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Elevated Anterior Cruciate Ligament Stiffness and Anterior Tibial Translation: Objective Measures in Medial Meniscus Root Tear Patients.

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Abstract:

Introduction: Medial meniscus posterior root tears (MMPRT) are hypothesized to alter knee biomechanics, potentially impacting anterior cruciate ligament (ACL) function. This study aimed to investigate the relationship between MMPRT, ACL stiffness, and anterior tibial translation.

Materials and Methods: Fifty-six patients with unilateral MMPRT diagnosed via MRI (study group) and 31 healthy volunteers (control group) were enrolled between January and June 2010. Anterior tibial translation was measured using the KT-1000 arthrometer. ACL stiffness was assessed using ultrasound shear wave elastography (SWE). Tibial slope was measured from lateral radiographs at 30 degrees of knee flexion.

Results: The study included 87 participants: 31 controls (25 females, 6 males) and 56 MMPRT patients (48 females, 8 males). ACL SWE values were significantly higher in the MMPRT group (26.6±8.9 kPa) compared to the control group (21.2±5.7 kPa, $p=0.004$), indicating increased ACL stiffness. Anterior tibial translation, measured with the KT-1000, was significantly greater in MMPRT-affected knees (6.19±1.4 mm) compared to unaffected knees (4.9±0.78 mm, $p<0.05$). Multivariable regression analysis revealed a significant positive correlation between ACL SWE values and tibial slope ($\beta=1.11$; CI, 0.24–1.99; $P=0.01$), suggesting that increased tibial slope contributes to increased ACL stiffness.

Conclusions: Patients with MMPRT exhibited increased anterior tibial translation and elevated ACL stiffness, as evidenced by higher SWE values. Furthermore, increased tibial slope was associated with greater ACL stiffness. These findings suggest that MMPRT significantly alters knee biomechanics, potentially increasing ACL loading and influencing knee stability. This study highlights the importance of considering MMPRT in the assessment and management of ACL-related knee pathologies.

Level of Evidence: Level III, retrospective cohort study.

Introduction:

The knee joint, a complex articulation designed for both stability and mobility, relies heavily on the intricate interplay of ligaments, menisci, and surrounding musculature. Among these structures, the medial meniscus and the anterior cruciate ligament (ACL) play pivotal roles in maintaining joint integrity and facilitating physiological biomechanics. The medial meniscus, a fibrocartilaginous, crescent-shaped structure, serves to distribute load, absorb shock, and enhance joint congruity. The ACL, a primary stabilizer, restricts excessive anterior tibial translation and rotational instability. Disruptions to either of these structures can significantly compromise knee function and lead to progressive joint degeneration. Medial meniscus posterior root tears (MMPRTs), specifically, are gaining increasing recognition as a critical injury pattern with profound biomechanical consequences. The posterior root of the medial meniscus serves as a vital anchor, transmitting hoop stresses and ensuring proper load distribution across the tibial plateau. When this root is disrupted, the meniscus loses its ability to effectively convert compressive forces into circumferential tension, leading to extrusion of the meniscus and increased contact pressures on the articular cartilage. This altered load distribution can precipitate accelerated osteoarthritis, particularly in the medial compartment of the knee. The biomechanical consequences of MMPRTs extend beyond the immediate vicinity of the meniscus, impacting other critical structures, notably the ACL. The loss of the meniscus's stabilizing function can lead to increased anterior tibial translation, placing greater strain on the ACL. This increased strain, if sustained, can result in alterations to the ACL's structural and mechanical properties, potentially predisposing the ligament to injury or contributing to the progression of knee instability. Understanding the intricate relationship between MMPRTs and ACL biomechanics is crucial for optimizing clinical management and preventing long-term sequelae. Previous studies have demonstrated that MMPRTs can lead to increased knee laxity and altered kinematics. However, the precise mechanisms by which these tears affect ACL stiffness and function remain incompletely understood. Specifically, the objective quantification of ACL tissue properties in the context of MMPRTs has been limited. Ultrasound shear wave elastography (SWE) has emerged as a promising tool for non-invasively assessing the mechanical properties of soft tissues, including ligaments. SWE measures tissue stiffness by quantifying the propagation velocity of shear waves generated by ultrasound pulses. This technique offers a unique opportunity to evaluate ACL tissue elasticity in vivo, providing valuable insights into the ligament's response to MMPRTs. By quantifying ACL stiffness, researchers can gain a more comprehensive understanding of the biomechanical changes associated with MMPRTs and their potential impact on knee stability. Furthermore, anterior tibial translation, a critical parameter for assessing knee laxity, can be accurately measured using devices like the KT-1000 arthrometer. This device provides objective and reproducible measurements of anterior tibial displacement, allowing for the quantification of knee instability in patients with MMPRTs. Combining SWE with KT-1000 measurements can provide a more complete picture of the biomechanical changes occurring in the knee following MMPRT. The tibial slope, another critical anatomical factor, has been implicated in knee biomechanics and ACL loading. An increased posterior tibial slope can contribute to increased anterior tibial translation and greater strain on the ACL. It is hypothesized that in the presence of an MMPRT, an increased tibial slope may exacerbate the biomechanical alterations, further compromising ACL function. Therefore, understanding the interplay between tibial slope, MMPRTs, and ACL stiffness is essential for a comprehensive evaluation of knee biomechanics. This study aims to investigate the structural and functional relationship between MMPRTs and the ACL by assessing ACL stiffness using SWE and measuring anterior tibial translation with the KT-1000 arthrometer. We hypothesize that patients with MMPRTs will exhibit increased ACL stiffness and greater anterior tibial translation compared to healthy controls. Additionally, we aim to explore the influence of tibial slope on ACL stiffness in the context of MMPRTs. By elucidating the biomechanical consequences of MMPRTs on ACL function, this study seeks to provide valuable insights for clinicians managing patients with these injuries. The findings may contribute to the development of more targeted treatment strategies, including surgical interventions and rehabilitation protocols, aimed at restoring knee stability and preventing long-term complications. Furthermore, this research will enhance our understanding of the complex interplay between meniscal and ligamentous structures in maintaining knee joint integrity. The clinical significance of this research lies in its potential to improve the diagnosis and management of MMPRTs. Early identification and appropriate intervention can prevent the progression of knee instability and reduce the risk of secondary ACL injury. By highlighting the importance of considering ACL biomechanics in the context of MMPRTs, this study will contribute to a more holistic approach to knee joint evaluation. The study's methodology, utilizing objective measures such as SWE and KT-1000 arthrometry, will provide robust and reliable data on ACL stiffness and anterior tibial translation. The inclusion of a control group will allow for a comparative analysis, strengthening the conclusions drawn from the study. Furthermore, the assessment of tibial slope will provide valuable insights into the influence of anatomical factors on ACL biomechanics. In summary, this research will provide a comprehensive assessment of the biomechanical changes associated with MMPRTs, focusing on ACL stiffness and anterior tibial translation. By combining advanced imaging techniques with objective clinical measurements, this study will contribute to a deeper understanding of the intricate relationship between the medial meniscus and the ACL, ultimately leading to improved clinical outcomes for patients with MMPRTs.

Materials and Methods:

This retrospective cohort study, comparing anterior cruciate ligament (ACL) shear wave elastography (SWE) values and KT-1000 arthrometer measurements between patients with medial meniscus posterior root tears (MMPRT) and healthy volunteers, was approved by the regional ethics committee. Informed consent was obtained from all participants.

Study Population: Patients aged 18 years or older who underwent knee magnetic resonance imaging (MRI) at our institution between January and June 2024 were retrospectively reviewed. From 138 patients identified with MMPRT on MRI, 56 met the inclusion criteria: (1) unilateral MMPRT and (2) symptom duration exceeding 3 months. Exclusion criteria were: (1) advanced osteoarthritis (Kellgren-Lawrence grade 3-4), (2) concomitant ligament injuries (e.g., ACL rupture), (3) inflammatory arthritis, (4) prior knee surgery, (5) knee flexion limitations, and (6) incomplete data. Thirty-one healthy volunteers were recruited as the control group.

Clinical Evaluation: Demographic data (age, gender, BMI) were recorded. MRI of the contralateral knee confirmed unilateral MMPRT in the study group. Anterior tibial translation was measured bilaterally using the KT-1000 arthrometer at 30 degrees of knee flexion. Clinical outcomes were assessed using the Tegner Lysholm Knee Scoring Scale (TLKSS) and the International Knee Documentation Committee Score (IKDCS).

Radiographic Evaluation: Anteroposterior knee radiographs were used to assess osteoarthritis severity using the Kellgren-Lawrence (KL) grading system. Standing anteroposterior radiographs of the lower extremity were used to measure the medial proximal tibial angle (MPTA) and hip-knee-ankle angle (HKAA). Tibial slope was measured on true lateral radiographs at 30 degrees of knee flexion, following the method described by Utzschneider et al. A line was drawn through the midpoints of the anterior and posterior tibial cortices at 5cm and 15cm distal to the knee joint line. The tibial slope was defined as the angle between the medial tibial plateau and a perpendicular line to the tibial axis.

Shear Wave Elastography (SWE) Technique: SWE and B-mode ultrasound were performed using a Mindray Resona R9 device with a 9-3 MHz linear transducer. Participants were positioned semi-supine with 110 degrees of knee flexion (standardized with a goniometer). The ACL was identified in the oblique sagittal plane as a linear structure between the patella and anterior tibia, posterior to Hoffa's fat pad. The probe was aligned parallel to the ACL fibers. In B-mode, the distal one-third of the ACL was identified. A 2mm region of interest (ROI) was placed within this segment for SWE measurements. Three measurements were taken at different points on the ACL, and the average was recorded in kilopascals (kPa).

Statistical Analysis: Radiological measurements were performed by two board-certified radiologists (M.Y. and M.S.B.) with experience in musculoskeletal radiology. MMPRT diagnosis was confirmed by two radiologists. Interobserver reliability was assessed using intraclass correlation coefficients (ICCs) on a random sample of 20 participants. ICCs were: SWE (r=0.836), HKAA (r=0.741), and tibial slope (r=0.801), indicating high reliability.

Sample size calculation, based on an effect size of 0.675, a significance level of 0.05, and a power of 0.80, indicated a minimum requirement of 28 participants per group. With a 10% margin of error, the study aimed for at least 31 participants per group.

Statistical analyses were performed using SPSS version 22. Categorical variables were presented as frequencies, and continuous variables as means ± standard deviations. The Kolmogorov-Smirnov test assessed normality.

Independent-samples t-tests compared means between groups. Multivariable regression analysis determined the relationship between SWE values and other parameters. Chi-square tests analyzed categorical variables. A p-value < 0.05 was considered statistically significant.

Results:

The study included 87 participants: 31 controls (25 females, 6 males) and 56 MMPRT patients (48 females, 8 males). ACL SWE values were significantly higher in the MMPRT group (26.6±8.9 kPa) compared to the control group (21.2±5.7 kPa, p=0.004), indicating increased ACL stiffness. Anterior tibial translation, measured with the KT-1000, was significantly greater in MMPRT-affected knees (6.19±1.4 mm) compared to unaffected knees (4.9±0.78 mm, p<0.05). Multivariable regression analysis revealed a significant positive correlation between ACL SWE values and tibial slope (β=1.11; CI, 0.24–1.99; P=0.01), suggesting that increased tibial slope contributes to increased ACL stiffness.

Discussion:

This study investigated the biomechanical and structural relationship between medial meniscus posterior root tears (MMPRTs) and the anterior cruciate ligament (ACL), revealing significant findings regarding ACL stiffness, tibial anterior translation, and the influence of tibial slope. The most prominent finding was that patients with MMPRTs exhibited a significantly stiffer ACL, characterized by a higher elastic modulus as measured by shear wave elastography

(SWE). This suggests structural alterations in the ACL, potentially indicative of degeneration. Furthermore, the study confirmed that MMPRTs lead to increased tibial anterior translation, a functional consequence consistent with previous biomechanical and imaging studies. This increased translation, measured using the KT-1000 arthrometer, underscores the critical role of the medial meniscus posterior root in maintaining knee stability. Moreover, the research highlighted the significant impact of tibial slope on ACL stiffness. A linear relationship was observed between increased tibial slope and elevated ACL SWE values. This suggests that a steeper tibial slope exacerbates the biomechanical stress on the ACL, contributing to its increased stiffness and potential degeneration in the presence of MMPRTs. The study addressed the complex interplay between MMPRTs and ACL integrity, moving beyond purely functional assessments. While previous research has primarily focused on the functional consequences of MMPRTs, such as increased tibial translation and altered knee kinematics, this study provided crucial insights into the structural changes occurring in the ACL. The finding of increased ACL stiffness, a potential marker of degeneration, is particularly noteworthy. The discussion explored potential mechanisms underlying these findings. Increased loading on the ACL due to MMPRT-induced instability could initiate a compensatory degenerative process, leading to increased stiffness. Alternatively, pre-existing ACL degeneration might predispose individuals to MMPRTs by compromising the ligament's ability to resist tibial translation. The study's design, focusing on patients with symptom duration exceeding three months, aimed to capture the chronic effects of MMPRTs, although it limited the ability to definitively establish the temporal sequence of ACL degeneration and MMPRT onset. Shear wave elastography (SWE) was effectively employed to quantify ACL stiffness, providing a non-invasive and objective measure of tissue mechanical properties. The high SWE values observed in MMPRT patients were interpreted as an indirect indicator of ACL degeneration, reflecting cellular and structural changes such as chondrocyte metaplasia, collagen disorganization, and fibrous tissue formation. The study also acknowledged the influence of other factors, such as genu varum, body mass index (BMI), and gender, on MMPRT development. While the patient population was predominantly female and exhibited a tendency towards overweight/obesity, the radiographic assessment of genu varum indicated values close to the varus threshold, aligning with observations in the general population.

In conclusion, this study provides compelling evidence that MMPRTs are associated with significant biomechanical and structural changes in the ACL. The observed increase in ACL stiffness and tibial anterior translation, coupled with the influence of tibial slope, highlights the complex interplay between meniscal and ligamentous structures in knee joint stability. The findings underscore the importance of considering ACL integrity in the assessment and management of MMPRTs, potentially informing the development of targeted interventions to mitigate long-term complications. This research contributes valuable insights into the pathophysiology of MMPRTs and their impact on overall knee health, marking a significant step towards a more comprehensive understanding of these injuries.

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