 1 winter (basketball) sports seasons. Certified athletic trainers submitted weekly team and individual injury reports for each study participant during the sports season. Team reports included the number of practice and competition exposures. An injury risk exposure was defined as one athlete participating in one practice or match. Individual injury reports detailed type and mechanism of injury and participation time lost due to injury. The mean period of time between initial biomechanical testing and ACL injury was 5.0 months (range, 0.6-13.1 months). The definition of an ACL injury was an ACL rupture that occurred during a game or practice of their competitive season. Our definition of noncontact was the absence of a direct blow to the involved lower extremity. All ACL injuries reported over the 13-month injury surveillance period were noncontact in nature.

Statistical Analyses

Statistical means and SDs for all measured variables were calculated for each subject group. An analysis of variance test was used to compare values between the subject groups, and paired *t* tests were used to compare differences between limbs. The 2 groups consisted of 9 subsequent ACL-injured knees versus the total tested population of knees of uninjured females (390 knees total; 2 nondominant knees excluded due to data collection error). The comparisons between different outcome variables emanated from different hypotheses, and therefore a Dunn-Bonferroni adjustment was unnecessary. For measures of relative correlation between parameters, the Pearson correlation coefficient was calculated. Statistical analyses were conducted in SPSS (SPSS for Windows, SPSS Science

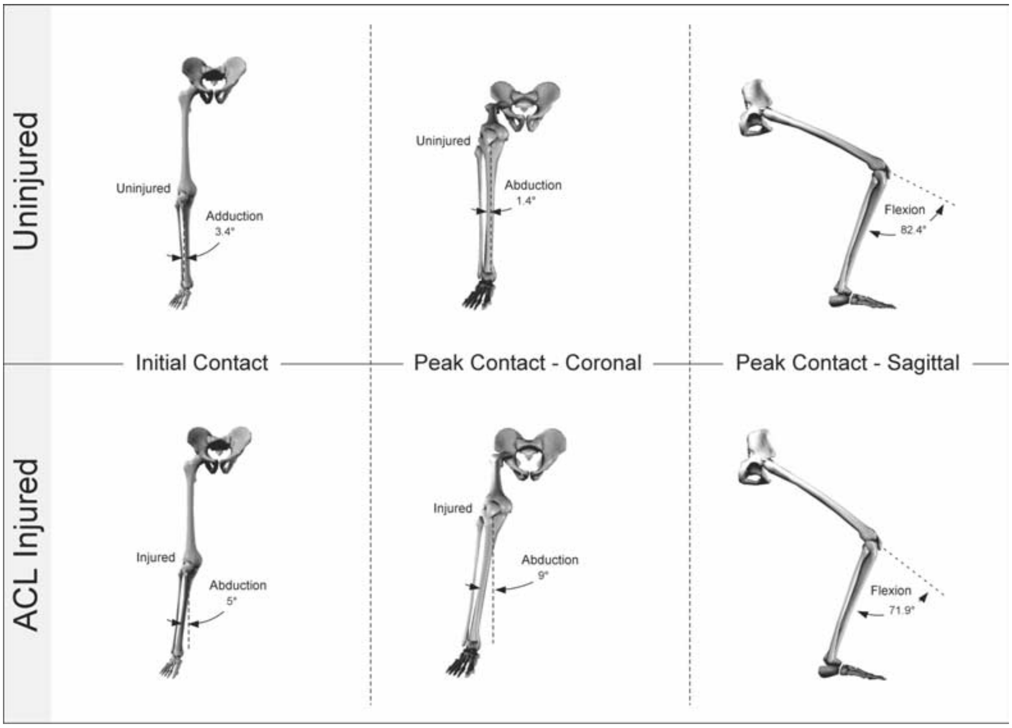

Figure 5. Biomechanical model depicting mean knee joint kinematics during the drop vertical jump at initial contact and maximal displacement in the ACL-injured and uninjured groups (n = 9 knees and n = 390 knees, respectively). Left, coronal plane view of knee abduction angle at initial contact in the ACL-injured and uninjured groups. Center, coronal plane view of maximum knee abduction angle in the ACL-injured and uninjured groups. Right, sagittal plane view of maximum knee flexion angle in the ACL-injured and uninjured groups.

Inc, Chicago, Ill) and SAS (SAS Institute, Cary, NC). The hypotheses were tested in linear regression and logistic regression models. All neuromuscular, moment, and force variables were introduced into a logistic regression model for injury. The generalized estimating equation model was estimated using a logit link, a binomial distribution for the outcomes, and a general (unstructured) covariance structure, which result in a repeated-measure logistic regression analysis for correlated binary (yes-no) outcomes. An alpha level of .05 was used to judge statistical significance in all models.

RESULTS

Knee abduction angles were significantly different between ACL-injured and uninjured groups both at initial contact and at maximum displacement. Specifically, female knees that went on to ACL injury had 8.4° greater knee abduction angles at IC, $P < .01$, and had 7.6° greater at maximum, $P < .01$ (Figure 5), than the noninjured knees of the controls had during landing. Significant correlations between knee abduction angle and peak vertical GRF were observed in ACL-injured ($R = .67$, $P < .001$) but not in uninjured athletes ($P = .44$).

No difference in knee flexion angle at IC was observed between the injured and uninjured athletes. Peak knee flexion moment ($P = .27$) values were similarly observed not to be different between groups. However, maximum knee flexion angle at landing was 10.5° less in injured (71.9° ± 12.0°) than in uninjured (82.4° ± 8.0°) athletes ($P < .05$) (Figure 5). A significant correlation between maximum knee flexion angle and peak force was present in uninjured ($R = 0.33$, $P < .001$) but not in ACL-injured athletes ($P = .55$).

Females who went on to ACL injury had a greater stance phase peak external knee abduction moment, –45.3 ± 28.5 N•m, compared to that of uninjured females, –18.4 ± 15.6 N•m ($P < .001$) (Figure 6). Vertical GRF was increased 20% in the injured cohort (1266.1 ± 149.9 N vs 1057.8 ± 289.9 N, $P < .05$) (Figure 7). Significant correlations existed between knee abduction moment and angle and peak GRF ($R = 0.74$ and 0.67, respectively; $P < .05$) in ACL-injured females. The hip adduction moment, although not greater than controls on average (Figure 6), was correlated to knee abduction moments in ACL-injured subjects ($R = 0.69$, $P < .05$). Females who went on to ACL injury had a 16% shorter stance time ($P < .01$) than did noninjured athletes. Significant correlations existed between knee abduction moment and angle and peak GRF ($R = 0.74$ and 0.67, respectively; $P < .05$) in ACL-injured females.

There was no difference between sagittal plane knee flexion-extension moments and ACL injury status. There was a correlation between knee flexion (quadriceps) moment and peak force in uninjured ($R = 0.63$, $P < .001$) but not in ACL-injured athletes ($P = .3$). Hip sagittal plane measures showed significant differences between groups. Peak external hip flexion moment was greater in the ACL-injured group (147.9 ± 33.5 N•m) in comparison to the uninjured athletes (106.8 ± 45.3 N•m; $P < .01$).

Significant leg-to-leg differences in knee load were observed in injured but not in uninjured females. Side-to-side knee abduction moment difference was 6.4 times greater in ACL-injured versus the uninjured females (Figure 8) ($P < .001$). There were 6 dominant-leg and 3 nondominant-leg injuries in the group of 9 ACL injuries.

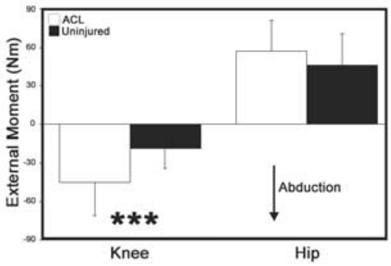

Figure 6. Mean ±1 SD knee abduction and hip adduction moment at landing. ***$P < .001$.

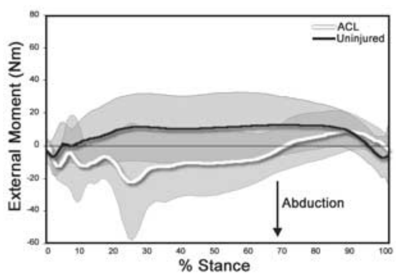

Figure 7. Vertical ground reaction force mean ±1 SD time normalized to 100% stance phase.

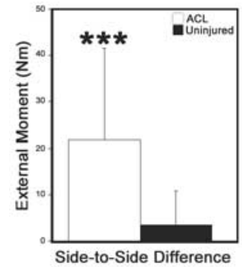

Figure 8. Dominant versus nondominant differences in measurements of components of dynamic valgus (knee abduction angle) in injured versus uninjured female athletes. ***$P < .001$.

There was not a significant effect of leg dominance on ACL injury status ($P = .5$, χ^2 test).

Logistic regression analysis demonstrated that knee abduction moments and angles (IC and peak values) were significant predictors of ACL injury status ($P < .001$). Knee abduction moments, which directly contribute to lower extremity dynamic valgus and knee joint load,[35] had a sensitivity of 78% and a specificity of 73% for predicting ACL injury status. A linear regression analysis using the most highly significant predictors (knee abduction angles, knee abduction moments, and side-to-side differences in these measures) of ACL injury showed a predictive r^2 value equal to 0.88. Knee flexion angle was removed from the model because it did not reach the 0.2 linear regression r^2 cutoff criterion to be included in the predictive model and was removed by a backward elimination technique. Scattergrams of measurements of peak knee abduction moment and knee abduction angle at IC in ACL-injured and uninjured athletes are shown in Figure 9. The data points from ACL-injured individuals are clearly in the high end of the range for both peak knee abduction moment and knee abduction angle at IC when grouped with the noninjured subjects.

DISCUSSION

Altered Neuromuscular Control in ACL-Injured Athletes

Gender differences in ACL injury rates and in neuromuscular control during potentially hazardous sporting movements are well documented in the literature.[8,12,19,30] However, the means by which neuromuscular control differences manifest in terms of injury risk to a large extent had remained unclear. This study compared 3D biomechanical measures in female athletes and compared data obtained from normal control athletes to data from those who went on to suffer ACL injury. Females suffering an ACL injury during competition demonstrated altered neuromuscular control characteristics compared to noninjured athletes, as evidenced by differences in lower limb biomechanics during jump-landing movement tasks. Specifically, injured subjects demonstrated significant increases in dynamic lower extremity valgus and knee abduction loading before sustaining their injuries compared to uninjured controls.

Dynamic Lower Extremity Valgus: Measurable Symptom and Sensitive Predictor

The link between valgus loading and resultant increases in ACL strain has been demonstrated experimentally through both cadaveric and in vivo research.[13,23,27,28] It is therefore likely that the increases observed in valgus measures in the injured cohort were a significant component of the mechanism that led to ACL rupture. Knee valgus angles and moments were the primary predictors of ACL injury risk. Valgus loading can increase ACL force.[27,28] Physiologic valgus torques on the knee can increase anterior tibial translation and loads on the ACL by several-fold.[13] Sagittal plane variables, however, specifically knee flexion and hip and knee flexion-extension moments, were not observed to be significant predictors of ACL injury potential. This observation is consistent with previous research in which multiple regression analysis incorporating flexion angles, flexion and extension moments, and valgus torque at the knee, hip, and ankle demonstrated that valgus torques at the knee were the sole significant predictors of peak landing forces.[22]

The potential link between excessive dynamic valgus and ACL injury risk has been suggested previously. It has been postulated, for example, that if an athlete is not properly aligned or if an unusual foot placement at landing occurs, he or she may be at increased risk for injury.[39] Landing in dynamic valgus (Figure 4) could be proposed as potentially injurious to the knee.[10,14] The current findings

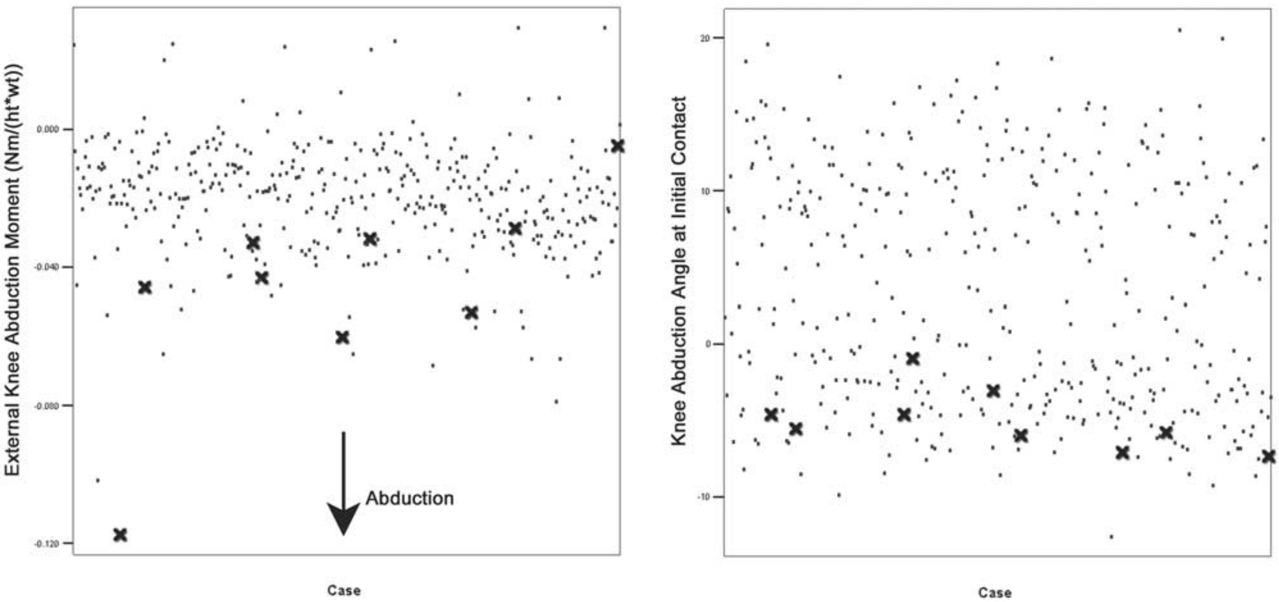

Figure 9. Scattergram of measurements of components of dynamic valgus (peak knee abduction moment and knee abduction angle at initial contact) in injured (data points shown as *X*s) versus uninjured female athletes. ht, height; wt, weight.

indicate that athletes should be encouraged to avoid excessive valgus alignment at landing, cutting, or decelerating to minimize their risk of knee injury.

Current observations also suggest that the gender-based disparity observed in ACL injury rates during sporting movements may, to a large extent, be explained by the concomitant differences displayed in the coronal plane joint motions and moments during these movements. The observed increased knee abduction motion and moments in females before ACL injury suggest decreased neuromuscular control of the lower extremity in the coronal plane. This likely reflects differences in contraction patterns or insufficient neuromuscular adaptation of the adductors of the hip and flexors of the knee to the high demands of sports.[27,40] Muscular contraction can decrease the dynamic valgus laxity of the knee 3-fold.[29] Joint compression through muscular co-contraction allows more of the knee adduction load to be absorbed by articular contact forces, which can protect the ligaments from high loads (Figure 10). It is likely that more equal distribution of forces transmitted across both the medial and lateral compartments of the knee joint would lead to decreased landing forces.[9,22] In addition, a decreased dynamic valgus moment would decrease the risk of medial femoral condylar liftoff from the tibial plateau. Biomechanical studies have previously established the relationship between femoral condylar liftoff and ACL injury risk.[29,40]

Although ACL injuries may occur too quickly for reflexive muscular activation, athletes may be able to adopt or "preprogram" safer movement patterns that reduce injury risk during landing or pivoting or unexpected loads or perturbations during sports movements. Preparticipation neuromuscular training may result in safer movement patterns that act to reduce or eliminate high knee abduction loads. Hamstrings and quadriceps can be 40% to 80% activated at the time that the foot touches the ground.[34] Coactivation of the hamstrings and quadriceps is proposed to protect the knee joint not only against excessive anterior drawer but also against knee abduction and dynamic lower extremity valgus.[3] If the hamstrings are under-recruited or weak, quadriceps activation may be reduced to provide the net flexor moment required to perform the movement. Deficits in strength and activation of the hamstrings may thus directly limit the potential for muscular co-contraction to protect ligaments. This potential absence of muscular control of the joint may lead to a "ligament-dominant" or "quadriceps-dominant" profile in the female athlete.[21] If hamstrings recruitment is high, the quadriceps can be activated more while still allowing for a net flexor moment. Similar mechanisms apply to muscular protection against torsional loading, in which gender differences have been identified.[45] Taking these facts into consideration in conjunction with the suggested link between valgus motion/loading and ACL injury, it is likely that more effective prevention strategies, aimed at improving the muscle contributions to dynamic knee stability, and in particular in the coronal plane control, can be developed with a strong potential for success.

Need for Injury-Prediction Measures in Athletes

There is a need for effective screening programs to be put into practice that would enable successful identification of athletes at risk of ACL injury.[17] The current findings demonstrate that decreased neuromuscular control as evidenced by increased dynamic valgus and external knee

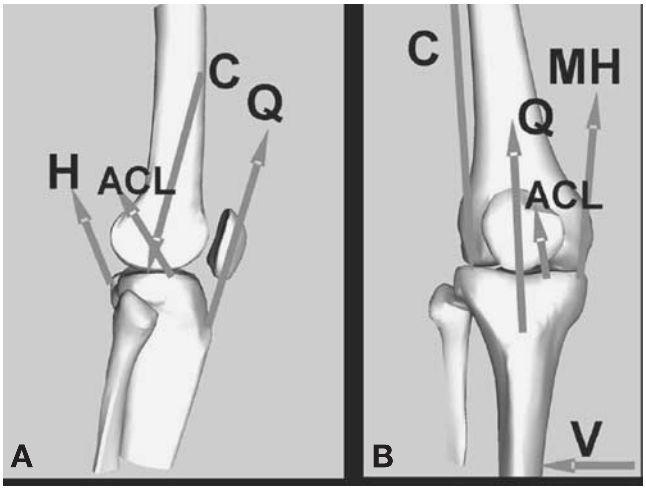

Figure 10. A, free body diagram of forces acting on the tibia, showing the sagittal plane equilibrium between articular contact force, hamstrings force, quadriceps force, and ACL force. In this example, quadriceps force contributes to ACL force, whereas hamstrings and articular contact force protect the ACL. B, free body diagram of forces acting on the tibia, showing the frontal plane equilibrium between external dynamic valgus load, articular contact force, quadriceps force, medial hamstrings force, and ACL force. Under external dynamic valgus loading, contact shifts to the lateral compartment. The moment balance with respect to the contact point shows that both quadriceps and medial hamstrings force help the ACL (and medial collateral ligament, not shown) stabilize the joint against dynamic valgus loading. Under a given dynamic valgus load, any reduction in these muscle forces will cause an increase in ligament loading. C, articular contact force; Q, quadriceps force; H, hamstrings force; MH, medial hamstrings force; V, valgus load.

abduction moments can predict increased ACL injury risk in a large percentage of individuals. The question remains, therefore, as to whether it is possible to accurately and consistently identify those individuals who display these potential causal factors. Current technologies afford the potential for lower limb kinematics and parameters linked to sporting movements to be measured with confidence.[4,12,22,31] This suggests that adequate screening strategies can be implemented using these technologies to successfully identify those individuals who are at risk of ACL injury. A potential limitation may be that 3D analysis of sporting movements comes at high financial and time costs, thus possibly limiting the potential for implementation of large-scale screening programs. Attempts should be made to correlate 3D measures of lower limb biomechanical data with more simple 2D measurements so that screening on a larger scale can be implemented. There is evidence to suggest that such correlations may be possible.[12] Research of this nature should be pursued in more detail considering the large number of athletes participating in sports in which ACL injury is prolific.

Neuromuscular Adaptations With Training: Potential for Intervention

Significant positive alterations in movement biomechanics and lower extremity muscle strength and recruitment are possible in female athletes after neuromuscular training.[22] Changes due to training are typically greater in females, as their baseline neuromuscular performance levels are often lower compared to those of males.[24] Previous studies, for example, have shown specifically that neuromuscular training can significantly decrease peak GRF and abduction motion and moments at the knee.[22] Intensive neuromuscular training can significantly increase fat-free mass, vertical jump height, and balance measures in females.[22,25,42] Muscular power has also been shown to increase up to 44% in females with 6 weeks of training. Prospective studies have demonstrated that training resulting in changes such as those mentioned above has the potential to decrease ACL injury rates in female athletes.[19,32] However, training regimens that specifically target the causal factors of ACL injury and reduce their impact via neuromuscular modifications need to be developed further. The results of the current study will enable evidence-based training protocols to be developed that aim specifically, which aim specifically to modify neuromuscular control patterns that contribute to increased valgus motion and valgus loading. If generalized training such as that discussed above can reduce injury rates, then the potential of training tailored to high-risk individuals with identified neuromuscular control deficits may prove more efficacious.

Further work also appears necessary to determine when these training programs should be implemented. Prospective randomized trials, for example, should be conducted to determine at what age or stage of development young athletes should begin to be trained.[20] This intensive neuromuscular training may induce a "neuromuscular spurt" in female adolescents that could dramatically increase neuromuscular control and decrease injury risk. This approach may decrease the number of high-risk individuals and may make subsequent training protocols more effective.

Limitations of the Study

It is likely that ACL injury has a multifactorial etiology, with unmeasured factors influencing outcome. Injury data demonstrate that many physical and psychological parameters affect injury rates. There are several possible contributing and confounding variables that were not controlled for in the study design, which included school, team, age/grade, aggressiveness, foot pronation, quadriceps angle, femoral notch width, reliable menstrual status reporting, and blood hormone levels. However, neuromuscular parameters appear to be a major determinant. Some of these potential factors may be alterable but are, at a minimum, controversial.

The use of only soccer, basketball, and volleyball players is a limitation to the generalizability of the findings of this study. However, gender differences in injury incidence have been demonstrated in several sports, including basketball, soccer, lacrosse, team handball, and volleyball. Differences in neuromuscular control measures probably exist in most gender-paired sports. Therefore, the associations between ACL injury status and neuromuscular control measures and injury in female basketball, volleyball, and soccer players should be comparable to those found in female athletes participating in other sports.

The significant effects of neuromuscular control measures on ACL injury status in female athletes were observed in this study. The observed differences were of a magnitude outside of the protocol's measurement error. However, long-term longitudinal studies testing the hypotheses of this study must be undertaken to better answer these questions. Future ACL ruptures are more likely to occur for individuals with similar kinematics and kinetic profiles to those who have already suffered an ACL event. The results of the present study may have been stronger with a longer survey period. All of those who were injured in the present study had been playing sports for multiple years. If the high-risk athletes have had excessive valgus for multiple years, this would mean that it may take years before excessive valgus results in an ACL injury. A weakness of this type of prospective study design is that there can be a substantial change in neuromuscular status (ie, excessive valgus) over the course of a long (multiyear) injury-tracking period. We are currently conducting studies to assess the effects of time, growth, and maturation on these neuromuscular indices.

Conclusion: Measures of Neuromuscular Control and Joint Load Predict Injury Risk in Athletes

Previously, it was known that ACL injury risk was greater in female than in male athletes. What was not known was the mechanism underlying this gender disparity, and there was no method that could identify those female athletes at increased ACL injury risk. In the current study, measures of neuromuscular control and knee joint load were prospectively examined relative to ACL injury status. These measurements were employed to help delineate whether lower limb neuromuscular control parameters could be used to predict ACL injury risk in female athletes. Specifically, it appears that increased valgus motion and valgus moments at the knee joint during the impact phase of jump-landing tasks are key predictors of an increased potential for ACL injury in females. Current technologies enable these data to be readily measured noninvasively in a large number of athletes, within a relatively short time period. Hence, such measurements appear necessary in future screening and prevention studies aimed at reducing ACL injury rates, particularly in females. Future research needs to focus on controlled, prospective longitudinal studies of defined populations of female athletes who are followed through multiple sports seasons to correlate changing neuromuscular profiles to injury risk, which predispose the athlete to ACL injury. Studies that test improved neuromuscular training approaches are also of the highest priority.

ACKNOWLEDGMENT

We acknowledge funding support from the National Institutes of Health Grant R101-ARO49735-01A1. We also acknowledge Ralph Buncher, PhD, for his assistance with the experimental design and for helping to perform the statistical analysis of the data, and Robert Mangine of Novacare Rehabilitation, Brian Colley of Wellington Orthopaedic and Sports Medicine Center, and Spectrum Rehabilitation for assisting in the recruitment of schools and athletes for participation in the studies. We thank Richelle Carlonas of Wellington Orthopaedic and Sports Medicine Center for her assistance with editing of the manuscript. In addition, we thank the school districts, the athletes, and the administrators involved in the study, especially Stu Eversole of the Lakota School District; the athletic trainers who participated in the study and who tracked injuries, including Pate Cagle, ATC, Jennifer Miller, ATC, Lisa Sweeterman, ATC, Cathy Conley, ATC, among others; and the coaches who were so pivotal in making this study a success, including Dan Purcell, Tara Schafer-Kalkhoff, Tracey Kornau, Kate Berz, and Heather Herweh.

REFERENCES

1. Abdel-Aziz YI, Karara HM. Direct linear transformation from comparator coordinates into object space coordinates in close-range photogrammetry. In: *Symposium on Close-Range Photogrammetry*. Falls Church, Va: American Society of Photogrammetry; 1971:1-18.
2. Arendt EA, Bershadsky B, Agel J. Periodicity of noncontact anterior cruciate ligament injuries during the menstrual cycle. *J Gend Specif Med*. 2002;5:19-26.
3. Besier TF, Lloyd DG, Ackland TR. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc*. 2003;35:119-127.
4. Besier TF, Lloyd DG, Cochrane JL, Ackland TR. External loading of the knee joint during running and cutting maneuvers. *Med Sci Sports Exerc*. 2001;33:1168-1175.
5. Beynnon B, Slauterbeck J, Padua D, et al. Update on ACL risk factors and prevention strategies in the female athlete. Paper presented at: National Athletic Trainers' Association 52nd Annual Meeting and Clinical Symposia; 2001; Los Angeles, Calif.
6. Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23:573-578.
7. Caraffa A, Cerulli G, Projetti M, Aisa G, Rizzo A. Prevention of anterior cruciate ligament injuries in soccer: a prospective controlled study of proprioceptive training. *Knee Surg Sports Traumatol Arthrosc.* 1996;4:19-21.
8. Chappell JD, Yu B, Kirkendall DT, Garrett WE. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *Am J Sports Med*. 2002;30:261-267.
9. Crenshaw SJ, Pollo FE, Calton EF. Effects of lateral-wedged insoles on kinetics at the knee. *Clin Orthop*. 2000;375:185-192.
10. Dufek JS, Bates BT. Biomechanical factors associated with injury during landing in jumping sports. *Sports Med.* 1991;12:326-337.
11. Ford KR, Myer GD, Hewett TE. Reliability of dynamic knee motion in female athletes. Paper presented at: American Society of Biomechanics Annual Meeting; September 25-27, 2003; Toledo, Ohio.
12. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc*. 2003;35:1745-1750.
13. Fukuda Y, Woo SL, Loh JC, et al. A quantitative analysis of valgus torque on the ACL: a human cadaveric study. *J Orthop Res*. 2003;21:1107-1112.

14. Gerberich SG, Luhmann S, Finke C, et al. Analysis of severe injuries associated with volleyball activities. *Phys Sportsmed*. 1987;15:75-79.
15. Griffin LY, American Academy of Orthopaedic Surgeons. *Prevention of Noncontact ACL Injuries*. Rosemont, Ill: American Academy of Orthopaedic Surgeons; 2001.
16. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng*. 1983;105:136-144.
17. Harmon KG, Dick R. The relationship of skill level to anterior cruciate ligament injury. *Clin J Sport Med*. 1998;8:260-265.
18. Hewett TE. Neuromuscular and hormonal factors associated with knee injuries in female athletes: strategies for intervention. *Sports Med.* 2000;29:313-327.
19. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes: a prospective study. *Am J Sports Med*. 1999;27:699-706.
20. Hewett TE, Myer GD, Ford KR. Puberty decreases dynamic knee stability in female athletes: a potential mechanism for increased ACL injury risk. *J Bone Joint Surg Am*. 2004;86A:1601-1608.
21. Hewett TE, Paterno MV, Myer GD. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clin Orthop*. 2002;402:76-94.
22. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes: decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996;24:765-773.
23. Kanamori A, Woo SL, Ma CB, et al. The forces in the anterior cruciate ligament and knee kinematics during a simulated pivot shift test: a human cadaveric study using robotic technology. *Arthroscopy*. 2000;16:633-639.
24. Kraemer WJ, Keuning M, Ratamess NA, et al. Resistance training combined with bench-step aerobics enhances women's health profile. *Med Sci Sports Exerc.* 2001;33:259-269.
25. Kraemer WJ, Mazzetti SA, Nindl BC, et al. Effect of resistance training on women's strength/power and occupational performances. *Med Sci Sports Exerc*. 2001;33:1011-1025.
26. Lloyd DG. Rationale for training programs to reduce anterior cruciate ligament injuries in Australian football. *J Orthop Sports Phys Ther*. 2001;31:645-654; discussion 661.
27. Lloyd DG, Buchanan TS. Strategies of muscular support of varus and valgus isometric loads at the human knee. *J Biomech*. 2001;34:1257-1267.
28. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res*. 1995;13:930-935.
29. Markolf KL, Graff-Redford A, Amstutz HC. In vivo knee stability: a quantitative assessment using an instrumented clinical testing apparatus. *J Bone Joint Surg Am*. 1978;60:664-674.
30. McLean SG, Lipfert S, van den Bogert AJ. Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Med Sci Sports Exerc*. 2004;36:1008-1016.
31. McLean SG, Neal RJ, Myers PT, Walters MR. Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. *Med Sci Sports Exerc*. 1999;31:959-968.
32. Myklebust G, Engebretsen L, Braekken IH, Skjolberg A, Olsen OE, Bahr R. Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. *Clin J Sport Med*. 2003;13:71-78.
33. National Federation of State High School Associations. *2002 High School Participation Survey*. Indianapolis, Ind: National Federation of State High School Associations; 2002.
34. Neptune RR, Wright IC, van den Bogert AJ. Muscle coordination and function during cutting movements. *Med Sci Sports Exerc*. 1999;31:294-302.
35. Schipplein OD, Andriacchi TP. Interaction between active and passive knee stabilizers during level walking. *J Orthop Res*. 1991;9:113-119.
36. Scoville CR, Williams GN, Uhorchak JM, et al. Risk factors associated with anterior cruciate ligament injury. In: *Proceedings of the 68th Annual Meeting of the American Academy of Orthopaedic Surgeons*. Rosemont, Ill: American Academy of Orthopaedic Surgeons; 2001:564.
37. Slauterbeck JR, Hardy DM. Sex hormones and knee ligament injuries in female athletes. *Am J Med Sci*. 2001;322:196-199.
38. Smith J, Laskowski E. The preparticipation physical examination: Mayo Clinic experience with 2,739 examinations. *Mayo Clin Proc.* 1998;73:419-429.
39. Steele J, Milburn P. Ground reaction forces on landing in netball. *J Hum Mov Stud.* 1987;13:399-410.
40. Tibone JE, Antich TJ, Fanton GS, Moynes DR, Perry J. Functional analysis of anterior cruciate ligament instability. *Am J Sports Med.* 1986;14:276-284.
41. Toth AP, Cordasco FA. Anterior cruciate ligament injuries in the female athlete. *J Gend Specif Med*. 2001;4:25-34.
42. Tropp H, Odenrick P. Postural control in single-limb stance. *J Orthop Res*. 1988;6:833-839.
43. Winter DA. *Biomechanics and Motor Control of Human Movement*. New York, NY: John Wiley; 1990.
44. Wojtys EM, Ashton-Miller JA, Huston LJ. A gender-related difference in the contribution of the knee musculature to sagittal-plane shear stiffness in subjects with similar knee laxity. *J Bone Joint Surg Am*. 2002;84:10-16.
45. Wojtys EM, Huston LJ, Schock HJ, Boylan JP, Ashton-Miller JA. Gender differences in muscular protection of the knee in torsion in size-matched athletes. *J Bone Joint Surg Am*. 2003;85:782-789.