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# Morphological Evaluation of The Anterolateral Ligament at Varying Knee Flexion Angles Using Wireless Meta Surface Technology: Implications for Clinical Reconstruction

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## ABSTRACT

Anterolateral ligament (ALL) reconstruction alongside the anterior cruciate ligament (ACL) improves recovery, stability, and reduces complications. However, the optimal knee position for ALL reconstruction remains debated. This study uses magnetic resonance imaging (MRI) to assess ALL morphology at various knee flexion angles, providing insights for better preoperative planning. In October 2022 and February 2023, 30 healthy adult participants underwent MRI scans of the left knee at 0°, 45°, and 90° flexion. Exclusion criteria included a history of knee surgery, injury, or lateral knee ligament tears. Two experienced radiologists independently evaluated the visibility of the ALL on multiplanar MRI reconstruction images, categorizing it as either fully or partially visible. Statistical analyses were performed to assess the differences in ALL length and thickness across flexion angles. Correlations between ALL dimensions and participant age, height, and weight were also analysed. The ALL was visible in 27 participants (90%), with visibility rates of 86.7% at 0°, and 83.3% at 45° and 90° flexion. Knee flexion was associated with an increase in ALL length (30.86 ± 3.45 mm at 0° to 33.57 ± 3.51 mm at 90°) and a decrease in its thickness (1.18 ± 0.16 mm at 0° to 0.93 ± 0.13 mm at 90°), both of which were statistically significant ($P < 0.05$). Additionally, a positive correlation was found between ALL thickness and participant weight. This study reveals significant variations in ALL length and thickness across knee flexion angles, offering insights to optimize diagnostics, surgery, and rehabilitation.

## INTRODUCTION

Over the past decade, research has definitively established that the anterolateral ligament (ALL) of the knee joint is a distinct and critical structure, connecting the femoral epicondyle to the anterior lateral border of the tibia Claes et al. (2013), Kosy et al. (2015). Biomechanical studies have demonstrated that the ALL serves as a secondary stabilizer to the anterior cruciate ligament (ACL), playing a crucial role in resisting anterior tibial translation and internal tibial rotation Kang et al. (2019). Injury or laxity of the ALL can result in excessive anterior translation, valgus deviation, and internal rotation of the knee, leading to abnormal motion, instability, and pain Nakamura et al. (2015), Padua et al. (2012).

Previous studies have reported a high incidence of ALL injuries accompanying ACL tears Claes et al. (2014). Recently, numerous investigations have focused on the simultaneous reconstruction of both the ACL and ALL following ACL rupture. These studies suggest that dual reconstruction of the ACL and ALL can significantly improve postoperative rehabilitation outcomes and overall ligament function Delaloye et al. (2020), Geeslin et al. (2018), Inderhaug et al. (2017), Park et al. (2023).

As a result, ALL reconstruction has gained increasing attention. However, there is still no consensus on the optimal intraoperative knee flexion angle for ALL reconstruction.

In a previous study, we developed an innovative wireless meta surface designed to enhance the signal-to-noise ratio (SNR) in magnetic resonance imaging (MRI) Chi et al. (2021). The wireless meta surface features an adaptive resonance mode, allowing it to switch seamlessly between transmission and reception. This effectively eliminates interference from RF signals, significantly improving the SNR. For instance, in wrist MRI imaging of human subjects, the meta surface demonstrated an SNR increase of 2-4 times compared to conventional techniques. The use of wireless meta surfaces offers several benefits, including shortened MRI scan times, reduced motion artifacts from organs like the heart, and enhanced tissue contrast.

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Additionally, the metasurface is compatible with all standard MRI sequences without requiring adjustments to scanning parameters. Being wireless, it also eliminates the need for interface communication protocols, introducing a novel approach to clinical applications of metasurfaces.

This study aims to employ the wireless metasurface to perform MRI scans at varying knee flexion angles, focusing on morphological changes in the ALL. The goal is to provide a non-invasive and valuable imaging method for preoperative clinical evaluation of the anterolateral ligament.

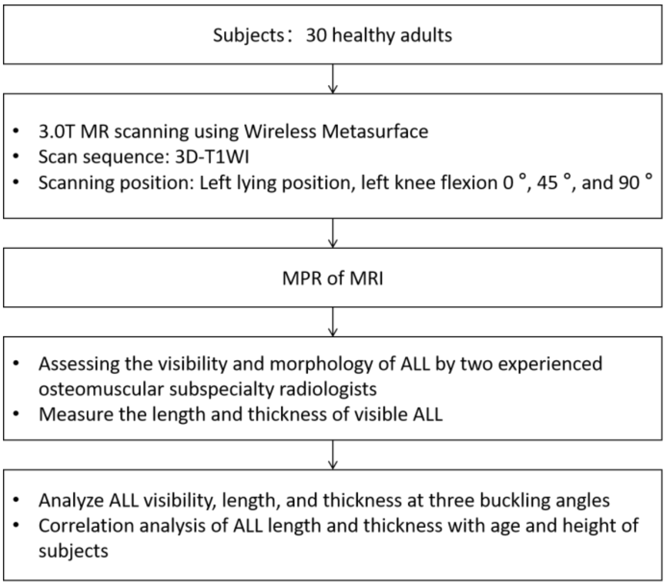
## MATERIALS AND METHODS

### Patients

This study is a prospective cohort involving 30 healthy adult volunteers with no history of left knee surgery, trauma, or congenital malformations. These participants underwent MRI examinations of the knee joint between October 2022 and February 2023. All subjects were recruited from a local hospital, and the study was approved by the hospital's ethics committee. A flowchart of the research protocol is shown in Fig. 1.

The cohort consisted of 30 participants, evenly split between 15 males and 15 females, aged 22-37 years (mean age: 25.8 ± 4.5 years). The height of the participants ranged from 154 to 178 cm (mean height: 168.3 ± 7.0 cm), and their weight ranged from 42 to 81 kg (mean weight: 62.5 ± 12.2 kg).

**Figure 1:** Flowchart of the study protocol.

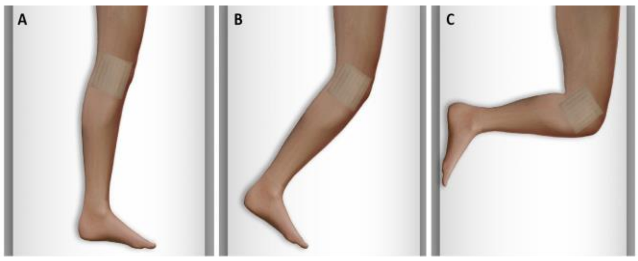



### MRI

All imaging was performed at our institution using a 3.0T clinical imaging system (Philips Ingenia CX) with a wireless meta surface (Fig. 2). Standard sagittal scans of each subject's knee was obtained using the 3D T1-weighted imaging (T1WI) sequence. Imaging parameters were as follows: repetition time (TR) = 110 ms, echo time (ET) = 85 ms, field of view (FOV) = 160 mm × 160 mm × 120 mm, slice thickness = 0.7 mm, interslice gap = -0.3 mm, flip angle = 90°, voxel size = 0.7 mm × 0.7 mm × 0.7 mm, and reconstructed voxel size = 0.4 mm × 0.4 mm × 0.4 mm. No fat suppression sequence was used. The coil was positioned on the lateral side of the subject's knee joint, approximately over the location of the lateral collateral ligament. Each subject underwent three scans of the left knee in a standardized left lateral decubitus position with knee flexion at 0°, 45°, and 90° (Fig. 3).

**Figure 2:** Front, rear, and oblique views of the wireless meta surface used in the study.

**Figure 3:** MRI scanning positions for the left knee joint. Subjects were positioned in a standardized left lateral decubitus position with knee flexion at 0° (A), 45° (B), and 90° (C) for the three scans.



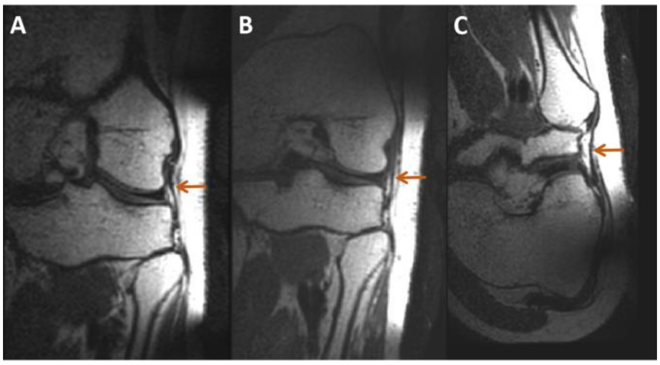

### Imaging analysis

Multiplanar reconstruction (MPR) was used to analyze the three-dimensional images, allowing free orientation of axial, coronal, and sagittal planes. Oblique coronal views parallel to the ALL were reconstructed to display the ligament as completely as possible Hecker, et al. (2021). Two experienced observers independently performed the MPR analysis on the MRI scans to assess the visibility of the ALL in all 30 subjects. The visibility of the ALL was classified into three categories: fully visible, partially visible, and invisible (Fig. 4). When the ALL was fully visible, the observers measured its length and thickness as accurately as possible along its trajectory.

### Statistical analysis

Data analysis was performed using IBM SPSS Statistics, Version 26 for Windows. Descriptive statistics were presented as mean ± standard deviation where applicable. Analysis of variance (ANOVA) was used to determine whether significant differences existed in the length and thickness of the ALL at different knee flexion angles. Pearson correlation coefficients were calculated to assess the relationship between ALL length and thickness with age, height, and weight. A correlation coefficient (r) of 0.1-0.3 was considered weak, 0.3-0.5 was considered moderate, and 0.5-1.0 was considered strong. Statistical significance was defined as a P-value of less than 0.05.

**Figure 4:** MPR images of the knee joint at 0° (A), 45° (B), and 90° (C) flexion angles, showing the visible ALL indicated by arrows.




## RESULTS

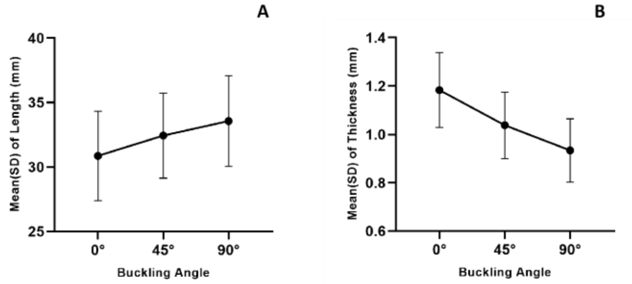
### Visibility and Morphological Characteristics of the ALL in MPR of MRI at Various Flexion Angles of the Knee Joint

Among all participants, three subjects did not exhibit a visible ALL in the MPR images at any of the three knee flexion angles. In the remaining 27 subjects, the ALL was visible in 26 cases at 0° flexion, yielding a visibility rate of 86.7%. At both 45° and 90° flexion, the ALL was visible in 25 cases, corresponding to a visibility rate of 83.3%. Although the highest visibility rate occurred at 0° flexion, no statistically significant difference was observed between the three flexion angles. Additionally, the MPR images revealed that the ALL appeared straight at 45° flexion, while varying degrees of tortuosity were noted at 0° and 90° flexion.

### Variations in Length and Thickness of the ALL in MPR of MRI across Different Knee Flexion Angles

A total of 24 participants with visible ALL in the MPR images at all three knee flexion angles were included in the analysis. The length and thickness of the ALL were measured at each flexion angle. The mean lengths at 0°, 45°, and 90° flexion were 30.86 ± 3.45 mm, 32.44 ± 3.29 mm, and 33.57 ± 3.51 mm, respectively. Corresponding thickness values were 1.18 ± 0.16 mm, 1.04 ± 0.14 mm, and 0.93 ± 0.13 mm, respectively. A clear trend was observed, indicating that the length of the ALL increased with greater knee flexion angles, while its thickness decreased simultaneously. These changes were statistically significant ($P < 0.05$), as shown in Fig. 5.

**Figure 5:** Changes in ALL morphology with increasing knee flexion angles: (A) demonstrates the elongation of the ALL, while (B) shows the corresponding reduction in ALL thickness.




### Correlation Analysis of Height and Weight with Length and Thickness of the ALL

A correlation analysis was conducted to assess the relationship between the length and thickness of the ALL during knee joint extension and the subjects' gender, height, and weight. The results indicated a significant positive correlation between ALL thickness and body weight ($r=0.412$, $P=0.037$). However, no significant correlations were identified between the other variables, including ALL length, gender, height, and weight.

## DISCUSSION

Injury or dysfunction of the ALL can significantly contribute to knee instability, particularly when combined with damage to other ligaments Sood et al. (2020). The importance of understanding the ALL has become particularly pronounced in the context of ACL reconstruction surgery, where persistent rotational instability often points to ALL involvement. Consequently, surgeons may opt to address the ALL during ACL reconstruction to enhance knee stability and reduce the likelihood of re-injury.

Assessing the integrity of the ALL is crucial in cases of knee injuries, and diagnostic tools like MRI and arthroscopy can help visualize the ligament and detect any abnormalities. This information is critical for guiding treatment decisions—whether conservative management, tailored rehabilitation, or surgical intervention is required. An improved understanding of the biomechanical role of the ALL can also aid in the development of rehabilitation protocols that target this ligament to restore function and improve knee stability.

Despite the growing recognition of the ALL's role, the indications for anterolateral ligament reconstruction (ALLR) remain debated, with no standardized guidelines established to date.

However, consensus has emerged around several scenarios where ALLR should be considered, including Delaloye et al. (2020), Neri et al. (2021), Park et al. (2023). (1) revision ACL reconstruction, (2) return to competitive pivoting sports, (3) high-grade pivot shift test (greater than grade 2), and (4) generalized ligamentous laxity. Currently, there is no consensus on the optimal intraoperative knee flexion angle for ALL reconstruction, nor is there a reference standard for the length and thickness of preoperative ligament preparation. This study aims to enhance the clinical applicability of non-invasive imaging by evaluating the morphology, length, and thickness of the ALL using MRI at different knee flexion angles.

Wireless metasurfaces, with their engineered electromagnetic properties, offer the potential to improve MRI systems by enhancing the SNR Chi et al. (2021), Engheta et al. (2006), Zhang et al. (2022). Traditional methods for increasing SNR, such as utilizing higher-field MRI systems or increasing channels, have technical limitations. The unique properties of metasurfaces allow precise control of electromagnetic waves, offering significant improvements in imaging quality without the need for hardware upgrades.

In this study, the visibility of the ALL varied across different knee flexion angles. The ALL was visible in 86.7% of subjects at 0° and 90° flexion, and in 83.3% of subjects at 45°. These results are consistent with prior research, which reports variability in ALL visibility across different study populations (Andrade et al. (2019), Eckhoff et al. (2016), Taneja et al. (2015). Overall, ALL visibility typically ranges from 50% to 100%. Our study also observed that the ALL appeared straight at 45° flexion, whereas it exhibited varying degrees of curvature at 0° and 90°. This finding aligns with previous studies, which suggest that the ALL tends to straighten at smaller flexion angles and becomes more curved as the knee flexes further Ferle et al. (2019), Kubo et al. (2006), Nasu et al. (2020).

The observation that the ALL appears straighter at 45° flexion suggests that this position might be ideal during ALL reconstruction surgery, as it may better replicate the ligament's natural alignment. Additionally, during postoperative rehabilitation, it may be beneficial to avoid prolonged periods with the knee in a 45° flexed position, as the ligament is under higher tension, which could adversely impact recovery if maintained for extended periods.

The lengthening and thinning of the ALL with increased knee flexion highlight the dynamic nature of ligament biomechanics. As flexion increases,

the ALL appears to play a more significant role in stabilizing the knee during deep flexion activities, such as squatting or kneeling.

The observed decrease in ligament thickness at higher flexion angles may reflect changes in tension and fiber alignment Belvedere et al. (2012), Helito et al. (2014), Stender et al. (2018). Understanding these variations may improve the accuracy of diagnostic imaging and aid clinicians in evaluating ligament function at different flexion angles.

The clinical implications of these findings are significant. Radiologists and orthopedic specialists can use this knowledge to better interpret imaging results, particularly in patients presenting with flexion angle-dependent symptoms or injuries. Surgeons involved in ALL reconstruction may benefit from considering the ligament's morphological changes at different flexion angles, enabling them to plan surgical techniques that restore ligament function across the full range of knee motion. Rehabilitation professionals can also apply this understanding to optimize rehabilitation protocols,

tailoring exercises to account for ligament adaptations at various flexion angles.

In a study focused on ACL reconstruction, Sadoghi et al. (2023) observed positive correlations between patient height, weight, and ACL length, as well as between weight and ACL thickness. In contrast, our study found a significant correlation only between body weight and ALL thickness, while other demographic factors showed no significant associations with ligament dimensions. The discrepancies between studies may be attributed to variations in research methodologies, sample sizes, and participant demographics. As such, there is no definitive evidence linking anthropometric factors with the dimensions of knee ligaments, including the ALL. Traditional considerations, such as gender, height, and weight, have often influenced surgical planning; however, the lack of correlation between these factors and ALL dimensions suggests that individualized preoperative imaging and patient-specific factors should be prioritized over demographic averages.

This study has several limitations. The relatively small sample size restricts the generalizability of our findings, and a larger cohort would provide more robust conclusions. Additionally, measurement errors, such as MRI resolution constraints and subjective variability between observers, may have affected the results. Future studies could enhance accuracy by employing higher-resolution imaging techniques and standardized protocols with inter-observer reliability assessments. The use of automated measurement tools could also minimize observer-related bias. Furthermore, the age range of participants (22-37 years) may limit the applicability of the findings to broader populations. Additional research, including biomechanical studies using cadavers or computational models, could offer deeper insights into the mechanical implications of ligament changes at different flexion angles. Finally, the clinical significance of these findings requires further validation, particularly through studies assessing the long-term outcomes of ligament variations.

## CONCLUSION

In conclusion, our study reveals substantial changes in the length and thickness of the ALL with increasing knee flexion angles. The morphology of the ALL also varies across different flexion angles, suggesting that 45° flexion may be an optimal position for ALL reconstruction. These findings enhance our understanding of knee joint stability and hold significant clinical relevance for diagnosis, surgical planning, and rehabilitation.

## DECLARATIONS

### Conflict of Interest

The authors declare that they have no conflict of interest.

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