Varus/Valgus and Internal/External Torsional Knee Joint Stiffness Differs Between Sexes

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Abstract:

Background: Torsional joint stiffness is thought to play a role in the observed sex bias in noncontact anterior cruciate ligament injury rates.
Hypothesis: Women will exhibit lower torsional stiffness values of the knee in response to varus/valgus and internal/external rotations than will men.
Study Design: Controlled laboratory study.
Methods: Knee kinematics of 20 university students (10 men, 27.3 ± 3.4 years, 177.3 ± 6.8 cm, 81.1 ± 7.0 kg; 10 women, 22.9 ± 1.5 years, 169.0 ± 7.1 cm, 66.1 ± 11.4 kg) were measured while 0 to 10 N · m of varus and valgus torques were applied with the subject nonweightbearing and while 0 to 5 N · m of internal and external torques were applied with the subject nonweightbearing and weightbearing with the use of a custom joint testing device. Joint stiffness values were calculated at 1-N · m increments.
Results: When low magnitudes of torque were applied to the knee, women had significantly lower stiffness values than did men. With the exception of applied external torque with the joint weightbearing and varus torque with the joint nonweightbearing, women demonstrated an increase in joint stiffness as the magnitude of torque increased from lower to higher magnitudes. In contrast, for the men, joint stiffness values remained unchanged as the magnitude of applied torque increased.
Conclusion: Women exhibited lower knee stiffness in response to low magnitudes of applied torque compared to men and demonstrated an increase of joint stiffness as the magnitude of applied torque increased.
Clinical Relevance: The decreased stiffness behavior of the knee in response to low torques that was observed for women may have a role in detrimentally affecting knee biomechanics and resulting neuromuscular function, particularly when an individual transitions from nonweightbearing to weightbearing.

Keywords: knee | biomechanics | incremental stiffness reliability

Article:

Joint stiffness is a biomechanical parameter that characterizes the deformation of the soft-tissue structures connecting one bone to another in response to applied load or torques. It is considered to have implications both for performance and for injury.[4] Human knee joint stiffness can be represented as a torsional spring,[7] which can be described through mechanical means. Stiffness of the knee in response to torques that flex and extend the joint (sagittal plane stiffness) has been included in studies of overall leg spring stiffness[1,6,7]; however, less is known about stiffness of the knee in response to varus (VR), valgus (VL), internal (INT), and external (EXT) torques.[3,9,11,12] Anterior cruciate ligament injury has been associated with VL and EXT torques about the knee,[14] and consequently stiffness characteristics in response to these torques may be important to examine relative to the sex bias in the incidence rate of ACL injury.[9]

There appears to be a paucity of studies that compare VR/VL and INT/EXT torsional knee stiffness between men and women. In cadaveric studies, it has been demonstrated that women have decreased knee stiffness compared with men when combined torques of 10 N · m VL and ± 5 N · m transverse plane tibial torque.[9] However, it remains unclear if there are sex differences in VR/VL or INT/EXT torsional stiffness in vivo in the healthy, intact knee joint. In addition, reported stiffness curves have traditionally been presented as 2 phases. This 2-phase, or breakpoint, analysis[9,13,17] is defined by a phase of "laxity" during low loads and a stiffness calculated as the slope of the load-displacement curve from the end of the laxity phase to a maximal applied load. Because of different ranges of applied load and tangent point choices in analysis of these curves, the use of a 2-phase stiffness model, although widely accepted, may be limited in its generalizability of overall knee biomechanics.

Furthermore, there is a possibility that examining stiffness only as the inverse of laxity, which is displacement in response to fixed load limits, may conceal important physiologic information. For example, in earlier work we have reported that women who demonstrate greater anterior knee laxity also demonstrate greater frontal and transverse plane knee joint laxity compared with men.[23]Examining the overall stiffness of this range would yield little new information. However, by gaining a more thorough understanding of stiffness throughout the load-displacement range, we may better determine where in the measured displacement range that the knee joint is more stiff (eg, more resistive to applied loads or torques) and, conversely, where the knee is less stiff (eg, less resistive to applied loads or torques). In turn, this may help us better understand the sex-dependent factors that may influence knee behavior during physiologic loading conditions.

Thus, the purposes of this study were (1) to determine stiffness values for each 1.0 N · m of applied VR/VL (non-weightbearing [NWB]) and INT/EXT (NWB and weight-bearing [WB]) torques and characterize the day-to-day measurement consistency of these stiffness values obtained from subjects with healthy knees in vivo and (2) to compare these stiffnesses between men and women. It was hypothesized that given greater laxity values observed in women compared with men, women would also exhibit lower incremental stiffness values than would men at some point in the range of applied torques.

MATERIALS AND METHODS

Data for this study were obtained from a larger project examining the clinical usefulness of the Vermont Knee Laxity Device (VKLD, University of Vermont, Burlington) to examine knee joint behavior in men and women[22,23] and consisted of 20 university students (10 men, 27.3 ± 3.4 years, 177.3 ± 6.8 cm, 81.1 ± 7.0 kg; 10 women, 22.9 ± 1.5 years, 169.0 ± 7.1 cm, 66.1 ± 11.4 kg). Whereas previous work reported on the capability of the VKLD to measure frontal and transverse plane laxity of the knee and compared these values in male and female subjects,[22,23] the current investigation is focused on reporting the incremental stiffnesses derived during applied VR/VL (NWB) and INT/EXT (NWB and WB) torques from the obtained data set. Subjects were included if they had no history of knee ligament injury or surgery, had no history of injury or chronic pain in both lower extremities within 6 months of enrollment into the study, and were otherwise healthy. Subjects read and signed a consent form that had been approved by the institutional research board before data collection.

To establish the reliability of the incremental stiffness data obtained, the first 10 subjects (5 male, 5 female) were asked to participate in a second identical data collection session within 24 to 48 hours of the initial test session. Data were collected from both the left and right knees.

Before data collection, electromagnetic position sensors (Mini Birds, Ascension Technologies, Colchester, Vermont) were attached to the lateral aspect of the thigh (just proximal to the thigh clamp portion of the VKLD along the iliotibial band) and to the tibial shaft (distal to the shank strap) to measure knee motion. Hip, knee, and ankle joint centers were determined, and segmental coordinate systems were constructed as previously described.[22]

Knee stiffnesses in response to VR/VL and INT/EXT torques were measured with the VKLD. In previous work, we have described in detail the measurement procedures for VR/VL and INT/EXT knee testing.[22] The first limb tested (left/right) and first direction of applied torque (ie, VR vs VL; INT vs EXT) were counterbalanced across all subjects. All testing began with application of VR/VL torques while the subject was NWB, followed by application of INT/EXT torques while the subject was NWB, and then INT/EXT torques while the subject was WB (defined as a compressive load of 40% body weight applied to the foot). This 40% load was chosen to replicate the double-leg stance loading condition (with 50% body weight on each leg minus the approximately 10% of body weight located below the knee).[21] The subject was positioned supine in the VKLD at 20 ° of knee flexion. With the thigh securely fixed and the foot and ankle tightly restrained in the foot cradle, counterweights were applied to the thigh and shank to create an initial condition of zero shear and compressive loads across the tibiofemoral joint (Figure 1). For VR/VL, an external force was applied to the lateral and medial aspects of the distal tibia using a handheld force transducer (Model SM-50, Interface, Scottsdale, Arizona) to produce the limits of 10 N · m VR and VL torque at the knee (Figure 2), respectively. The INT and EXT torques were applied about the long axis of the tibia to the limit of 5 N · m using a T-handle connected to a 6 degrees of freedom force transducer (Model MC3A, Advanced Medical Technology, Inc, Watertown, Massachusetts) affixed to the foot cradle (Figure 3). After 3 familiarization trials, 3 loading cycles were collected for each motion.

Figure 1. Vermont Knee Laxity Device.

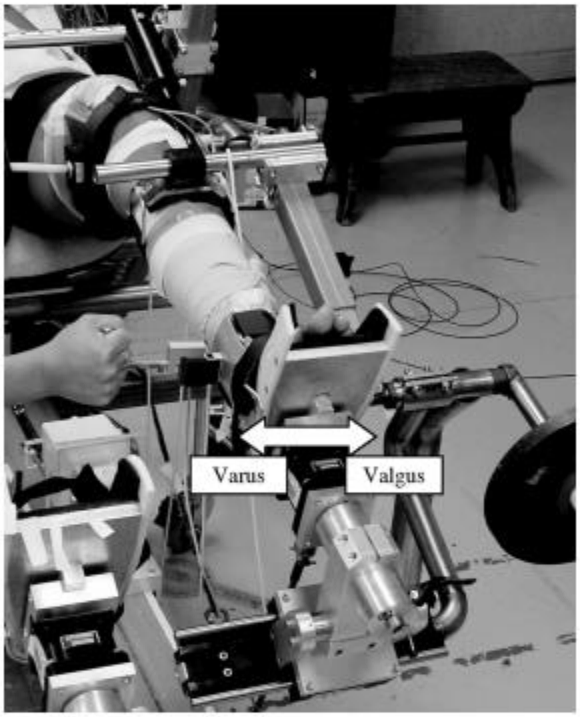

Figure 2. A handheld force transducer applied resistance to the medial and lateral aspect of the distal tibia to create a 10 N·m varus and valgus torque at the knee.

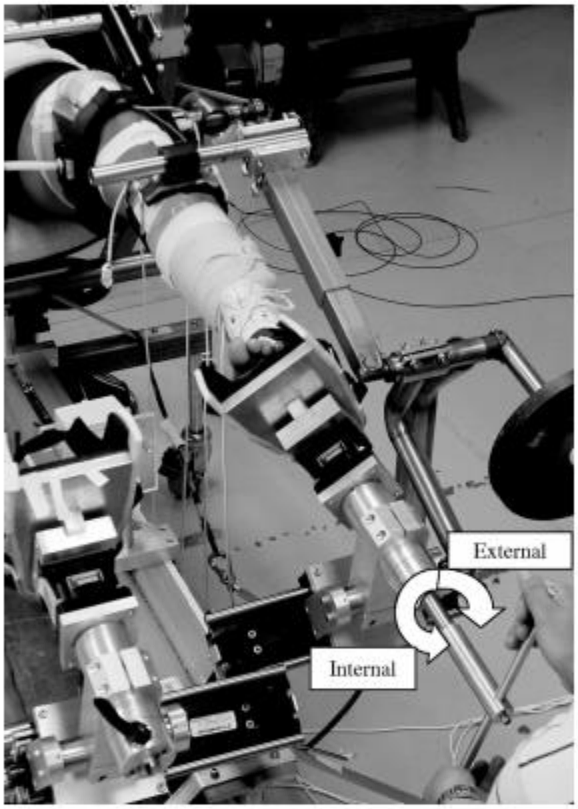

Figure 3. Internal and external rotation torques from 0 to 5 N·m were applied to the knee using a T-handle connected to a 6 degrees of freedom force transducer firmly fixed to the foot cradle.

Signals from all force transducers and electromagnetic position sensors were interfaced with the data collection software (Motion Monitor, Innovative Sports Training, Chicago, Illinois) to allow simultaneous collection of force and displacement measures at 100 Hz. Signals from the position sensors and both handheld and 6 degrees of freedom force transducers were low-pass filtered at 10 Hz and 20 Hz, respectively, using a fourth-order, zero-lag Butterworth filter. For each segment, the + y-axis was directed superiorly, the + z-axis directed laterally for the right leg and medially for the left leg, and the + x-axis directed anteriorly. Euler's equations describe knee joint motion using a rotational sequence of z y' x."[10]

Data Reduction

To form torque-displacement curves, displacements at each 0.1 N · m of applied torque were plotted for each trial. For each condition, the displacements for each of 3 trials were averaged at each 0.1-N · m torque increment. This yielded an ensemble torque-displacement curve for each subject for each test condition.

Each ensemble curve was then divided into increments of 1.0 N · m torques (eg, 1–2, 2–3, 3–4 N · m, etc). For each increment, an incremental stiffness was calculated as the change in applied torque divided by the change in displacement (N · m/deg). This resulted in 10 incremental stiffnesses for the VR loadings (0–10 N · m), 10 for the VL loading, 5 for the INT loading (0–5 N · m), and 5 for the EXT loading.

Data Analyses

On close inspection of the incremental stiffness data, it was revealed that during VL and VR loading, the stiffness values obtained from the increment of 0 to 1 N · m were abnormally high when compared with the mean stiffness values obtained for applied torques between 1 and 10 N · m (VL, 11.57 vs 2.17 N · m/deg [8 SDs greater]; VR, 21.37 vs 2.34 N · m/deg [14 SDs greater]). These abnormally high values were attributed to overcoming any static friction in the device and limb rotational inertia at the point of loading during initial loading. These factors would all result in little to no bony segment movement with the onset of applied loading, thus giving the abnormally high stiffness values. On the basis of this finding, the increment of 0 to 1 N · m was eliminated from the VL and VR analyses. This phenomenon was not observed for INT/EXT measures, likely due to less rotational inertia about the longitudinal axis of the tibia.

Furthermore, a few individual subjects recorded incremental stiffnesses that were negative (a physiologic impossibility) during a loading condition, and therefore these subjects were eliminated from the respective statistical analyses. These negative stiffness values were likely the result of uneven manual application of loads or inadvertent muscle guarding produced by the study participant. This consideration resulted in the elimination of 1 female and 2 male subjects for VR loading (N = 34 total remaining knees), which in turn resulted in the elimination of 2 subjects from the VR measurement consistency analysis. All other conditions retained the full complement of subjects.

In an effort to evaluate the first aim of our study and determine the between-day measurement consistency of incremental stiffness values for the first 10 subjects, separate repeated-measures analyses of variance for each direction and condition (VL, VR, INT [WB and NWB], and EXT [WB and NWB]), increment of applied torque (1–10 VR/VL, 0–5 INT/EXT), and side were used to calculate intraclass correlation coefficient ($ICC_{2,k}$) and standard errors of measurement.

To evaluate the second aim of our study and determine the effect of sex on knee stiffness, 6 separate repeated-measures analyses of variance were performed for VL, VR, INT (WB and NWB), and EXT (WB and NWB) incremental stiffness values, with sex as the between-subjects factor and side (right/left) and increment of applied torque as the within-subject factor. The alpha level was set a priori at $P < .05$, and Tukey’s post hoc testing was used. Given the relatively small sample size, effect sizes were calculated for significant and nonsignificant sex differences.

RESULTS

Measurement Consistency

Median and ranges for ICC values and standard errors of measurements for each loading condition are found in Table 1. The VL, VR, and EXT-WB all demonstrated median ICCs that were acceptable (range, 0.66—0.81). The INT-NWB, EXT-NWB, and INT-WB median ICC values were lower (range, −0.15 to 0.75). Although only the ranges are presented here, it is important to note that there was a general trend in the data that ICC values typically were lower during the higher loading ranges.

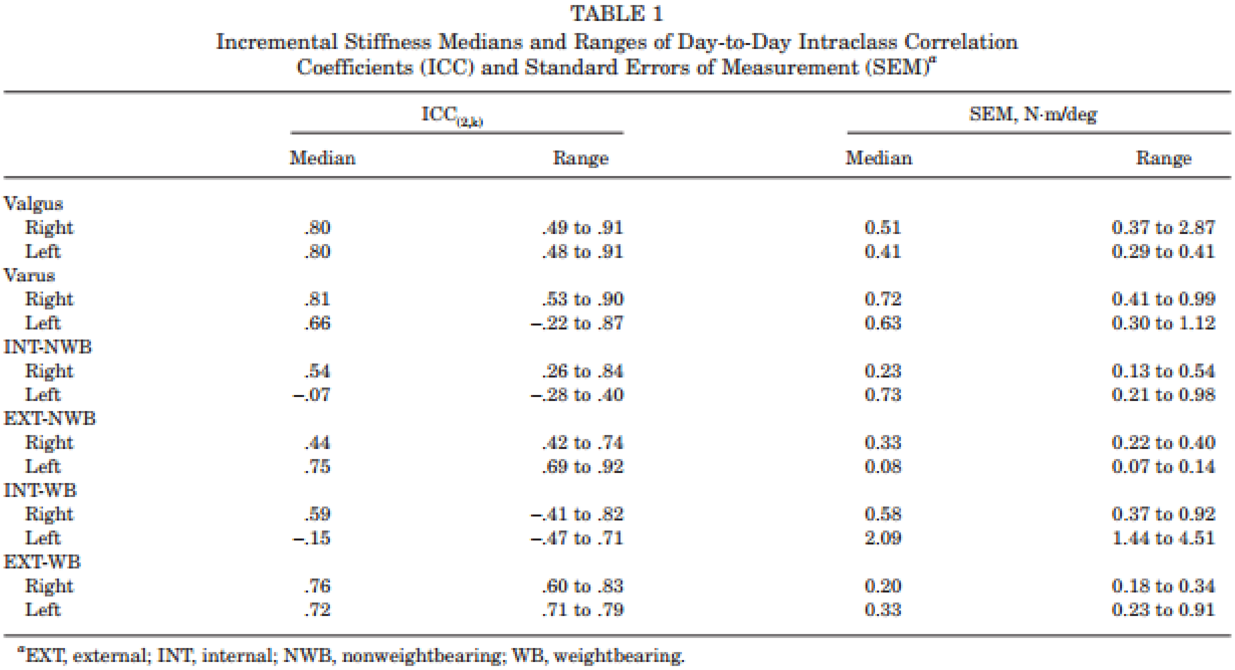

TABLE 1
Incremental Stiffness Medians and Ranges of Day-to-Day Intraclass Correlation Coefficients (ICC) and Standard Errors of Measurement (SEM)[a]

	$ICC_{(2,k)}$		SEM, N·m/deg	
	Median	Range	Median	Range
Valgus				
Right	.80	.49 to .91	0.51	0.37 to 2.87
Left	.80	.48 to .91	0.41	0.29 to 0.41
Varus				
Right	.81	.53 to .90	0.72	0.41 to 0.99
Left	.66	−.22 to .87	0.63	0.30 to 1.12
INT-NWB				
Right	.54	.26 to .84	0.23	0.13 to 0.54
Left	−.07	−.28 to .40	0.73	0.21 to 0.98
EXT-NWB				
Right	.44	.42 to .74	0.33	0.22 to 0.40
Left	.75	.69 to .92	0.08	0.07 to 0.14
INT-WB				
Right	.59	−.41 to .82	0.58	0.37 to 0.92
Left	−.15	−.47 to .71	2.09	1.44 to 4.51
EXT-WB				
Right	.76	.60 to .83	0.20	0.18 to 0.34
Left	.72	.71 to .79	0.33	0.23 to 0.91

[a] EXT, external; INT, internal; NWB, nonweightbearing; WB, weightbearing.

Sex Comparisons

The VL incremental stiffness differed by sex and increment of applied torque ($F_{8,144} = 2.68$, $P = .009$). The VL incremental stiffness values obtained from the female subjects were less than those obtained from the male subjects for applied torques between 1 and 4 N · m (effect sizes, 0.74–1.14). However, the incremental stiffness values between male and female subjects were not significantly different for torques between 4 and 10 N · m (effect sizes, 0.08–0.57). For the female subjects, VL incremental stiffness increased as the magnitude of applied torque increased from 2 to 3 N · m to 9 to 10 N · m. In contrast, male subject incremental stiffness values remained unchanged across these same torque magnitudes (Figure 4).

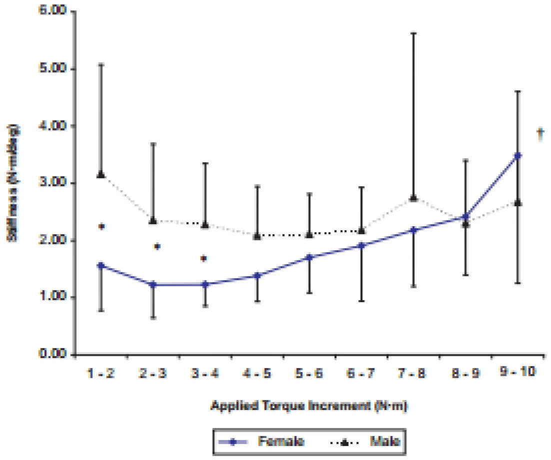

Figure 4. Valgus torsional stiffnesses of the knee for men and women (mean ± SD). *Males' stiffness value significantly greater than that of females. †Females' stiffness significantly greater than the lowest stiffness value for females.

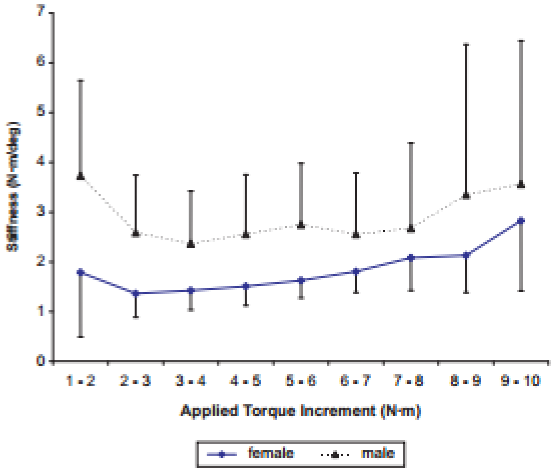

Figure 5. Varus torsional stiffnesses of the knee for male and female subjects (mean ± SD). Main effect for sex as male stiffness was greater than for female stiffness.

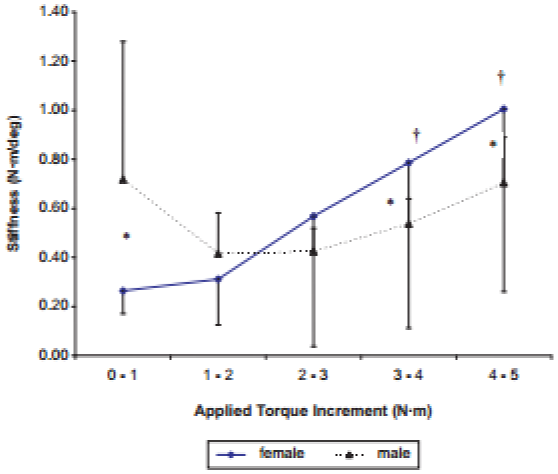

Figure 6. Internal torsional stiffnesses of the knee with the joint unweighted for male and female subjects (mean ± SD). *Stiffness value for one sex significantly greater than that of the other at applied torque increment. †Females' stiffness significantly greater than the lowest stiffness value for females.

The VR incremental stiffness was less in female subjects than in the male subjects ($F_{1,15}$ = 10.62, *P* = .005; effect size, 0.30), and this was not dependent on magnitude of applied torque (Figure 5).

For INT incremental stiffness with the knee unweighted, a significant interaction between sex and increment of applied torque ($F_{4,72}$ = 6.41, *P* < .001) revealed that female subjects had lower stiffness values in response to 0 to 1 N · m of torque (effect size, 0.98) but greater stiffness values for 3 to 5 N · m of applied torque compared with male subjects (effect sizes, 0.59–0.65) (Figure 6). No sex differences were observed between 1 and 3 N · m of applied torque (effect sizes, 0.24–0.33). This interaction was primarily owing to female subjects demonstrating increased knee stiffness values as the applied torques increased from 0 to 1 N · m to 3 to 5 N · m, whereas male incremental stiffness values remained unchanged across these same increments of torque.

For EXT incremental stiffness with the knee unweighted, a significant interaction between sex and increment of applied torque ($F_{4,72} = 3.00$, $P = .02$) again demonstrated lower stiffness values in female subjects for 0 to 1 N · m of applied torque (effect size, 1.18) (Figure 7). No sex differences were observed between 1 and 5 N · m of applied torque (effect sizes, 0.00–0.41) As with INT, female subjects' stiffness values increased as the magnitude of torque increased from 0 to 1 N · m to 3 to 5 N · m, whereas male stiffness values remained unchanged in response to these same torques.

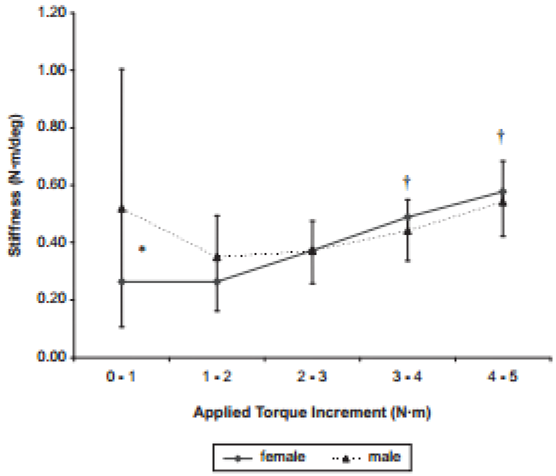

Figure 7. External torsional stiffnesses of the knee with the joint unweighted for male and female subjects (mean ± SD). *Males' stiffness value significantly greater than that of females. †Females' stiffness significantly greater than the lowest stiffness value for females.

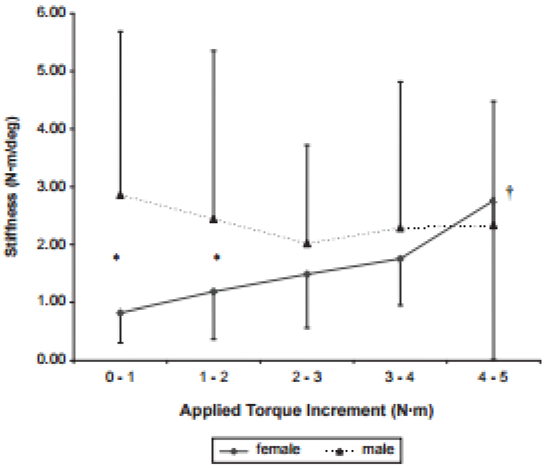

Figure 8. Internal torsional stiffnesses with the knee weight-bearing for male and female subjects (mean ± SD). *Males' stiffness values significantly greater than that of females. †Females' stiffness significantly greater than the lowest stiffness value for females.

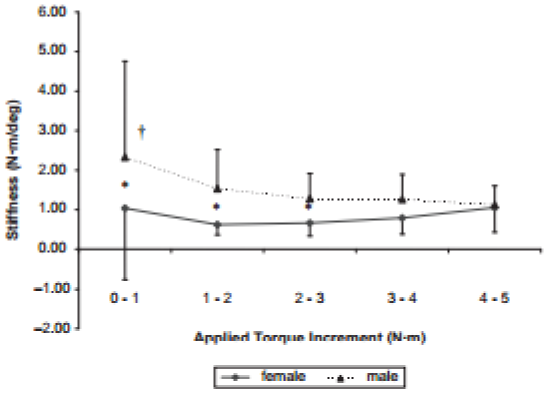

Figure 9. External torsional stiffnesses with the knee weight-bearing for male and female subjects. *Males' stiffness value significantly greater than that of females. †Male knee stiffness greater than the least male stiffness mean.

During the INT with the knee WB, an interaction between sex and increment of applied torque was observed ($F_{4,72} = 3.45$, $P = .01$), revealing female knee stiffness was less than that of male subjects from 0 to 2 N · m of applied torque (effect sizes, 0.61–0.99) (Figure 8). No sex differences were observed for torque magnitudes between 2 and 5 N · m (effect sizes, 0.21–0.26). The stiffness values for the female subjects increased from 0 to 1 N · m to 4 to 5 N · m, whereas stiffness was unchanged for the male subjects.

In EXT with the knee WB, an interaction between sex and increment of applied torque ($F_{4,72}$ = 2.75, $P = .04$) revealed female subjects were less stiff than were male subjects from 0 to 3 N · m of applied torque (effect sizes, 0.53–1.11) (Figure 9). No sex differences were observed between 3 and 5 N · m of applied torque (effect sizes, 0.06–0.41). Stiffness values in both female and male subjects remained relatively unchanged across force increments, with the exception of the initial force increment in males (0–1 N · m), which was slightly higher than their stiffness at the increment from 4 to 5 N · m.

DISCUSSION

This study introduces the use of the VKLD to quantify incremental stiffness values of the knee in response to VR/VL and INT/EXT torques in vivo. Our primary findings confirm that consistent measures can be obtained from 1 day to the next and that women generally exhibited lower knee stiffness in response to low magnitudes of applied torque than do men and demonstrated an increase of joint stiffness as the magnitude of applied torque increased. The discussion will first address our measurement consistency and then explore the implications of the sex differences observed.

Measurement Consistency

Across the entire loading cycle, VL, VR, and EXT-WB median incremental stiffness values were the most consistent measures from day to day ($ICC_{2,k}$ median, .66–.81) (Table 1). For INT, EXT, and INT during WB, the $ICC_{2,k}$ median was much lower (range, −.15 to .75) (Table 1). A detailed examination of the sources of variance used in the calculation of individual incremental reliability coefficients revealed that lower ICC values were owing to both decreased variability between subjects and increased random error as INT and EXT torque magnitudes increased. In addition, the INT-WB condition revealed the ratio of random error relative to the between-subjects variability increased as the magnitude of torque increased. The increased random error associated with lower reliability coefficients observed at higher torque ranges for the INT, EXT, and INT during WB conditions could be explained by various involuntary muscle-guarding responses invoked by the subjects in response to higher loads and the fact that variability in the joint stiffness values decreases between study subjects at higher magnitudes of torque. Although every attempt was made to ensure that the subject was relaxed and did not activate his or her muscles during the NWB conditions, it is possible that subjects may have reacted to the applied loads with different strategies. It is reasonable to assume that if the study participants guarded by contracting their leg muscles, they would do so in ways that would diminish reliability. In addition, through qualitative assessment, these torques often felt the most “unnatural” to the subjects, and this may have created the potential for more neuromuscular guarding. It is important to note that in our previous work addressing knee laxity of the loading conditions derived from this same data set, ICCs, with the exception of INT-WB (.20–.32), ranged between good and excellent (.68–.96).[22,23] When studying these smaller incremental stiffnesses, it is not surprising there is an inherent difficulty in obtaining more precise, reliable measures.

The occurrence of greater reliability when low magnitudes of torque were applied to the knee is important to the discussion of male-female stiffness differences that were observed. Where reliability is decreased owing to increased measurement error, meaningful differences in stiffness would be more difficult to detect in the high torque ranges, and our findings should be viewed in that light. Because of the inability to locate other studies that have reported within-day or between-day measurement consistencies for stiffness values, we are unable to compare our reliability results with previous work.

Differences in Incremental Stiffness by Sex

The main finding of this study is that in response to low magnitudes of torque applied to the tibiofemoral joint, stiffness values measured from the female subjects were less than those of the male subjects. During VL and VR testing, it has been reported that women have, on average, knee stiffness values that are 35% less than that of men.[3] Although this same observation was noted throughout our VR testing, women were less stiff than were men only between 1 and 4 N · m during VL testing. This finding suggests that quantifying an overall stiffness of the knee, as defined by a large magnitude of torque, may not allow a complete understanding of the biomechanical behavior of the knee.

Similar sex differences were noted in response to low magnitudes of torque for all INT and EXT incremental stiffnesses from 0 to 1 N · m. Cadaveric work has shown that women have significantly lower torsional stiffness of the knee (as defined as the slope of the torque-displacement relationship between 2.5 and 5 N · m of INT tibial torque with a simultaneous 10 N · m VL torque).[9] The current study identified that in response to low torques (0–1 N · m), the INT and EXT stiffnesses were less for the female subjects than for the male subjects, and as the magnitude of torque increased (3–5 N · m), there were similar stiffness values between male and female subjects. Although the differences between the current study and previously reported work are likely produced by methodological differences (ie, unidirectional vs multidirectional loading responses), these studies appear to be consistent in reporting decreased joint stiffness in women compared with men.

The incremental stiffness values obtained in the current study are similar to those of previous reports.[3,12] Although in vivo comparisons are few, the VL (range, 1.23–3.49 N · m/deg) and VR (range, 1.36–3.73 N · m/deg) incremental stiffness values obtained with the knee NWB are comparable with terminal or overall VL and VR stiffness previously reported as 3.05 ± 1.02 N · m/deg and 2.94 ± 0.89 N · m/deg, respectively.[3] It must be noted that this prior study applied a 20-N · m torque with the knee extended (at about 0 ° of flexion), whereas our study applied a 10-N · m torque with the knee at 20 ° of flexion. Our study was limited to a 10-N · m threshold, as we have found that study subjects cannot maintain relaxed muscles beyond this magnitude of applied torque. In vivo comparison to our NWB INT (range, 0.26–1.01 N · m/deg) and EXT (range, 0.26–0.58 N · m/deg) incremental stiffness values reveals similar stiffness at 5 N · m NWB INT and EXT as 0.57 ± 0.12 N · m/deg and 0.56 ± 0.12 N · m/deg, respectively.[12] We have been unable to locate previous in vivo INT and EXT stiffnesses with the knee WB.

To the best of our knowledge, this is the first study that has attempted to quantify incremental stiffness values of the knee in response to applied torques. With the exception of WB EXT stiffness (the finding of decreased male knee stiffness in this condition from low to high magnitudes of torque is puzzling but likely the result of both slight malalignment of the VKLD's INT-EXT axis of rotation relative to the tibia's longitudinal axis of rotation and slightly more static friction in the system experienced during the WB condition), women demonstrated an increase of joint stiffness as the magnitude of torque increased from low to high magnitudes, whereas the men's stiffness values were unchanged across the same torque magnitudes. Combined with the result of decreased stiffness for low torque magnitudes in women compared with men, the tissue response suggests women have decreased stiffness in response to low loads followed by increasing incremental stiffness values similar to and in some cases exceeding male values at higher loads. Possible explanations for these differences in joint stiffness values between men and women include differences in the material properties of the ligaments and geometry of the tibiofemoral joint.

This sex-specific tissue response to increasing loads fits well with the previous work of Markolf et al,[12] who suggested that during diagnostic anterior/posterior knee joint laxity evaluation, the examiner should "feel low" when assessing the stiffness of the joint. It was suggested that anterior stiffness changes were best noticed in response to low load levels.[12] Given the current findings, it is possible that a similar suggestion is applicable to the testing of VR/VL and INT/EXT motions of the knee joint.

Previous work by our group demonstrated that women exhibited significantly greater VR/VL and INT/EXT laxities than did men.[23] Although laxity is also a useful measure to assess joint function, stiffness simply reported as the inverse of an overall laxity measure (also described as compliance) may not provide a complete picture of subtle sex differences during the loading process, whereas the observed sex differences in incremental stiffness values may increase our understanding of sex-specific joint function. Although joint stiffness appears to be a function of the magnitude of applied torque for women (through increasing stiffness values across the loading cycle), it appears to be less important in determining joint stiffness for men. Thus, the way in which one defines stiffness (eg, the magnitudes of applied toques that are chosen to measure displacement) has an effect on the data and ultimately the outcome of the analysis.

It is important to note that our approach of measuring stiffness at smaller increments of torque allowed us to demonstrate sex-specific effects at low torque magnitudes but not at high torques. If the study followed previously reported methods and only measured stiffness in response to high torques,[9] a sex effect may not have been found. Although many different techniques could have been used to analyze the data (eg, a logistic fit or polynomial fit to the data), allowing us to compare the coefficients or slopes of these fits between sexes, we believe that our current approach allowed us to characterize and ultimately understand joint stiffness behaviors throughout the entire loading cycles. With this approach, a more comprehensive description of joint biomechanics was obtained.

Clinical Implications

Studies of ACL injury mechanisms typically describe an injury that occurs at or near foot strike with the knee near full extension.[2,14] The observation that women have lower knee stiffness values than do men when low magnitudes of torque are applied may have important implications when impulsive loads are transmitted across the joint during the onset of WB. For example, research has shown that during the transition from NWB to WB, there is an anterior translation of the tibia relative to the femur that is restrained by the ACL, and this translation is greater in those with increased knee laxity.[21] Although these prior findings are restricted to the anteroposterior direction, they suggest that during common athletic tasks such as the heel strike phase of gait, when landing from a jump, or during a plant-and-cut maneuver, decreases in knee stiffness may be associated with alterations in early joint positioning that could produce corresponding effects on the sequence and magnitude of muscle contractions.[9] This, in turn, could produce sex differences in neuromuscular strategies for controlling potentially injurious motion. Given the recent finding of a VL mechanism of ACL injury,[8] our observation of decreased female knee stiffness in response to VL torques highlights the need for alternate strategies of neuromuscular control to augment joint stiffness and protect the knee ligaments. Studies examining sex differences in neuromuscular recruitment have demonstrated that women activate their muscles sooner[5,20] in response to perturbing activities that have been reported to include components of VL and EXT rotations of the tibia relative to the femur.[16]The finding that women activate their muscles sooner in response to a perturbation may be a neuromuscular adaptation to the decreased joint stiffness for women as demonstrated in the current study. This contention is supported by studies that have observed increased muscle activation (both preparatory and reactive), particularly in the lateral hamstrings, during WB activity in women who have greater knee laxity values.[15,18] It may also be an adaptation to help mitigate the increased stiffness values that were associated with high magnitudes of torque during NWB VL, NWB INT/EXT, and WB EXT loadings.

Limitations

Although great care was taken to control all aspects of the study, several limitations exist. Extensive pilot testing was performed to ensure the most stable sensor position possible, but it should be recognized that the superficial skin markers used may not exactly represent true skeletal motion. This same concern exists for all approaches that attempt to measure lower limb biomechanics with the use of external markers attached to the skin. Furthermore, although the same examiner applied torques in a consistent manner, the torque loading rate was controlled by the investigator and was not mechanically standardized. It should also be noted that the 40% body weight load used is well below body weight loads incurred during dynamic activity (eg, walking, running); thus, our WB results should be viewed in reference to the foot contact that occurs during the early foot phase of weight acceptance. Finally, the efforts undertaken to control for neuromuscular effects on stiffness included oral instructions, practice trials for acclimation of subjects, and visual observation on the part of the researcher; however, EMG data were not included, and therefore the level of muscular activation was not documented.

In addition, certain subject characteristics were not controlled that may influence the data. Hormone level or cycle phase in women was not documented for day-to-day reliability testing.

As ligamentous laxity has been shown to be affected by fluctuations in hormone levels,[19] it is possible that small fluctuations in joint laxity could have occurred between repeat measures taken within 24 to 48 hours of the first test session and, in turn, affected the reliability of incrementally derived stiffness measurement between days. Although subjects were carefully questioned to ascertain the health history of their knees and lower extremity, a formal knee examination was not performed to screen out any potential joint abnormalities, nor was level of physical activity controlled.

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Footnotes

No potential conflict of interest declared.

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