Medial Tibiofemoral-Joint Stiffness in Males and Females Across the Lifespan

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Context: Analyzing ligament stiffness between males and females at 3 maturational stages across the lifespan may provide insight into whether changes in ligament behavior with aging may contribute to joint laxity.

Objective: To compare the stiffness of the medial structures of the tibiofemoral joint and the medial collateral ligament to determine if there are differences at 3 distinct ages and between the sexes.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: A total of 108 healthy and physically active volunteers with no previous knee surgery, no acute knee injury, and no use of exogenous hormones in the past 6 months participated. They were divided into 6 groups based on sex and age (8–10, 18–40, 50–75 years).

Main Outcome Measure(s): Ligament stiffness of the tibiofemoral joint was measured with an arthrometer in 0° and

 20° of tibiofemoral-joint flexion. The slope values of the force-strain line that represents stiffness of the medial tibiofemoral joint at 0° and the medial collateral ligament at 20° of flexion were obtained.

original research

Results: When height and mass were controlled, we found a main effect (P < .001) for age group: the 8- to 10-year olds were less stiff than both the 18- to 40- and the 50- to 75-year-old groups. No effects of sex or tibiofemoral-joint position on stiffness measures were noted when height and mass were included as covariates.

Conclusions: Prepubescent medial tibiofemoral-joint stiffness was less than postpubescent knee stiffness. Medial tibiofemoral-joint stiffness was related to height and mass after puberty in men and women.

Key Words: medial collateral ligament, arthrometry, hormones, sex differences

Key Points

• Medial tibiofemoral-joint stiffness was less in prepubescents than in postpubescents.

• After puberty, medial tibiofemoral-joint stiffness was influenced by height and mass in both men and women.

The mechanical properties of connective tissue with respect to sex have been studied mainly in an effort to explain the greater risk of knee ligament injury in female athletes than in male athletes. Most authors^{1–3} have focused on the laxity of the anterior cruciate ligament (ACL) in postpubertal men and women. Theories have been generated and extensive research has been conducted to explain the two- to eightfold increase in ACL injuries in female athletes over male athletes.^{1–4} Although a single cause has not been identified, risk factors have been generalized into 4 categories⁵: environmental (external factors such as surface and footwear),⁵ anatomic and postural,^{1–4} hormonal,^{6–13} and biomechanical^{14–16} (such as kinematics^{16,17} and neuromuscular factors^{15,18,19}).

The injury rate to the collateral ligaments of the knee is also greater in females than males but not to the same extent as for ACL injury.^{1,2} However, the medial collateral ligament (MCL), a major stabilizing structure in the tibiofemoral joint, remains a prevalent source of injury in the general population,²⁰ particularly as a result of sport participation.^{1–3} As males and females mature from prepuberty, through puberty and adulthood, and then reach the postfertile years, the material properties and structure of the joints change, as do hormonal levels.^{21–23} In this study, we examine the mechanical and material properties of the MCL and other supporting structures of the tibiofemoral joint in vivo in prepubertal and postpubertal males and females and older adults, including postmenopausal females. These properties in these groups of participants have not been previously described in the literature. Examining the material properties of a ligament, such as stiffness, provides a way to detect joint structural differences between sexes and across age groups, thus elucidating structural differences in the ligament material properties secondary to the exposure to sex hormones. Aronson et al^{24,25} measured stiffness of the medial

Aronson et $al^{24,25}$ measured stiffness of the medial tibiofemoral joint in full extension because of the important role the medial joint structures play in minimizing valgus positioning (abduction of the joint), which has been suggested to contribute to ACL injury risk.^{3,5,15–17} Additionally, Aronson et $al^{24,25}$ examined the extracapsular MCL in 20° of flexion to reduce the confounding contributions of possible changes in intracapsular structures, such as meniscal injury and articular degeneration, to stiffness measurements.

The purpose of our investigation was to assess the stiffness of the medial tibiofemoral joint in full extension and the MCL in 20° of flexion in males and females in 3



Figure 1. Plot of a force-strain line demonstrates the stiffness of a child's medial tibiofemoral joint in 0° of flexion (gray line) and in 20° of flexion (black line). The joint structures are more resistant to force in full extension than when the joint is flexed. The inflection points characterize the stiffness measurement for this participant, as the slope value is calculated where the linear lines begin to become curvilinear. The difference in the inflection points in this person is 0.79 mm.

distinct age groups (prepubertal children, postpubertal young adults, and older adults).

METHODS

We performed an observational study that used a crosssectional design. The 3 independent variables were sex (male, female), knee position (0° , 20° of flexion) and age group (8–10, 18–40, and 50–75 years). The dependent variable was the slope value (sv) of the force-strain curve, which represents stiffness of the medial tibiofemoral joint.

Participants

We recruited a convenience sample of 108 healthy and physically active volunteers from 2 universities and the surrounding communities. Exclusion criteria were previous knee surgery and any acute knee injury or pain. None of the participants reported a history of hip replacement or reproductive system surgery. Participants had not used exogenous sex hormones, including oral contraceptives, hormone replacement therapy, or anabolic steroids, in the past 6 months; therefore, any circulating hormones could be assumed endogenous.

We considered females in the 8- to 10-year-old age category prepubescent because they denied reaching menarche. All females in the 18- to 40-year-old age category reported a regular menstrual cycle (10–12 periods per year).²⁶ Further, we elected to test women in the 18- to

40-year-old age category while they were menstruating (days 1–4 of the menstrual cycle) for consistency. Females recruited in the 50- to 75-year-old age category were considered postmenopausal because they denied menstruating for at least 1 year before the study. All males recruited were in the same age groups as the females.

We obtained informed consent, including parental assent for minors, before the study, which was approved by the institutional review boards of the 2 universities where the data were collected.

Instrumentation

We used the LigMaster system (version 1.26; Sport Tech. Incorporated, Charlottesville, VA) to generate slope values from the force-strain relationship that constituted our unit of measurement. We used another version (1.36) of the LigMaster software to retrieve the portion of the data points that best represented the force-strain relationship of each individual participant. A typical force-strain relationship produced by the LigMaster software is shown in Figure 1. The plot features an initial linear portion up to approximately 6 dN of force, beyond which the line curves upward. The initial part represents the stretching of only the MCL, but as the force increases further, other medial structures (such as the skin and joint capsule) are expected to contribute to the resistance. The point of change in slope (ie, the inflection point) varies with the habitus of the individual and occurs at lower force in children. To



Figure 2. Setup for measuring the right medial tibiofemoral joint on a child. Bony landmarks are identified for positioning. Sensors from a biofeedback device will be placed on the right thigh muscles when positioning is complete. This participant's limb is too small to use the footplate.

determine the range of the initial linear part of the line consistently and, thereby, the slope that represents the MCL only, we used a special software feature of the LigMaster system. This feature allowed us to determine, within the specified percentage of accuracy, the linearity of collected data points. Thus, the extent of initial linearity and, thereby, the true value of the initial slope could be established objectively for each individual (Figure 1). We used the slope value generated by the software, representing the stiffness of the tissue, for statistical analysis.

We used a dual-channel EMG Retrainer (model BF; Chattanooga Group, Inc, Chattanooga, TN) to confirm the medial muscles surrounding the knee were electrically inactive. We also used a standard goniometer (model G 800; Whitehall Manufacturer, City of Industry, CA) to accurately place the knee in 0° and 20° of tibiofemoral joint flexion, following procedures suggested by Norkin and White.²⁷

Testing Procedures

We asked participants to refrain from exercise within 1 hour of testing. Each person was examined in a single



Figure 3. Patient and leg positioning in the arthrometer for testing the left medial tibiofemoral joint in full extension (0° of flexion) in an adult.



Figure 4. A child's knee joint in full extension (0° of flexion) with 10 dN of force applied to the lateral aspect of the medial tibiofemoral joint line. The valgus positioning is a result of the force applied.

testing session. The positioning of each participant has been described previously in detail.^{24,25} We positioned and secured the side arms of the LigMaster in place at equal distance from the pressure plate and just superior to the lateral aspect of tibiofemoral joint line. In addition, we positioned the side arms closer to the pressure plate in the children to accommodate shorter legs (Figure 2). Further, we changed the setting on the LigMaster software to allow for smaller joint circumferences in the children. To determine leg dominance, each participant was asked which leg he or she would use to kick a ball a long distance. This leg was positioned in the arthrometer with the foot on a footplate to secure the leg and reduce rotation of the tibia and femur during testing (Figure 3). We did not use the footplate while testing children because their legs would not reach the device when placed in the arthrometer. Additionally, rotation of the tibia and femur was less in children because of the smaller force applied to the joint.

We placed sensors from a superficial biofeedback device on the vastus medialis and the medial hamstring muscle bellies to confirm that these muscles were relaxed (Figure 3). Muscle contraction would add dynamic stability²⁸ to the joint, which we wanted to minimize to study the passive noncontractile restraints to the valgus force. We encouraged participants to relax the muscles of the leg we were testing, especially if the biofeedback instrument detected muscle activity with any auditory feedback, and we initiated data collection once the biofeedback device was quiet.

The examiner manually applied a gradual and slow force of 50 to 120 N (5–12 dN) to the lateral tibiofemoral joint line; children withstood only 5 to 10 dN force, whereas adults received 12 dN of force. A child's tibiofemoral joint under strain as the force reached 10 dN is shown in Figure 4. We repeated trials until we achieved 2 trials within 5% of each other. Once we finished testing the joint in 0° of flexion (neutral), the participant sat on the table with arms outstretched behind his or her back to relax the muscles inserting at the hip, with the leg placed over a 4-in (10.16cm) foam roller to test the knee in 20° of knee flexion. The foam roller was rolled under the thigh until the proper joint



Figure 5. Patient and leg positioning in the arthrometer for testing the right medial tibiofemoral joint with the knee in 20° of flexion.

angle was achieved and was left in place, allowing the participant to passively place the joint over the roller and relax the hip and knee musculature (Figure 5).

Statistical Analysis

We calculated intraclass correlation coefficients (ICCs [3,1]) and standard errors of measurement (SEMs) for each age group in flexion and extension from the 2 recorded trial measures to assess intratester reliability and precision of measurement. The SEMs were calculated in the unit of measurement (slope values).

We computed a $3 \times 2 \times 2$ mixed-model analysis of covariance to assess the effect of age group (children, young adults, older adults), sex (males, females), and position (extension, flexion) on medial tibiofemoral-joint stiffness. We entered each participant's body mass and height as covariates because of obvious differences in these measures between children and adults. Age group and sex were treated as between-groups factors and position as a within-group factor. We used the Fisher least significant difference test for appropriate post hoc comparisons. The level of significance was set a priori at P < .05. We used SPSS (version 19.0; IBM Corporation, Somers, NY) to conduct all analyses.

RESULTS

We demonstrated excellent reliability and precision of measure with repeated measures: children in extension, ICC = 0.99, SEM = 0.16 sv; children in flexion, ICC = 0.94, SEM = 0.24 sv; young adults in extension, ICC = 0.99, SEM = 0.27 sv; young adults in flexion, ICC = 0.99, SEM = 3.02 sv; older adults in extension, ICC = 0.98, SEM = 0.39 sv; and older adults in flexion, ICC = 0.98, SEM = 0.45 sv.

Table 1. Participants' Demographic Information

No differences were noted in the mean ages of males and females within each group. Although the girls in the 8- to 10-year-old range were, on average, taller and heavier than their male counterparts, their heights and masses were not statistically different. We found no differences in the mean height or mass of the 18- to 40-year-old group or the 50- to 75-year-old group, but men in these groups were taller and heavier than women (Table 1).

After normalizing body mass and height of participants, we identified a main effect for age group (P < .001). When males and females and flexion and extension values were pooled, children (mean = 8.77 sv, 95% confidence interval [CI] = 7.03, 10.51) exhibited less medial tibiofemoral-joint stiffness than both young adults (mean = 14.43 sv, 95% CI = 13.66, 15.20) and older adults (mean = 14.12 sv, 95% CI = 13.32, 14.92). We identified no other main effects or interactions. The height and mass unadjusted means and 95% CIs are reported in Table 2 and the adjusted values in Table 3. Careful examination of these tables reveals that, although the 95% CIs generally did not overlap between adult males and females for the unadjusted means, they did overlap considerably for the adjusted means. Therefore, in adults, body size appears to have a more substantial influence on medial knee stiffness measures than does sex. Although children showed less medial stiffness than the younger and older adults, we observed no differences in stiffness between the sexes in any age group when stiffness was normalized to height and mass.

DISCUSSION

Our primary findings were that, when controlling for height and mass, children had less medial knee stiffness than younger and older adults and that males and females did not differ in this respect. Some differences were noted between males and females in unadjusted stiffness measures; for example, women had less knee stiffness in flexion than men in both the younger and older adult groups. However, these differences were absent once the influences of height and mass were added to the statistical model. Thus, height and mass appear to have more influence on medial knee stiffness measures than age or sex.

Comparable results were observed by Anderson et al,²⁹ who used 5 different arthrometers and found no difference in average anterior translation laxity of normal knees in men compared with women. However, Markoff et al,²⁸ who were among the first to use an arthrometer to assess knee laxity in vivo, observed that women have greater joint laxity than men after puberty.^{10,11,23} They found 37% greater knee valgus stiffness in the MCL of men than in women at full extension.²⁸

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Sex	n	Age Range, y	Age, y (Mean \pm SD)	Mass, kg (Mean \pm SD)	Height, cm (Mean \pm SD)
Males	13	8–10	8.92 ± 0.86	32.16 ± 7.04	132.08 ± 7.12
Females	13	8–10	9.31 ± 0.75	34.04 ± 5.54	137.38 ± 6.99
Males	23	20–40	29.13 ± 6.28	85.43 ± 15.55	177.22 ± 5.94
Females	23	19–40	30.48 ± 7.67	69.26 ± 12.48	164.86 ± 6.92
Males	18	52-74	60.83 ± 6.31	86.11 ± 12.88	176.97 ± 7.97
Females	18	53-73	60.06 ± 6.19	70.76 ± 6.95	162.81 ± 5.67
Total	108				

Table 2. Unadjusted Medial Collateral Ligament Stiffness Measures Across Age Groups, Sexes, and Knee Positions

	Slope Value, ^a Mean (95% Confidence Interval)					
	Males		Females			
Age Group	Extension	Flexion	Extension	Flexion		
Children	7.13 (5.80, 8.45)	5.49 (4.08, 6.90)	7.29 (5.97, 8.61)	5.74 (4.34, 7.15)		
Younger adults	17.56 (16.57, 18.55)	14.82 (13.76, 15.88)	15.88 (14.89, 16.87)	12.28 (11.22, 13.34)		
Older adults	17.72 (16.60, 18.84)	14.45 (13.25, 15.65)	15.47 (14.35, 16.59)	12.05 (10.86, 13.25)		

^a Force-strain line.

Age Differences in Ligament Structure

Prepubescent girls and boys are structurally and hormonally more alike than at other ages,²² with no differences in the blood concentrations of the 2 major sex hormones (testosterone [androgen] and estrogen²¹) or cumulative joint-laxity scores.²³ Our results showed that ligament stiffness was also similar in male and female children, at least for the MCL and medial knee joint capsule. Other ligamentous tissues may respond differently. It is important to note that greater ligament stiffness does not translate into greater protection against the risk of joint injury. Knee injury rates in children are lower than in young adults, even when they participate in similar activities.²⁰ Children are exposed to smaller forces and may be at lower risk of ligament injury as a result. Thus, the differences in injury rates between prepubescent and adult athletes may have little to do with ligament stiffness.

Age-related changes in the musculoskeletal system include first an increase and then attenuation of bone mass, skeletal muscle, and articular cartilage. Intervertebral discs, tendons, ligaments, and joint-capsule fibrous tissue all degenerate with age after puberty.³⁰ Collagen tissue strength increases as cross-bridges increase in number, but as aging progresses past 20 years, the collagen content in ligaments decreases and strength, stiffness, and resistance to force also decrease.³¹ Joint stability declines with the regression of physical conditioning and adaptive muscular control. 30,32 With age, we experience a loss of strength with inactivity; the mechanism by which tensile strength of the ligament decreases after immobilization is believed to be the same as with aging.^{31,33} Ligaments are "passive restraints" of joints in concert with joint geometry; thus, they provide the knee with functional stability.³² Injury and resultant laxity of the joint may lead to joint wear and arthritis over time. Ligament stiffness also changes with osteoarthritis.³⁴ However, no participants with documented osteoarthritis were included in this study.

Our results support earlier findings that ligament stiffness increases with maturation, ie, from prepubescence to adulthood. The physiologic mechanism by which a ligament stiffens through puberty and full maturation, linear or curvilinear over time, is unknown. These findings do not support the theory that ligament stiffness decreases with advanced aging in those who are healthy, physically active, and free of osteoarthritis and who have suffered no diagnosed injuries to the knee joints.

Sex Differences and Joint Laxity

Dragoo et al⁸ have found that ligamentous tissue goes through variations in laxity during the menstrual cycle and that collagen remodeling probably cannot keep pace with monthly hormone changes. Because the turnover of collagen in ligaments is slow (100-500 days), an increase in circulating female hormones for 2 to 3 days per month would be unlikely to change the structure or the mechanical properties of a ligament, or even if these properties do change, they are probably insufficient to increase joint laxity during the high estrogen-production phase of the menstrual cycle.^{6,8} This is a reasonable conclusion to the question of whether estrogen surges have an effect on any ligament's ability to stabilize the knee joint throughout the female's menstrual cycle. Whether a 40-year exposure to estrogen and other female hormones changes the structural and mechanical properties of ligaments is still an open question. The results of our study suggest that medial tibiofemoral-joint and MCL stiffness do not differ in 18- to 40- or 50- to 75-year-old men and women when mass and height are considered and that mass contributes the greatest amount of variance in this measurement. Further research may involve measuring sex hormones at the time of stiffness measurements to reveal whether this finding is consistent in other participants studied throughout the lifespan.

Other authors have studied the properties of the in vivo healthy MCL and supporting structures in the tibiofemoral joint in adult females using oral contraceptives. In 1 study,¹² males displayed greater passive frontal-plane stiffness than females, even after normalizing mass and height. Also, knee diameter was positively correlated with knee stiffness.¹² Although we did not find differences in male and female medial tibiofemoral-joint stiffness after

Table 3. Medial Collateral Ligament Stiffness Measures Across Age Groups, Sexes, and Knee Positions Adjusted for Mass and Height^a

Age Group	Slope Value, ^b Mean (95% Confidence Interval)					
	Ma	lles	Females			
	Extension	Flexion	Extension	Flexion		
Children	8.90 (6.48, 11.32)	8.51 (6.09, 10.92)	9.00 (6.85, 11.16)	8.66 (6.50, 10.81)		
Younger adults	16.62 (15.18, 18.05)	13.23 (11.80, 14.66)	15.78 (14.79, 16.77)	12.11 (11.12, 13.10)		
Older adults	16.74 (15.23, 18.26)	12.78 (11.27, 14.30)	15.26 (14.16, 16.36)	11.69 (10.59, 12.80)		

^a Mass and height treated as covariates.

^b Force-strain line.

normalizing mass and height, we concur that knee size relates to mass and height in both sexes, especially in postpubertal development. The difference in results between these studies may be due to the differences in methods used to quantify joint stiffness.

When comparing stiffness across age groups and sexes, it is important to understand the meaning of the slope values in the force-strain relationships. Joint stiffness is defined as the rate of change of load with deformation.²⁸ In previous studies,^{13,25,34} a linear first-order approximation has been used to determine the slope of the load-elongation curve. With the LigMaster arthrometer, the encoders record forcedisplacement (load-deformation) data that the software subsequently processes to produce second-order plots of applied force against induced strain, rather than stress against strain.³⁵ Therefore, when we plot force against strain, the slope of the initial linear part equals the product of the cross-sectional area of the unstretched ligament (Ao) and its elastic modulus (E).^{31,36} An observed decrease in the slope could therefore represent a decrease in either Ao or E or both, depending on the circumstances. For instance, in acute ligament injury, a decrease in joint stiffness, as represented by a decreased slope value, would be due to a decrease in Ao as the result of a partial tissue tear.³⁷ However, an increase in slope is likely due to a higher value for E, as we expect to see in the chronic setting when scar tissue has replaced much of the normal elastin or when calcification has occurred. In still other cases, both Ao and E can be affected simultaneously when, for instance, both ligament attenuation and scarring or calcification are present. However, we found no differences between younger and older adults in joint stiffness, indicating that, after the tissues mature and in the absence of acute injury, both values remain consistent over time during aging.

CONCLUSIONS

Prepubescent medial tibiofemoral-joint stiffness was less than postpubescent knee stiffness. Medial tibiofemoraljoint stiffness was substantially influenced by height and mass after puberty in both men and women. After puberty, once the data were adjusted for height and mass, the sexes did not differ in medial tibiofemoral-joint stiffness in full extension or when the MCL was isolated by flexing the knee. Also, medial tibiofemoral-joint stiffness did not differ between adults 18 to 40 and 50 to 75 years old. We found no age-by-sex interaction, indicating that the effect of sex did not differ across the 3 age groups. Thus, we believe that hormonal differences between sexes are less significant than the effect of the individual's postpubertal height and mass on MCL knee stiffness.

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