Joint Laxity Is Related to Lower Extremity Energetics during a Drop Jump Landing

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Abstract:
Purpose: To examine the relationships between anterior knee laxity (AKL), genu recurvatum (GR), and general joint laxity (GJL) with sagittal plane energetics in males and females during a drop jump task. Methods: A total of 68 females and 50 males were measured for AKL, GR, and GJL and were instrumented to obtain neuromuscular and biomechanical data on their dominant limb during the initial landing phase of a 45-cm drop jump. Multiple linear regressions determined the extent to which the three joint laxity variables combined to predict hip, knee, and ankle work absorption and stiffness. Associations between joint laxity and joint kinematics, joint kinetics, and muscle activation amplitudes were also investigated to further interpret significant relationships. Results: Higher AKL and GJL and lower GR combined to predict greater knee work absorption (R^2= 0.210, P = 0.002) and stiffness (R^2 = 0.127, P = 0.033) and lower ankle stiffness (R^2= 0.115, P = 0.048) in females. These associations were modulated through greater peak knee extensor moments and flexion angles, lower hamstring activation, and lower ankle extensor moments. In males, joint laxity had little impact on knee energetics, but a significant association was observed between greater GJL and decreased ankle stiffness (R^2= 0.209, P = 0.012), a product of both greater peak ankle flexion and decreased ankle extensor moment. Conclusions: Females with greater AKL and GJL and lower GR demonstrated a landing strategy that increased work absorption and stiffness about the knee, whereas females with greater GR demonstrated a landing style that reduced knee work absorption and stiffness. The findings suggest that AKL, GR, and GJL may represent distinct risk factors and support the need to consider more comprehensive laxity profiles as they relate to knee joint function and anterior cruciate ligament injury risk. Key Words: JOINT WORK ABSORPTION, JOINT STIFFNESS, KNEE BIOMECHANICS, SEX DIFFERENCES, ACL INJURY RISK FACTORS

Article:
Both retrospective (16,19,26,28,39) and prospective (21,37) studies have identified an association between risk of anterior cruciate ligament (ACL) injury and greater values of anterior knee laxity (AKL), genu recurvatum (GR), and general joint laxity (GJL). However, whereas several of these studies have examined more than one of these laxity variables relative to injury risk, few have examined their collective impact in a multivariate model (16,21,37) to determine the extent to which these three laxity measures represent similar or distinct risk factors.

In a prospective study of noncontact ACL injuries in West Point cadets, Uhorchak et al. (37) reported a greater relative risk associated with both AKL and GJL in females who had values that were one SD above the mean when examined as independent factors. Because the strongest multivariate predictive model in females was similar when either AKL or GJL was combined with body mass index and femoral notch width, this may suggest that these laxity measures represent the same risk factor. However, only GJL was found to be a risk factor in males because AKL had no relationship with injury either independently or in the multivariate model. Others have reported that when GJL and GR (16) or GR and side-to-side difference in AKL (21) were considered in combination with other risk factors, each laxity measure contributed unique variance in the overall injury risk model. These limited findings and a previous report of low correlation (r = 0.184) between AKL and GR (36) suggest that AKL, GR, and GJL may contribute unique information to the injury risk equation, and their contribution may not be the same for both males and females. Understanding the extent to which these laxity measures are related and combined to impact knee joint function is an important step in determining the most important risk factors for injury and whether one or all of these measures should be addressed in future multifactorial injury risk models.

Although greater magnitudes of joint laxity have been consistently related to an increased risk of ACL injury, information regarding the mechanisms for this relationship is lacking. Therefore, one approach to examine the relationships among AKL, GR, and GJL is to examine their collective impact on energy dissipation strategies during tasks associated with the ACL injury mechanism. ACL injury is reported to occur most often when the knee is relatively extended at the time of ground contact and the individual is performing a task that requires quick deceleration of the body's momentum to stop or change in direction (e.g., landing and plant and cut maneuvers) (3,17,23). Energetic analyses offer the ability to determine the work done by the extensor muscles through integration of the entire net joint powers (20). Such analyses offer the researcher the ability to gain insight into more global energy dissipation strategies that individuals use to handle the various mechanical demands during deceleration tasks (41). It is possible that those individuals with greater laxity may have chronic movement strategy adaptations that could be assessed through the study of energy dissipation.

To date, AKL seems to be the only laxity variable examined for its impact on knee joint neuromechanics of any kind. Anterior tibial translation relative to the femur is a naturally occurring motion during the transition from non-weight bearing to weight bearing that is restrained by the intact ACL (11). Research has shown that the magnitude of anterior translation is related to both the individual's AKL (34) and the magnitude of the applied axial load to the knee (35). Further, Rozzi et al. (27) reported that females who had greater AKL compared with males demonstrated greater lateral hamstring activation amplitude when landing from a jump, which they suggested may represent an adaptive strategy to compensate for inherent joint laxity and enhance joint stabilization. Collectively, these findings suggest that individuals with greater AKL may use alternative energy dissipation strategies when landing from a jump to reduce high axial loads and control tibiofemoral joint motion. However, these findings are limited to AKL, and we are not aware of any studies that have examined the impact of GR and GJL on landing neuromechanics. Examining how AKL, GR, and GJL may be associated with the neuromechanical strategies that females and males use to dissipate forces at the joints during a deceleration task may provide further insight as to how these laxity variables may be related to one another and how they may influence knee joint function and ACL injury risk.

The purpose of this study was to examine the collective relationships of AKL, GR, and GJL with sagittal plane energetics in males and females during the initial landing (deceleration) phase of a drop jump task. On the basis of the limited information available on the relationship among AKL, axial loads, and anterior tibial translation during the transition from non-weight bearing to weight bearing, our expectation was that individuals with higher magnitudes of AKL would demonstrate softer landing strategies as demonstrated by increased joint work absorption and decreased joint stiffness and that these relationships would be further magnified in individuals who also possessed higher magnitudes of GR and GJL.

MATERIALS AND METHODS

Sixty-eight females (21.5 ± 2.6 yr, 163.8 ± 6.6 cm, 60.6 ± 8.5 kg) and 50 males (22.2 ± 2.8 yr, 177.9 ± 9.3 cm, 80.9 ± 13.3 kg) were measured for clinical laxity and instrumented to obtain kinematic and kinetic measures during the initial landing phase of a drop jump task. The sample population was obtained as part of a larger project examining the effects of hormone-mediated changes in joint laxity on weight bearing knee joint function. Participants were included if they had a body mass index (BMI = weight/height^2) < 30 kg·m^{-2}, were able to abstain from alcohol for 24 h before any testing, had no history of vestibular or balance disorders, and had AKL values that fell within a predetermined distribution matrix designed to ensure inclusion of participants with a broad range of knee laxity values. Additional inclusion criteria for female participants were self-reported normal menstrual cycles lasting 26-32 d for the past 6 months, consistent cycle lengths that varied no more than +1 d from month to month for the past 6 months, nonuse 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 study. All participants enrolled in the larger study to date were included in the current study.

Height and weight were obtained during an initial intake session, and participants were evaluated for AKL, GR, and GJL and landing neuromechanics after being familiarized to all testing procedures approximately 2 wk before actual testing. Females were tested during the first 6 d of menses (per self-report of the onset of menstrual bleeding) to control for any cycling hormone effects on laxity (33) or knee joint neuromechanics (9,24). The dominant stance limb (stance leg when kicking a soccer ball) was measured on all participants. Before participation, participants were informed of all study procedures and signed a consent form approved by the Institution's Review Board for the Protection of Human Subjects.

Clinical laxity measurement. AKL was assessed with a KT-2000 Knee Arthrometer (Medmetric Corp, San Diego, CA) with the subject supine and the knee flexed 25° ± 5° over a thigh bolster. To control rotation of the lower extremity, a Velcro strap was placed around the subject's thighs while the feet/ankles rested in the foot cradle. The examiner first applied a posterior-directed force of 90 N then an anterior-directed force of 133 N where the amount of anterior displacement (mm) of the tibia on the femur was recorded by computer software. Three measures were obtained and averaged for analyses. The same researcher who had established excellent test-retest measurement consistency [$ICC_{2,k}$(SEM) = 0.96 (0.3) mm] measured all participants.

GR was assessed with a standard handheld goniometer with the subject laying supine on a table with the distal tibia elevated on a 4-inch bolster. The subject was instructed to actively and maximally extend his/her knee while the researcher obtained the amount of knee hyperextension in degrees (31). Three measures were obtained and averaged for analyses. The same researcher with established test-retest measurement consistency [$ICC_{2,k}$(SEM) = 0.97° (0.5°)] measured all participants.

GJL was assessed with the Beighton and Horan Joint Mobility Index at five different anatomical sites (2). A point was scored for each finding of 1) hyperextension of the fifth finger > 90°, 2) ability to passively abduct the thumb and touch the volar aspect of forearm with the wrist in flexion, 3) ability to actively hyperextend the elbow ≥10°, 4) postural knee hyperextension ≥10° while standing in a bilateral relaxed stance with body weight equally distributed between each limb, and 5) ability to place the palms flat on the floor while keeping the knees fully extended. A standard goniometer confirmed positive findings. The first four criteria were measured bilaterally, and the total GJL score (range = 0-9) was recorded for each participant. The same researcher who had established excellent test-retest measurement consistency [$ICC_{2,k}$ (SEM) = 0.99 (0.3)] measured all participants.

Drop jump procedures. Procedures for the current study are consistent with methods previously described (32). In preparation for normalization of prelanding and postlanding muscle activation during the landing task, surface EMG (sEMG) data were collected during maximal voluntary isometric contractions (MVIC) of the quadriceps, hamstring, and gastrocnemius muscles while seated in an instrumented dynamometer (Biodex System 3; Biodex Medical Systems, Inc., Shirley, NY). The skin was shaved and cleaned with isopropyl alcohol, and the 10-mm bipolar Ag-AgCl surface electrodes (Blue Sensor N-00-S; Ambu Products, Ølstykke, Denmark) with a center-to-center distance of 20 mm were placed in a parallel arrangement, at a location estimated to be midway between the motor point and the distal tendon of the vastus lateralis, vastus medialis, biceps femoris, medial hamstrings, and medial and lateral gastrocnemius muscles, and oriented perpendicular to the length of the muscle fibers (1). The reference electrode was attached over the flat portion of the anteromedial aspect of the tibia. The potential for crosstalk was minimized by consistently placing the electrodes over the midline of the muscle belly, minimizing the recording area via small electrode size and interelectrode distance, and visually confirming the acquired signal at each electrode location on a real-time oscilloscope during isolated manual muscle testing (7).

A 16-channel Myopac telemetric system (Run Technologies, Mission Viejo, CA) with an amplification of 1 $mV \cdot V^{-1}$, frequency bandwidth of 10-1000 Hz, common-mode rejection ratio of 90 dB min at 60 Hz, input resistance of 1 MΩ, and an internal sampling rate of 8-kHz recorded maximal sEMG signal amplitudes while the participants maximally extended and flexed their knee at a fixed knee angle of 25°. To account for differences in thigh strength that have been shown to explain some of the variance in muscle activation amplitudes (32), maximal isometric torques for the quadriceps and hamstring were recorded by the isokinetic dynamometer concurrently and normalized to body weight ($N \cdot m \cdot kg^{-1}$). To obtain maximal sEMG signals of the gastrocnemius muscle, the knee and ankle were positioned in 25° of flexion and 10° of dorsiflexion, respectively. Participants were then asked to maximally plantar flex against a fixed resistance applied to the plantar surface of the foot by the examiner aided by a stabilizing strap. sEMG signals were acquired, stored, and analyzed using DataPac 2K2 laboratory application software (Version 3.13; Run Technologies).

Participants were then instrumented with six-degree of freedom electromagnetic position sensors (Ascension Technologies, Burlington, VT) attached with double-sided tape and elastic wrap over 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 stance limb. Two additional sensors were placed on the sacrum and over the C7 spinous process. Joint centers were determined by digitizing the midpoint between the medial and lateral malleoli for the ankle and the midpoint between the medial and lateral femoral epicondyles for the knee and by a method for the hip by Leardini et al. (18).

Once instrumented and digitized, five double-leg drop jumps were performed with the subject barefoot, dropping from a wooden platform measuring 0.45 m in height and placed 0.1 m behind the rear edge of the force plate (Type 4060 Nonconducting; Bertec Corporation, Columbus, OH). Participants began in a standardized takeoff position in which the toes were aligned along the leading edge of the wooden platform and the hands placed at the level of the ears. Participants were then instructed to drop off the platform then perform a maximal vertical jump upon landing. Participants were not given any special instructions with regard to their drop jump mechanics to prevent experimenter bias. The hands remained at ear level throughout the task to eliminate variability in jumping mechanics due to arm swing. In addition to the familiarization session, practice repetitions (typically three) were allowed before test trials to ensure the subject remained comfortable with the task (both visually and subjectively). Kinematic data sampled at 100 Hz and kinetic and sEMG data sampled at 1000 Hz were then collected during five successful drop jump trials. All neuromuscular and bio-mechanical data were synchronized using the software's trigger sweep acquisition mode, using a foot contact threshold of 10 N to trigger data collection. A trial was discarded, and participants were asked to repeat the trial if they lost their balance, if they did not land bilaterally, if their hands dropped below the level of the ears, or if they failed to land back onto the force plate after the maximal vertical jump.

Data reduction and analyses. To analyze muscle activation amplitude, the sEMG signals from the medial and lateral aspects of the quadriceps, hamstring, and gastrocnemius muscles were band-pass filtered from 10 to 350 Hz, using a fourth-order, zero-lag Butterworth filter then processed using a centered root-mean-square (RMS) algorithm using a 100-ms time constant for MVIC trials and a 25-ms time constant for the drop jump trials. The mean RMS amplitudes obtained from each muscle during the 150-ms interval immediately before (pre) and after (post) initial ground contact of the first landing phase were obtained for each of the five landing trials and then averaged. Pre- and postlanding sEMG amplitudes for each respective muscle were normalized using the average of the peak sEMG amplitude obtained for that muscle during the three MVIC trials and expressed as percent MVIC. Percent MVIC values for the medial and lateral aspects of each muscle were then averaged to represent a single amplitude value for each of the quadriceps, hamstring, and gastrocnemius muscle groups, respectively. Torque data obtained for the quadriceps and hamstring muscles during the maximal effort contractions were normalized to body mass ($N \cdot m \cdot kg^{-1}$).

All biomechanical data were obtained during the initial landing phase of the drop jump (defined from initial contact to peak knee flexion) and processed using MotionMonitor Software (InnSport, Chicago, IL). Kinematic data from the position sensors were linearly interpolated to force plate data and, subsequently, low-pass filtered at 12 Hz using a fourth-order, zero-lag Butterworth filter. A segmental reference system was defined for all body segments with the positive z-axis defined as the medial-to-lateral axis, the positive y-axis defined as the distal-to-proximal longitudinal axis, and the positive x-axis defined as the posterior-to-anterior axis. Knee angles were calculated using Euler angle definitions with a rotational sequence of z, y', x'' (15). Hip, knee, and ankle flexion angles were each extracted at initial ground contact ($FLEX_{INT}$) and at maximum knee flexion angle ($FLEX_{PK}$), and the excursion values were calculated ($FLEX_{EXC}$ = peak — initial) and averaged across the five drop jump trials. Kinetic data were also low-pass filtered at 12 Hz using a fourth-order, zero-lag Butterworth filter. Peak internal joint moments for the hip, knee, and ankle were calculated via an inverse dynamics model (12) and were normalized to each participant's height and weight ($N \cdot m \cdot BW(N)^{-1} \cdot Ht(cm)^{-1}$). Net joint powers were calculated as the product of the joint moment and joint angular velocity at each time point. Then, work done on the extensor muscles was calculated by integrating the negative portion of the joint power curve as this represented energy absorption by the extensor muscles (20). Work was then normalized to percent body weight (N) and height (cm) (4). Sagittal plane hip, knee, and ankle torsional joint stiffnesses were calculated as the change in net internal moment divided by the change in angular position from initial contact to peak flexion excursion (10) and then normalized to percent body weight (N) and height (cm). For consistency purposes and to better describe directional relationships be tween joint laxity and the various neuromechanical variables, all kinematic flexion and all kinetic extension values are reported as positive values.

To test the stated research hypothesis, a multiple linear regression analysis with all laxity variables entered simultaneously determined the extent to which AKL, GR, and GJL combined to predict hip, knee, and ankle work absorption and stiffness. To further interpret significant relationships between joint laxity, stiffness, and energetics, secondary multiple linear regression analyses examined the extent to which the three laxity variables predicted the joint kinematic (initial and peak flexion values) and kinetic (internal extension moments) variables and pre- and postlanding muscle activation amplitudes that contribute to work absorption strategies.

When examining the relationship between joint laxity and pre- and postlanding muscle activation amplitudes, the influence of thigh strength was also accounted for because previous work has shown a negative association between thigh strength and activation (32). Because of the observed sex-specific injury risk models associated with joint laxity and ACL injury (37), and reported sex differences in joint laxity (22,27,28,37) and work absorption strategies during both double-leg (4) and single-leg (29) landings, males and females were examined separately because it was anticipated that the relationship between joint laxity and the dependent variables may not be the same for each sex. Further, stratifying by sex allowed us to better control for sex and other covariates highly correlated with sex, and thus better able to derive reliable estimates of the relationship between the laxity variables and the outcomes of interest. On the basis of sample sizes of 50 males and 68 females, three predictor variables and an α level of 0.05, we had 80% power to detect a combined R^2value of 0.15 for females and 0.20 for males, which represent moderate effect sizes.

RESULTS

Means and SD for each variable and sex are reported in Table 1. Table 2 reports the bivariate correlations between each of the laxity variables by sex. Table 3 reports the multiple R^2values, partial correlation coefficients (correlation with the dependent variable once the other laxity variables were accounted for), and β coefficients representing the relationships between the three laxity variables and the primary variables of work absorption and torsional stiffness for each joint by sex. To further interpret significant relationships observed between joint laxity and knee and ankle joint energetics, Tables 4 and 5 present the secondary regression analyses for knee and ankle kinematics and internal moments, and pre- and postlanding activation amplitudes, respectively.

TABLE 1. Means ± SD for each predictor and dependent variable by sex.[a]

Variables	Females (n = 68)	Males (n= 50)

Joint laxity		
AKL (mm)	6.6 ± 2.0	6.6 ± 1.8
GR(°)	3.4 ± 3.4	3.7 ± 3.9
GJL (score)	1.9 ± 1.7	0.9 ± 1.3
Work absorption ($J \cdot N^{-1} \cdot cm^{-1}$) × 10^2		
Hip	7.95 ± 3.20	8.14 ± 3.83
Knee	4.26 ± 2.17	2.64 ± 1.19
Ankle	8.66 ± 2.73	8.30 ± 3.02
Joint stiffness ($N \cdot m \cdot N^{-1} \cdot cm^{-1} \cdot deg^{-1}$) × 10^2		
Hip	0.30 ± 0.13	0.47 ± 0.30
Knee	0.14 ± 0.05	0.13 ± 0.07
Ankle	0.20 ± 0.05	0.23 ± 0.05
Internal joint moments ($N \cdot m \cdot N^{-1} \cdot cm^{-1}$)		
Hip	0.176 ± 0.040	0.193 ± 0.042
Knee	0.074 ± 0.028	0.061 ± 0.025
Ankle	0.116 ± 0.024	0.125 ± 0.030
Joint kinematics (°)		
Hip		
Initial	23.0 ± 7.5	23.0 ± 9.1
Peak	71.7 ± 14.0	65.6 ± 20.6
Excursion	48.7 ± 13.8	42.6 ± 17.2
Knee		
Initial	15.5 ± 6.4	17.1 ± 6.6
Peak	88.3 + 11.9	84.1 ± 13.1
Excursion	72.8 ± 12.1	67.0 ± 12.0
Ankle		
Initial	41.2 ± 7.3	41.8 ± 7.0
Peak	100.3 ± 7.0	96.4 ± 6.2
Excursion	59.2 ± 7.8	54.6 ± 8.3
Muscle activation (%MVIC)		
Prelanding		
Quadriceps	18.1 ± 8.3	12.9 ± 6.3
Hamstring	20.2 ± 12.0	13.9 ± 5.9
Gastrocnemius	50.9 ± 18.2	51.0 ± 21.4
Postlanding		
Quadriceps	92.4 ± 32.3	76.8 ± 26.2
Hamstring	52.6 ± 33.7	23.5 ± 11.1
Gastrocnemius	70.5 ± 45.3	63.7 ± 42.5

[a]Sex comparisons have been previously reported in a smaller subset of these data (32).

TABLE 2. Bivariate (Pearson's R) correlations for AKL, GR, and GJL by sex.

Pearson Correlation	Females (n = 68)			Males (n = 50)		
	AKL	GR	GJL	AKL	GR	GJL
AKL (mm)	1.000	0.533*	-0.017	1.000	0.344*	0.481*
GR (°)		1.000	0.360*		1.000	0.275*
GJL (score)			1.000			1.000

* P < 0.05.

Females. Analysis of the primary variables of work absorption and torsional stiffness revealed significant relationships between joint laxity and knee work absorption, knee stiffness, and ankle stiffness in females (Table 3). Joint laxity explained 21% of the variance in knee work absorption, with all three laxity variables contributing significantly to the model. For knee stiffness, joint laxity explained 12.7% of the variance, with AKL being the strongest predictor in the model both in the magnitude of the estimated regression coefficient and statistical significance. For ankle stiffness, joint laxity explained 11.5% of the variance, with GJL ($P = 0.007$) being the strongest predictor in the model, followed by GR ($P = 0.072$) and AKL ($P = 0.238$). On the basis of the direction of the β coefficients in each of these models, once all three laxity variables were accounted for, a combination of higher AKL and GJL and lower GR values was associated with greater knee work absorption and stiffness and lower ankle stiffness.

To gain a clinical sense of the magnitude of change in the dependent variables associated with changes in joint laxity values, the regression coefficients obtained for each prediction model (Table 3) were used to compare a female ("female A") with average AKL (6.6 mm), GJL (1.9), and GR (3.5°) values, with a female ("female B") with above-average AKL (8.6 mm) and GJL (3.6) but average GR (3.5°) values (i.e., holding GR constant). We also compared female B with female C, a female with average AKL (6.6 mm) and GJL (3.6) and above-average GR (6.9°) (i.e., holding AKL and GJL constant). In this example, the above-average values for AKL, GR, and GJL were chosen because they represent one SD increases from mean laxity values obtained from the sample population (Table 1). On the basis of the estimated model, female B with 2 mm greater AKL (2 mm) and a 1.7 higher GJL score (but no difference in GR) had 43% higher predicted knee work absorption, 18% higher predicted knee stiffness, and 13% lower predicted ankle stiffness compared with female A with average laxity values. Conversely, female C with 3.4° greater GR (6.9°) but no difference in AKL and GJL values resulted in 15% lower predicted knee work absorption, 5% lower predicted knee stiffness, and 7% higher predicted ankle stiffness values compared with female A with average GR values.

To further explore the underlying kinematic, kinetic, and neuromuscular factors associated with these findings in females, secondary analyses revealed significant relationships among AKL, GR, and GJL with knee and ankle extensor moments, peak knee flexion angle, and pre- and postlanding hamstring and gastrocnemius activation (Tables 4 and 5). When all three laxity variables were accounted for in the multivariate model, the direction of the β coefficient for each laxity variable consistently revealed that a combination of greater AKL and GJL and lower GR values was associated with greater knee extensor moments and peak knee flexion angles, lower ankle extensor moments, and decreased hamstring prelanding activation. However, for pre- and postlanding gastrocnemius activation and prelanding hamstring activation, AKL contributed little to the model (all $P > 0.709$), and greater GJL and lower GR were the strongest predictors of lower activation levels in each model (all $P < 0.200$). Using the same laxity values for comparative purposes as in the example for joint energetics, predicted values for female B with a 2-mm increase in AKL, a 1.7 score increase in GJL, and no change in GR values resulted in 29% higher predicted knee extensor moment, 7% higher predicted peak knee flexion angle, 14% lower predicted ankle extensor moment, 28% and 10% lower predicted hamstring and gastrocnemius prelanding activation levels, and 10% and 2% lower predicted hamstring and gastrocnemius postlanding activation levels compared with female A with average laxity values. Conversely, female C with a 3.4° increase in GR and no change in AKL or GJL values resulted in 9% lower predicted peak knee extensor moment, 6% higher predicted peak ankle extensor moment, 4% lower predicted peak knee flexion angle, 25%

and 11% higher predicted hamstring and gastrocnemius prelanding activation levels, and 6% and 3% higher predicted hamstring and gastrocnemius postlanding activation levels compared with female A with average GR values. On the basis of these secondary findings, the association between joint laxity and ankle stiffness seems to be primarily modulated through changes in torque production of the ankle plantarflexors (rather than changes in range of motion), whereas the association between joint laxity and knee work absorption and stiffness is modulated primarily through alterations in net internal knee extensor torque production and, to a lesser extent, knee range of motion.

TABLE 3. Relationships (R^2 and β coefficients) among AKL, GR, and GJL with hip, knee, and ankle joint energetics for females and males.

Dependent Variable				Partial Correlations			Unstandardized Coefficients			
	Sex	Multiple R^2	P	AKL	GR	GJL	Intercept	AKL	GR	GJL
Work absorption ($J \cdot N^{-1} \cdot cm^{-1}$)										
Hip	Female	0.069	0.203	-0.183	0.048	-0.187	10.81	-0.350	0.057	-0.390
	Male	0.054	0.460	-0.085	0.146	-0.152	9.45	-0.205	0.151	-0.527
Knee	Female	0.210	0.002*	0.401	-0.250	0.342	0.63	0.513*	-0.190*	0.467*
	Male	0.112	0.138	0.078	-0.115	0.269	2.12	0.057	-0.036	0.289**
Ankle	Female	0.057	0.284	-0.229	0.192	-0.092	10.80	-0.379**	0.197	-0.163
	Male	0.060	0.407	0.070	0.165	-0.204	7.47	0.133	0.135	-0.562
Joint stiffness ($N \cdot m \cdot N^{-1} \cdot cm^{-1} \cdot deg^{-1}$) × 10^2										
Hip	Female	0.025	0.650	-0.116	0.040	-0.113	0.371	-0.009	0.002	-0.010
	Male	0.030	0.699	-0.049	-0.101	-0.055	0.575	0.009	-0.008	-0.015
Knee	Female	0.127	0.033*	0.335	-0.092	0.049	0.068	0.011*	-0.002	0.002
	Male	0.016	0.860	0.014	-0.067	0.104	0.123	0.001	0.001	0.006
Ankle	Female	0.115	0.048*	-0.153	0.223	-0.331	0.229	-0.004	0.004**	-0.010*
	Male	0.209	0.012*	-0.001	-0.028	0.402	0.249	-0.00004	-0.000	-0.019*

* P< 0.05.

**P< 0.10.

AKL in millimeters, GR in degrees, and GJL as score.

TABLE 4. Relationships (R^2 and β coefficients) among AKL, GR, and GJL with hip, knee, and ankle joint kinematics and internal moments for females and males.

				Partial Correlations			Unstandardized Coefficients			
Dependent Variable	Sex	Multiple R^2	P	AKL	GR	GJL	Intercept	AKL	GR	GJL
Internal joint moments										
Knee	Female	0.198	0.003*	0.429	-0.233	0.233	0.026	0.007*	-0.002**	0.004**
	Male	0.063	0.388	0.132	-0.074	0.142	0.046	0.002	-0.001	0.003
Ankle	Female	0.142	0.019*	-0.236	0.274	-0.350	0.140	-0.003**	0.002*	-0.006*
	Male	0.099	0.184	0.052	0.026	-0.300	0.126	0.001	0.000	-0.008*
Initial contact position										
Knee	Female	0.038	0.473	0.084	-0.150	0.179	13.2	0.319	-0.360	0.756
	Male	0.085	0.248	-0.241	-0.084	0.217	23.0	-1.014**	-0.147	1.285
Ankle	Female	0.035	0.515	0.149	-0.140	0.146	36.8	0.657	-0.385	0.705
	Male	0.043	0.563	-0.087	-0.160	0.115	44.8	-0.385	-0.305	0.726
Peak flexion angle										
Knee	Female	0.117	0.046*	0.147	-0.210	0.336	79.8	1.009	-0.913**	2.651*
	Male	0.006	0.967	-0.038	-0.052	0.015	86.3	-0.319	-0.186	0.538
Ankle	Female	0.057	0.289	0.015	-0.083	0.233	98.6	0.062	-0.215	1.082**
	Male	0.147	0.061**	0.061	-0.147	0.325	94.0	0.227	-0.235	1.814*
Joint excursion										
Knee	Female	0.057	0.289	0.096	-0.123	0.236	66.5	0.691	-0.554	1.896**
	Male	0.009	0.935	0.090	-0.012	-0.068	63.3	0.695	-0.039	-0.747
Ankle	Female	0.028	0.605	-0.125	0.057	0.075	61.8	-0.586	0.166	0.383
	Male	0.073	0.315	0.118	0.031	0.147	49.3	0.612	0.069	1.087

* $P < 0.05$.

**$P < 0.10$.

AKL in millimeters, GR in degrees, and GJL as score.

Males. Ankle stiffness was the sole joint energetic variable where a significant relationship was observed with joint laxity in males. Joint laxity explained 20.9% of the variance in ankle stiffness, with greater GJL being the most important predictor of decreased ankle stiffness. Post hoc removal of AKL and GR from the model resulted in no change in the R^2value or the regression coefficient for GJL. These findings were supported by the secondary analyses, where relationships were noted between GJL and peak ankle extensor moment and peak ankle flexion. Although the overall $R^2$for these models did not reach a level of significance, the regression coefficient for GJL was significant in both models ($P < 0.05$) and indicated that the relationship between greater GJL and decreased ankle stiffness was a product of both greater peak ankle flexion and lower internal ankle moments in these individuals.

TABLE 5. Relationships ($R^2$and β coefficients) among AKL, GR, and GJL with pre- and postlanding muscle activation in females.

Partial Correlations Unstandardized Coefficients

Dependent Variable	Multiple R^{2a}	P	AKL	GR	GJL	Intercept	AKL	GR	GJL	QPTQ	HPTQ
Prelanding activation											
Quadriceps	0.048	0.295	0.067	0.004	-0.200	0.416	0.003	0.000	-0.010	-0.051	-0.069
Hamstring	0.115	0.030*	-0.187	0.349	-0.262	0.267	-0.012	0.015*	-0.019*	0.106*	-0.144*
Gastrocnemius	0.287	<0.001	0.089	0.355	-0.450	0.670	0.008	0.022*	-0.051*	-0.040	-0.061
Postlanding activation											
Quadriceps	0.051	0.233	0.162	-0.119	-0.124	1.969	0.028	-0.013	-0.023	-0.254*	-0.325*
Hamstring	0.112	0.048*	0.058	0.139	-0.300	0.917	0.011	0.017	-0.066*	0.090	-0.358*
Gastrocnemius	0.086	0.075**	0.112	0.140	0.220	1.938	0.027	0.021	-0.060**	-0.135	-0.625*

[a]Represents the R^2change (variance explained by laxity values) once thigh strength was entered and accounted for.

* P < 0.05.

** P < 0.10.

AKL in millimeters, GR in degrees, and GJL as score.

HPTQ, hamstrings peak torque ($N{\cdot}m{\cdot}kg^{-1}$); QPTQ, quadriceps peak torque ($N{\cdot}m{\cdot}kg^{-1}$).

DISCUSSION

The collective association of AKL, GR, and GJL with sagittal plane energetics in females has not been previously reported. In a study identifying GJL as a risk factor for ACL injury in female athletes, it was suggested that ACL injury risk may increase when ligaments and tendons that provide structural integrity are insufficiently taut to "stabilize the knee joint and absorb ground reaction forces" (21). Energetic analyses performed in the current investigation allow insights as to how measures of laxity may impact the previously hypothesized function. Our primary findings revealed that once all three laxity variables were accounted for, females with a combination of greater AKL and GJL and lower GR demonstrated a landing strategy that shifted more of the workload to the knee, as evidenced by greater knee work absorption and knee stiffness and decreased ankle stiffness. Greater joint laxity had relatively no impact on knee energetics in males, but a significant association was observed between greater GJL and decreased ankle stiffness, which was reflected in both greater peak ankle flexion and decreased ankle extensor moment.

When considering the relationships observed in females, the association with increased knee work absorption as well as increased knee joint stiffness is initially somewhat confusing because landings actively manipulated to be classified as "stiff" have been associated with decreased energy absorption (41). However, much of what is currently known about landing energetics is largely based on studies using landing only models (8,29,41). Because injury commonly occurs as an individual performs one task while readying themselves for another (3), we chose the drop jump task because it required the individual to decrease their downward momentum while readying themselves for a rapid subsequent task. As such, we compared the percent contribution of each joint to total work absorption during this countermovement task to previous reports of unconstrained, simple drop landings (where no subsequent rapid concentric action is required) from similar heights (32-62 cm) (4,41). These comparisons suggest the demands and associated landing strategies of these two tasks might be quite different, as we observed greater contributions at the hip (42% vs 30%-34% in males, 38% vs 17.5% in females) and ankle (44% vs 20%-29% in males, 42% vs 35% in females) and substantially less contribution at the knee (14% vs 41%-47% in males, 21% vs 47% in females) with the drop jump task.

Our findings of both increased work absorption and stiffness at the knee and reduced stiffness at the ankle during a drop jump task suggest that individuals with greater AKL and GJL and less GR may be attempting to increase stabilization at the knee while at the same time working to limit high axial forces. This may be viewed as a protective response strategy to reduce loading of the capsuloligamentous restraints because the concept of coaching "soft" landings is common to injury prevention programs. However, previous studies of drop jump performance suggest the type of strategy observed in our participants with greater AKL and GJL and less GR may also lead to reduced athletic performance. Specifically, reduced takeoff velocity was associated with an "absorbing type" of drop jump characterized by higher initial kinetic values at landing and followed by greater "absorbing" action about the knee joint (14). This type of behavior relates well to the current study because such physiologic action would likely result in greater knee work absorption along with greater knee stiffness (likely driven by larger initial kinetic values). In addition, the decreased ankle stiffness associated with the identified laxity profile is congruent with the concept of an "absorbing type" of drop jump because lesser ankle stiffness has also been associated with decreased drop jump performance (as measured by jump height) (40). Further, it was suggested that the "absorbing type" of drop jump was the result of centrally driven programs (14). Hence, whereas individuals with a laxity profile of greater AKL and GJL along with lesser GR may have adapted their central neural strategies to reduce the loads applied to the ligamentous tissue, the decreased performance associated with an "absorbing type" landing may result in a lesser ability of the individual to respond to a potentially injurious stimulus. This in turn could decrease their ability to successfully react to unexpected stimuli common in athletic participation, thus rendering them more at risk for injury during these demanding, unexpected situations.

A related concern in females is the relationship observed between greater AKL and GJL and reduced pre- and post-landing hamstring activation amplitude. It is well accepted that co-contraction of the hamstring muscles can reduce ACL tensile forces during a strong quadriceps contraction (30). This may be particularly important during the transition from non-weight bearing to weight bearing (e.g., initial foot contact upon landing) when the tibia naturally tends to translate anterior relative to the femur (11) and a strong eccentric quadriceps force is needed to decelerate the body's momentum. The neuromuscular landing strategy demonstrated by individuals with increased AKL and GJL (reduced hamstring pre- and postlanding activation but similar quadriceps activation levels) coupled with greater net internal knee extensor moments further suggests a landing strategy that may place the ACL at a greater risk for injury.

The results for females also indicate that measures of AKL, GR, and GJL do not describe the same laxity phenomenon because each variable contributed significantly to models for many of the variables examined. It should be noted that although knee hyperextension was accessed in both GJL and GR, they represent quite different measures. As noted in our measurement methods for GJL, postural knee hyperextension >10° was ascertained with participants standing in a bilateral relaxed stance with body weight equally distributed between each limb. We did not specifically instruct them to actively extend the knee during this component of GJL testing. Using these methods, only two female subjects and one male subject received a rating of 1 on knee hyperextension, and higher GJL scores were largely driven by increased mobility at the thumb, fifth finger, and with trunk flexion (Table 6). As such, and given the continuous nature of the GR score, there was little overlap between the two measures.

TABLE 6. Frequency distribution of positive laxity scores by joint in the measurement of GJL.

	Frequency (%) of Positive Score	
GJL Component	Females	Males
Right fifth finger	14 (20.6%)	13 (26%)
Left fifth finger	16 (23.5%)	14 (28%)
Right thumb	30 (44.1%)	9 (18%)
Left thumb	27 (39.7%)	8 (16%)
Right elbow	1 (1.5%)	1 (2%)
Left elbow	1 (1.5%)	0 (0%)
Right knee	2 (2.9%)	0 (0%)
Left knee	2 (2.9%)	0 (0%)
Trunk flexion (palms to floor)	35 (51.5%)	4 (8%)

When considering the combined laxity profile that was associated with landing energetics, most interesting is the difference in the sign of the β coefficient for GR compared with that for AKL and GJL. Careful inspection of the data relative to the direction and strength of the regression coefficients obtained suggests that the magnitude of change in knee joint energetics (and related kinematic and kinetic variables) associated with greater AKL and GJL is modulated by the amount of GR. This is demonstrated in the examples provided in the results when holding either GR constant, or AKL and GJL constant. These findings suggest that if an individual has high GR, AKL, and GJL values, his/her predicted knee joint neuromechanics would actually be closer to those of an individual with average laxity values, although the overall laxity profile may be higher. The modifying effect of GR is further reinforced by the fact that when entering GR as the sole predictor in the model, GR had absolutely no relationship with any of the dependent variables. Therefore, the balance between AKL and GJL with GR may ultimately impact the strategy used to dissipate landing forces.

Because the underlying causes of AKL, GR, and GJL are relatively unknown, it is difficult at this time to explain these opposing relationships, particularly because greater magnitudes of GR have also been associated with a greater risk of ACL trauma (16,19,21,26,28). However, no study to date has examined the combined relationship of AKL, GR, and GJL to ACL injury risk using a multivariate model. Although four of these studies reported an association between ACL injury and greater magnitudes of both GR and GJL (16,26,28), only one study measuring GR also measured AKL (21), and in this study, only side-to-side differences were compared between ACL injured and uninjured groups in the multivariate model. Further, the magnitude of GR that differentiated between injured and noninjured individuals was quite variable between studies. On the basis of careful observation of the current data, we have found it to be relatively uncommon for a female to possess high GR without also possessing high AKL, although it is not uncommon for a female to have high AKL without also having high GR. These inconsistent relationships are supported by the moderate correlations noted between GR and AKL in both males and females in the current study (Table 2) and in a previous work (36) and suggest that factors beyond a general hyperlaxity syndrome influence these measures.

For example, De Jour et al. (5) have reported that excessive GR can result from bony deformation of the proximal end of the tibia (usually reflecting a decrease or reversal of the posterior inferior slope of the tibia), excessive capsuloligamentous laxity, or a combination of both. When the posterior inferior tibial slope is normal, GR is considered to be of capsuloligamentous origin (25). Conversely, an increase in the anterior-to-posterior tibial slope is thought to contribute to greater AKL because of evidence of greater anterior tibial translation with axial loading (6). Reported associations between lower extremity alignment and AKL further suggest that anatomical factors may contribute to abnormal loading patterns at the knee, which may differentially stress the various capsuloligamentous structures and promote varying degrees of laxity (31). Future work is needed to explore the underlying factor(s) associated with AKL, GR, and GJL to further clarify their relationships to one another and their collective impact on dynamic joint stability and energy dissipation strategies during deceleration tasks. Future work should also examine these relationships during other functional tasks (e.g., cutting) because the relationships noted may be task-specific and dependent on the passive restraints required to resist externally applied loads.

The collective association of AKL, GR, and GJL with sagittal plane energetics was not observed in males. Although males had a similar distribution of AKL and GR compared with females, these laxity variables had little to no impact on joint energetics. The only significant relationship observed in males was greater GJL predicting decreased ankle stiffness as a product of both lower peak ankle extension moment and greater peak ankle flexion. To give a sense of the magnitude of this effect, males in this sample with a GJL score of 3 or more (n = 6) demonstrated 5.6° greater peak ankle flexion (94.7° ± 6.1° vs 100.3° ± 6.4°) and 26% lower peak ankle extensor moments (0.133 ± 0.03 vs 0.100 ± 0.03 $N \cdot m \cdot N^{-1} \cdot cm^{-1}$), resulting in 42% lower ankle stiffness (1.70 ± 0.04 vs 2.49 ± 0.04 $N \cdot m \cdot N^{-1} \cdot cm^{-1} \cdot deg^{-1} \times 10^2$) compared with males with a GJL score of 0. Further analysis of these same individuals suggests that this decrease in ankle stiffness may be accompanied by a greater amount of work transferred to the knee (3.46 ± 1.48 vs 2.40 ± 1.03 $J \cdot N^{-1} \cdot c \cdot m^{-1} \times 10^2$), which is supported by a near significant regression coefficient for GJL when predicting knee work absorption ($P = 0.064$; Table 2). Although it is difficult to directly relate these findings to injury risk, it is interesting to note the consistency between our findings of GJL as the primary laxity variable modulating sagittal plane energetics and those of Uhorchak et al. (37), who reported that GJL, and not AKL, was a significant predictor of ACL injury risk in male cadets.

These findings are limited to the sagittal plane during a double-leg drop jump task. Research has shown that landing strategies are very different in single-leg and double-leg landings, and future studies should examine these relationships during other tasks that place increased demands on the lower extremity, including greater frontal and transverse plane torsional loads. Further, work absorption in the current study was calculated using the integral of the entire negative power curve from foot contact to peak knee flexion rather than the integral of the power curve during the first 100 ms after foot contact (4). Our rationale for studying the entire flexion motion was to best represent all work absorption of the extensor muscles during the initial landing phase of the drop jump task. Although our method of quantifying work absorption has been used previously to represent eccentric action of the muscles (8,20), the inverse dynamics used by the current investigation provides no mechanism to account for the energy absorbed by the muscles versus the energy absorbed by the connective tissue. Results of the current investigation suggest that joint laxities should be included in future high-level musculoskeletal modeling. Another potential limitation is that landing biomechanics were measured with the participant barefoot. The rationale for testing participants barefoot was to ensure more stable sensor placement on the foot (vs shoe) to reduce movement artifact and to avoid different shoe wear as a potential confounding variable. Although this may have caused participants to use a different landing strategy to absorb a barefoot landing, it was assumed this would be uniform across participants. Although research comparing single-leg landing biomechanics from a 15-cm height with and without footwear in healthy limbs found no difference in landing mechanics (38), there is a lack of comparative literature on joint energetics during a double-leg drop jump versus a double-leg drop landing task and during footwear versus no-footwear conditions. More research is needed to fully understand the potential alterations in landing strategies that may occur between these conditions. Finally, only laxity measures of AKL, GR, and GJL were examined. It is well accepted that many factors may interact to influence energy absorption strategies, and future studies should examine laxity along with other known risk factors to determine the most important combination of factors that modulate work absorption strategies during deceleration tasks.

In summary, there is growing evidence of an association between greater joint laxity and an increased risk of ACL injury. Because joint laxity is largely considered an unmodifiable risk factor, it is important to understand the implications of greater joint laxity on weight bearing knee joint function so that we may better tailor our prevention strategies to potentially compensate for this intrinsic risk. In the current study, females with greater AKL and GJL and lower GR demonstrated a landing strategy that shifted more of the workload to the knee, which may represent an attempt to stabilize the knee and reduce the loads applied to the ligamentous tissue but may also render the knee less able to respond to injurious forces. The observed energetics associated with this laxity profile seem to be a product of greater peak knee extensor moments, lower peak ankle extensor moments, and lower hamstring and gastrocnemius muscle prelanding activation. Hence, neuromuscular training programs using plyometric activity and movement training may be particularly effective in these individuals because these interventions are thought to improve dynamic joint stability (e.g., muscle coactivation), movement efficiency (e.g., improved biomechanical positioning, reduced joint moments), and corrective actions to sudden, unanticipated external loads (13). Appreciating that greater joint laxity in itself cannot be modified through neuromuscular training, the beneficial effects of neuromuscular training for these individuals would likely be compensatory rather than corrective in nature. Hence, it may be important for individuals with greater joint laxity to consistently reinforce positive neuromuscular adaptations throughout their career.

Finally, the substantially different relationships observed between joint laxity and lower extremity energetics in females and males reinforce earlier work that the risk associated with greater joint laxity is not the same for males and females (37) and suggest the need for continued investigations into sex-specific injury risk models and associated injury prevention strategies. The low-to-moderate correlations observed among AKL, GR, and GJL in females, coupled with their combined contribution when predicting lower extremity energetics, suggest that these laxity measures do not describe the same phenomenon and should be considered collectively in future risk factor models to identify the laxity profile most predictive of injury risk.

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