

Delayed ACL Maturation Compared to Menisci During Skeletal Growth Implications for Knee Instability and ACL Injury Risk

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DISCLOSURE: M. Aghaalikhani: None. M. Hurley: None. B. Brook: None. A. Santos: None. N. Tavabi: 4; BonePixel. M. Movahhedi: 4; BonePixel. A.M. Kiapour: 3B; MIACH Orthopedics, 4; BonePixel, 8; BMC Musculoskeletal Disorders and American Journal of Sports Medicine.

INTRODUCTION: Meniscus and ACL both act as major stabilizers of the knee against anterior shear forces and rotational moments. Despite significant rates of isolated and combined ACL and meniscal tears, little is known on the interaction between these structures during skeletal growth and maturation. To address this knowledge gap, we used a robust deep-learning pipeline to survey a large database of knee MRIs taken from children, adolescents, and young adults. We hypothesized that while both ACL and menisci undergo significant age-related changes, they follow different time frames to complete their growth (maturation).

METHODS: Following IRB approval, we utilized a multi-modal AI-driven pipeline to identify 3,111 knee MRIs with no documented skeletal disorders and injuries to the knee structures (mean age: 13.9 ± 4.6 years; range, 1–30 years; 66% female) from an institutional archive spanning 2000–2023. MRIs were segmented using a validated 3D deep learning model (Dice >0.98) to quantify ACL and medial/lateral meniscus volumes. Age- and sex-related changes were assessed using a generalized linear model. Analyses were repeated after normalizing ACL and menisci volumes by bicondylar width to account for variations in knee size. ACL and Menisci maturation was defined as the inflection point on the volume vs age graph (point where the growth starts to plateau). The age at maturation was compared between the tissues for each sex.

RESULTS: All quantified features (raw and normalized) increased with age in both males and females ($P < 0.001$). ACL volume rose steeply through early-late adolescence and then plateaued by young adulthood (Figure 1). Males had larger raw ACL volumes ($P < 0.001$), but this sex gap largely collapsed after BW normalization ($P < 0.001$), indicating proportional scaling with joint size. In contrast, meniscal volumes showed persistent sex differences even after normalization ($P < 0.001$ for both raw and normalized measurements), consistent with intrinsic dimorphism. In males, the lateral meniscus achieved maturation at 13 years of age, followed by the medial meniscus and ACL at 14.5 years (Figure 1B). A similar trend was observed after normalization to the bicondylar width (Figure 1C). In females, the lateral meniscus achieved maturation at 10 years of age, followed by the medial meniscus at 11.5 years and the ACL at 12.5 years (Figure 2B). A similar trend was observed after normalization to the bicondylar width (Figure 2C).

DISCUSSION: In the largest MRI cohort of uninjured pediatric and young-adult knees to date, we showed that there are substantial differences in time to maturation for menisci and ACL in both males and females. The observed age and sex differences in tissue size are consistent with existing literature. However, we showed that the time to maturation is tissue specific, starting with the lateral meniscus, then the medial meniscus, and the ACL. While both males and females followed the same order, the maturation period was substantially earlier and longer in females (10–13 years) than in males (13–15 years). These timings correspond to the previously reported ages with the highest rate of ACL injuries in each sex. Considering the role of menisci and ACL in anterior knee stability, the findings suggest that a lack of meniscal maturation at early ages (prior to ACL maturation) may be a risk factor for ACL injury.

SIGNIFICANCE: Meniscal development and maturation (measured by size and morphology) may assist with ACL injury risk screening to guide injury prevention and post-op rehab protocols to minimize the risk of primary and secondary ACL injuries.

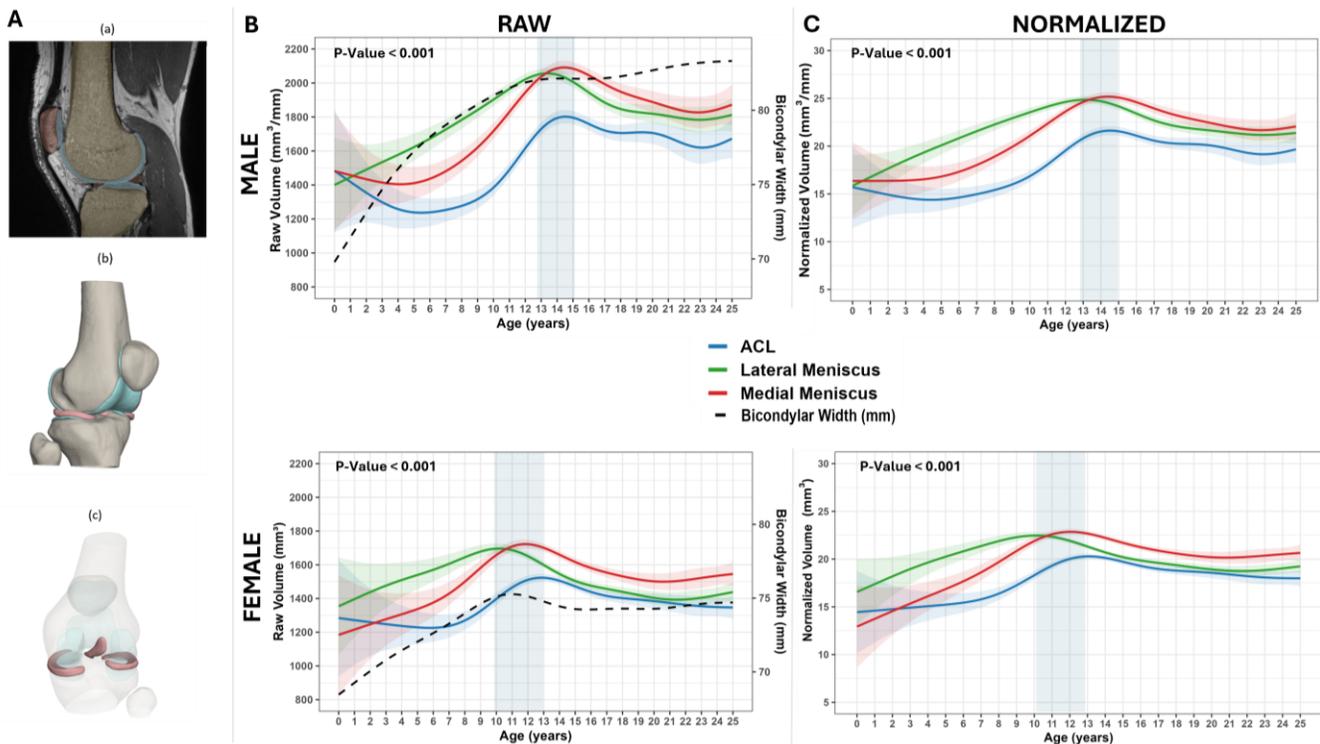


Figure 1: (A) Developed 3D models for the automated segmentation pipeline. (B) Developmental curves of ACL and meniscus volumes (Raw). (C) Developmental curves of ACL and meniscus volumes (Normalized). The dotted curve shows the Bicondylar width at the same ages.