Published in final edited form as:

Am J Sports Med. 2009 September ; 37(9): 1821–1830. doi:10.1177/0363546509334225.

Effects of Transverse and Frontal Plane Knee Laxity on Hip and Knee Neuromechanics During Drop Landings

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Abstract

Background—Varus-valgus (LAX_{VV}) and internal-external (LAX_{IER}) rotational knee laxity have received attention as potential contributing factors in anterior cruciate ligament injury. This study compared persons with above- and below-average LAX_{VV} and LAX_{IER} values on hip and knee neuromechanics during drop jump landings.

Hypothesis—People with greater LAX_{VV} and LAX_{IER} values will have greater challenges controlling frontal and transverse plane knee motions, as evidenced by greater joint excursions, joint moments, and muscle activation levels during the landing phase.

Study Design—Descriptive laboratory study.

Methods—Recreationally active participants (52 women and 44 men) between 18 and 30 years old were measured for LAX_{VV} and LAX_{IER} and for their muscle activation and transverse and frontal plane hip and knee kinetics and kinematics during the initial landing phase of a drop jump. The mean value was obtained for each sex, and those with above-average values on LAX_{VV} and LAX_{IER} (LAX_{HIGH} = 17 women, 16 men) were compared with those with below-average values (LAX_{LOW} = 18 women, 17 men).

Results—Women with LAX_{HIGH} versus LAX_{LOW} were initially positioned in greater hip adduction and knee valgus and also produced more prolonged internal hip adduction and knee varus moments as they moved toward greater hip adduction and internal rotation as the landing progressed. These patterns in LAX_{HIGH} women were accompanied by greater prelanding and postlanding muscle activation amplitudes. Men with LAX_{HIGH} versus LAX_{LOW} also demonstrated greater hip adduction motion and produced greater internal hip internal rotation and knee varus and internal rotation moments.

Conclusion—Participants with greater LAX_{VV} and LAX_{IER} landed with greater hip and knee transverse and frontal plane hip and knee motions.

Clinical Relevance—People (especially, women) with increased frontal and transverse plane knee laxity demonstrate motions associated with noncontact anterior cruciate ligament injury mechanisms.

Keywords

anterior cruciate ligament injury; injury mechanism; joint laxity; landing mechanics

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No potential conflict of interest declared.

Noncontact anterior cruciate ligament (ACL) injury mechanisms are consistently reported as rapid deceleration, plant and cut maneuvers, and 1-foot stopping/landing.[2,11] The position of no return has often been implicated in the ACL injury mechanism and has been described as having components of tibial external rotation and knee valgus.[11] Systematic video observation of team handball players sustaining an ACL injury supports this position of no return, revealing a mechanism of forceful valgus collapse (5° to 20°) with the knee in 5° to 25° of flexion, combined with 5° to 15° of external or internal rotation of the tibia.[23] Moreover, women tend to demonstrate these at-risk frontal and transverse plane knee motions[3,7,17,18,20] and moments[20,21,34,36] more often than men do during landing and cutting maneuvers, which are thought to contribute to their greater risk of suffering ACL trauma. However, factors underlying excessive transverse and frontal plane knee motions and moments are still unknown. Given that the knee is frequently exposed to considerable frontal and transverse plane torques during sport activity, understanding the factors that contribute to excessive transverse and frontal plane motion may be critical to maximizing our prevention strategies.

The potential consequences of varus-valgus (LAX_{VV}) and internal-external (LAX_{IER}) rotational knee laxity on functional knee joint neuromechanics and ACL injury risk have been recently noted. Compared with men, women are reported to have approximately 25% to 30% greater LAX_{VV} and LAX_{IER}, whether[19,32] or not[10,28] sex differences in anterior knee laxity are also observed. This greater LAX_{VV} and LAX_{IER} is also associated with decreased torsional stiffness in women, compared with men.[10,24,27] On the basis of these findings and reports of ACL injury being associated with a combination of valgus and internal-external motions about the knee,[23] greater LAX_{VV} and LAX_{IER} may affect the orientation of the tibiofemoral joint and so place greater challenges on the neuromuscular system to stabilize the joint during weightbearing.[10,24,27,32] To date, we are not aware of any study that has examined the consequence of greater LAX_{VV} and LAX_{IER} on weight-bearing knee joint neuromechanics. We therefore compared participants who were above and below average on both LAX_{VV} and LAX_{IER} on their muscle activation and transverse and frontal plane hip and knee biomechanics during the initial phase of a drop jump landing. Our expectation was that individuals with greater LAX_{VV} and LAX_{IER} would have greater challenges controlling frontal and transverse plane knee motions, as evidenced by greater joint excursions, joint moments, and muscle activation levels during the landing phase. Given that men and women are already known to differ on joint laxity and knee joint neuromechanics, we examined the effects of laxity in men and women separately to control for other sex-dependent confounding variables.

MATERIALS AND METHODS

Ninety-six people participated: 52 women aged 22 ± 3 years (163 ± 6 cm tall, 60 ± 8 kg) and 44 men aged 22 ± 3 years (178 ± 10 cm tall, 81 ± 14 kg). Participants were recreationally active (2.5–10.0 hours per week) and did not smoke. They had no history of knee injury involving the osteochondral surface, ligament, tendon, capsule, or menisci; no history of vestibular or balance disorders; and no medical conditions affecting the connective tissue. Participants were recruited from the university and surrounding community as part of a larger ongoing project examining the effect of sex hormone–mediated knee laxity changes on weightbearing knee joint neuromechanics. Other inclusion criteria for the larger project were a body mass index ≤ 30, an ability to abstain from alcohol for 24 hours before any testing, and no history of vestibular or balance disorders. Additional criteria for female participants included self-reported normal menstrual cycles lasting 26 to 32 days for the past 6 months, consistent cycle lengths that varied no more than 1 day from month to month for the past 6 months, no use of oral contraceptives or other hormone-stimulating medications for the past 6 months, and no history of pregnancy or planning to become pregnant during the course of the study. All participants who were enrolled in the larger study were initially included in the current study.

Data were obtained during a single test session where participants were measured on their dominant stance limb (ie, stance leg when kicking a ball) for anterior knee laxity, LAX_{VV} and LAX_{IER}, and hip and knee neuromechanics during the initial landing phase of a drop jump. Participants were familiarized to all testing procedures approximately 2 weeks before the actual testing. Female participants were tested during the first 6 days of their menstrual cycle (based on self-report of the first day of menstrual bleeding) to control for cyclic hormone effects on baseline laxity values. Before participation, participants were informed of all study procedures and then signed a consent form approved by the institutional review board. Specific procedures for obtaining each measure follow.

Anterior knee laxity was measured with a KT-2000 knee arthrometer (Medmetric Corp, San Diego, California) with the participant supine and the knee flexed 25° ± 5° over a thigh bolster.[30] Anterior knee laxity was measured (in millimeters) as the anterior displacement of the tibia relative to the femur when a 133-N anterior-directed load was applied to the posterior tibia. The same researcher who had established excellent test-retest reliability, intraclass correlation $coefficient_{2,k}$ (standard error of the mean) = 0.96 (0.3 mm), measured all participants. The average of 3 measures represented the participant's anterior knee laxity value.

Participants were measured for LAX_{VV} and LAX_{IER} using the Vermont Knee Laxity Device (University of Vermont, Burlington, Vermont).[33] Detailed methods for these procedures have been reported and have been shown to yield consistent measures over repeated tests with acceptable measurement error: intraclass correlation $coefficient_{2,k}$ (standard error of the mean) = 0.91 (0.87°) for LAX_{VV}, 0.89 (2.80°) for LAX_{IER}.[33] In brief, the participant was positioned supine in the Vermont Knee Laxity Device, with the knee flexed to 20°, the thigh securely fixed, the foot and ankle tightly restrained in the foot cradle, and with counterweights applied to the thigh and shank to create an initial zero shear and compressive load across the tibiofemoral joint. LAX_{VV} was assessed when valgus and varus torques of 10 N·m were created about the knee through the application of known forces applied to the medial and lateral aspect of the distal tibia at a known distance from the knee with a handheld force transducer (model SM-50, Interface, Scottsdale, Arizona). LAX_{IER} was assessed when internal and external rotation torques of 5 N·m were applied about the long axis of the tibia using a T-handle connected to a 6-degree-of-freedom force transducer (model MC3A, Advanced Medical Technology Inc, Watertown, Massachusetts) affixed to the foot cradle. Joint displacements were collected (100 Hz) using Minibird Electromagnetic hardware (Ascension Technology Corporation, Burlington, Vermont) and MotionMonitor software (Innovative Sports Training, Chicago, Illinois). The average of 3 trials represented the participant's laxity value.

In preparation for surface electromyography (sEMG) measurements during the drop jump landing, the skin was shaved and cleaned with isopropyl alcohol, and 10-mm bipolar Ag-AgCl surface electrodes (Blue Sensor N-00-S, Ambu Products, Ølstykke, Denmark) were positioned midway between the motor point and the distal tendon of the lateral and medial quadriceps, hamstrings, and gastrocnemius muscles, oriented perpendicular to the length of the muscle fibers with a center-to-center distance of 20 mm. Absence of cross talk was visually confirmed during manual muscle testing. To normalize the sEMG signal, participants completed 3 maximal voluntary isometric contractions (MVICs) on a Biodex System 3 Dynamometer (Biodex Medical Systems Inc, Shirley, New York) at 25° of knee flexion and 90° of ankle flexion while sEMG signals were obtained using a 16-channel Myopac telemetric system (Run Technologies, Mission Viejo, California) with an amplification of 1 mV/V, a frequency bandwidth of 10 to 1000 Hz, a common mode rejection ratio of 90 dB minimum at 60 Hz, an input resistance of 1 MΩ, and an internal sampling rate of 8 kHz. All sEMG data were acquired, stored, and analyzed using DataPac 2K2 lab application software (version 3.13, Run Technologies, Mission Viejo, California). Torque data obtained during the MVIC knee extension and knee flexion contractions were also recorded and normalized to the participant's body weight to confirm that LAX groups within each sex were similar in their strength values; that is, previous work has shown a negative association between thigh strength and activation.[29]

All biomechanical data were collected and processed using MotionMonitor software. With sEMG electrodes still attached, position sensors (Motion Star, Ascension Technologies, Burlington, Vermont) were attached to the sacrum, the C7 spinous process, the anterior midshaft of the third metatarsal, the midshaft of the medial tibia, and the lateral aspect of the midshaft of the femur of the dominant limb using previously described methods.[29] Joint centers were determined as the midpoint between the medial and lateral malleoli for the ankle, as the midpoint between the medial and lateral joint line for the knee, and by the Leardini method for the hip.[16] Once instrumented, the participants performed 5 barefoot drop jump landings from a 0.45-m wooden platform placed 0.1 m behind the rear edge of the force plate (type 4060, Bertec Corp, Columbus, Ohio). Participants began with toes aligned along the leading edge of the wooden platform and with hands placed at the level of the ears. They were instructed to drop off the platform and perform a maximal vertical jump upon landing, keeping their hands at ear level to eliminate variability attributed to arm swing. To prevent experimenter bias, no other specific instructions were provided with regard to landing mechanics. Along with the familiarization session, practice repetitions (typically, 3) were allowed before test trials to ensure that the participant remained comfortable with the task. Kinematic (100 Hz) and sEMG and kinetic (1000 Hz) data were simultaneously collected during 5 successful drop jump trials and synchronized by the software using a foot contact threshold of 10 N to trigger data collection. A trial was discarded and repeated if the participants lost their balance, did not land bilaterally, let their hands drop below ear level, or failed to land back onto the force plate after the maximal vertical jump.

Data Reduction and Analyses

Kinematic signals were linearly interpolated to force plate data and low-pass filtered at 12 Hz using a fourth-order, zero-lag Butterworth filter. The segmental reference system for all body segments was defined as the positive Z-axis for the medial to lateral axis, the positive Y-axis for the distal to proximal longitudinal axis, and the positive X-axis for the posterior to anterior axis. Knee motions were calculated using Euler angle definitions with a rotational sequence of Z Y′ X″.[13] Kinetic data were low-pass filtered at 60 Hz using a fourth-order, zero-lag Butterworth filter. Intersegmental data were calculated via inverse dynamics[9] and normalized to each participant's height and weight: $N \cdot m \times \text{body weight}^{-1} \times \text{height}^{-1}$. Kinematic and kinetic data for the initial landing phase (initial contact to peak knee flexion angle) were then normalized to 101 points and averaged across the 5 drop jump trials. Signals (sEMG) of the lateral and medial quadriceps, hamstrings, and gastrocnemius were band-pass filtered from 10 Hz to 350 Hz, using a fourth-order, zero-lag Butterworth filter,[15] then processed using a centered root mean square algorithm for the MVIC trials (100-millisecond time constant) and drop jump trials (25-millisecond time constant). After the 5 landing trials were ensemble averaged, the peak root mean square amplitude obtained from each muscle during the 150 milliseconds immediate before (pre-activation) and after (postactivation) initial ground contact were then normalized using the average of the peak sEMG amplitudes obtained over 3 MVIC trials (% MVIC).

Within each sex, mean LAX_{VV} and LAX_{IER} were calculated, based on the total range of motion observed during the varus-valgus and internal-external torque loadings, respectively. Participants were then classified as having above- or below-average values on each measure and so were included in the analyses if they were classified with above-average values on both LAX_{VV} and LAX_{IER} (LAX_{HIGH}) or below-average values on both LAX_{VV} and LAX_{IER} (LAX_{LOW}). Participants were excluded if they were above average on 1 laxity value but below average on the other; that is, our goal was to have a clear separation of those with a high envelope of knee laxity and those with a low envelop of knee laxity. Our rationale for combining the 2 measures to determine laxity status is that knee joint biomechanics represent coupled knee motions and rarely do these motions occur in isolation during sport activity.

On the basis of these criteria, 17 women were identified as LAX_{HIGH} (LAX_{VV} > 13.0°, LAX_{IER} > 25.5°) and 18 as LAX_{LOW} (LAX_{VV} ≤ 13.0°, LAX_{IER} ≤ 25.5°), and 16 men were identified as LAX_{HIGH} (LAX_{VV} > 8.3°, LAX_{IER} > 19.3°) and 17 as LAX_{LOW} (LAX_{VV} ≤ 8.3°, LAX_{IER} ≤ 19.3°) using the mean values for each sex as the cut point. With a conservative sample size of 32 (16 per group), an alpha level of $P = .05$, and a correlation among repeated measures of $r = .5$, we had 80% power to detect a moderate effect size (f >.36) for overall group main effects and a small effect size (f >.09) for group × time interactions.[4,6] Given that our main interest was to identify meaningful differences in joint motion and moment patterns over the landing phase (group × time), this sample size and associated statistical power were considered acceptable.

To analyze the data, simple t tests compared groups on LAX_{VV}, LAX_{IER}, anterior knee laxity, body mass index, and maximal voluntary isometric strength of the thigh muscles. Separate group × time (LAX_{LOW}, LAX_{HIGH} × percentage landing phase increments) repeated measures analysis of variance compared LAX groups on hip abduction/adduction (HIP_{AA}), hip internal/external rotation (HIP_{IER}), knee varus/valgus ($KNEE_{VV}$), and knee internal/external rotation ($KNEE_{IER}$) motions and internal moments across the entire landing phase for each sex. Alpha level was set for each analysis at $P < .05$. Trend analyses (polynomial contrasts), along with graphical presentation of the data, were used to explore significant group × percentage-increment interactions. Trend analysis determines the most reasonable description of how groups differ in the pattern in the data across time (whether linear or nonlinear).[25] This process was followed by selected pairwise comparisons with Bonferroni corrections to compare the magnitudes of the greatest observed mean differences where trends in the data diverged. To examine group differences in muscle activation, separate group × muscle × side (LAX_{LOW}, LAX_{HIGH} × quadriceps, hamstring, gastrocnemius × lateral, medial) repeated measures analysis of variance compared LAX groups on prelanding and postlanding activation amplitude within each sex. For significant interactions, post hoc comparisons consisted of repeated contrasts within groups using Bonferroni corrections. All analyses were performed with SPSS 15.0.01 for Windows (SPSS Inc, Chicago, Illinois).

RESULTS

Table 1 compares laxity profiles and body size and strength demographics for each group and sex. On average, compared with the men, the women had 4.3° and 6.1° greater LAX_{VV} and LAX_{IER} values ($P < .05$) but similar anterior knee laxity values (6.6 vs 6.8 mm; $P = .627$). Although LAX_{LOW} and LAX_{HIGH} groups within each sex were significantly different in their laxity profiles, they were similar in their body mass index and thigh strength.

Hip and Knee Joint Kinematic Curves

Appendix 1 (available in the online version of this article at http://ajs.sagepub.com/supplemental/) presents kinematic curves for each variable and sex, and Table 2 presents analysis of variance summary results. In comparison of LAX_{LOW} and LAX_{HIGH} women, group differences were observed for HIP_{AA}, and group differences across time were observed for HIP_{AA}, HIP_{IER}, and $KNEE_{VV}$ (Figure 1). No group ($P = .633$) or group × time effects ($P = .674$) were noted for $KNEE_{IER}$.

For HIP_{AA}, LAX_{LOW} women averaged 4.7° of hip abduction, whereas LAX_{HIGH} women averaged −1.6° of adduction across the entire landing phase. The trend analysis revealed that groups differed in the 2 directional changes (cubic pattern) noted in the data (*P* = .030). This can be seen in Figure 1A beginning near 30% of the landing phase, where LAX_{LOW} women maintained their hip in 4.0° to 4.5° of abduction and where LAX_{HIGH} women moved into 2.0° greater hip adduction. This resulted in a significant increase in hip adduction across the entire landing phase for LAX_{HIGH} women (4.3°) but not for LAX_{LOW} women (2.2°; $P < .025$).

Similar group differences in the cubic pattern of the data were observed for HIP_{IER} motions ($P = .011$) and $KNEE_{VV}$ motions ($P = .010$) (Figures 1B and 1C). In both cases, 2 clear directional changes are noted in LAX_{HIGH} women near 25% and 60% of the landing phase. Early in the landing (from 0% to 27%), the hips of LAX_{HIGH} women internally rotated 3.0° (1.8° to −1.2°; $P < .017$), whereas the hips of LAX_{LOW} women remained externally rotated (2.6° to 3.2°; $P > .017$). However, in an examination of the largest magnitude of difference between groups in this early part of the landing, this difference was not significant (3.0°; $P > .017$). For $KNEE_{VV}$ motion, women with LAX_{HIGH} knees initially landed in 3.8° more valgus (3.1° vs −0.7°), which then decreased as women with LAX_{LOW} knees moved toward valgus earlier than those with LAX_{HIGH} knees. By midlanding, the curves once again diverged, with greater knee valgus angles observed in LAX_{HIGH} versus LAX_{LOW} knees. In a comparison of the peak differences at initial contact (3.8°) and midlanding (2.4°), only the difference at initial contact was significantly different between groups ($P < .025$).

In an evaluation of hip and knee motion in men, LAX_{LOW} men remained in 5.3° more relative hip abduction throughout the landing phase (4.4° vs −0.9°; $P = .029$). No other group or group × time differences were noted for HIP_{AA}, HIP_{IER}, $KNEE_{VV}$, or $KNEE_{IER}$ joint angles between LAX_{LOW} and LAX_{HIGH} men (all $P \geq .642$).

Hip and Knee Joint Moment Curves

Appendix 2 (available in the online version of this article at http://ajs.sagepub.com/supplemental/) presents hip and knee joint moment curves for each variable and sex, and, as mentioned, Table 2 presents analysis of variance summary results.

When comparing LAX_{LOW} and LAX_{HIGH} women, significant group × percentage landing phase interactions were noted for HIP_{AA} moments ($P < .001$) and $KNEE_{VV}$ moments ($P = .025$) (Figure 2) but not for HIP_{IER} or $KNEE_{IER}$ moments ($P > .289$). For HIP_{AA}, the trend analysis revealed that groups differed in the quadratic pattern (a single directional change) of the moment curve ($P = .010$). This can be seen during 20% to 55% of the landing phase (Figure 2A), where greater hip adduction moments were observed for a longer period in LAX_{HIGH} women compared with LAX_{LOW} women. The greatest group mean difference was observed at the 34th increment. A single pairwise comparison at this select time point revealed that LAX_{HIGH} women had a 0.033 N·m × body weight^{-1} × height^{-1} (175%) greater hip adduction moment than did LAX_{LOW} women ($P = .008$).

Although the curve patterns for $KNEE_{VV}$ were graphically similar to those of HIP_{AA} (Figure 2B), the trend analysis failed to identify a clear group difference in the pattern at lower-order polynomials. This is likely due to little crossing of the curve patterns for $KNEE_{VV}$; that is, varus moments in LAX_{HIGH} women were slightly higher than they were in LAX_{LOW} women through much of the landing phase. The greatest group mean difference in varus moments was again observed at the 34th increment. A single pairwise comparison at this time point revealed that LAX_{HIGH} women had a 0.023 N·m × body weight^{-1} × height^{-1} (138%) greater internal knee varus moment than LAX_{LOW} women had. However, this difference did not reach a level of significance ($P = .074$).

In a comparison of LAX_{LOW} and LAX_{HIGH} men, significant group differences across the landing phase were observed for HIP_{AA}, $KNEE_{VV}$, and $KNEE_{IER}$ moments (all $P < .001$) but not for HIP_{IER} (P = .239). Trend analyses revealed that the group differences were best described by a quadratic pattern (2 directional changes) in the moment curve for HIP_{AA} (P = .06) and $KNEE_{VV}$ (P = .005) (Figures 3A and 3B). As with women, differences in these curve patterns between LAX_{LOW} and LAX_{HIGH} groups were similar for both HIP_{AA} and $KNEE_{VV}$. Graphic representation of the data reveals that groups began to diverge near 30% of the landing phase; that is, LAX_{HIGH} men maintained greater internal hip adduction and knee varus moments for a longer period than LAX_{LOW} men did. The greatest group mean difference was observed at the 53rd increment for both hip adduction, LAX_{HIGH} 0.034 (212%) > LAX_{LOW} (P = .119), and knee varus, LAX_{HIGH} 0.022 (146%) > LAX_{LOW} (P = .124), but these pairwise comparisons were not significantly different.

For $KNEE_{IER}$ (Figure 3C), group differences were best described by a linear pattern in the curve (P = .06). This can be seen graphically as a greater increase in internal knee rotation moments in LAX_{HIGH} men compared with LAX_{LOW} men from 35% to 99% of the landing (0.017 vs 0.006 N·m × body weight^{-1} × height^{-1}; P = .025). However, this difference in the pattern of knee rotation moments did not result in a significant group difference when evaluated at its largest magnitude (0.008 N·m × body weight^{-1} × height^{-1}; P = .280).

Prelanding and Postlanding Muscle Activation Amplitudes

Figure 4 presents prelanding and postlanding muscle activation amplitudes for each sex. During prelanding (33.2% vs 27.8% MVIC, P = .035) and postlanding (83.3% vs 66.0% MVIC, P = .020), the combined mean muscle activation amplitude was higher in LAX_{HIGH} women, compared with LAX_{LOW} women. LAX group differences were not observed in men for either prelanding (P = .310) or postlanding activation (P = .798). Although muscle, side, and muscle × side effects were observed in men and women, there was no difference in these patterns by sex or LAX group (P range, .060–.900). General data patterns relative to muscle and side effects (regardless of sex or laxity status) indicate that during the prelanding phase, (1) the gastrocnemius muscle was activated to a higher level than that of the quadriceps and hamstring muscles and (2) the medial muscles were activated to a higher level than that of the lateral muscles (all P < .007). During the postlanding phase, quadriceps activation was more dominant than hamstring and gastrocnemius activation (P < .001), and the lateral muscles were more dominant than the medial muscles (P < .029).

DISCUSSION

Our primary findings were that transverse and frontal plane hip and knee kinematics and kinetics were different between LAX_{LOW} and LAX_{HIGH} men and women, whereas muscle activation differences between laxity groups were observed only in women. In a comparison of female laxity groups on hip and knee neuromechanics, LAX_{HIGH} women were positioned in more hip adduction and knee valgus early in the landing phase, then moved toward greater hip adduction and internal rotation, and were positioned in more hip adduction throughout much of the latter half of the landing phase, compared with LAX_{LOW} women. The observed frontal plane knee motions are similar to previous reports of greater valgus motion in women, compared with men, early in the landing cycle,[7,14] thus suggesting that the greater joint laxity often observed in women may have been a contributing factor in previous work. These kinematic patterns in LAX_{HIGH} women were accompanied by more prolonged internal hip adduction and knee varus moments during midlanding and by greater prelanding and postlanding muscle activation amplitudes.

When considering the combined dynamic posture demonstrated in LAX_{HIGH} women, compared with LAX_{LOW} women (greater knee valgus, hip internal rotation and hip adduction), these integrated positions are often considered to be a dynamic alignment associated with ACL injury risk during landing.[12] Thus, LAX_{HIGH} women may have developed strategies that resulted in the dynamic alignment observed. Interestingly, the valgus collapse mechanism commonly associated with ACL injury[12] was observed in LAX_{HIGH} women even though they activated their muscles to a higher level and were accompanied by greater internal hip adduction and knee varus moments, compared with LAX_{LOW} women. These findings are consistent with the suggestion that those with greater laxity may need greater muscle forces during weightbearing activity.[32] Because these muscle adaptations were found both prelanding and postlanding in LAX_{HIGH} individuals, this increased activation appears to be a mediating response to improve joint stability (rather than a purely reactive response) and so may represent a mechanism to increase knee joint stiffness in the presence of reduced passive restraints.

However, even with this increased activation, considerable kinematic and kinetic differences were observed between LAX_{HIGH} and LAX_{LOW} women. Previous work on secondary transverse plane knee motions during non-weightbearing and weightbearing activities suggested that an envelope of dynamic laxity could help to identify functional knee instabilities.[5] This idea is based on the premise that during weightbearing, these secondary motions typically fall within an envelope of motion that is constrained by the passive knee joint restraints and driven by the magnitude of the forces acting about the knee.[5] Thus, those with excessive passive laxity or lack of muscular control may be predisposed to functional knee instabilities. This previous work and the findings of the current investigation collectively suggest that passive laxity and active muscular control likely affect resulting joint function and dynamic restraint.

Although similar differences in hip adduction motion were observed between LAX_{LOW} and LAX_{HIGH} men (in both pattern and magnitude), no other kinematic or neuromuscular differences were observed between male laxity groups. Lack of significant differences in joint angles between male laxity groups may be due to the overall lower magnitude of joint laxity in men. Although both sexes had a broad distribution of laxity values that resulted in similar relative differences in the mean values between LAX_{HIGH} and LAX_{LOW} groups in women and men, respectively (5.6° vs 4.5° for LAX_{VV}, 14.6° vs 13.7° for LAX_{IER}), the absolute magnitude of laxity observed was significantly lower in men (Table 1). Previous work has identified greater joint laxity as a risk factor for injury.[22,35] As such, a critical level of laxity may be necessary before hip and knee motions are adversely affected, and the observed laxity in men may not have been large enough in magnitude to effect a change in the resultant biomechanics. Alternatively, men may be more effective in resisting the motions associated with a functional valgus collapse; that is, compared with LAX_{LOW} men, LAX_{HIGH} men in the mid- to late phases of the landing maintained greater internal hip adduction and knee varus moments for a longer period and demonstrated greater incremental increases in knee internal rotation moments. Functionally, this can be interpreted as LAX_{HIGH} men producing greater moments for a longer period to overcome external loads that would cause hip abduction and knee valgus motions. Partially supporting this theory is the fact that both men and women generally demonstrated the same movement patterns across the landing phase, yet men demonstrated smaller joint angles. To build on these findings, future work should compare LAX_{HIGH} and LAX_{LOW} female and male groups who are strictly matched on absolute laxity values.

This study is limited to the assessment of in vivo dynamic knee function in participants with high and low frontal and transverse plane knee laxity, using skin-mounted motion sensors. We fully acknowledge the potential for errors in the use of such sensors in assessing in vivo dynamic function.[1,26] However, skin-mounted motion sensors have been extensively used to assess joint kinematics during high-impact activities[8,14,21] because alternative methods of assessing dynamic joint kinematics pose significant invasive risk to the participants.[1,26] In addition, because this study is the first of its nature, we chose to investigate only the effect of frontal and transverse plane knee laxity on joint neuromechanics. Given that the interaction of multiple potential risk factors in a single study may help to better explain integrated dynamic function,[31] future work should examine the effect of frontal and transverse plane knee laxity, along with other predictive factors of increased frontal and transverse plane motions (eg, lower extremity alignment). We did, however, examine multiple outcome variables to gain a more comprehensive understanding of the impact of transverse and frontal plane knee laxity on weightbearing knee joint neuromechanics. Although a comprehensive examination of kinetic, kinematic, and neuromuscular variables increases the chance of finding a significant difference simply attributed to chance, current consensus calls for these comprehensive assessments to best understand the movement patterns linked to increased risk for knee injury.[31] As we learn the most important factors associated with the injury mechanism, fewer variables may be studied in the future.

In conclusion, individuals (particularly, women) with greater frontal and transverse plane laxity demonstrated many of the hip and knee biomechanics often associated with noncontact ACL injury mechanisms. Although the association between greater joint laxity and hip and knee biomechanics during landing is compelling, the direction of this association cannot be determined from the current study. Greater joint laxity in women may represent an underlying risk factor leading to the greater functional valgus collapse often observed in women; however, greater laxity may also be a consequence of the greater secondary knee motions observed, which over time may cause mechanical loading of the collateral and cruciate ligaments. Further work is needed to determine whether increased laxity is a precursor to the dynamic malalignments observed or whether dynamic alignments are a precursor to chronic loading and elongation of the passive restraints that produce greater laxity. Examining these associations in a maturing youth population may further elucidate when each of these risk factors emerges and how they are associated with one another.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The project described was supported by Grant No. R01 AR053172 of the National Institute of Arthritis and Musculoskeletal and Skin Diseases, National Institutes of Health.

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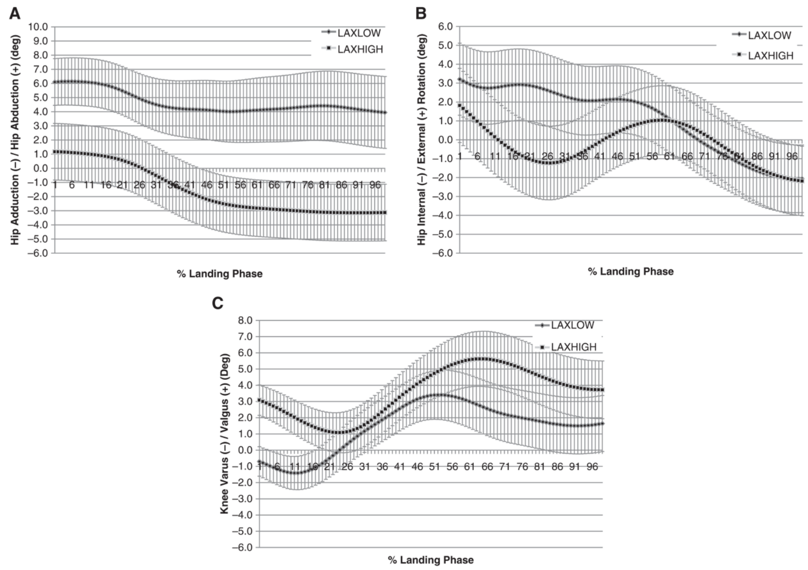

Figure 1.

Comparison of women with below- and above-average laxity values (ie, LAX_{LOW} and LAX_{HIGH}, respectively) on motion patterns across the landing phase of a drop jump: A, hip adduction (−)/abduction (+); B, hip internal (−)/external (+) rotation; C, knee varus (−)/valgus (+). Values are means ± standard errors.

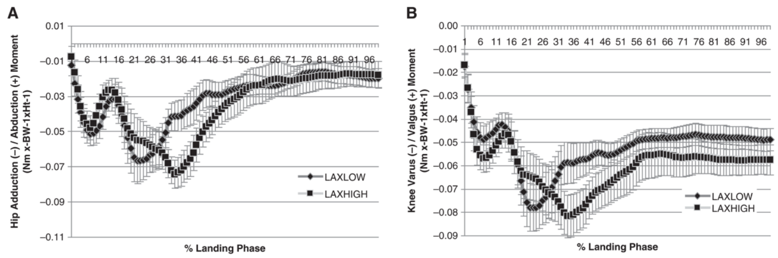

Figure 2.

Comparison of women with below- and above-average laxity values (ie, LAX_{LOW} and LAX_{HIGH}, respectively) on hip (A) and knee (B) frontal plane moments across the landing phase of a drop jump. Values are means ± standard errors.

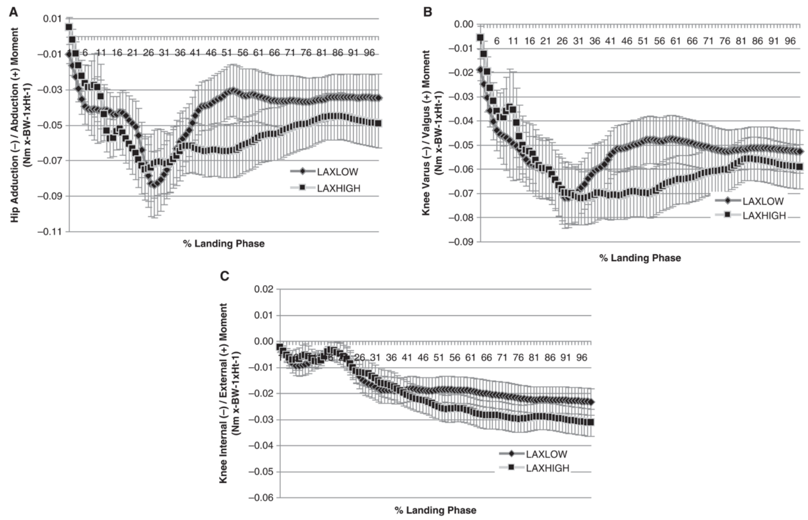

Figure 3.

Comparison of men with below- and above-average laxity values (ie, LAX_{LOW} and LAX_{HIGH}, respectively) on frontal plane hip (A) and knee (B) moments and transverse plane knee moments (C) across the landing phase of a drop jump. Values are means ± standard errors.

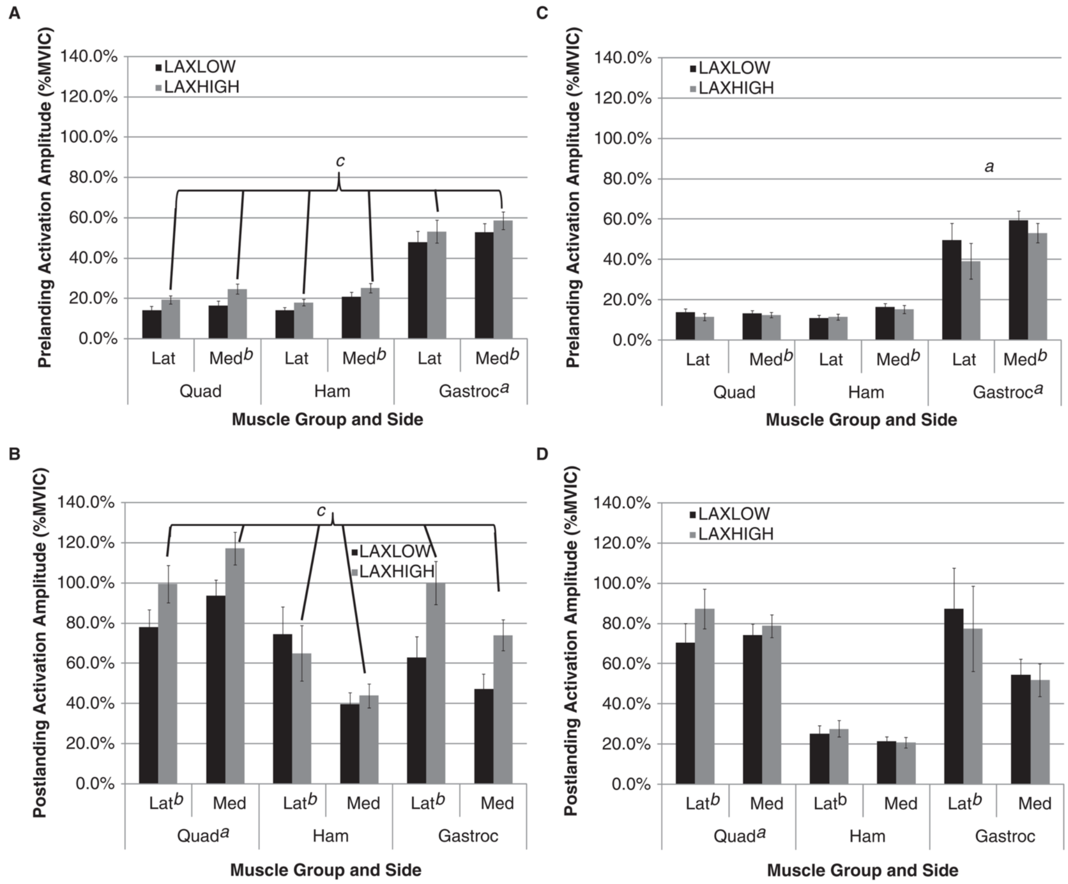

Figure 4.

Comparison of women (A, B) and men (C, D) with below- and above-average laxity values (ie, LAX_{LOW} and LAX_{HIGH}, respectively) on prelanding and postlanding muscle activation amplitudes (% maximal voluntary isometric contraction). Values are means ± standard errors. ^{a}Greater activation compared to the other muscles. ^{b}Greater overall activation on the medial or lateral side. ^{c}Greater overall muscle activation in LAX_{HIGH} versus LAX_{LOW} groups.

TABLE 1

Laxity Profiles and Demographics for Below- and Above-Average Women and Men[a]

	LAX_{VV} (°)	LAX_{IER} (°)	AKL (mm)	BMI	MVIC (N·m/kg)	
					Quad	**Ham**
Women						
LAX_{LOW}	10.9 ± 2.7	19.9 ± 4.3	5.5 ± 1.5	22.0 ± 2.4	2.3 ±0.4	1.8 ± 0.3
LAX_{HIGH}	16.3 ± 2.7[b]	34.5 ± 4.8[b]	7.9 ± 2.2[b]	22.9 ± 2.7	2.3 ±0.4	1.7 ± 0.2
Total	13.4 ± 3.0[c]	26.8 ± 7.5[c]	6.6 ± 2.2	22.4 ± 2.6[c]	2.3 ±0.4[c]	1.7 ± 0.3[c]
Men						
LAX_{LOW}	7.0 ± 0.8	14.2 ± 4.1	6.6 ± 2.3	26.4 ± 3.4	2.6 ±0.3	2.2 ± 0.3
LAX_{HIGH}	11.5 ± 1.8[b]	27.9 ± 4.9[b]	7.1 ± 1.5	24.7 ± 3.5	2.7 ±0.5	2.1 ± 0.3
Total	9.1 ± 2.4	20.7 ± 7.5	6.8 ± 1.8	25.6 ± 3.5	2.6 ±0.4	2.1 ± 0.3

[a] LAX_{VV}, varus-valgus laxity; LAX_{IER}, internal-external rotation laxity; AKL, anterior knee laxity; BMI, body mass index; MVIC, maximal voluntary isometric contraction; LAX_{LOW}, below-average laxity values; LAX_{HIGH}, above-average laxity values.

[b] $LAX_{HIGH} > LAX_{LOW}$ ($P < .05$).

[c] F ≠ M ($P < .05$).

TABLE 2

Analysis of Variance Summary Results With Calculated Effect Sizes: Joint Kinematic and Moment Comparisons Between Women and Men With Below- and Above-Average Laxity Values[a]

	Women		Men	
Variable	**Group**	**Group × Time**	**Group**	**Group × Time**
Joint kinematics				
HIP_{AA}	0.041 (0.37)	0.002 (0.21)	0.029 (0.41)	0.675 (0.09)
HIP_{IER}	0.582 (0.10)	<0.001 (0.28)	0.642 (0.08)	0.779 (0.09)
$KNEE_{VV}$	0.265 (0.20)	0.004 (0.21)	0.654 (0.08)	0.713 (0.10)
$KNEE_{IER}$	0.633 (0.08)	0.674 (0.09)	0.763 (0.05)	0.868 (0.04)
Joint moments				
HIP_{AA}	<0.001 (0.08)	0.002 (0.22)	0.530 (0.11)	<0.001 (0.24)
HIP_{IER}	0.619 (0.09)	0.560 (0.17)	0.813 (0.05)	0.239 (0.19)
$KNEE_{VV}$	0.223 (0.22)	0.025 (0.20)	0.621 (0.27)	<0.001 (0.09)
$KNEE_{IER}$	0.554 (0.11)	0.289 (0.17)	0.555 (0.11)	<0.001 (0.25)

[a]Effect size index is defined by square root × (sum of squares for the between-group or between-group × time term/sum-of-squares error term). Effect sizes of 0.10, 0.25, and 0.40 equate to small, medium, and large effects, respectively.[4] HIP_{AA}, hip abduction/adduction; HIP_{IER}, hip internal/external rotation; $KNEE_{VV}$, knee varus/valgus; $KNEE_{IER}$, knee internal/external rotation.