

Associations Among Eccentric Hamstrings Strength, Hamstrings Stiffness, and Jump-Landing Biomechanics

Derek R. Dewig, MA, ATC*; Jonathan S. Goodwin, PhD, DPT, PT†; Brian G. Pietrosimone, PhD, ATC*; J. Troy Blackburn, PhD, ATC*

*MOTION Science Institute, University of North Carolina at Chapel Hill; †Department of Physical Therapy Education, Elon University, NC

Context: Anterior cruciate ligament (ACL) injury risk can be assessed from landing biomechanics. Greater hamstrings stiffness is associated with a landing-biomechanics profile consistent with less ACL loading but is difficult to assess in the clinical setting. Eccentric hamstrings strength can be easily evaluated by clinicians and may provide a surrogate measure for hamstrings stiffness.

Objective: To examine associations among eccentric hamstrings strength, hamstrings stiffness, and landing biomechanics linked to ACL injury risk.

Design: Cross-sectional study.

Setting: Research laboratory.

Patients or Other Participants: A total of 34 uninjured, physically active participants (22 women, 12 men; age = 20.2 ± 1.6 years, height = 171.5 ± 9.7 cm, mass = 67.1 ± 12.7 kg).

Intervention(s): We collected eccentric hamstrings strength, active hamstrings stiffness, and double- and single-legged landing biomechanics during a single session.

Main Outcome Measure(s): Bivariate associations were conducted between eccentric hamstrings strength and hamstrings stiffness, vertical ground reaction force, internal knee-extension moment, internal knee-varus moment, anterior tibial

shear force, knee sagittal-plane angle at initial ground contact, peak knee-flexion angle, knee frontal-plane angle at initial ground contact, peak knee-valgus angle, and knee-flexion displacement using Pearson product moment correlations or Spearman rank-order correlations.

Results: We observed no association between hamstrings stiffness and eccentric hamstrings strength ($r = 0.029$, $P = .44$). We also found no association between hamstrings stiffness and landing biomechanics. However, greater peak eccentric strength was associated with less vertical ground reaction force in both the double-legged ($r = -0.331$, $P = .03$) and single-legged ($r = -0.418$, $P = .01$) landing conditions and with less internal knee-varus moment in the single-legged landing condition ($r = -0.326$, $P = .04$).

Conclusions: Eccentric hamstrings strength was associated with less vertical ground reaction force during both landing tasks and less internal knee-varus moment during the single-legged landing but was not an acceptable clinical estimate of active hamstrings stiffness.

Key Words: kinematics, kinetics, knee, anterior cruciate ligament

Key Points

- Eccentric hamstrings strength was not an acceptable clinical estimate of active hamstrings stiffness.
- Eccentric hamstrings strength was associated with less vertical ground reaction force in both the double- and single-legged landing conditions and less internal knee-varus moment during the single-legged landing and may be assessed clinically.
- Interventions targeting eccentric hamstrings strength may be important to incorporate into anterior cruciate ligament injury-prevention programs to develop a biomechanical profile associated with less anterior cruciate ligament loading.
- Researchers should focus on assessing other indices of hamstrings function, specifically passive stiffness, to determine their roles in knee-joint stability.

Anterior cruciate ligament (ACL) injury is a common orthopaedic injury in physically active people and typically results in ACL reconstruction. The US annual ACL reconstruction rate is approximately 129 836,¹ with secondary reinjury rates ranging from 3% to 37%.² Moreover, 36% to 46% of patients develop osteoarthritis within the first 12 years postreconstruction.^{3,4} Patients with ACL injury also incur an annual lifetime economic burden of \$7.6 billion for ACL reconstruction or \$17.7 billion when treated nonoperatively.⁵ Therefore, ACL

injury causes large physical and economic burdens, and attempts to reduce this injury risk should be implemented.

Researchers^{6–10} have demonstrated that anterior tibial translation, axial rotation, valgus moment, vertical ground reaction force (vGRF), and anterior tibial shear force load the ACL. In a prospective study, Leppanen et al¹¹ reported that higher vGRF during landing was associated with ACL injury risk. Hamstrings activity can limit these biomechanical stresses, potentially limiting the load placed on the ACL.⁹ The hamstrings function as dynamic stabilizers and

act to resist anterior tibial translation, internal rotation, valgus loading, and anterior tibial shear force.^{9,10,12} *Stiffness* refers to the ratio of change in force to change in length and quantifies a muscle's resistance to lengthening.¹³ Hamstrings stiffness may play an important role in limiting ACL loading, given that greater hamstrings stiffness is associated with less anterior tibial translation during controlled joint perturbation.¹⁴ Similarly, individuals with greater hamstrings stiffness display smaller peak knee-valgus moments and peak anterior tibial shear force during dynamic landing tasks.¹⁵ These findings suggest that greater hamstrings stiffness may reduce ACL loading.

Several modes of exercise have been demonstrated to enhance musculotendinous stiffness.^{16,17} Thus, musculotendinous stiffness is a modifiable risk factor that could have implications for injury prevention and rehabilitation efforts. It is unfortunate that musculotendinous stiffness cannot be plausibly measured in the clinical setting due to the need for sophisticated laboratory equipment. Determining a clinically based measurement of hamstrings stiffness may be beneficial for identifying individuals with insufficient stiffness as part of preparticipation screenings and for tracking the progression of hamstrings stiffness throughout rehabilitation after ACL injury. Conversely, strength can be easily measured in the clinic, but isometric hamstrings strength may not be associated with musculotendinous stiffness and does not differ between individuals with high and low amounts of anterior tibial translation.¹⁴ Functionally, eccentric hamstrings strength may be a more important factor in providing dynamic joint stability than isometric strength. However, the relationships among eccentric hamstrings strength, hamstrings stiffness, and ACL-loading mechanisms have not been evaluated. Therefore, the purpose of our study was to examine the associations among eccentric hamstrings strength, hamstrings stiffness, and landing biomechanics linked to ACL injury. We hypothesized that hamstrings stiffness would be positively associated with eccentric hamstrings strength and that both greater eccentric hamstrings strength and stiffness would be associated with landing profiles consistent with less ACL loading.

METHODS

Study Design

In this cross-sectional study, all data were collected during a single testing session in which eccentric hamstrings strength, hamstrings stiffness, and landing biomechanics were assessed. The order of assessments was determined by a balanced Latin square. All measures were performed in the participants' right lower limb because hamstrings stiffness does not differ between limbs in healthy individuals.¹⁸ A 5-minute rest was given between assessments.

Participants

A total of 34 uninjured volunteers (22 women, 12 men; age = 20.2 ± 1.6 years, height = 171.5 ± 9.7 cm, mass = 67.1 ± 12.7 kg) participated. An a priori power analysis based on correlations from data obtained in our laboratory¹⁵ indicated that a sample of 34 participants would provide a power of 0.80 to identify a relationship between hamstrings

stiffness and peak internal knee-varus moment during landing ($\alpha = .05$). All variables were evaluated using 1-tailed hypotheses because researchers¹⁴ found that greater hamstrings stiffness was associated with less ACL loading during landing. Participants had no history of lower extremity surgery or lower extremity musculoskeletal injury in the 6 months before the study and were involved in ≥ 30 minutes of physical activity 3 times per week. Physical activity status was assessed using the Tegner Activity Scale. All participants provided written informed consent, and the study was approved by the University of North Carolina at Chapel Hill Biomedical Institutional Review Board.

Hamstrings Stiffness Assessment

Active hamstrings stiffness was assessed as described by Blackburn et al.¹⁵ Maximal voluntary isometric contraction (MVIC) was performed first to determine standardized loading conditions for the stiffness assessment. For the MVIC assessment, the participant was positioned prone with the hip and thigh supported in 30° of flexion just off the edge of a plinth. The foot was fixed to a loading device such that the knee was maintained in 30° of flexion with the calcaneus in contact with a load cell (model 41; Honeywell Sensotec, Columbus, OH). The participants placed the upper limbs by their sides without grasping the edge of the table and performed a submaximal warm-up contraction, followed by a series of three 5-second maximal knee-flexion efforts during which load-cell data were sampled at 1000 Hz. Load-cell data were low-pass filtered at 10 Hz, and the MVIC was calculated using a 100-millisecond moving average from which we selected the largest hamstrings force value to represent the MVIC. The MVIC value was then used to determine the applied load for the stiffness assessment (ie, 45% MVIC).

The knee was modeled as a single-degree-of-freedom spring-mass system during the hamstrings stiffness assessment, and we observed the damping effect imposed by the hamstrings on oscillatory knee flexion and extension. Each participant was positioned on the plinth as for MVIC testing but with the foot and shank free to move. A splint was secured to the plantar aspect of the foot and the posterior distal portion of the shank to maintain neutral talocrural position and to keep gastrocnemius length consistent, and an accelerometer (model 356A32; PCB Piezotronics, Inc, Depew, NY) was attached to the splint to measure the tangential acceleration of the shank segment. Weights representing 45% of MVIC were secured near the ankle. The investigator (D.R.D.) positioned the shank parallel to the floor, which placed the knee in 30° of flexion, and the participant contracted the hamstrings to support the limb in the testing position. Within 5 seconds after this contraction, the investigator applied a downward manual perturbation to the calcaneus that forced the knee into extension and initiated oscillatory sagittal-plane knee motion. The participant was instructed to allow the shank to oscillate but to try to maintain the initial level of hamstrings activity and not intervene with the perturbation (Figure 1).

The oscillatory motion was recorded via the tangential acceleration of the shank segment, and the damped frequency of oscillation was calculated as the inverse of the time interval between the first 2 oscillatory peaks (t_1



Figure 1. Hamstrings stiffness assessment.

and t_2) in the acceleration signal (Figure 2). Stiffness was calculated using the equation $k = 4\pi^2mf^2$, where k is stiffness, m is the total mass of the system (shank and foot segment + 45% MVIC), and f is the damped frequency of oscillation. Shank-and foot-segment mass was calculated as 6.1% of total body mass.¹⁹ Participants performed 5 trials separated by 30-second rest periods to reduce the likelihood of fatigue. Acceleration during the stiffness assessment was sampled at 1000 Hz and low-pass filtered at 10 Hz.

Landing Biomechanics

Landing biomechanics were assessed during 5 double-legged (DL) and single-legged (SL) jump landings from a 30-cm height located 50% of the participant's height away from 2 force plates (model 4060-NC; Bertec Corporation, Columbus, OH). For the DL task, participants were instructed to land with each foot centered on a single force plate, minimize upward displacement on leaving the box, and immediately perform a maximal vertical jump after the initial landing as described by Padua et al.²⁰ For the SL task, participants were instructed to land with their right foot on the right force plate and to minimize upward displacement on leaving the box. Pilot testing revealed participants had difficulty completing a countermovement after SL landing; therefore, no vertical jump was required after landing for the SL condition. Each trial was visually inspected in real time, and trials that did not meet these criteria were eliminated and repeated until 5 successful trials were performed.

Landing biomechanics were obtained via an electromagnetic motion-capture system (model trakSTAR; Ascension Technology Corp, Shelburne, VT) interfaced with nonconductive force plates. Motion-capture sensors were placed on the pelvis over the sacrum, lateral midthigh, proximal anteromedial shank, and dorsum of the foot to measure lower extremity kinematics. The left and right anterior-superior iliac spines, medial and lateral femoral epicondyles, and medial and lateral malleoli were digitized to create a segment linkage model of the lower extremity. Locations of the *knee- and ankle-joint centers* were defined as the midpoints between the femoral epicondyles and malleoli, respectively. The *hip-joint center* was estimated as a function of the 3-dimensional distance between the digitized left and right anterior-superior iliac spines, as described by Bell et al.²¹ Participants performed 3 practice trials, followed by 5 recorded trials of each task. They were given no feedback or coaching on landing technique unless

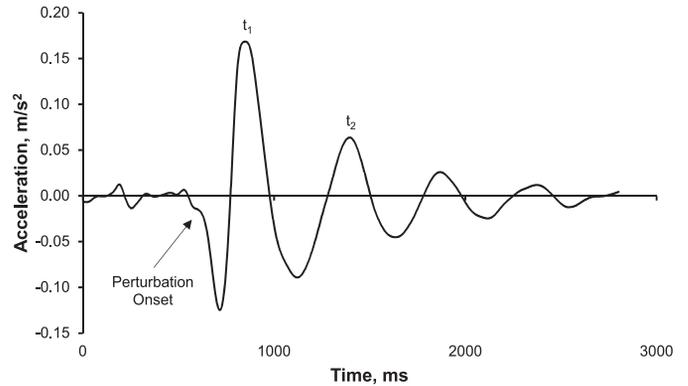


Figure 2. Hamstrings stiffness acceleration signal data.

the task was completed incorrectly.²⁰ To reduce the likelihood of fatigue, 30-second rest periods were given between trials. Three-dimensional coordinate data and ground reaction forces were sampled during the landing task at 100 Hz and 1000 Hz, respectively, via The Motion Monitor motion-capture software (Innovative Sports Training, Inc, Chicago, IL). Kinematic and kinetic data were low-pass filtered at 10 Hz and 75 Hz, respectively, and combined via a standard inverse-dynamics solution to yield net internal joint moments and forces.²² *Knee-joint angles* were calculated as the motion of the shank relative to the thigh using Grood and Suntay angles. Kinematic and kinetic variables were identified during the *loading phase* of the landing, defined as the interval from initial ground contact (point at which vGRF was >10 N) to the peak knee-flexion angle.²⁰ Peak vertical ground reaction force, internal knee-extension moment (ie, the internal response to external flexion loading), internal knee-varus moment (ie, the internal response to external valgus loading), anterior tibial shear force, knee sagittal-plane angle at initial ground contact, knee-flexion angle, frontal-plane angle at initial ground contact, knee-valgus angle, and knee-flexion displacement were identified for each trial. Forces were normalized to body weight (xBW), and joint moments were normalized to the product of body weight and height (xBW × Ht).

Eccentric Hamstrings Strength Assessment

During the eccentric hamstrings assessment, the participant was seated in a dynamometer (model HUMAC Norm; CSMi, Stoughton, MA) with the hip in 55° of flexion to minimize passive resistance from the hamstrings and permit full knee extension. The distal shank of the right limb was strapped into the leg attachment of the device with the foam pad placed approximately 3 cm proximal to the medial malleolus and the knee-joint sagittal-plane axis of rotation aligned with the axis of rotation of the dynamometer. Eccentric hamstrings strength was tested at 60°/s because this isokinetic speed has the greatest reliability and has been used extensively.^{23–25} Strength was tested in the concentric-eccentric mode over a range of 10° to 90° of flexion. The participant performed 1 practice trial of 3 knee-flexion and knee-extension actions, followed by 3 maximal-effort trials of 3 knee-flexion and knee-extension actions with 2 minutes of rest between trials. The peak torque was derived as the largest value for each of the 9

Table 1. Correlations Between Hamstrings Stiffness and Double-Legged Landing Biomechanics

Variable	Stiffness	
	<i>r</i> or ρ Value	<i>P</i> Value
Peak vertical ground reaction force	0.166 ^a	.17
Peak internal knee-extension moment	-0.153 ^a	.19
Peak internal knee-varus moment	0.135 ^a	.22
Peak anterior tibial shear force	-0.228 ^a	.10
Knee sagittal-plane angle at initial ground contact	-0.185 ^a	.15
Peak knee-flexion angle	0.021 ^a	.45
Knee frontal-plane angle at initial ground contact	0.075 ^a	.34
Peak knee-valgus angle	0.126 ^a	.24
Knee-flexion displacement	0.177 ^b	.16

^a Pearson product moment correlation (*r*) value is reported.

^b Spearman rank-order correlation (ρ) value is reported.

eccentric actions and averaged for analysis. Peak eccentric torque was also evaluated specifically from 10° to 30° of knee flexion because the ACL undergoes greater strain as the knee approaches full extension.⁸ Eccentric peak torque was normalized to body mass. Eccentric torque was sampled at 1000 Hz and low-pass filtered at 10 Hz.

Statistical Analyses

All dependent variables were derived using custom LabVIEW software (National Instruments Corp, San Antonio, TX). Mean values for each dependent variable were calculated across all trials for each task. Normality was assessed using the Shapiro-Wilk test. We performed bivariate Pearson product moment correlations for the normally distributed variables and the Spearman rank-order correlation (ρ) for the nonnormally distributed variable to determine relationships between eccentric hamstrings strength and (1) hamstrings stiffness and (2) landing biomechanics outcomes. All dependent variables were normally distributed except for knee-flexion displacement. All analyses were evaluated using 1-tailed hypotheses with the α level set a priori at .05. We used SPSS (version 22; IBM Corp, Armonk, NY) for all analyses. Gimbal lock was observed in multiple trials for SL landing trials for 3 participants; thus, we removed these participants' data from our SL landing correlations.

RESULTS

We observed no correlations between hamstrings stiffness and DL or SL landing biomechanics (Tables 1 and 2). In addition, neither overall eccentric strength ($r = 0.029$, $P = .44$) nor eccentric hamstrings strength at 10° to 30° of knee flexion ($r = 0.000$, $P = .50$) was associated with hamstrings stiffness. However, greater overall eccentric hamstrings strength ($r = -0.331$, $P = .03$; Table 3, Figure 3) and eccentric hamstrings strength from 10° to 30° ($r = -0.307$, $P = .04$; Table 3) were correlated with lesser vGRF in the DL landing task. Similarly, greater overall eccentric hamstrings strength ($r = -0.418$, $P = .01$; Table 4, Figure 4) and eccentric hamstrings strength from 10° to 30° ($r = -0.431$, $P = .008$; Table 4) were correlated with less vGRF in the SL landing task. Less peak internal knee-varus moment was also correlated with greater overall eccentric

Table 2. Correlations Between Hamstrings Stiffness and Single-Legged Landing Biomechanics

Variable	Stiffness	
	<i>r</i> or ρ Value	<i>P</i> Value
Peak vertical ground reaction force	0.137 ^a	.23
Peak internal knee-extension moment	-0.057 ^a	.38
Peak internal knee-varus moment	0.005 ^a	.49
Peak anterior tibial shear force	0.193 ^a	.15
Knee sagittal-plane angle at initial ground contact	-0.248 ^a	.09
Peak knee-flexion angle	-0.139 ^a	.23
Knee frontal-plane angle at initial ground contact	0.015 ^a	.47
Peak knee-valgus angle	0.099 ^a	.30
Knee-flexion displacement	0.055 ^b	.38

^a Pearson product moment correlation (*r*) value is reported.

^b Spearman rank-order correlation (ρ) value is reported.

hamstrings strength ($r = -0.326$, $P = .04$; Table 4) and eccentric hamstrings strength from 10° to 30° ($r = -0.383$, $P = .02$; Table 3) in the SL landing task. Descriptive statistics for hamstrings stiffness and eccentric hamstrings strength are detailed in Table 5. No other correlations between eccentric hamstrings strength were found in either DL or SL landing conditions (Tables 3 and 4). Given that we eliminated 3 participants from our SL landing correlations, we completed exploratory post hoc power analyses to evaluate the observed power of associations that were not correlated. Observed power from the SL landing associations that were not correlated ranged from 0.064 to 0.468 and indicated that at least 75 additional participants would be necessary to obtain a priori power of 0.80, thus suggesting that omitting data from 3 participants had a negligible effect on the results.

DISCUSSION

Individuals with greater eccentric hamstrings strength displayed less vGRF during both DL and SL landing conditions, as well as less peak internal knee-varus moment during SL landing. Hewett et al²⁶ reported that greater peak external knee-valgus moment predicted greater ACL injury risk. Our findings indicated that greater eccentric hamstrings strength was associated with less peak internal knee-varus moment (ie, the internal response to external valgus moment) during SL landing. Therefore, greater eccentric hamstrings strength may assist in mitigating the ACL injury risk. It is unclear, however, why this association was observed during SL landing but not during DL landing. The hamstrings may be more active during SL landing to accommodate the greater relative lower extremity loading and joint stability demands.²⁷ In addition, the DL task involved a countermovement jump, whereas the SL task did not, so the SL task potentially required participants to “stick the landing” using greater quadriceps-hamstrings coactivation. Consistent with this notion, Dashti Rostami et al²⁸ found that individuals with ACL injury and greater preparatory quadriceps-hamstrings coactivation during SL landing displayed less vGRF. These factors potentially explain the influence of eccentric hamstrings strength on frontal-plane loading during the SL task but not the DL task. Participants with greater eccentric hamstrings strength also had less vGRF in both landing conditions. Greater

Table 3. Correlations Between Eccentric Hamstrings Strength and Double-Legged Landing Biomechanics

Variable	Eccentric Peak Strength		Eccentric Peak Strength (10°–30°)	
	<i>r</i> or ρ Value	<i>P</i> Value	<i>r</i> or ρ Value	<i>P</i> Value
Peak vertical ground reaction force	−0.331 ^a	.03 ^b	−0.307 ^a	.04 ^b
Peak internal knee-extension moment	0.146 ^a	.21	0.143 ^a	.21
Peak internal knee-varus moment	−0.127 ^a	.24	−0.160 ^a	.18
Peak anterior tibial shear force	−0.258 ^a	.07	−0.277 ^a	.056
Knee sagittal-plane angle at initial ground contact	−0.126 ^a	.24	−0.059 ^a	.37
Peak knee-flexion angle	−0.123 ^a	.24	−0.019 ^a	.46
Knee frontal-plane angle at initial ground contact	0.226 ^a	.10	0.238 ^a	.09
Peak knee-valgus angle	0.143 ^a	.21	0.128 ^a	.24
Knee-flexion displacement	0.094 ^c	.30	−0.005 ^c	.49

^a Pearson product moment correlation (*r*) value is reported.

^b Indicates correlation.

^c Spearman rank-order correlation (ρ) value is reported.

vGRF has been associated with greater ACL injury risk¹¹ and ACL loading.⁶ Cerulli et al²⁹ determined that peak ACL strain and peak vGRF occurred at roughly the same time. Hewett et al²⁶ observed that vGRF was 20% greater in individuals who went on to injure their ACLs than in those who did not. Podraza and White³⁰ described greater vGRF in a more extended knee position during landing, both of which are disadvantageous for ACL injury.¹⁰ Therefore, a smaller vGRF may be favorable in ACL injury-prevention programs and may be achieved by enhancing eccentric hamstrings strength. Researchers should evaluate the effects of enhancing eccentric hamstrings strength on the biomechanical variables associated with ACL loading and injury risk.

The lack of association between strength and our other biomechanical variables agrees with the previous literature. Shultz et al³¹ reported no association between isometric hamstrings strength and biomechanical factors in landing, such as anterior shear force and knee-extensor moment. Homan et al³² noted that isometric hip-abduction strength was not associated with landing biomechanics. These findings are consistent with ours and may indicate that strength (ie, maximal force-production capacity) is not an adequate indicator of biomechanical function during dynamic tasks. The evaluation of both the quadriceps and hamstrings may have provided a more holistic representation of influences on landing profiles. The biarticular nature of the hamstrings muscle group may also explain some

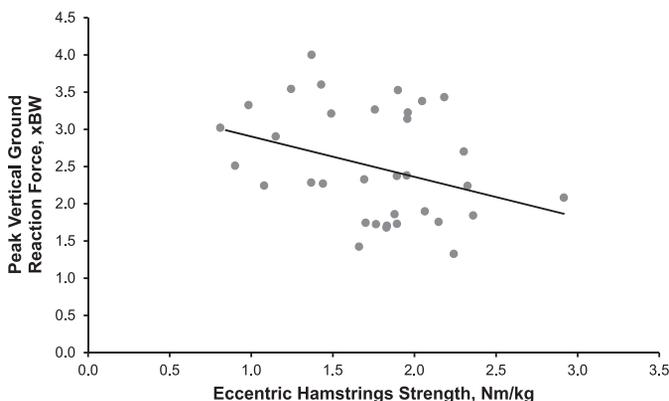


Figure 3. Eccentric hamstrings strength versus double-legged vertical ground reaction force.

disparity in correlation between eccentric hamstrings strength and other biomechanical variables. During the impact phase of landing, both the hip and knee flex. This causes proximal lengthening of the hamstrings due to hip flexion but distal shortening due to knee flexion. Furthermore, our method of assessing hamstrings strength specifically addressed the knee-flexion component of hamstrings function, as hip positioning was held constant. However, Schoenfeld et al³³ observed a difference in proximal versus distal hamstrings activity during the stiff-legged deadlift and lying leg curl: nonuniform muscle activation occurred in the medial hamstrings, suggesting that the proximal and distal portions of the muscle can be preferentially recruited. Thus, isolated isokinetic measurement of strength at the knee may not adequately represent the function of the hamstrings during a dynamic task.

Researchers^{14,15} have linked hamstrings stiffness with ACL loading such that greater hamstrings stiffness was associated with less anterior tibial translation during controlled joint perturbations. Furthermore, individuals with greater hamstrings stiffness demonstrated smaller peak knee-valgus and knee-extension moments and greater knee flexion at the instant of peak anterior tibial shear force,¹⁵ suggesting less ACL loading. However, we did not find relationships between hamstrings stiffness and our biomechanical variables of interest. A possible reason for this discrepancy may be that we did not stratify participants into high- and low-stiffness groups, as described by Blackburn et al.¹⁵ This approach effectively maximized variance in the earlier study and facilitated the identification of statistical differences. In addition, investigators¹² have demonstrated less hamstrings stiffness in women than in men. Our sample consisted primarily of women (65%), and our group mean stiffness value was similar to that of the low-stiffness group of Blackburn et al.¹⁵ The higher percentage of women in our sample may have lowered the group mean stiffness value and restricted the associated variance, thereby decreasing the likelihood of correlations with biomechanical landing outcomes. Hamstrings stiffness was also not correlated with eccentric hamstrings strength in our study. This result was consistent with the conclusions of previous researchers,³⁴ who demonstrated that strength was not associated with muscle stiffness, although their study evaluated isometric rather than eccentric strength. The hamstrings strength assessment requires maximal contraction of the hamstrings, whereas the stiffness assessment only requires a submaximal contraction to

Table 4. Correlations Between Eccentric Hamstrings Strength and Single-Legged Landing Biomechanics

Variable	Eccentric Peak Strength		Eccentric Peak Strength (10°–30°)	
	<i>r</i> or ρ Value	<i>P</i> Value	<i>r</i> or ρ Value	<i>P</i> Value
Peak vertical ground reaction force	−0.418 ^a	.01 ^b	−0.431 ^a	.008 ^b
Peak internal knee-extension moment	0.283 ^a	.06	0.111 ^a	.28
Peak internal knee-varus moment	−0.326 ^a	.04 ^b	−0.383 ^a	.02 ^b
Peak anterior tibial shear force	−0.225 ^a	.11	−0.098 ^a	.30
Knee sagittal-plane angle at initial ground contact	0.050 ^a	.39	0.159 ^a	.20
Peak knee-flexion angle	−0.077 ^a	.34	0.028 ^a	.44
Knee frontal-plane angle at initial ground contact	0.075 ^a	.34	−0.034 ^a	.43
Peak knee-valgus angle	0.023 ^a	.45	−0.072 ^a	.35
Knee-flexion displacement	0.074 ^c	.35	−0.079 ^c	.34

^a Pearson product moment correlation (*r*) value is reported.

^b Indicates correlation.

^c Spearman rank-order correlation (ρ) value is reported.

support the shank and 45% of the participants' MVIC. Moreover, eccentric strength was assessed through an entire range of motion, whereas the stiffness assessment was confined to approximately 30° of knee flexion. As such, the lack of correlation between the assessments may have stemmed from varying muscle-fiber lengths and lengthening velocities and the inherent difference in the hamstrings stiffness assessment being predicated on isometric hamstrings capacity instead of eccentric strength. In addition, eccentric strength is likely influenced by both active and passive stiffness characteristics,³⁵ although we only evaluated active stiffness. Authors should consider the effects of both passive stiffness characteristics (ie, presence of connective and noncontractile tissue) and active stiffness characteristics on eccentric hamstrings strength to further elucidate a possible relationship between eccentric strength and stiffness. The lack of association between hamstrings strength and stiffness indicated that isokinetic eccentric strength, as measured in this study, was not an acceptable clinical estimate of active hamstrings stiffness. However, the assessment of eccentric hamstrings strength may be clinically useful, given that this measure was positively related to landing biomechanics.

Our study had limitations that should be considered when interpreting the results. First, ACL loading in vivo is multifactorial and occurs in multiple planes. During our study, ACL loading factors were assessed independently and only in the sagittal and frontal planes. Similarly, our

stiffness assessment modeled the knee as a single-degree-of-freedom mass-spring system in which motion was restricted to the sagittal plane. During the stiffness assessment, the perturbation was intended to produce isolated flexion-extension but likely also produced frontal- and transverse-plane motion due to its open chain nature. Furthermore, we measured only active hamstrings stiffness, which probably does not entirely explain the role other indices of hamstrings stiffness have in strength and landing biomechanics. We also evaluated our dependent variables in a healthy cohort, and these findings cannot be assumed to be directly translatable to patients after ACL injury and ACL reconstruction. Finally, hamstrings stiffness differs between men and women,^{12,15} but we studied both sexes to create generalizability for clinicians. Moreover, our purpose was to evaluate the effects of stiffness on jump-landing biomechanics rather than account for the influence of sex.

CONCLUSIONS

Eccentric hamstrings strength, as measured in this study, was not an acceptable clinical estimate of active hamstrings stiffness. However, eccentric hamstrings strength was associated with less vGRF in both DL and SL landing conditions and less internal knee-varus moment during SL landing and may be assessed clinically. Furthermore, targeting eccentric hamstrings strength may be important for ACL injury-prevention programs because it is related to a biomechanical profile associated with less ACL loading. Researchers should focus on assessing other indices of hamstrings function, specifically passive stiffness, to determine their roles in knee-joint stability. Given that injury-prevention programs are becoming commonplace in clinical practice, investigators need to determine the most appropriate means of quantifying clinical assessments that are related to biomechanical risk factors for ACL injury.

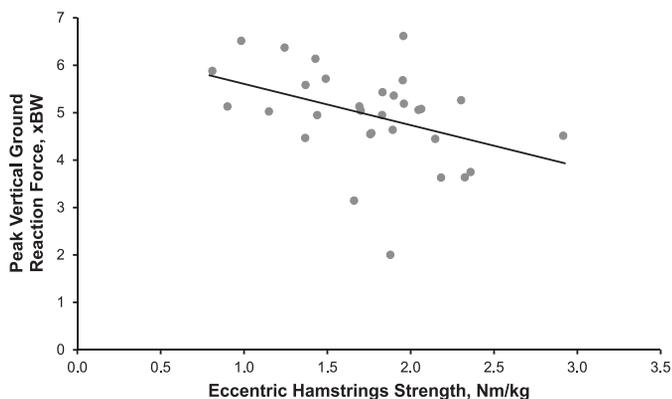


Figure 4. Eccentric hamstrings strength versus single-legged vertical ground reaction force.

Table 5. Descriptive Statistics

Dependent Variable	Mean ± SD
Hamstrings stiffness, N/m·kg ^{−1}	15.81 ± 2.41
Eccentric hamstrings strength, Nm·kg ^{−1}	1.90 ± 0.52
Eccentric hamstrings strength (10°–30°), Nm·kg ^{−1}	1.89 ± 0.52

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Address correspondence to Derek R. Dewig, MA, ATC, MOTION Science Institute, University of North Carolina at Chapel Hill, Campus Box 8700 Fetzer Hall, Chapel Hill, NC 27599-8700. Address e-mail ddewig@live.unc.edu.