Original Article

Meniscal Bone Angle Is a Strong Predictor of Anterior Cruciate Ligament Injury

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Purpose: To evaluate the influence of lateral posterior tibial slope (LPTS) and meniscal bone angle (MBA) on primary anterior cruciate ligament (ACL) tear risk in an adult population through the LPTS−MBA ratio. **Methods:** A retrospective case−control study was performed with patients from a tertiary hospital who underwent primary ACL surgery and had preoperative magnetic resonance imaging (MRI). These subjects were matched by age and sex in a 1:1 ratio to patients who had an MRI without ACL tear. LPTS and MBA were measured on MRI scan. Quantitative data are presented in the median ± interquartile range (IQR). Identification of independent risk factors for primary ACL tear was performed using multivariable logistic regression. Receiver operating characteristics curves detected any variable with strong discriminative capacity. **Results:** In total, 95 patients with primary ACL tear confirmed on MRI were matched with 95 controls (N = 190). Nearly 80% were male subjects, with a median age of 26 years. In the ACL tear group, the median value of LPTS−MBA ratio was 0.20 (IQR 0.11-0.37) versus 0.12 (IQR 0.08-0.19) in the control group (P = .001). LPTS had a median value of 4.20° in the ACL tear group (IQR 2.05-7.35°) and 2.90° in the control group (IQR, 2.05-5.00°) (P = .026), whereas MBA was 19° (IQR, 16-24°) versus 26° (IQR, 24-30°) (P = .001), respectively. Logistic regression showed that LPTS (odds ratio 1.20, 95% confidence interval 1.03-1.42, P = .021) and MBA (odds ratio 0.78, 95% confidence interval 0.71-0.85, P = .001) were independent predictors. The area under the curve (AUC) of LPTS−MBA ratio was 0.69, greater than that of LPTS alone (AUC = 0.61) but lower than that for MBA (AUC = 0.82). **Conclusions:** In this study, a reduced MBA was the strongest predictive variable associated with a primary ACL tear. A threshold of 22.35° of MBA was associated with an increased risk of ACL tear, with a sensitivity of 70% and specificity of 84%. A cut-off of 0.22 of LPTS−MBA was associated with an increased risk of ACL tear, with a sensitivity of 55% and specificity of 87%. **Level of Evidence:** Level III, case−control study.

The incidence of primary anterior cruciate ligament (ACL) tear is approximately 1.5% to 1.7% per year in healthy athletic populations, with more than 70% occurring via a noncontact mechanism.[1-3] Due to its social and financial burden, it is essential to identify and prevent ACL tear.[4] Among the anatomical risk factors, the lateral posterior tibial slope (LPTS) is one of the most-studied measures.[5] During weight-bearing activities, an increased LPTS produces a greater anterior translation force of the distal component, as an axial compression force is applied across the knee joint, which increases ACL stress and can lead to its tear.[6] Moreover, numerous studies have shown a correlation between increased LPTS and susceptibility to ACL injury.[7-11] However, no consensus regarding a specific cut-off of LPTS value related to the high risk of ACL injury has been achieved so far. DePhillipo et al.[12] observed in ligament-intact patients a mean value for LPTS of 5.6°, and de Sousa et al.[13] identified an increased value of LPTS over 8° among patients with ACL injury.

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The authors report that they have no conflicts of interest in the authorship and publication of this article. Full ICMJE author disclosure forms are available for this article online, as supplementary material. The first two authors contributed equally to this paper and share co-first authorship.

Received April 5, 2022; accepted August 27, 2022.

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2666-061X/22433

https://doi.org/10.1016/j.asmr.2022.08.008

Another anatomical parameter of interest is the meniscal bone angle (MBA), which is the angle between the superior lateral meniscal surface and the subchondral bone of the tibial plateau.[14] As the lateral meniscus plays an important role in rotatory knee stability, hampering the posterior translation movement of the lateral femoral condyle on the tibia can substantially impact the ACL injury mechanism.[14-16] Sturnick et al.[14] found that reduced MBA may increase the risk of ACL injury, mostly in men. Despite not having a statistically significant value, a mean MBA value of 28.6° in the ACL tear group versus 29.6° in the control group was achieved in a recent study.[17]

Furthermore, the LPTS−MBA ratio can be a suitable measure, as MBA may neutralize or potentiate LPTS and vice versa. Both LPTS and MBA are independent geometrical factors that can be measured on magnetic resonance imaging (MRI) on the same slide with high reliability.[14] An investigation by Sauer et al.[16] in 2018 highlighted the importance of the geometry of the tibiofemoral meniscal−cartilage interface. This study also showed that the LPTS−MBA ratio can help predict ACL reconstruction failure more accurately than LPTS.

It also seems to be a strong predictive variable in the pediatric population once a threshold of 0.36 had a sensitivity of 75% and specificity of 90% to predict ACL injury.[18] Bojicic et al.[17] found an intraclass correlation coefficient (ICC) intraobserver of 0.9 in the measurement of MBA ratio, and, in a study with a pediatric population by Edwards et al.,[18] intra- and interobserver reliability showed excellent results in LPTS and MBA with a intraclass correlation coefficient of 0.82 to 0.93. However, only a few studies have assessed the relevance of the LPTS−MBA ratio in ACL tears or retears;[16-18] therefore, it is important to investigate this ratio in the primary setting of the ACL tear in the adult population. The purpose of this study was to evaluate the influence of LPTS and MBA on primary ACL tear risk in an adult population through the LPTS−MBA ratio. We hypothesized was that the LPTS−MBA ratio would be increased in patients with primary ACL tear.

Methods

Patient Selection

This project was approved by the Ethics Committee of the authors' hospital. A retrospective case−control study was conducted in the Department of Traumatology and Orthopaedics at the authors' Hospital. Data of consecutive patients who underwent primary ACL reconstruction and had a preoperatory MRI between January 2016 and July 2021 were collected from the same institution. All patients were adults at the time of the study. Exclusion criteria comprised unavailable MRI and/or MRI report and a previous ipsilateral knee surgery history. The current study included an injured group of consecutive patients older than 18 years who, between January 2016 and July 2021, underwent primary ACL reconstruction and had a preoperative MRI scan. Exclusion criteria comprised unavailable MRI and/or MRI report and a previous ipsilateral knee surgery history. The control group consisted of subjects with uninjured knees, matched by age (maximum difference of 2 years) and sex, to the injured group, from the Radiology department MRI database. Most variables, including age, sex, and body mass index (BMI), were collected through the clinical electronic reports. Absent complementary variables, such as physical activity level and mechanism of lesion, were obtained by phone call. A Tegner activity scale (TAS) was used to evaluate physical activity at the time of the injury.[19]

MRI Measurements

MRI measurements were made by one observer (T.A.) in similar cuts at sagittal 3-mm MRI T2-weighted slices with fat saturation, using the Sectra PACS program (Sectra AB, Linköping, Sweden; Fig 1). The scans were collected on a 1.5-T MRI, with a 160-mm field of view. For this procedure, patients were placed in the supine position with the knee extended. MRI was used to determine LPTS based on the method described by Hudek et al.[20] The first step is to find the central sagittal image and draw 2 circles in the tibial head: the cranial circle must pass over the anterior, posterior, and superior cortex and the caudal circle should reach the anterior and posterior cortex (Fig. 1.1). The line that passes in both circles' centers is defined as MRI longitudinal tibial axis. Copying this line to a sagittal slice where the lateral tibial plateau can be identified, LPTS and were MBA calculated. LPTS is the angle between the perpendicular line to the MRI longitudinal tibial axis and the tangent to subchondral bone of the lateral tibial plateau (Fig 1.2). In the same slice, MBA was measured, as described by Sturnick et al.,[14] as the angle between the tangent to the superior meniscal surface and the tangent to the subchondral bone of the tibial plateau.

Statistical Analysis

Since measurements results had a nonnormal distribution, a nonparametric test (Wilcoxon rank sum test) was used to analyze differences between groups. The Pearson χ^2 test was used to compare the distribution of binary or categorical variables. Quantitative data are presented as the median ± interquartile range (IQR), and missing data were excluded from statistical analysis. Calculations were performed using the R language.[21] Violin plots were used to evaluate data distribution, whereas the boxplot inside illustrates the median and IQR. Multivariable logistic regression was used to determine independent risk factors for primary ACL tear. Receiver operating characteristic (ROC)

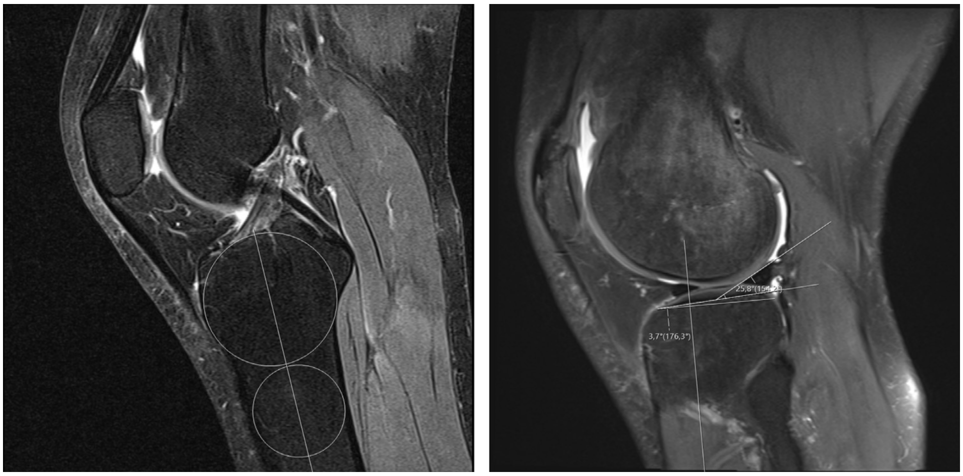

Fig 1. (1.1 + 1.2) T2-weighted with fat saturation sagittal MRI slices of a patient's left knee explaining the method of measuring LPTS and MBA. The longitudinal tibial axis was previously calculated in the central sagittal image and then that line was copied to the sagittal slice where lateral tibial plateau was best noticed. A perpendicular line to the longitudinal tibial axis is defined. After, the tangent to the subchondral bone of lateral tibial plateau is drawn, as well as a tangent line to the superior surface of lateral meniscus. LPTS is calculated as the angle between the perpendicular line to the longitudinal tibial axis and the tangent to the subchondral bone of the lateral tibial plateau. MBA is calculated as the angle between the tangent line to the subchondral bone of the lateral tibial plateau and the superior surface of the lateral meniscus. (LPTS, lateral posterior tibial slope; MBS, meniscal bone angle; MRI, magnetic resonance imaging.)

curves were used to detect the optimum cut-off values and check if any variable had strong discriminative ability. The Youden index was computed to determine the cut-off value with the highest sensitivity and specificity. The area under the curve (AUC) compared the discriminative capacity of predictor variables. For all analyses, a P value less than .05 was considered significant. For sample size determination, calculations were made on G*Power software using effect sizes calculated from the literature, for a power of 80% and α of 0.05. The minimum sample size of 21 patients per group was found to attain a significant difference, using the size of effects reported from a similar study by Sauer et al.[16] (effect size d = 0.918).

Results

In total, 106 patients who underwent primary ACL surgery with a preoperative MRI between January 2016 and July 2021 were identified. Eleven patients were excluded from the primary ACL tear group (9 due to unavailable MRI and/or MRI reports and 2 because of previous knee surgery history). The remaining 95 patients who met inclusion criteria were matched with 95 control patients (Fig 2). The ACL tear group included 77 men and 18 women, and 74 men and 21 women in the control group. Participant height, age, weight, and BMI data are presented in Table 1. No significant differences regarding age or sex were found.

Injury characteristics assessed on MRI or MRI reports are also shown in Table 1. Supplementary data from the ACL tear group are presented in Table 2. Measurements made on MRI, such as LPTS and MBA, are also presented in Table 3. The median value of the LPTS-MBA ratio was 0.20 (IQR 0.11-0.37) in ACL tear versus 0.12 (IQR 0.08-0.19) in the control group ($P < .001$). LPTS was also significantly greater in knees with primary ACL tear with a median value of 4.20° (IQR 2.05-7.35°) versus 2.90° (IQR 2.05-5.00°) ($P = .026$). MBA was significantly reduced in the ACL tear group as 19° (IQR, 16-24°) for 26° in controls (IQR, 24-30°) ($P < .001$) (Fig 3 and Fig 4).

Subgroup analysis of patients with normal lateral meniscus is presented in Table 3. LPTS, MBA, and the LPTS−MBA ratio differed significantly between the primary ACL tear and control groups. Violin plots of the subgroup of patients with normal lateral meniscus showed that LTPS and MBA had similar values to those including all primary ACL tears (Fig 5). The LPTS−MBA ratio was nearly the same as the previous analysis (0.26 in primary ACL tears vs 0.14 in the control group) (Fig 6).

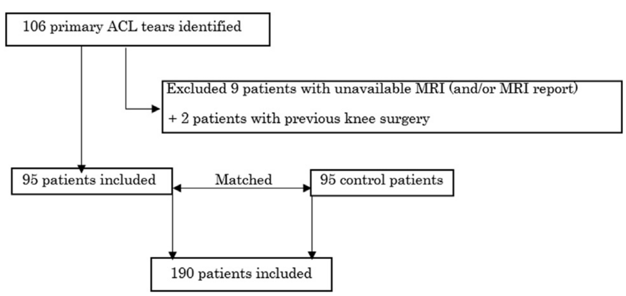

Fig 2. Flowchart of selection of patients included in the study.

Table 1. Characteristics of Study Population and Knee MRI Scans

Data	Overall (N = 190)*	Cases (n = 95)*	Controls (n = 95)*	*P* Value†
Age, y	26 (21-33)	26 (21-32)	27 (21-33)	.8
Sex				.6
Women	39 (21%)	18 (19%)	21 (22%)	
Men	151 (79%)	77 (81%)	74 (78%)	
Heigh, m‡	1.75 (1.69-1.80)	1.77 (1.71-1.80)	1.73 (1.67-1.78)	.014§
Weight, kg‡	74 (63-85)	77 (69-87)	70 (60-82)	.005§
BMI‡	24.4 (22.4-27.4)	25.1 (22.8-27.8)	24.1 (21.6-26.9)	.049§
Injured knee				.042§
Right	94 (49%)	54 (57%)	40 (42%)	
Left	96 (51%)	41 (43%)	55 (58%)	
Medial meniscus				<.001§
Injured	72 (38%)	62 (65%)	10 (11%)	
Normal	118 (62%)	33 (35%)	85 (89%)	
Lateral meniscus				<.001§
Injured	54 (28%)	46 (48%)	8 (8%)	
Normal	136 (72%)	49 (52%)	87 (92%)	
Bone				<.001§
Injured	126 (66%)	45 (47%)	81 (85%)	
Normal	64 (34%)	50 (53%)	14 (15%)	
PCL				0.7
Injured	6 (3%)	2 (2%)	4 (4%)	
Normal	184 (97%)	93 (98%)	91 (96%)	
MCoL				<.001§
Injured	28 (15%)	24 (25%)	4 (4%)	
Normal	162 (85%)	71 (75%)	91 (96%)	
LCoL				.4
Injured	5 (3%)	4 (4%)	1 (1%)	
Normal	185 (97%)	91 (96%)	94 (99%)	
LPTS, °	3.45 (2.02-6.05)	4.20 (2.05-7.35)	2.90 (2.05-5.00)	.026§
MBA, °	24 (19-28)	19 (16-24)	26 (24-30)	<.001§
LPTS−MBA ratio	0.15 (0.08-0.27)	0.20 (0.11-0.37)	0.12 (0.08-0.19)	<.001§

BMI, body mass index; LCoL, lateral colateral ligament; LPTS, lateral posterior tibial slope; MBA, meniscal bone angle; MCoL, medial colateral ligament; MRI, magnetic resonance imaging; PCL, posterior cruciate ligament.
*Data presented as median (interquartile range) or n (%).
†Wilcoxon rank sum test; Pearson χ^2 test; Fisher exact test for count data with simulated *P* value.
‡Missing values of 17 patients (3 cases and 14 controls).
§Statistically significant result.

The multivariable logistic regression model is presented in Table 4. LPTS was identified as an independent risk factor for primary ACL tear (odds ratio [OR] 1.20, 95% confidence interval [CI] 1.03-1.42, *P* = .021), and the lesion of lateral meniscus was associated with primary ACL tear (OR 20.6, 95% CI 6.73-80.7, *P* < .001). MBA, however, is a protective factor (OR 0.78, 95%CI 0.71-0.85, *P* < .001). In contrast, age, sex, and BMI are not independent risk factors for primary ACL tear.

ROC curves for evaluating predictor variables are shown in Figure 7. The AUC of LPTS−MBA (0.69; 95% CI 0.59-0.79) was bigger than that of LPTS (0.61; 95% CI 0.50-0.71); however, it was smaller than the AUC of MBA (0.82; 95% CI 0.74-0.90). By Youden index, a calculated cut-off value of 3.45° of LPTS was associated with an increased risk of ACL tear, with a sensitivity of 61% and specificity of 62% to predict ACL tear. A

Table 2. Features of Primary ACL Tear Group (N = 95)

Data	N (%)
Season of injury	
Winter	28 (29%)
Autumn	15 (16%)
Spring	19 (20%)
Summer	33 (35%)
Mechanism of injury*	
Traumatic contact	21 (28%)
Noncontact	54 (72%)
TAS*	
0-2	6 (8%)
3-5	27 (36%)
6-8	36 (48%)
9-10	6 (8%)
Familiar history*	
Positive	10 (13%)
Negative	65 (87%)

ACL, anterior cruciate ligament; TAS, Tegner activity scale.
*In total, 20 of the total 95 patients missed reporting these features.

Table 3. Characteristics and Measurements in the Subgroup of Patients With Normal Lateral Meniscus (N = 136)

Data	Overall (N = 136)	Case (n = 49)	Control (n = 87)	*P* Value
Age, y	26 (21-33)	27 (21-34)	26 (21-33)	.7
Sex				.4
Women	31 (23%)	13 (27%)	18 (21%)	
Men	105 (77%)	36 (73%)	69 (79%)	
BMI*	24.4 (22.3-27.5)	25.6 (22.9-28.7)	24.1 (22.1-26.9)	.045†
Injured knee				.077
Right	64 (47%)	28 (57%)	36 (41%)	
Left	72 (53%)	21 (43%)	51 (59%)	
LPTS, °	3.25 (2.00-5.50)	4.30 (2.00-7.40)	2.80 (2.05-4.80)	.042†
MBA, °	24 (20-29)	20 (16-24)	27 (24-30)	<.001†
LPTS−MBA ratio	0.14 (0.08-0.24)	0.24 (0.12-0.32)	0.11 (0.08-0.18)	<.001†

BMI, body mass index; LPTS, lateral posterior tibial slope; MBA, meniscal bone angle.

*Unknown values in 12 patients (2 cases and 10 controls).

†Statistically significant result.

threshold of 22.35° of MBA was associated with an increased risk of ACL rupture, with a sensitivity of 70% and specificity of 84%. A cut-off of 0.22 of LPTS−MBA was associated with an increased risk of ACL tear, with a sensitivity of 55% and specificity of 87%. The greater the LPTS−MBA ratio, the greater the risk of ACL tear.

Discussion

The primary finding of the study was that MBA was considered the strongest predictor variable for a primary ACL tear and that MBA values less than 22° can be associated with an increased risk of ACL tear. Also, the LPTS−MBA ratio was significantly increased in the ACL tear group, whether lateral meniscus was injured or not. The use of MRI scan was an important detail once both ligament and meniscal integrity could be clearly identified on MRI. In addition, some studies have shown the important role of lateral meniscus in the rotatory mechanism of the knee joint, since it was revealed that, when a lateral meniscectomy is performed, the internal rotation of the tibia is increased.[22,23] Therefore, once a lesion in lateral meniscus may interfere on MBA and consequently on LPTS-MBA ratio, an analysis was conducted in a subgroup of patients with normal lateral meniscus. Both analyses, either with normal or injured lateral meniscus, showed a significantly higher LPTS-MBA ratio, higher LTPS and a significantly reduced MBA in the primary ACL tear group.

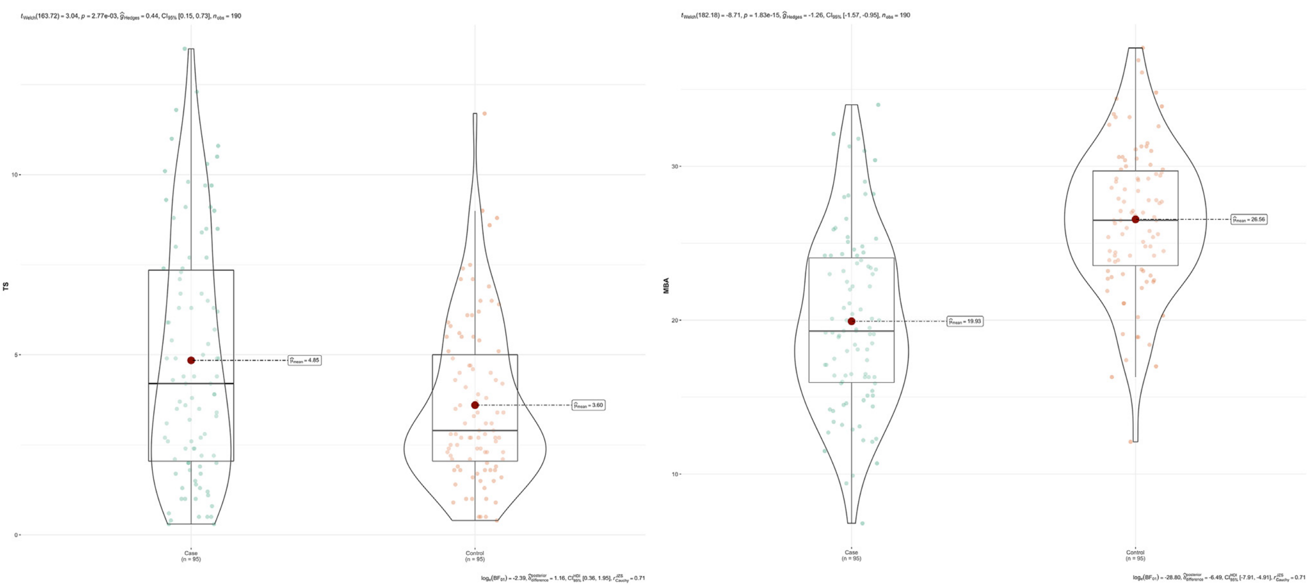

Fig 3. (3.1 + 3.2) Violin box plots demonstrate differences in (LP)TS and MBA between ACL injured patients and controls. The top and bottom of the box indicate the interquartile range and the line within the box indicates the median. The biggest dot inside the box shows the mean value. LPTS had a mean value of 4.85° in primary ACL tears versus 3.60° in the control group (*P* < .001). MBA had a mean value of 19.93° in primary ACL tears versus 26.56° in the control group (*P* < .001). (ACL, anterior cruciate ligament; LPTS, lateral posterior tibial slope; MBS, meniscal bone angle.)

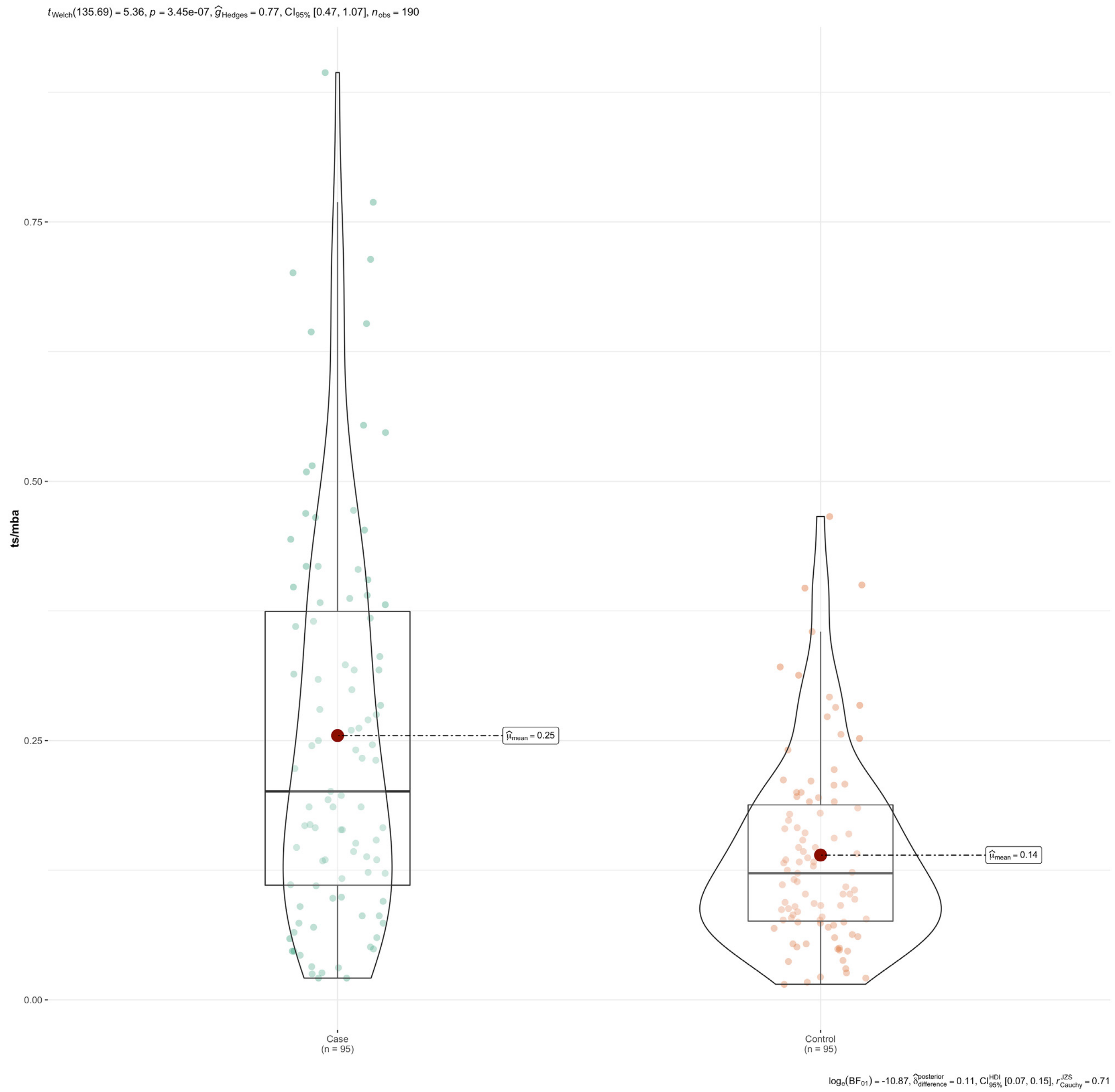

Fig 4. Violin and box plots demonstrating differences in LPTS−MBA ratio between ACL injured patients and controls. LPTS−MBA ratio had a mean value of 0.25 in primary ACL tears versus 0.14 in the control group ($P < .001$). (ACL, anterior cruciate ligament; LPTS, lateral posterior tibial slope; MBS, meniscal bone angle.)

Sauer et al., in a study with patients who underwent ACL reconstruction, showed that an LTPS−MBA ratio of less than 0.27 was associated with a 28% risk of ACL failure, and a ratio upper than 0.42 with a greater percentage of 82% risk of ACL failure. Edwards et al. studied a pediatric population and found a LPTS−MBA threshold of 0.36 with the AUC of 0.88, which yielded a sensitivity of 75% and a specificity of 90% to predict primary ACL tears.[16,18] In patients with normal lateral meniscus, the results showed a significant value of 0.24 for the LPTS−MBA ratio, which may indicate that, compared with previous studies, a lower value can already be linked to a relevant ACL tear risk. However, the ROC analysis for detecting an optimal cut-off value for the LPTS−MBA ratio was not as expected due to its low sensitivity.

As LPTS−MBA ratio, MBA was also significantly different in both groups, even in knees with normal lateral meniscus. Some studies reported that MBA could be the most relevant anatomic predictor in male patients with ACL injury, but not in female patients.[14,16] Despite not comparing sexes, MBA was

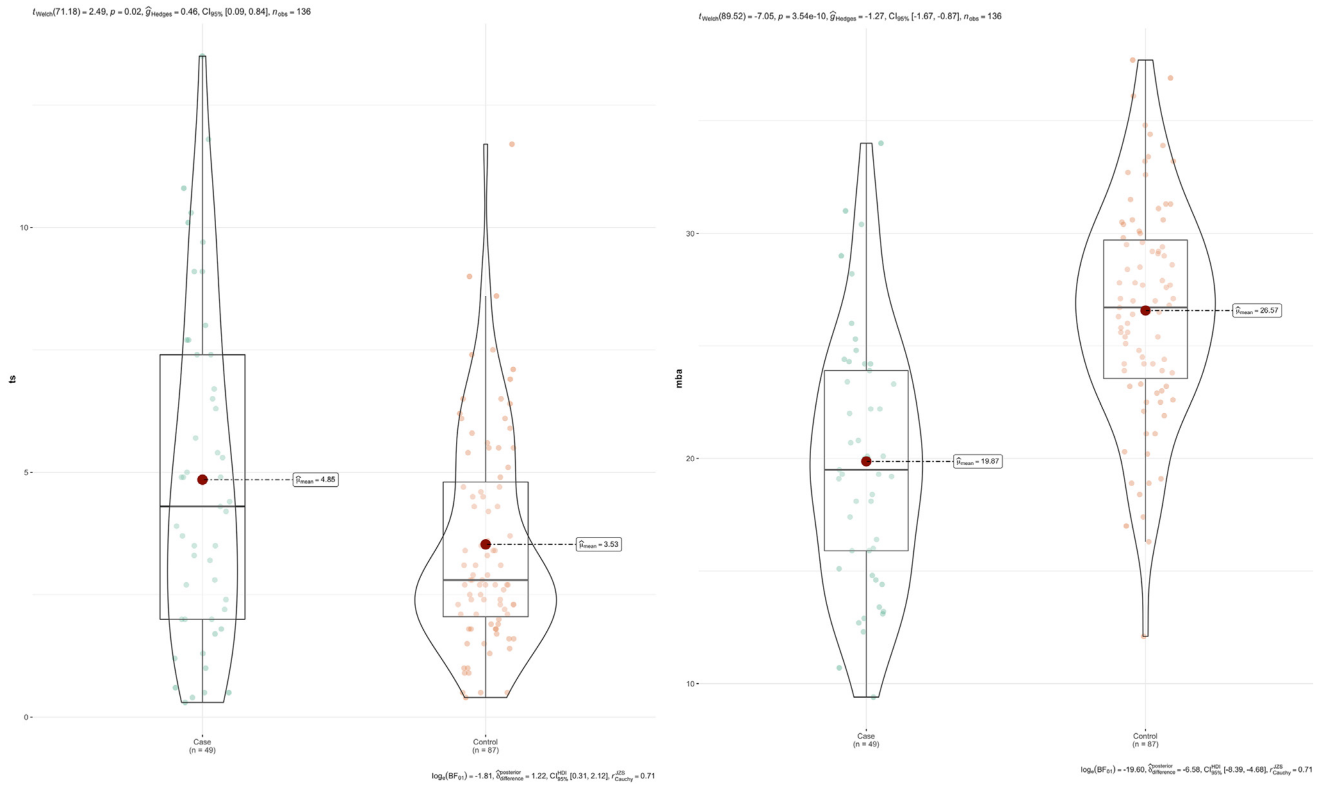

Fig 5. (5.1 + 5.2) Violin and box plots demonstrating differences in (LP)TS and MBA between ACL injured patients and controls, with normal lateral meniscus. LPTS had a mean value of 4.85° in primary ACL tears versus 3.53° in the control group ($P = .02$). MBA had a mean value of 19.87° in primary ACL tears versus 26.57° in the control group ($P < .001$). (ACL, anterior cruciate ligament; LPTS, lateral posterior tibial slope; MBS, meniscal bone angle.)

indeed the strongest predictor variable for a primary ACL tear, because the AUC of MBA was greater than both the AUC of LPTS−MBA and LPTS. Thus, MBA values equal or below 22° may be associated with an increased risk of ACL tear. Nevertheless, further studies are needed to evaluate the potential of this measurement.

In several previous studies, LPTS has been extensively identified as a strong predictor of ACL injury, which is a finding also confirmed by the current results.[5,24-26] However, no reliable cut-off value can be assumed, because, according to the sensitivity analysis, LPTS was the weakest of the 3 measurements to predict a primary ACL injury.

The study is useful to understand the influence of these 3 MRI measurements on ACL tear, once it comprises a large sample size and may be helpful to take some solid conclusions. However, the susceptibility of primary ACL tear is multifactorial, including patient age, activity level, acquired concomitant injuries, neuromuscular conditions, and structural anatomy of knee joint.[27] Regarding TAS, it was clear that most cases with primary ACL tear were sportively active, most engaging levels 6 to 8 of the TAS. BMI differed slightly between groups, which could be regarded as a weakness of the study, since there is evidence of patients' BMI interference in ACL injury risk.[28-30] However, such as age and sex, BMI was not considered a potential confounder.

Finally, the multivariable logistic regression analysis showed that LPTS could be considered an independent risk factor for ACL tear and MBA a protective factor. The greater MBA value, the lesser the risk of ACL tear, and the opposite is also true. Still, caution is needed when LPTS and MBA measurements are calculated in lateral meniscus injured patients, once lateral meniscus injury can be a potential confounder. This must be taken into count because the ACL tear mechanism is often concurrent with meniscal injuries.[31] Lastly, the LPTS−MBA ratio was not included in the logistic regression analysis once that variable has a high correlation with LPTS and MBA variables, which are already presented in the model. According to the OR of both LPTS and MBA calculated by the model, it was concluded that LPTS-MBA ratio might also be considered an independent risk factor for primary ACL tear.

Limitations

The main limitations of this study are the inherent risk of bias of a retrospective study, the incapacity of

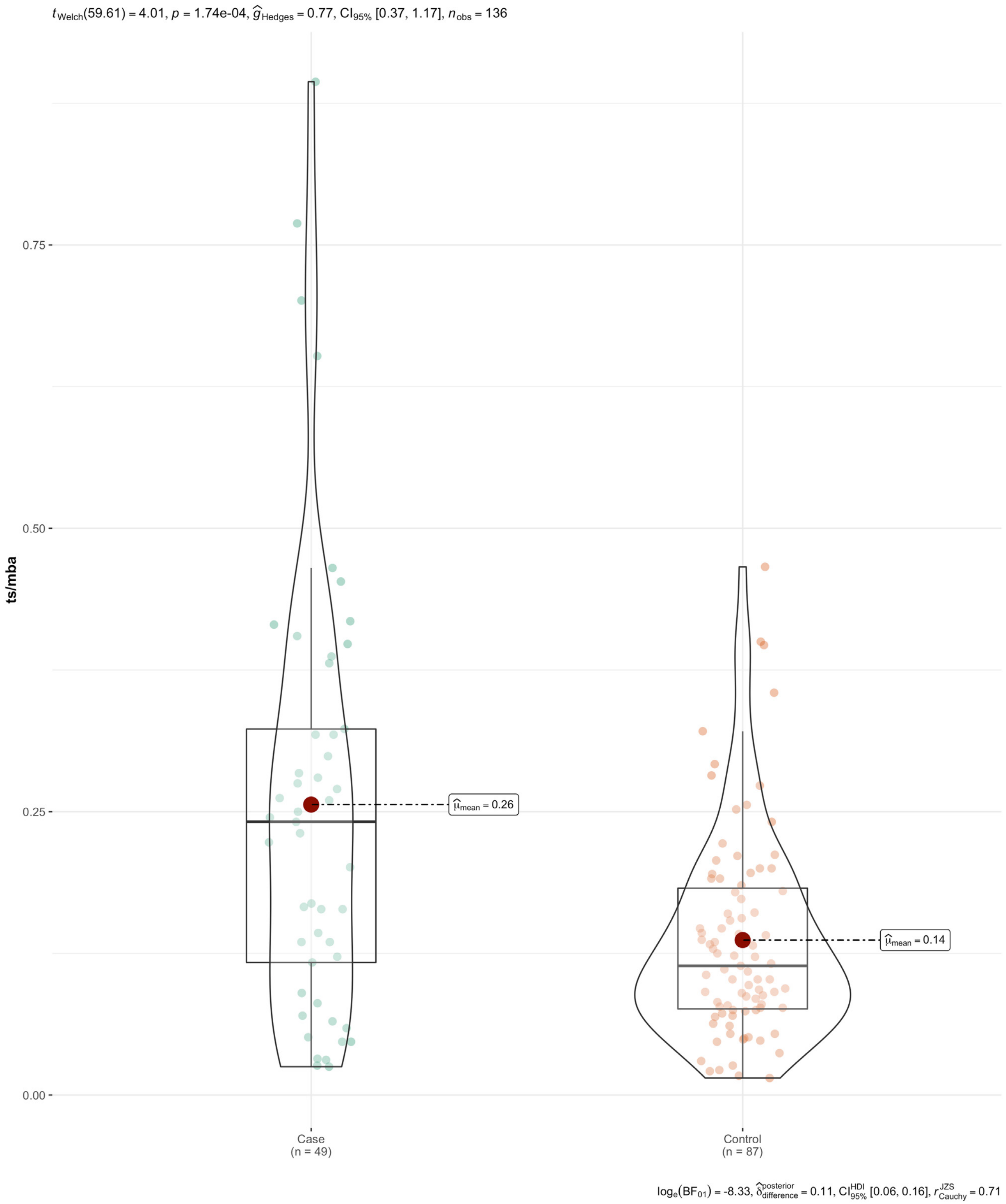

Fig 6. Violin box plots demonstrate differences in LPTS-MBA ratio between ACL injured patients and controls, with normal lateral meniscus. LPTS-MBA ratio had a mean value of 0.26 in primary ACL tears versus 0.14 in the control group ($P < .001$). (ACL, anterior cruciate ligament; LPTS, lateral posterior tibial slope; MBS, meniscal bone angle.)

entirely patient sex matching, and the MRI measurements performed by only one observer. In addition, the MRI evaluation of cartilage and meniscus morphologic characteristics of ACL injured and control subjects can be influenced by different activity levels before image acquisition, which was not evaluated in this study.[32]

Table 4. Multivariable Logistic Regression Analysis

Data	OR	95% CI	*P* Value
Age	0.98	0.92-1.03	.4
Sex			
Women	–	–	
Men	0.79	0.26-2.33	.7
BMI	1.09	0.98-1.23	.12
Lateral meniscus			
Normal	–	–	
Injured	20.6	6.73-80.7	<.001*
LPTS	1.20	1.03-1.42	.021*
MBA	0.78	0.71-0.85	<.001*

CI, confidence interval; BMI, body mass index; LPTS, lateral posterior tibial slope; MBA, meniscal bone angle; OR, odds ratio.
*Statistically significant result.

And despite MRI having high sensitivity (88%) and specificity (94%) in diagnosing meniscal tears, there is room to misdiagnose.[33] Also, the relationship between meniscal injury and MBA is not clearly defined and was not evaluated in this study. Meniscal tears are heterogeneous, and it is likely that certain types of meniscal tears, such as meniscal root tears, may impact MBA, while others may not.

Conclusions

In this study, a reduced MBA was the strongest predictive variable associated with a primary ACL tear. A threshold of 22.35° of MBA was associated with an

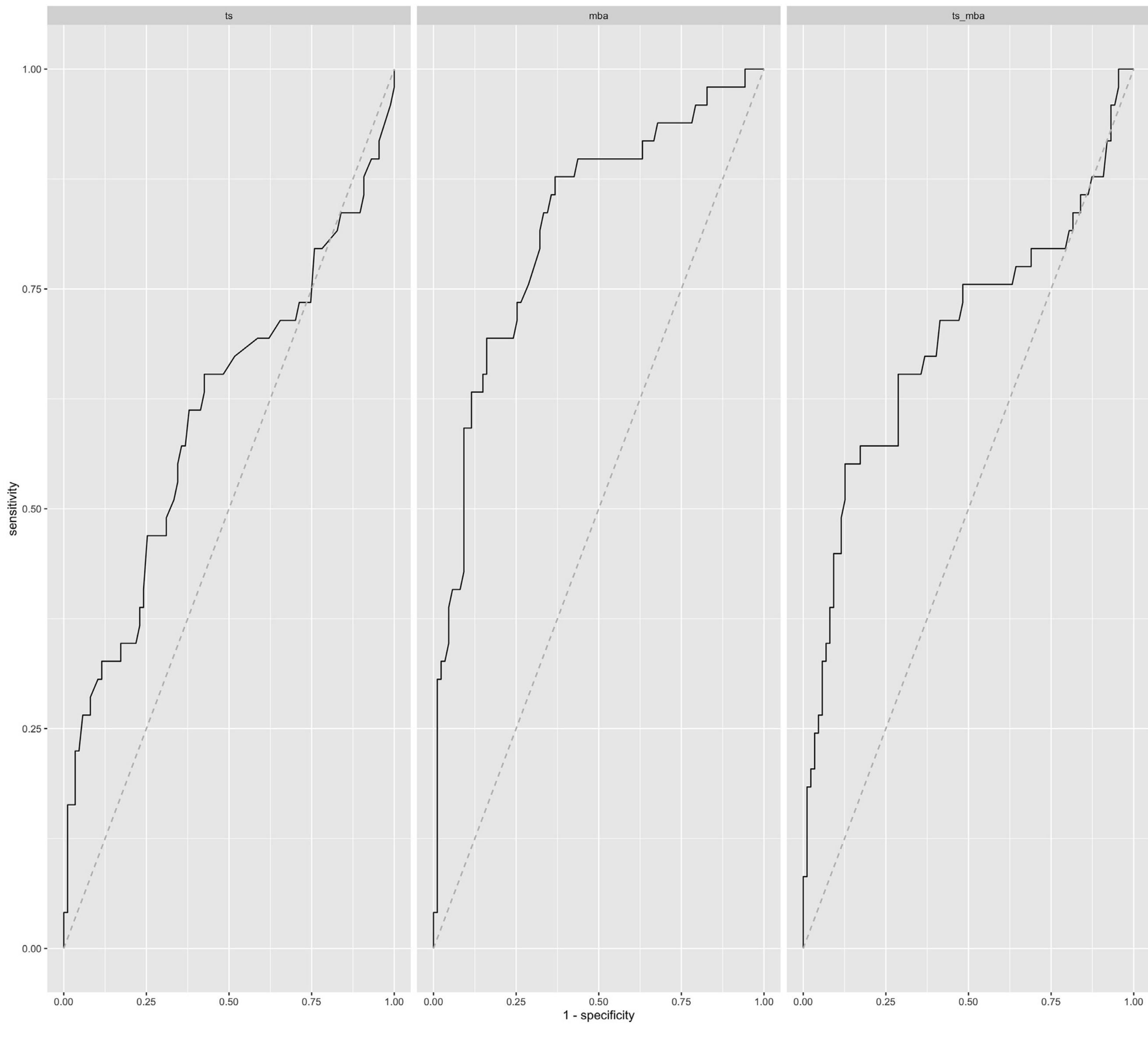

Fig 7. Receiver operating characteristics (ROC) analysis for predictor variables. Reference line (diagonal): AUC = 0.5. (AUC, area under the curve; LPTS, lateral posterior tibial slope; MBS, meniscal bone angle.)

increased risk of ACL tear, with a sensitivity of 70% and specificity of 84%. A cut-off of 0.22 of LPTS−MBA was associated with an increased risk of ACL tear, with a sensitivity of 55% and specificity of 87%.

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