3D Geometry Scanning and Structural Integrity Assessment to Support Meniscus Allograft Transplantation

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INTRODUCTION: Meniscal surgery alleviates pain and restores mobility, but tissue removal through partial or total meniscectomy often leads to long-term complications including recurrent effusion and osteoarthritis. Meniscus allograft transplantation offers a promising alternative by restoring joint biomechanics and achieving high patient satisfaction, yet its use is constrained by the shortage of size-matched, structurally intact donor tissues. Tissue banks are central to addressing this gap, but current donor tissue evaluation methods are inadequate: 2D measurements neglect complex 3D geometry, visual defect inspection is subjective, and CT/MRI are impractical for routine workflows. In addition, scanning methods must be compatible with preservation protocols, as air exposure can compromise cell viability and reduce graft usability. These limitations underscore the need for a reliable, efficient, and affordable system that can capture donor geometry, assess surface defects, and maintain viability. To address this gap, we developed and validated a 3D optical scanning and curvature-based analysis system to provide tissue banks with an objective tool for donor screening and graft quality assurance.

METHODS: We developed an integrated system for 3D geometry scanning and curvature-based defect assessment of meniscus allografts. System performance was validated in three experiments. (1) Scanning accuracy: volumetric and surface metrics from porcine menisci were compared with high-resolution µCT as the reference standard, and the effects of scanning in air versus in PBS-filled storage bags were assessed. (2) Tissue viability: live/dead fluorescence imaging was performed after scanning under different conditions and durations to determine acceptable scanning windows. (3) Defect detection: standardized radial tears, longitudinal tears, and surface wear were created in porcine menisci. Defect sizes quantified by our curvature-based software were compared with stereomicroscopy ground-truth measurements. Statistical analyses included one-way ANOVA for cell viability and two one-sided tests (TOST) for equivalence of volumetric and defect size measurements

RESULTS SECTION: Our system enabled rapid scanning (2 minutes vs 60 minutes for µCT). Compared with µCT, the 3D scanner achieved a mean relative volume error of 6.9% (TOST equivalence confirmed) and a surface deviation of 8.3%. When comparing scanner results obtained in air versus in PBS-filled sterile bags, the relative volume difference was 7.2% (TOST equivalence confirmed) and the surface deviation was 12.5%. Cell viability tests revealed that air-exposed samples dropped below the clinically acceptable 70% threshold within 10 minutes, whereas PBS-immersed samples preserved >94% viability throughout 20 minutes (ANOVA, $p<0.05$). For defect detection, curvature-based analysis successfully identified all defect types with 100% detection. Optimal indicators differed by defect: mean curvature for radial tears, minimum curvature for longitudinal tears, and maximum curvature for surface wear. The equivalence between stereomicroscopy and software measurements was confirmed for longitudinal tears and surface wear within a ±20% margin, but not for radial tears.

DISCUSSION: This study developed and validated an integrated system that combines optical 3D scanning with curvature-based structural integrity assessment to support meniscus allograft transplantation. The system provides rapid 2-minute scans with µCT-comparable accuracy, preserves cell viability under storage conditions, and reliably detects representative defects. By providing foundation for 3D donor-recipient shape matching and standardized defect quantification, the system addresses key limitations of current tissue bank workflows. These capabilities not only improve graft quality and transplantation outcomes but also support graded allocation of donor tissues, reserving intact grafts for full transplantation, partially damaged grafts for partial transplantation, and severely compromised tissues for research. While validation was performed on porcine tissues with generated defects, ongoing work will extend the system to human donor menisci and naturally occurring damage. The framework also holds promise for application to other fibrocartilaginous and osteochondral tissues.

SIGNIFICANCE/CLINICAL RELEVANCE: For clinicians, accurate donor–recipient shape matching and standardized defect detection can improve graft quality, enhance transplantation outcomes, and reduce postoperative complications. For tissue banks, the system offers a practical, efficient, and objective tool that streamlines evaluation and enables graded allocation of donor tissues.

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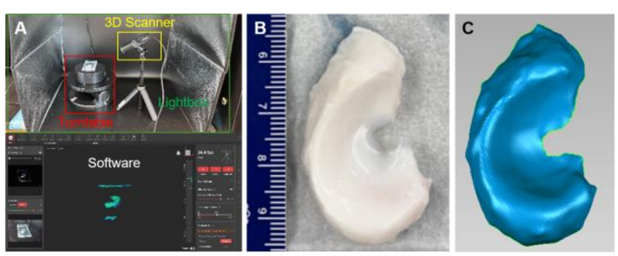

Figure 1: 3D Scanning system, including: (A). 3D optical scanner, turntable, lightbox, and software for 3D scanning. (B). Example pig meniscus. (C). Pig meniscus geometry scanned by our system.

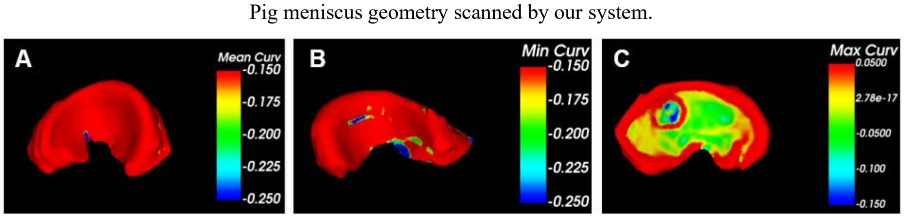

Figure 2: Damage identified by structure integrity assessment software, including: (A). Radial tear. (B). Longitudinal damage. (C). Surface wear.