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An analysis of radiologic and anatomical parameters associated with traumatic isolated medial meniscus tear patterns in Ligament-Intact knees

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Abstract

Background The purpose of the study was to analyze the radiologic and anatomical parameters associated with traumatic isolated medial meniscus tear patterns in ligament-intact knees.

Methods This retrospective case-control study included 195 patients aged 18–45 years who experienced traumatic knee pain and were diagnosed with isolated medial meniscal tears via magnetic resonance imaging (MRI) between 2014 and 2021. Patients were categorized according to tear patterns into longitudinal, bucket-handle, radial, and complex tear groups. The control group consisted of 61 healthy individuals aged 18–45 years who underwent knee MRI for unrelated symptoms and had no detectable intra- or extra-articular knee abnormalities. Radiologic and anatomical parameters were measured on MRI scans, and statistical analyses were performed using Kruskal-Wallis tests, multinomial logistic regression analysis, and Spearman's correlation tests.

Results No significant differences were observed between the groups in terms of age, gender, and BMI ($P < 0.05$). Study results indicated that increased tibial tubercle-to-trochlear groove (TT-TG) distance ($P < 0.001$) and medial tibial slope ($P < 0.001$) are risk factors for developing longitudinal, bucket-handle, and complex medial meniscus tears. Additionally, low medial meniscal bone angle (MBA) ($P = 0.019$) and medial meniscal cartilage angle (MCA) ($P = 0.004$) values were linked to an increased risk of radial tears. These findings suggest that specific anatomical and radiological factors predispose individuals to certain types of medial meniscus tears.

Conclusion In ligament-intact knees, increased TT-TG distance and increased medial tibial slope were associated with longitudinal, bucket-handle, and complex tear patterns in the medial meniscus, while low MBA and MCA values were associated with radial tears. Findings of this study offer valuable insights for orthopedics and traumatology specialists in enhancing prevention and management strategies for medial meniscal tears, laying a foundational basis for further research.

Keywords Medial meniscus tears, Knee trauma, Ligament-intact knees, Radiologic parameters, Anatomical factors

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Introduction

The meniscus plays a crucial role in various aspects of the knee joint, such as load transmission, lubrication, shock absorption, proprioception, and stabilization [1, 2]. The damage in the meniscus tissue may lead to increased tibiofemoral contact pressure, which can cause susceptibility to osteoarthritis [3]. Traumatic tears, which occur when the meniscus tissue is subjected to a sudden overload beyond its normal capacity, are more prevalent among young patients [4]. Traumatic meniscus tears are often observed with knee ligament injuries, although they can also occur independently. In fact, approximately 6% of acutely injured knees in the general population exhibit an isolated meniscus tear in ligament-intact knees, with the medial meniscus being affected in 75% of these cases [5, 6]. The most frequently encountered types of traumatic meniscus tears include longitudinal tears, radial tears, bucket-handle tears, and complex tears. Longitudinal tears are typically oriented parallel to the circumferential fibers of the meniscus, while bucket-handle tears represent displaced longitudinal tears creating instability within the joint. Radial tears extend from the inner edge of the meniscus toward the periphery, disrupting the circumferential fibers. Complex tears are characterized by multiple tear configurations coexisting, often combining longitudinal and radial components [7].

While the connection between meniscal tears and osteoarthritis is well established, our current understanding of the factors contributing to meniscal tears remains limited. Defined risk factors include advanced age (over 60 years), increased body weight, male gender, and a high level of sports activity [8]. Although previous studies have identified morphological parameters such as high tibial slope and increased TT-TG distance as risk factors for meniscal tears, these studies primarily focused on knees with concomitant ligament injuries, particularly ACL tears [9–11]. In contrast, there is a lack of research in the literature specifically examining isolated medial meniscal tears in ligament-intact knees, limiting our understanding of how these anatomical parameters independently contribute to specific meniscal tear patterns.

It is expected that instability, which occurs due to damage to the knee ligaments from high-energy traumas, will lead to meniscus tears [12]. However, we have limited knowledge regarding the anatomical and radiological factors that contribute to different patterns of meniscus tears occurring from less severe trauma. These factors may play a role in the development of meniscus tear patterns in low-energy trauma. Therefore, identifying anatomical and radiological risk factors associated with specific meniscal tear patterns is essential, as this can enhance our understanding of injury mechanisms and inform preventive strategies.

The purpose of the study was to provide a comprehensive analysis of the radiologic and anatomical parameters associated with traumatic isolated medial meniscus tear patterns in ligament-intact knees. Moreover, the results of this study can contribute to the development of preventive measures and strategies targeting the reduction of the occurrence and severity of isolated medial meniscus tears.

Materials and methods

This retrospective case-control study was initiated after approval by the Erciyes University ethics committee institutional review (Approval Date: 20/12/2023, Approval Number: 2023/822). The requirement for informed consent was waived because of the radiologic and retrospective nature of the study. The data of 1315 consecutive patients who applied to the University Hospital between 2014 and 2021 with sudden onset of knee pain due to trauma and were diagnosed with isolated medial meniscal tear on MR images were retrospectively analyzed. Inclusion criteria were individuals between 18 and 45 years of age, absence of a lateral meniscal tear, available clinical and radiological records, and BMI < 30. Exclusion criteria were patellofemoral instability or dysplasia; a concomitant ligamentous injury (anterior cruciate ligament, posterior cruciate ligament, lateral collateral ligament, medial collateral ligament, posterolateral corner, posteromedial corner, and medial patellofemoral ligament); age > 45 years; BMI > 30; previous fractures or surgery; inadequate quality of magnetic resonance imaging (MRI) scans and radiographs. Horizontal tears, which are considered a degenerated tear type, were also excluded from the study. Patients aged over 45 and those with a BMI greater than 30 were excluded because these factors are known to increase the likelihood of degenerative joint changes and meniscal degeneration, potentially confounding the direct association between traumatic injury patterns and the measured radiologic/anatomical parameters.

As the control group, 61 healthy participants were selected from patients who underwent a physical examination, radiography, and MRI for other reasons, such as benign extra-articular soft tissue tumors, pain radiating from the hip to the knee, soft tissue edema, and superficial soft tissue infections, but who did not have intra- or extra-articular abnormalities. Leg dominance was determined based on a previously published questionnaire regarding the preferred limb used to execute an action (e.g., the leg used to propel a ball and the preferred leg for standing on one leg), as described by [13].

Radiological measurement and examination parameters

The anteroposterior and lateral knee radiographs, radiographs of the complete lower extremity, and MRI scans

were evaluated. The radiologic records of the patients were reviewed by an orthopedic surgeon and an experienced musculoskeletal radiologist. According to meniscus tear type, patients were divided into 5 groups for the analysis: longitudinal tear, bucket-handle tear, radial tear, complex tear, and uninjured control group. Tears involving at least two of longitudinal tear, bucket-handle tear, and radial tear were considered complex tears.

A 1.5-T scanner (Magnetom Symphony; Siemens) with a dedicated knee array coil was used to conduct MRI. The entire anatomy between the proximal end of the patella and the distal end of the tibial tubercle was scanned with MRI using a 3-mm slice thickness configuration. All MRI scans were performed using a standardized protocol, employing sagittal, axial, and coronal proton-density (PD) weighted sequences (repetition time [TR]: 2500–3000 ms, echo time [TE]: 30–35 ms), with a field of view (FOV) of approximately 16 cm and a matrix size of 256 × 256 pixels. MRI scans were evaluated by an orthopedic surgeon and musculoskeletal radiologist who were blinded to the initial reports, the purpose of the study, and the protocol. 10 morphological parameters were measured using coronal, sagittal, and axial proton density MRI scans that may be associated with meniscal tear patterns when the cross-linking function was active. All of the measurements were performed using a picture documenting and communication system (Sectra IDS 7) with a linear measurement accuracy of 0.1 mm and an angular measurement accuracy of 0.1. Each reviewer repeated all measurements twice at a 2-month interval to evaluate intraobserver and interobserver reliability. Any discrepancies between observers were resolved by consensus after joint re-evaluation of the MRI scans.

On MRI scans of the coronal, sagittal, and axial planes, the following morphological parameters were measured and calculated: tibial tubercle-to-trochlear groove (TT-TG) distance (Fig. 1) [14], notch width (NW) [14], notch width index (NWI) [14], medial meniscal bone angle (MBA) (Fig. 2) [15], medial meniscal cartilage angle (MCA) (Fig. 3) [15], medial meniscal cartilage height (MCH) [15], medial meniscal cartilage bone high (CBH) [15], medial tibial slope (Fig. 4) [16], anterior tibial slope [9], tibial proximal anteroposterior distance [15].

Statistical analysis

The data were analyzed with IBM SPSS V23. Compliance with the normal distribution was examined by the Shapiro-Wilk test. The Kruskal-Wallis test was used to compare the parameters that did not conform to the normal distribution, and multiple comparisons were made with Dunn's test. Multinomial logistic regression analysis was used to analyze the risk factors affecting meniscal type. Spearman's correlation analysis was used to evaluate potential correlations between the TT-TG distance and medial tibial slope. The analysis results were presented as mean ± standard deviation and median (minimum - maximum). The significance level was set at $P < 0.05$. The agreement for the ICC values was defined in accordance with the research of Landis and Koch as follows: Slight agreement, 0.01 to 0.20; fair agreement, 0.21 to 0.40; moderate agreement, 0.41 to 0.60; substantial agreement, 0.61 to 0.80; and perfect agreement, 0.81 to 1.00. A post-hoc power analysis was performed using G*Power

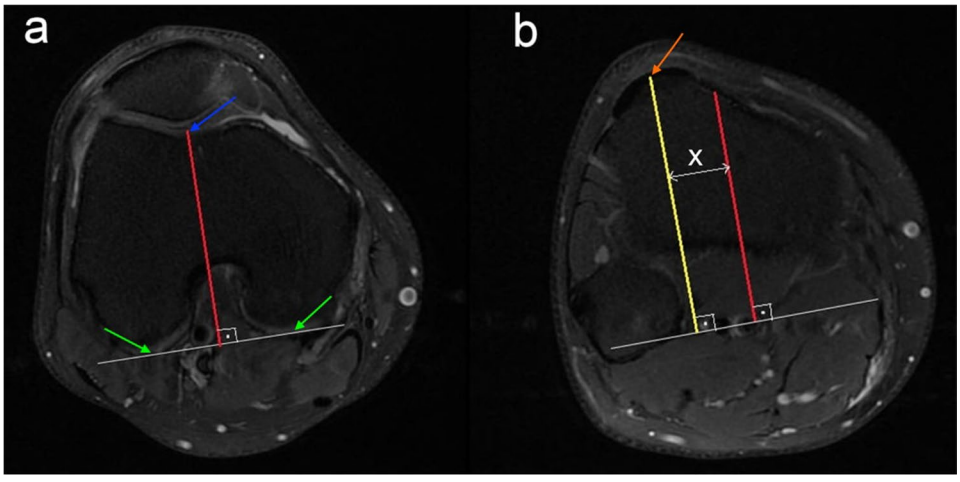


Fig. 1 Measurement of the TT-TG distance: (**a**) In the axial MRI section where the trochlear groove (blue arrow) is most prominent, a line (red line) is drawn perpendicular to the line (white line) connecting the posterior condyles (green arrows) from the center of the trochlear groove. (**b**) Maintaining the reference line (white line) connecting the posterior condyles), the axial MRI section demonstrating the most prominent tibial tuberosity (orange arrow) is selected. Another perpendicular line (yellow line) is drawn from the center of the tibial tuberosity. The distance between these two perpendicular lines (x) represents the TT-TG distance. These specific slices are standardly selected because they provide the most reproducible landmarks for accurate measurement of the TT-TG distance, which is critical for assessing knee alignment and patellofemoral biomechanics. (TT-TG, tibial tubercle-trochlear groove)



Fig. 2 Measurement of the MBA. The MBA is measured on a sagittal MRI section. It is defined as the angle (x) between the tangent line (blue line) drawn along the superior surface of the medial tibial plateau subchondral bone (red arrows) and a tangent line (orange line) drawn along the superior surface of the medial meniscus (yellow arrows). Measuring the MBA is clinically relevant because lower MBA values have been associated with decreased knee stability and a higher risk of specific meniscal tear types, particularly radial tears. (MBA, meniscal bone angle)

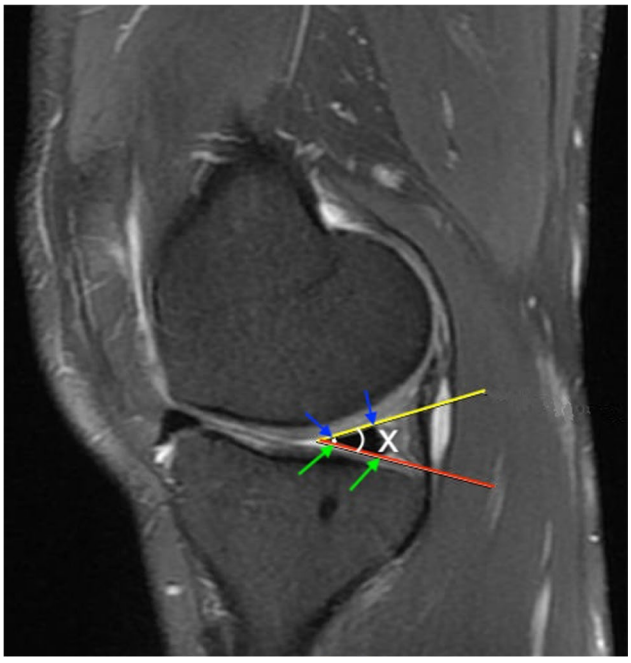


Fig. 3 Measurement of the MCA. The MCA is measured on a sagittal MRI section. It is defined as the angle (x) formed between the tangent line (yellow line) drawn along the superior surface of the medial meniscus (blue arrows) and the tangent line (red line) drawn along the articular cartilage surface of the medial tibial plateau (green arrows). Assessment of MCA is clinically important since altered MCA values may indicate meniscal instability and predispose individuals to certain tear patterns such as radial tears. (MCA, meniscal cartilage angle)

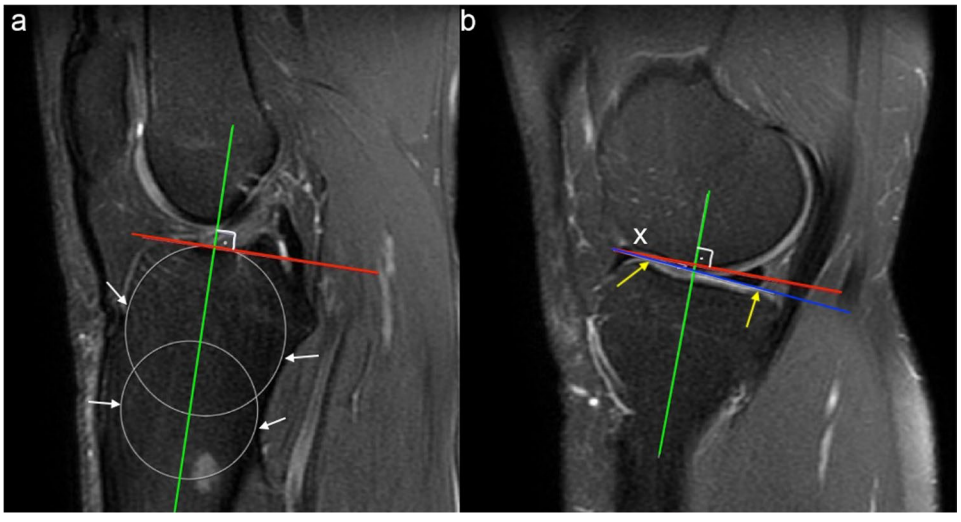


Fig. 4 Measurement of the medial tibial slope. (**a**) On the sagittal MRI image, the longitudinal tibial axis is determined by drawing two circles fitting within the proximal tibial shaft walls (white arrows), and a line (green line) passing through their centers. A perpendicular reference line (red line) is then drawn to this longitudinal tibial axis. (**b**) The medial tibial slope angle (x) is defined as the angle between this perpendicular reference line (red line) and a tangent line (blue line) drawn along the superior articular surface of the medial tibial plateau (yellow arrows). Variations in medial tibial slope influence knee biomechanics by altering anterior tibial translation and rotational stability, potentially leading to increased mechanical stress on the menisci and specific tear patterns

Table 1 Demographic data of all groups

Variables	Longitudial (*n* = 71)	Bucket-handle (*n* = 39)	Radial (*n* = 40)	Complex (*n* = 45)	Control (*n* = 61)	*p*
Age (year)	28.7 ± 8.7	27.2 ± 8	32.8 ± 8.5	28.3 ± 8.6	29.5 ± 7.5	0.083
	(18–45)	(18–45)	(20–45)	(18–44)	(18–45)	
BMI	25.2 ± 3.9	25.7 ± 4.0	25.1 ± 3.7	26.8 ± 4.1	25.8 ± 4	0.362
	(19–32)	(19–33)	(19–30)	(19–33)	(19–33)	
Gender n, % Female	12 (16.9%)	8 (20.5%)	8(20%)	9 (20%)	11(18%)	0.568
Male	59 (83.1%)	31 (79.5%)	32(80%)	36 (80)	50(82%)	

BMI Body mass index

Table 2 Comparison of parameters according to meniscal tear patterns

	Longitudial (*n* = 71)	Bucket-handle (*n* = 39)	Radial (*n* = 40)	Complex (*n* = 45)	Control (*n* = 61)	*p*
TT-TG distance, mm	7.7 ± 4.3	12.5 ± 3	9 ± 3.6	13 ± 4	9.6 ± 3.5	< 0.001
	(0–19.5)	(6–18.9)	(1.9–15.6)	(6.6–19.5)	(4–17.1)	
NW, mm	19.3 ± 1.8	19.3 ± 1.6	19.4 ± 1.7	19.1 ± 2.1	19.7 ± 2.2	0.267
	(16–25)	(15–25.3)	(15–25)	(15.1–25.3)	(16–25.5)	
NW index	0.25 ± 0.02	0.26 ± 0.03	0.25 ± 0.02	0.25 ± 0.03	0.26 ± 0.02	0.087
	(0.2–0.3)	(0.2–0.3)	(0.2–0.3)	(0.2–0.3)	(0.21–0.29)	
MBA, deg	25.1 ± 1.5	25.3 ± 1.3	21.5 ± 1.2	25.3 ± 0.9	24.8 ± 1	< 0.001
	(19.5–29.5)	(14–30)	(14–27)	(22–28.5)	(21–29)	
MCA, deg	23.1 ± 1.1	23.2 ± 1.4	19.5 ± 1.6	23.3 ± 1.5	22 ± 1.3	< 0.001
	(18–27.5)	(18–28)	(17–25)	(19–27)	(19–27)	
MCH, mm	6.4 ± 0.7	6.4 ± 0.6	6.68 ± 0.58	6.9 ± 0.7	6.6 ± 0.6	0.251
	(5–8)	(4.8–7.7)	(5.1–7.1)	(5.5–7.8)	(5–7.8)	
CBH, mm	1.3 ± 0.5	1.3 ± 0.4	1.5 ± 0.6	1.4 ± 0.3	1.5 ± 0.4	0.068
	(0.8–2.5)	(0.8–2.1)	(0.9–2.5)	(1- 2.1)	(0.8–2.5)	
Medial tibial slope, deg	6.4 ± 2.4	5.1 ± 1.8	4.5 ± 1.7	4.8 ± 1.9	4.8 ± 1.7	< 0.001
	(2–11)	(1.5–10)	(2–10)	(2–11)	(2–11)	
Anterior tibial slope, deg	9.9 ± 1.5	10.2 ± 1.9	9.5 ± 1.7	9.5 ± 2.1	9.5 ± 1.6	0.079
	(6–18)	(6–18)	(6–20)	(5–20)	(6–19)	
Tibial proximal anteroposterior length, mm	64.7 ± 4.4	63 ± 5.2	62 ± 5.8	65.5 ± 5.3	65 ± 4.7	0.061
	(58–74)	(53–75)	(53–69.2)	(57–75)	(57.5–75)	

*Kruskal Wallis Test; Mean ± standard deviation; Median (min - max); *P*<0.05 statistically significant; *TT-TG* tibial tubercle-to-trochlear groove; *NW* notch width; *MBA* meniscal bone angle; *MCA* meniscal cartilage angle; *MCH* meniscal cartilage height; *CBH* meniscal cartilage bone height

software (version 3.1) to evaluate whether the selected control group size was sufficient to detect clinically meaningful differences for key radiologic and anatomical parameters (TT-TG distance, medial tibial slope, MBA, and MCA). The analysis indicated that our control group ($n = 61$) provided ≥80% statistical power at an alpha level of 0.05, assuming clinically relevant differences of approximately 2 mm for TT-TG distance, 1.5° for medial tibial slope, and approximately 2° for MBA and MCA.

Results

After applying exclusion criteria, 195 patients and 61 control participants were included in the study with a mean age of 29.9 ± 8.1 years (range, 18–45 years) and a mean BMI of 27.2 ± 4.4 (range, 21.6–29.5). In the patient groups, 37 (18.9%) were female and 158 (81.1%) were male, while in the control group, 11 (18%) were female and 50 (82%) were male. In the patient group, side dominance was 90.4%, while in the control group it was 90.1%. The intraobserver reliability and interobserver reliability ICCs were 0.81 ($P < 0.001$) and 0.83 ($P < 0.001$), respectively. Although the number of male participants was notably higher than females, subgroup analyses performed separately within male and female participants revealed no statistically significant differences regarding the radiologic and anatomical parameters evaluated ($p > 0.05$). Thus, gender disparity is unlikely to have influenced the study outcomes. Regarding demographic characteristics, no significant differences were observed between the groups in terms of age, gender, and BMI ($P > 0.05$) (Table 1).

However, several parameters showed statistically significant differences among the groups. Particularly, the TT-TG distance, medial tibial slope, MBA, and MCA exhibited highly significant differences ($P < 0.001$) (Table 2).

Table 3 Multinomial logistic regression analysis demonstrating anatomical and radiologic risk factors independently associated with specific medial meniscal tear patterns

Meniscus tear patterns	Anatomic Parameters	OR (%95 CI)	*p*
Longitudial	TT-TG distance, mm	1.84 (1.43–2.37)	< 0.001
	Medial tibial slope, deg	1.95 (1.25–3.05)	< 0.001
Bucket-handle	TT-TG distance, mm	3.10 (1.72–5.60)	< 0.001
Complex	TT-TG distance, mm	3.85 (2.05–7.24)	< 0.001
	Medial tibial slope, deg	2.75 (1.55–4.86)	< 0.001
Radial	MBA, deg	3.11 (1.20–8.03)	0.019
	MCA, deg	2.03 (1.00–6.33)	0.004

*Multinominal Logistic Regression Analysis; $P < 0.05$, statistically significant; *TT-TG* tibial tubercle-to-trochlear groove; *MCA* meniscal cartilage angle; *MBA* meniscal bone angle

Post-hoc analyses following the Kruskal-Wallis test revealed that TT-TG distance was significantly higher in the complex and bucket-handle groups compared to the longitudinal, radial, and control groups ($P < 0.001$). The medial tibial slope was significantly higher in the longitudinal group compared to the other groups ($P < 0.001$). Additionally, MBA and MCA values were significantly lower in the radial tear group compared to all other groups (MBA: $P = 0.019$; MCA: $P = 0.004$). Multinomial logistic regression analysis showed that increases in TT-TG distance and medial tibial slope were independently associated with specific tear patterns. Specifically, increased TT-TG distance was significantly associated with complex (OR: 3.85, $P < 0.001$), bucket-handle (OR: 3.10, $P < 0.001$), and longitudinal tears (OR: 1.84, $P < 0.001$). Increased medial tibial slope was significantly associated with complex (OR: 2.75, $P < 0.001$) and longitudinal tear patterns (OR: 1.95, $P < 0.001$). Higher MBA (OR: 3.11, $P = 0.019$) and MCA values (OR: 2.03, $P = 0.004$) were independently associated with radial tears (Table 3). Furthermore, correlation analysis between TT-TG distance and medial tibial slope demonstrated no significant correlation (Spearman's rho = 0.092, $P = 0.187$), indicating these parameters independently influenced meniscal tear patterns.

Discussion

The most important finding of this study is that in ligament-intact knees, while an increased TT-TG distance is associated with bucket-handle tears, both an increased TT-TG distance and a greater medial tibial slope are related to longitudinal and complex tears of the medial meniscus. Additionally, lower MBA and MCA values were associated with radial tears. Findings suggest that specific anatomical and radiological factors may predispose individuals to certain types of medial meniscus tears.

An excessively high TT-TG distance induces lateral displacement of the patella, resulting in heightened rotational stresses on the knee due to dominant lateral force vectors. This, consequently, has been associated with anterior knee pain and patellar instability. Moreover, an elevated TT-TG distance may cause damage to the trochlear cartilage and meniscal tears [11, 17]. Atay et al. also confirmed the association between TT-TG distance and trochlear cartilage damage as well as meniscal tears [18]. Stumetz et al. identified TT-TG distances exceeding 12 mm as a cause for concern regarding meniscal and ACL tears [19]. It is important to highlight that most of these studies involved participants with ACL injuries. The current study shows that increased TT-TG distance is a risk factor for certain types of medial menisceal tears in ligament-intact knees. In addition, while studies demonstrate a clear relationship between TT-TG distance and meniscal tears, the specific meniscal tear patterns associated with this distance remain unclear. We believe that the greater lateral stresses and rotational pressures on the knee joint during dynamic motion cause this new link between increased TT-TG distances and longitudinal, bucket-handle, and complex meniscal tears, which was demonstrated in our study. The outcomes of our study strongly suggest that an escalation in TT-TG distance not only poses a risk for patellar instability or cartilage damage but also increases the likelihood of experiencing certain traumatic meniscal tears in ligament-intact knees. Our findings expand upon those of Atay et al. [18], who demonstrated associations between increased TT-TG distance and cartilage injuries, by specifically identifying the association between TT-TG distance and traumatic isolated medial meniscal tear patterns in ligament-intact knees. The differences between our results and previous studies [11, 17–19] might be attributed to variations in study populations, as prior studies typically included patients with concurrent ligamentous injuries, whereas we focused specifically on isolated medial meniscal injuries.

It was suggested that the increased sagittal slope of the tibial plateau is a risk factor for ACL injury and medial meniscus tears because it influences load transmission in the knee joint [9, 20–23]. Biomechanical studies have demonstrated that a high medial tibial slope and altered knee joint alignment enhance anterior tibial translation and rotational forces under loading conditions, thus increasing the risk of specific meniscal tear patterns, such as longitudinal and complex tears [24, 25]. These biomechanical forces may explain the associations observed between elevated medial tibial slope, increased TT-TG distance, and specific tear patterns in our findings. Such forces likely contribute to tears parallel to the peripheral fibers of the menisci, resulting in longitudinal and complex tear patterns. There is a lack of information in the literature about the specific types of meniscal tears that are linked to medial tibial slope, despite the fact that high

slope has been related to meniscal tear risk in clinical and biomechanical research. The high medial tibial slope leading to longitudinal and complex tears is therefore a novel finding of our study. Understanding the relationship between the slope of the medial tibial plateau and specific types of meniscal tears may provide valuable information for orthopedic surgeons in the future in terms of risk factors for the assessment and management of meniscal tears, ultimately leading to more targeted treatment strategies and better patient outcomes. Additionally, the absence of a significant correlation between TT-TG distance and medial tibial slope further supports the independent role of these anatomical factors in predisposing individuals to specific medial meniscal tear patterns.

Previous research has connected the MBA and MCA to a higher incidence of ACL rerupture. This has been explained by the fact that menisci with low MBA and MCA values have less wedge effect and, as a result, cannot offer enough knee stability. These studies have also shown that the anterior cruciate ligament (ACL) may have a compensatory stabilizing effect on the knee joint, potentially influencing the relationship between MBA/MCA and meniscal tear patterns. To eliminate this confounding factor, our study exclusively included ligament-intact knees, thereby ensuring that the observed associations between MBA/MCA and meniscal tear patterns were not influenced by any compensatory effect of the ACL [26, 27]. A study in elderly patients showed that varus knee alignment and joint degeneration increased the incidence of radial tears in the medial meniscus. The cause of the radial tear was claimed to be excessive traction forces on the roots holding the meniscus in place in the narrowed joint space [28]. Our research provides novel findings not previously reported in the literature, specifically that low MBA and MCA values are associated with an increased risk of radial tears. It is conceivable that menisci with lower MBA and MCA values exhibit a flatter profile, potentially rendering them more susceptible to radial tears when subjected to traction forces. These results provide useful information on the mechanisms of meniscal tears, and future studies, such as biomechanical ones, should help us learn even more. Our comprehension of these mechanisms may directly inform orthopedic surgeons in tailoring interventions and surgical strategies, ultimately leading to enhanced clinical outcomes for patients. With this understanding, orthopedic surgeons may be more qualified to make predictions and apply treatments.

There is still ample scope for further investigations to enhance our understanding of meniscal injuries and their underlying mechanisms. Future studies could consider incorporating biomechanical analyses to complement our radiological findings. Biomechanical studies using cadaveric or computational models could explore the load distribution and stress patterns within the knee joint under different loading conditions. These analyses could simulate various meniscus tear patterns and assess how alterations in radiological parameters, such as TT-TG distance, medial meniscal angles, and tibial slopes, impact the susceptibility to specific tear types. Furthermore, investigating the effects of ligament injuries on meniscal tears in low-energy traumas could provide valuable insights into the interplay between joint stability, meniscal function, and injury patterns. Longitudinal studies tracking patients over time could also be undertaken to establish causal relationships between anatomical variations and the development of meniscal tears. Moreover, investigating the role of muscle forces and joint kinematics in relation to the identified risk factors may contribute to a comprehensive understanding of meniscal injury mechanisms. By combining radiological data with biomechanical approaches, future research can bridge the gap between anatomical predisposition and biomechanical forces, ultimately leading to more effective preventive measures and management strategies for meniscus tears. Results from the current study are crucial for further research into these relationships.

Limitations

While this study provides valuable information about the radiological and anatomical parameters associated with traumatic isolated medial meniscal tear patterns, there are some limitations. Firstly, this study is retrospective, inherently carrying a risk of selection bias. The stringent exclusion criteria applied may have led to the exclusion of certain patient populations, potentially limiting the generalizability of the findings. Although the sample size was significant, it was obtained from a single institution over a specific time period, possibly introducing bias related to institutional practices or patient demographics. Specifically, the relatively small control group size ($n = 61$, approximately 5% of the total cohort) resulted directly from strict inclusion and exclusion criteria and the limited availability of suitable retrospective MRI data, representing the maximum possible cohort that met these rigorous conditions. However, a post-hoc power analysis indicated that our control group size provided sufficient statistical power (≥ 80%) to detect clinically meaningful differences for key parameters (TT-TG distance, medial tibial slope, MBA, and MCA) at an alpha level of 0.05. Nevertheless, future multicenter studies with larger control groups would strengthen external validity and further validate these findings. Additionally, this study exclusively analyzed isolated medial meniscal tears; thus, findings may not be directly applicable to lateral meniscal tears or cases involving concurrent injuries to other knee structures. Finally, despite a considerable difference in

gender distribution, our subgroup analysis demonstrated no statistically significant differences in radiologic and anatomical measurements between genders. Nevertheless, future research with more balanced gender representation is recommended for further confirmation.

Conclusion

This study provides novel evidence demonstrating that specific anatomical and radiologic parameters significantly contribute to distinct traumatic medial meniscus tear patterns in ligament-intact knees. Increased TT-TG distance was notably associated with bucket-handle, complex, and longitudinal tears, while elevated medial tibial slope showed strong relationships specifically with complex and longitudinal tear patterns. Additionally, reduced MBA and MCA measurements emerged as significant independent risk factors for radial tears. These findings underscore the importance of individualized anatomical evaluation in patients with traumatic knee injuries. The identification of these specific risk factors may enable orthopedic surgeons and clinicians to predict the likelihood of particular meniscal tear patterns, thereby facilitating early diagnosis, targeted preventive strategies, and tailored treatment approaches aimed at optimizing patient outcomes. Further biomechanical and longitudinal clinical studies are warranted to deepen the understanding of these relationships and enhance the management of traumatic meniscal injuries.

Abbreviations

TT-TG	Tibial tubercle-to-trochlear groove
NW	Notch width
NWI	Notch width index
MBA	Meniscal bone angle
MCA	Meniscal cartilage angle
MCH	Meniscal cartilage height
CBH	Meniscal cartilage bone height
MRI	Magnetic resonance imaging
ICC	Intraclass correlation coefficient
BMI	Body mass index
OR	Odds ratio
CI	Confidence interval
ACL	Anterior cruciate ligament

Author contributions

FG, SO, MFU, AA, BK, EU contributed substantially to the research design or the acquisition, analysis, or interpretation of data. FG, SO, MFU, AA, BK, EU contributed to drafting the paper or revising it critically. FG, SO, MFU, AA, BK, EU are involved in the approval of the submitted and final versions. All authors read and approved the final manuscript.

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Data availability

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Erciyes University ethics committee institutional review (Approval Date: 20/12/2023, Approval Number: 2023/822). The requirement for informed consent was waived because of the radiologic and retrospective nature of the study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Clinical trial number

Not applicable.

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