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original research

Knee Proprioception and Strength and Landing Kinematics During a Single-Leg Stop-Jump Task

Takashi Nagai, PhD, ATC; Timothy C. Sell, PhD, PT; Anthony J. House, MS, ATC; John P. Abt, PhD, ATC; Scott M. Lephart, PhD, ATC

Neuromuscular Research Laboratory, University of Pittsburgh, PA

Context: The importance of the sensorimotor system in maintaining a stable knee joint has been recognized. As individual entities, knee-joint proprioception, landing kinematics, and knee muscles play important roles in functional joint stability. Preventing knee injuries during dynamic tasks requires accurate proprioceptive information and adequate muscular strength. Few investigators have evaluated the relationship between knee proprioception and strength and landing kinematics.

Objective: To examine the relationship between knee proprioception and strength and landing kinematics.

Design: Cross-sectional study.

Setting: University research laboratory.

Patients or Other Participants: Fifty physically active men (age = 26.4 ± 5.8 years, height = 176.5 ± 8.0 cm, mass = 79.8 ± 16.6 kg).

Intervention(s): Three tests were performed. Knee conscious proprioception was evaluated via threshold to detect passive motion (TTDPM). Knee strength was evaluated with a dynamometer. A 3-dimensional biomechanical analysis of a single-legged stop-jump task was used to calculate initial contact (IC) knee-flexion angle and knee-flexion excursion.

Main Outcome Measure(s): The TTDPM toward knee flexion and extension, peak knee flexion and extension torque, and IC knee-flexion angle and knee flexion excursion. Linear correlation and stepwise multiple linear regression analyses were used to evaluate the relationships of both proprioception and strength against landing kinematics. The α level was set a priori at .05.

Results: Enhanced TTDPM and greater knee strength were positively correlated with greater IC knee-flexion angle (r range = 0.281–0.479, P range = .001–.048). The regression analysis revealed that 27.4% of the variance in IC knee-flexion angle could be accounted for by knee-flexion peak torque and TTDPM toward flexion (P = .001).

Conclusions: The current research highlighted the relationship between knee proprioception and strength and landing kinematics. Individuals with enhanced proprioception and muscular strength had better control of IC knee-flexion angle during a dynamic task.

Key Words: threshold to detect passive motion, peak knee flexion and extension torque, initial contact knee-flexion angle, knee-flexion excursion

Key Points

- Enhanced knee proprioception and greater knee strength were correlated with greater knee-flexion angle at initial contact during a single-legged stop-jump task.
- Greater knee-extension strength was correlated with greater knee-flexion excursion during a single-legged stop-jump task.
- Knee proprioception and strength were not strong predictors of the knee-flexion excursion.

The importance of sensory information, central processing and integration, and neuromuscular control to achieve a stable knee joint is widely recognized.[1–3] Individually, knee-joint proprioception, knee strength, and landing technique play important roles in functional joint stability. Previous studies evaluating modifiable neuromuscular and biomechanical characteristics in female athletes, who are at greater risk than male athletes for noncontact anterior cruciate ligament (ACL) injury,[4] have demonstrated diminished knee proprioception, landing techniques with less knee-flexion angle, and weaker quadriceps and hamstrings muscular strength than their male counterparts.[5–7] However, the relationships among these entities rarely have been evaluated.

Most knee-joint proprioception assessments are used to evaluate the integrity and function of conscious proprioception.[8] *Threshold to detect passive motion* (TTDPM), which is the ability to detect the initiation and direction of passive joint movement, is influenced by afferent mechanoreceptors within the articular surfaces of the joint, musculotendinous tissues, and cutaneous structures.[8] Investigators[9,10] have indicated enhanced TTDPM in individuals with years of training in highly coordinated sports, such as gymnastics and dance. Based on the physiologic role of proprioception in providing conscious sensations and adjusting movement programs, we speculated that enhanced TTDPM would be correlated with greater knee-flexion angles.

Muscular strength is defined as the capacity of the muscles to exert force and is fundamental to the performance of many tasks that are encountered in daily living.[11] Female athletes demonstrate less absolute strength than their male counterparts, suggesting a potential link between insufficient muscular strength and noncontact

ACL injuries in female athletes.[5,12,13] Given that the knee-extensor muscles eccentrically contract to control knee flexion during landing, researchers have suggested that less initial contact (IC) knee-flexion angle and knee-flexion excursion might be related to weak knee-extensor strength.[5] In addition, weak knee-flexor strength has been implicated as a potential risk factor for noncontact ACL injuries.[14–16] Salci et al[13] reported that knee-extensor and -flexor strength are positively correlated with knee-flexion excursion in male volleyball players.

Landing technique plays an important role in knee-joint stability. A *soft landing technique*, defined by a peak knee-flexion angle greater than 90°, attenuates impact forces by 19% compared with landing with a stiff leg.[17] In contrast, a *stiff landing* is characterized by less IC knee flexion and knee excursion, and several investigators[5,6,18] have indicated stiff landings in females. Landing with a stiff leg could compromise joint stability by increasing the ground reaction forces and decreasing energy absorption by the musculature, resulting in musculoskeletal injury.[18] These studies have highlighted the importance of IC knee flexion and knee-flexion excursion to maintain functional knee stability.

We have explained the importance of proprioception, strength, and landing mechanics; however, the direct correlations between TTDPM and landing kinematics and between knee strength and landing kinematics rarely have been examined. Understanding the relationships would be beneficial to researchers and clinicians in the field of musculoskeletal injury prevention and rehabilitation. Therefore, the purpose of our study was to examine the relationships between knee proprioception and strength and landing kinematics. We had 2 hypotheses: (1) enhanced TTDPM would be correlated with greater IC knee-flexion angle and knee-flexion excursion, and (2) greater knee-flexion and -extension strength would be correlated with greater IC knee-flexion angle and knee-flexion excursion.

METHODS

Participants

Sex and a history of lower extremity musculoskeletal injury have been shown to affect neuromuscular and biomechanical characteristics.[19] To meet the purpose of this investigation and improve homogeneity in the sample population, we recruited 50 physically active men with no history of lower extremity injury requiring surgery. At the time of testing, all participants were free of injury and reported being physically active at least 30 minutes daily. Demographic data are presented in Table 1. All participants provided written informed consent, and the study was approved by the University of Pittsburgh Institutional Review Board.

Table 1. Participant Demographics

Characteristic	Mean ± SD
Age, y	26.4 ± 5.8
Height, cm	176.5 ± 8.0
Mass, kg	79.8 ± 16.6

Figure 1. Threshold to detect passive motion.

Protocol

All participants completed 3 tests in the following order: proprioception, knee strength, and motion capture. The *dominant leg*, which was defined operationally as the leg preferred to kick a ball, was used for all tests. Proprioception and strength data were assessed with Biodex System 3 Multi-Joint Testing and Rehabilitation System (Biodex Medical Systems, Inc, Shirley, NY). Motion-analysis data were collected with 6 high-speed cameras (Vicon, Centennial, CO) and a force plate (model 9286A; Kistler Instrument Corporation, Amherst, NY) with sampling frequencies of 200 and 1200 Hz, respectively. The motion-capture system was calibrated, and the global coordinate system was established according to the manufacturer's guidelines before each test session.

For the knee conscious proprioception test, TTDPM was used instead of joint position sense procedures because of its reliability and precision.[20,21] The TTDPM procedures were similar to those used by Lephart et al.[9] First, participants were seated in the Biodex chair and wore a blindfold and headphones, which were playing white noise, to eliminate visual and auditory cues, respectively (Figure 1). An inflated pneumatic sleeve (PresSsion Multi 3 Gradient Sequential compression unit; Chattanooga Group, Hixson, TN) was placed around the lower leg to minimize any tactile feedback between the dynamometer and the limb.[22] The test was initiated with the knee positioned at 45°.[9,23] The participants were instructed to press a button to stop as soon as they perceived motion in the knee and could identify the direction. The detection of direction in addition to the sense of movement was used to minimize false responses, as suggested in previous studies.[24,25] At an unannounced time (0–30 seconds after instruction), the knee was moved passively toward either flexion or extension at a rate of 0.25°/s. Practice trials were provided for participants to become familiar with the testing procedures. Five repetitions toward the flexion direction and 5 repetitions toward the extension direction were performed randomly. If a participant indicated the wrong direction, the trial was discarded and repeated. Our pilot study indicated intrasession reliability and precision (intraclass correlation coefficient [ICC] [3,k] range = 0.879–0.917, standard error of measurement [SEM] range = 0.194°–0.216°). Portney and Watkins[26] suggested that ICC values greater than 0.75 indicate good reliability.

For the knee strength test to control the variability of peak torque values that largely were due to the force-length relationship, force-velocity relationship, and modes of contraction,[27,28] we used a maximal voluntary isometric protocol to measure knee-flexion and -extension peak torque at 45° of knee flexion. First, participants were seated in an upright position on the dynamometer with their torso, waist, and leg strapped to minimize extraneous movement (Figure 2). Torque values were adjusted automatically for gravity by the Biodex Advantage Software (version 3.2; Biodex Medical Systems, Inc). We calibrated the dynamometer according to the specifications outlined by the manufacturer's service manual. A previous pilot study conducted in our research center showed good intrasession reliability and precision in the strength test procedures (ICC [3,k] range = 0.914–0.943; SEM range = 0.082–0.170 Nm/kg). Participants performed practice trials to increase understanding and familiarity. The practice trials consisted of 3 submaximal contractions followed by 3 maximal contractions. Participants rested for 1 minute after the practice trials. During data collection, participants were instructed to perform 3 alternating maximal contractions toward extension and flexion for 5 seconds per contraction with a 10-second rest between contractions.


Figure 2. Isometric knee-flexion and -extension testing.

For the motion-capture test, participants performed a single-legged stop-jump task. This task was used in a previous investigation and simulates athletic maneuvers, such as a basketball rebound and handball jump shot.[29] We took the following anthropometric measurements using a height and weight scale (Seca North America, East Hanover, MD), anthropometric caliper (Lafayette Instrument Company, Lafayette, IN), and tape measure: height, mass, lower extremity length, knee diameter, and ankle intermalleolar distance. Passive reflective markers (Vicon) with a diameter of 0.014 m were placed bilaterally on the following anatomic landmarks: anterosuperior iliac crest, posterosuperior iliac crest, femoral epicondyles, lateral malleolus, second metatarsal head, heel, midshank, and midthigh. All markers were secured to participants with double-sided tape. First, participants stood in an anatomic position for a static trial. Second, participants stood on the starting line set at 40% of their height away from the closest edge of the force plate. They stood on their dominant lower extremities, hopped toward the center of the force plate, and jumped up as high as possible immediately after initial foot contact (Figure 3). All participants were instructed in the task with oral and

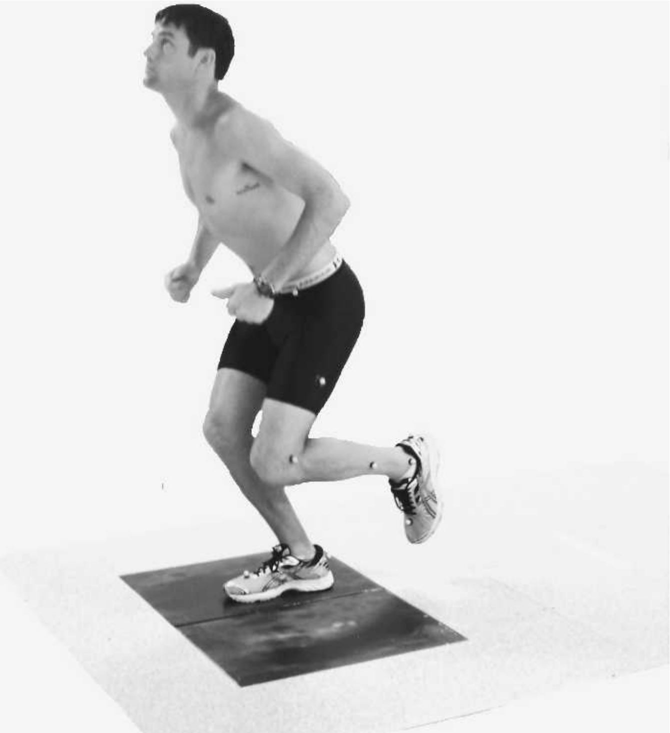
Figure 3. Single-legged stop-jump motion analysis.

Table 2. Descriptive Statistics for Knee Strength Characteristics, Proprioception, and Landing Kinematics

Variable	Mean ± SD	Minimum	Maximum
Knee-flexion peak torque, % body mass	137.5 ± 35.5	61.6	220.2
Knee-extension peak torque, % body mass	239.9 ± 47.5	152.4	368.3
Threshold to detect passive motion toward flexion, °	1.4 ± 1.5	0.2	8.1
Threshold to detect passive motion toward extension, °	1.7 ± 1.4	0.4	7.6
Initial contact knee-flexion angle, °	9.9 ± 6.1	−3.6	25.4
Knee-flexion excursion, °	50.4 ± 8.1	32.7	66.2

visual demonstrations and were allotted 3 practice trials. They performed 3 single-legged stop-jump trials. If they missed the force plate or did not perform the vertical jump after initial foot contact, the trial was discarded and repeated.

Data Reduction

Proprioception data were analyzed using the Biodex Research Toolkit (Biodex Medical Systems, Inc). Threshold was determined by calculating the difference between the initial joint position and the final joint position in degrees. We used the average of 5 recorded trials for final data analysis. The TTDPMs toward flexion and extension were analyzed separately because of the direction-specific nature of TTDPM.[23]

Muscular strength data were analyzed using the Biodex Advantage Software. The average of the peak torque from 3 isometric trials was calculated and then expressed in a percentage of the participant's body mass (% BM). Both knee-flexion and -extension peak torque were used for statistical analyses.

We used Nexus software (version 1.3; Vicon) to process the lower extremity marker trajectories according to the Plug-in Gait model. The Plug-in Gait model is based on the Helen Hayes rigid-link model developed by Kadaba et al[30,31] and Davis et al.[32] Three-dimensional marker trajectories defined in the global coordinate system were passed through a Woltring filtering routine with the general cross-validation option. Using embedded anatomic reference systems, the Plug-in Gait model incorporates relative Euler rotation angles using the proximal to distal convention for the hip, knee, and ankle joint.

After successful Plug-in Gait modeling, relative knee joint angle in the sagittal plane and vertical ground reaction force were exported for processing in MATLAB (release 12; The MathWorks, Natick, MA) to identify IC knee flexion angle and knee-flexion excursion. *Initial contact* was defined as the instant the vertical ground reaction force was greater than 5 N. *Knee-flexion excursion* was determined as the difference between the IC knee and peak knee-flexion angles. Both IC knee-flexion angle and knee-flexion excursion were averaged across 3 trials and expressed in degrees, with 0° indicating full knee extension.

Data Analysis

All statistical analyses were performed using SPSS (version 15.0; SPSS Inc, Chicago, IL). Descriptive statistics (means, standard deviations, minimums, and maximums) were identified for all variables. The relationships between dependent variables were evaluated by a pairwise correlation analysis. Given the positive skewness in TTDPM data (TTDPM toward flexion = 3.0, TTDPM toward extension = 2.4), the assumption of the distribution normality was violated on both TTDPM toward flexion (Shapiro-Wilk = 0.627, $P < .001$) and TTDPM toward extension (Shapiro-Wilk = 0.714, $P < .001$). The TTDPM data were transformed using the reciprocal transformation formula ($X' = 1/X + 1$).[26] The transformed TTDPM data were used for linear correlation analyses and stepwise multiple linear regression analyses.

To explore the relationships between both proprioception and strength and landing kinematics, 2 stepwise multiple linear regression models were applied to the cross-sectional data. The IC knee-flexion angle served as the response variable for the first regression model, and knee-flexion excursion served as the response variable for the second regression model. The prediction variables entered into each model were TTDPM toward flexion, TTDPM toward extension, knee-flexion peak torque, and knee-extension peak torque. The F probability for variable entry was set at 0.05 and for variable removal was set at 0.10. The α level of the final model was set a priori at .05.

RESULTS

Descriptive statistics on TTDPM toward flexion and extension, knee-flexion and -extension peak torque, IC knee-flexion angle, and knee-flexion excursion are shown in Table 2. Enhanced TTDPM toward flexion was correlated with greater IC knee-flexion angle ($r = 0.281$, $P = .048$). Similarly, enhanced TTDPM for extension was correlated with greater IC knee-flexion ($r = 0.338$, $P = .02$). However, we found no correlation between TTDPM toward flexion and knee-flexion excursion ($r = -0.196$, $P = .17$). We found no correlation between TTDPM toward extension and knee-flexion excursion ($r = -0.126$, $P = .39$).

Knee-flexion peak torque was correlated positively with IC knee-flexion angle ($r = 0.479$, $P = .001$). Similarly, knee- extension peak torque was correlated positively with IC knee-flexion angle ($r = 0.358$, $P = .01$). The knee-extension peak torque was correlated with knee-flexion excursion ($r = 0.279$, $P = .049$). However, we found no correlation between the knee-flexion peak torque and knee-flexion excursion ($r = 0.246$; $P = .09$).

Results for the regression analyses are shown in Tables 3 and 4. Knee-flexion peak torque and TTDPM toward flexion are the 2 predictor variables selected in the first regression model (adjusted $R^2 = 0.274$, $P = .001$). Knee-extension peak torque is the only predictor variable selected in the second regression model (adjusted $R^2 = 0.059$, $P = .049$).

DISCUSSION

Our first hypothesis, that enhanced TTDPM would be associated with greater IC knee-flexion angle and excursion, partially was supported, because enhanced TTDPM was correlated with greater IC knee-flexion angle (Figure 4), but

Table 3. Stepwise Linear Regression Analysis Data for Initial Contact Knee-Flexion Angle

Multiple Linear Regression Analysis

Source	Sum of the Squares	Degrees of Freedom	Mean Squares	*F*	*P*	R^2	Adjusted R^2	Standard Error of the Estimate
Regression	551.244	2	275.622	10.259	.001	0.304	0.274	5.183
Residual	1262.738	47	26.867					
Total	1813.981	49						

Predictor	Coefficient	Standardized Coefficient	*t*	*P*
Constant	−5.891		−1.648	.11
Flexion torque	0.081	0.475	3.898	.001
TTDPM flex	2.116	0.273	2.241	.030

Table 4. Stepwise Linear Regression Analysis Data for Knee-Flexion Excursion

Multiple Linear Regression Analysis

Source	Sum of the Squares	Degrees of Freedom	Mean Squares	*F*	*P*	R^2	Adjusted R^2	Standard Error of the Estimate
Regression	252.999	1	252.999	4.066	.049	0.078	0.059	7.889
Residual	2986.982	48	62.229					
Total	3239.981	49						

Predictor	Coefficient	Standardized Coefficient	*t*	*P*
Constant	38.907		6.715	<.001
Extension torque	0.048	0.279	2.016	.049

it was not correlated with knee-flexion excursion. Our second hypothesis, that greater torque would be associated with greater IC knee-flexion angle and excursion, partially was supported, because greater knee-flexion angle and -extension torque were correlated with greater IC knee-flexion angle (Figure 5), but only knee-extension peak torque was correlated with knee-flexion excursion (Figure 6).

TTDPM and Landing Kinematics

The TTPMD values in our study were, on average, 1.4° toward flexion and 1.7° toward extension, which are similar to previously reported values (range, 1.1°–1.9°).[9,20] The IC knee-flexion angle and knee-flexion excursion values in our study were, on average, 9.9° and 50.4°, respectively. In a comparable investigation, Benjaminse et al[29] demonstrated similar IC knee-flexion angle (12.2°) and knee-flexion excursion (41.0°). In our investigation, TTDPM was associated with IC knee-flexion angle, suggesting an important role of knee proprioception in landing techniques.

To our knowledge, this is the first study to report the positive relationship between enhanced TTDPM and greater IC knee-flexion angle during a single-legged stop-jump task. In this joint position, proprioception may be enhanced because of increased afferent mechanoreceptor

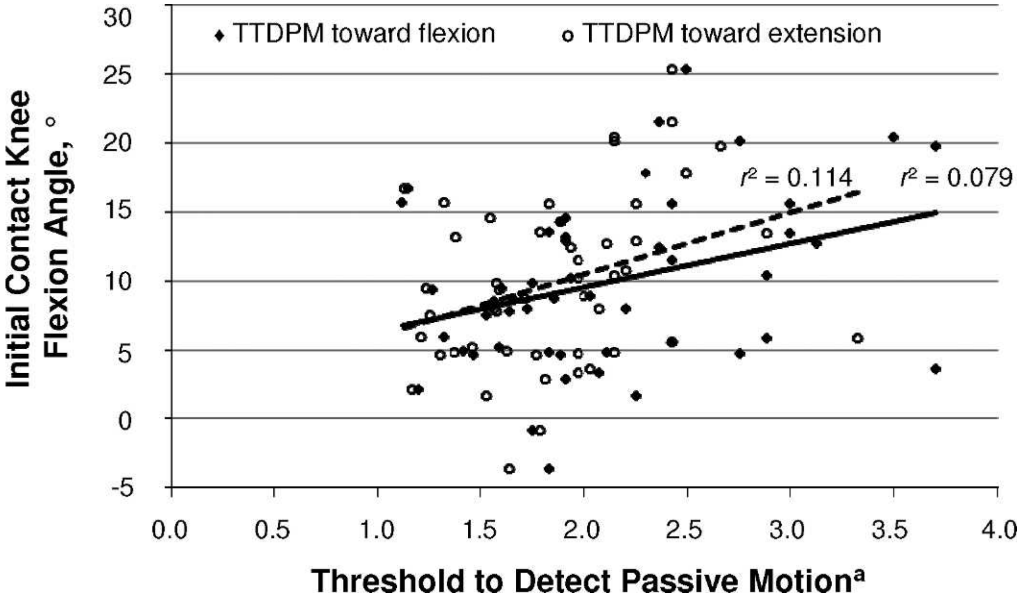

Figure 4. Scatter plots: threshold to detect passive motion versus initial contact knee-flexion angle. ^a Indicates transformed threshold to detect passive motion data ($X' = 1/X + 1$).

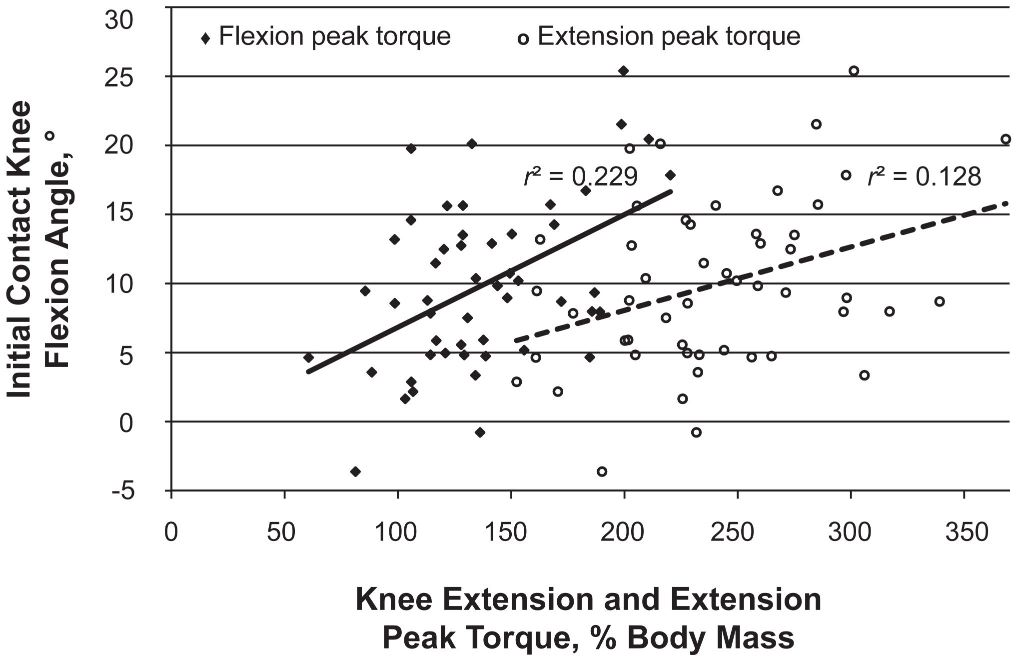

Figure 5. Scatter plots: peak torque versus initial contact knee-flexion angle.

feedback associated with loading of the ACL.[21,23] Given that ligament injury is thought to occur by landing with an extended knee near initial foot contact,[33,34] the IC knee-flexion angle might be regulated tightly within the sensorimotor system to prevent loading conditions of the ACL that may result in ligament rupture. The current results suggest that individuals with better proprioception may recognize movement at dangerous landing positions better and use safer positions.

Strength and Landing Kinematics

The knee-flexion and -extension peak torque were, on average, 137.5% BM and 239.9% BM, respectively. In a comparable investigation, Lephart et al[5] demonstrated similar knee-flexion peak torque (131.7% BM) and knee-extension peak torque (271.7% BM). In our study, knee-extension peak torque was associated with both IC knee-flexion angle and knee-flexion excursion, suggesting an important role of knee muscular strength in landing techniques.

Previous studies[5,12,13] have indicated sex differences in strength and landing kinematics. Males have greater knee-flexion and -extension strength than females, but reports of landing kinematics are mixed.[5,12,13] Whereas Shultz et al[12] noted that males landed with less knee-flexion excursion than females, Lephart et al[5] and Salci et al[13] observed that males landed with greater knee-flexion excursion than

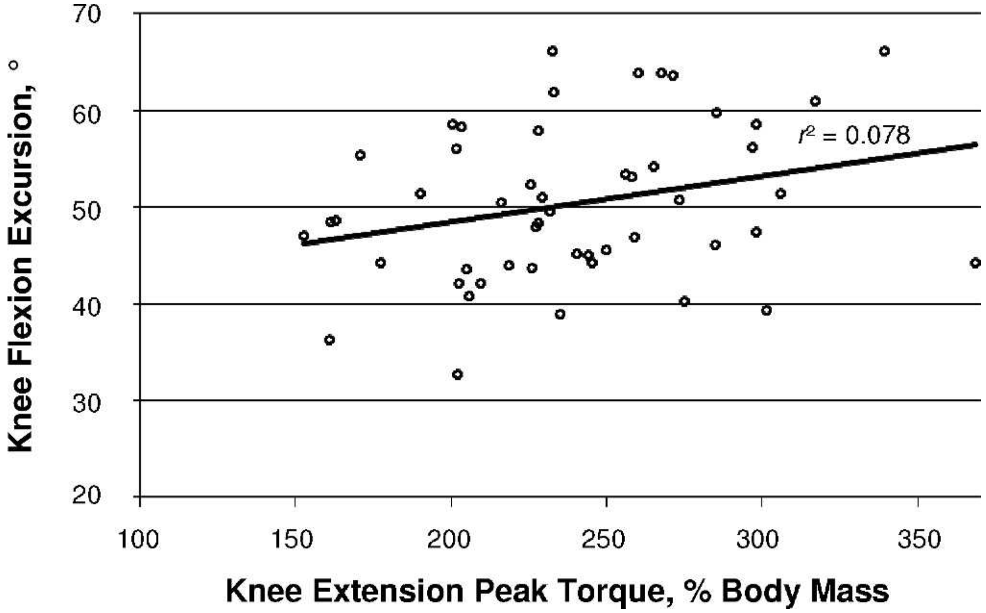

Figure 6. Scatter plots: knee-extension peak torque versus knee-flexion excursion.

females. Inconsistent findings in these studies might be due to differences in participants' athletic backgrounds and landing tasks. Given that the quadriceps muscle eccentrically contracts to control knee flexion during landing, Lephart et al[5] suggested that minimal knee flexion at impact, less knee-flexion excursion, and less time to peak knee-flexion angle in the female athletes might be related to weak quadriceps muscles. Our results support this contention, because individuals with less quadriceps strength landed with less IC knee flexion and knee-flexion excursion during a single-legged stop-jump task.

From a biomechanical perspective, landing with greater knee flexion has mechanical advantages.[14,35] At greater knee-flexion angles, anterior tibial shear force by the quadriceps is minimized, ACL strain is minimal, and the hamstrings provide posterior tibial shear force to stabilize the knee joint.[14,35] We speculated that individuals with greater strength learn to position their knees so the quadriceps and hamstrings perform at optimal capacity to stabilize the joint.

Regression Analyses

The first regression analysis revealed that 27.4% of the variance in IC knee-flexion angle can be accounted for by knee-flexion peak torque and TTDPM toward flexion. Based on the standardized coefficient values, knee-flexion peak torque (standardized coefficient = 0.475) had a greater influence on predicting the IC knee-flexion angle than TTDPM toward flexion (standardized coefficient = 0.273). Clinically, hamstrings resistance exercises should be incorporated to help participants land with greater IC knee flexion.

Knee-extension peak torque was the only variable selected in the second regression model. It revealed that 5.9% of the variance in knee-flexion excursion was accounted for by knee-extension peak torque. Thus, the results suggest that knee proprioception and strength are not strong predictors of the knee-flexion excursion. Our results are in accordance with those of Shultz et al,[12] who reported that thigh strength was not related to knee-flexion excursion.

Limitations

Our investigation had limitations. We included only men. We used several references on sex differences and ACL injuries to demonstrate the role of proprioception and strength on landing kinematics. If the investigation had been conducted with both sexes, the correlation outcomes might have been different. Therefore, our results are not to be interpreted as risk factors for female ACL injury. The purpose of our study was to examine the relationships between knee proprioception and muscular strength and landing kinematics; it was not to examine sex differences. If the mechanisms of noncontact ACL injuries are similar between males and females,[36] identifying participants with less strength and proprioception and impaired landing kinematics is valuable to sports medicine care providers, coaches, and athletes.

CONCLUSIONS

We established 3 important relationships: (1) enhanced TTDPM was related to greater IC knee-flexion angle, (2) greater knee-extensor and -flexor peak torque were related to greater IC knee-flexion angle, and (3) knee proprioception and strength were not strong predictors of the knee-flexion excursion. As we gain more perspective into contributors to functional joint stability, researchers should continue investigating these relationships and focus on understanding optimal strategies to improve each variable.

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Address correspondence to Takashi Nagai, PhD, ATC, Neuromuscular Research Laboratory, University of Pittsburgh, 3830 South Water Street, Pittsburgh, PA 15203. Address e-mail to tnagai@pitt.edu.