

Title: 3D Shape Scanning and Structural Integrity Analysis to Advance Meniscus Allograft Transplantation

Authors: ^{1,2}Shuchun Sun[†], ¹Ge Pan[†], ¹Jichao Zhao, ²William Michael Pullen, ¹Jian Chen, ¹Haiyang Ma, ^{1,2}Dustin Mueller, ^{1,2}Hai Yao, ¹Shangping Wang*

Affiliations: ¹Clemson University, Clemson, SC, ²Medical University of South Carolina, Charleston, SC

Background: Meniscus allograft transplantation can restore knee function yet remains vastly underutilized due to challenges in tissue matching and integrity assessment. Current tissue bank practices rely on 2D measurements and subjective inspections, which are inadequate for capturing complex 3D geometry and subtle defects. A cost-effective, efficient, and accurate system for 3D shape matching and structural integrity assessment could significantly improve graft selection, reduce surgical complications, and enhance transplantation success.

Hypothesis: We hypothesized that a structured-light-based 3D optical scanning system combined with curvature-based surface analysis software can (1) measure meniscal 3D geometry with accuracy comparable to micro-CT, and (2) objectively detect surface defects with high accuracy.

Methods: We developed a system which combines portable 3D optical scanning system with our software for curvature-based structural integrity assessment (**Fig. 1**).

We validated geometric

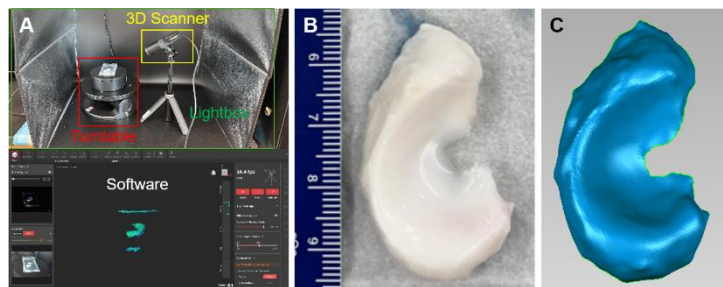


Fig. 1: 3D Scanning Toolset, including: (A). 3D optical scanner, turntable, lightbox, and software for data collection. (B). Example pig meniscus. (C). Pig meniscus geometry scanned by our system.

accuracy by comparing pig meniscus scans from our system to micro-CT with and without preservation solution and bags. Cell viability was also assessed under each scanning condition to determine maximum dehydration time tolerable for viable transplantation. Structural integrity detection was validated using porcine menisci with simulated wear, radial, and longitudinal defects. Surface curvatures (maximum, mean, minimum) were computed and

optimized to detect defect types. Detected defect sizes were compared to those measured during defect creation.

Results: With our protocol, each scan of the meniscus took less than 2 minutes. The average surface deviation was less than 7%, and volume deviation was negligible without preservation solution and bag. However, both deviations increased significantly when the preservation solution and bag were present. Fluorescence live/dead imaging shows that meniscal tissue viability declines significantly after just 2 mins of dehydration ($p=0.0466$), dropping below 70% within 5 mins ($p<0.0001$), below clinical threshold for transplantation. These findings underscore the importance of scanning menisci within preservative solutions and storage bags. Structural assessment showed maximum curvature best detected wear, mean curvature captured radial defects, and minimum curvature identified longitudinal tears (**Fig. 2**). Defect sizes detected differed $<10\%$ from actual, with all defect types successfully identified.

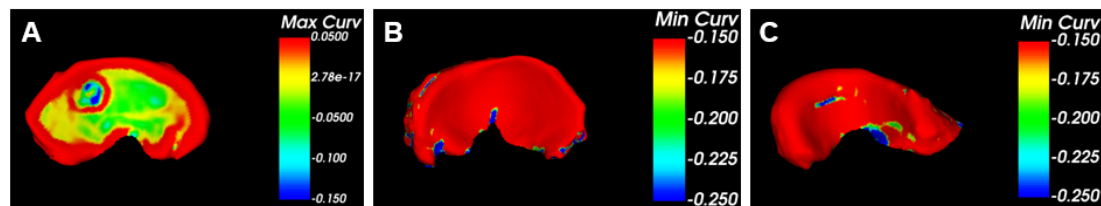


Fig. 2: Damage identified by structure integrity assessment software, including: (A). Surface wear. (B). Radial damage. (C). Longitudinal damage.

Conclusions: Our novel 3D scanning and curvature-based analysis system enables accurate, rapid, and non-destructive evaluation of meniscal allografts. It preserves cell viability during scanning and detects clinically relevant surface defects with high fidelity. This technology can improve tissue bank matching workflows, maximize graft utility, and reduce transplant failure risk. Future work will validate the system on human tissues and integrate AI-driven shape matching and defect classification. The system is also adaptable for other orthopedic applications, such as TMJ disc and osteochondral graft assessments.

Funding: The American Association of Tissue Banks (AATB), NIH P20GM121342

Corresponding Author*: shangpw@clemson.edu (SW)

Equal Contribution[†]: SS and GP

BACKGROUND AND OBJECTIVE

Burden of meniscus injury

- The meniscus is essential for knee shock absorption and stability.
- More than 1 million injuries occur annually in the U.S.; ~80% require surgery (**Fig. 1**).
- Meniscectomy (>850,000 cases/year) is common but increases the risk of osteoarthritis up to 89%

Promise but underuse of transplantation

- Meniscus allograft transplantation (MAT) improves outcomes and achieves >80% patient satisfaction.
- From 2010–2020, ~2 million meniscectomies were performed but only ~2,000 MAT procedures.
- The major barrier is limited availability of size-matched, structurally intact donor grafts.
- Tissue banks are central to alleviating this shortage.

Current limitations in tissue banks

- 2D geometry measurement methods cannot capture complex 3D geometry.
- Graft evaluation relies on 2D photographs and visual inspection, which is subjective and unreliable (**Fig. 2**).

Objective

- To develop and validate a system that integrates 3D optical scanning with curvature-based surface defect detection, providing tissue banks with an accurate, efficient, and affordable tool for donor graft evaluation.

METHODS

System Development

- The system consists of a photo studio light box, a motorized turntable, and a stereo depth-sensing 3D camera. This setup enables consistent illumination and rotation of the specimen, allowing a complete 360-degree meniscus scan in approximately 30 seconds (**Fig. 3**). The system outputs interactive STL models that can be rotated, measured, and analyzed for both geometric accuracy and surface integrity.
- Custom software was developed with a Qt-based graphical interface and VTK visualization. Using curvature algorithms implemented with Libigl, the software computes principal and derived curvature measures, generating color-coded defect maps directly on the scanned model (**Fig. 4**).

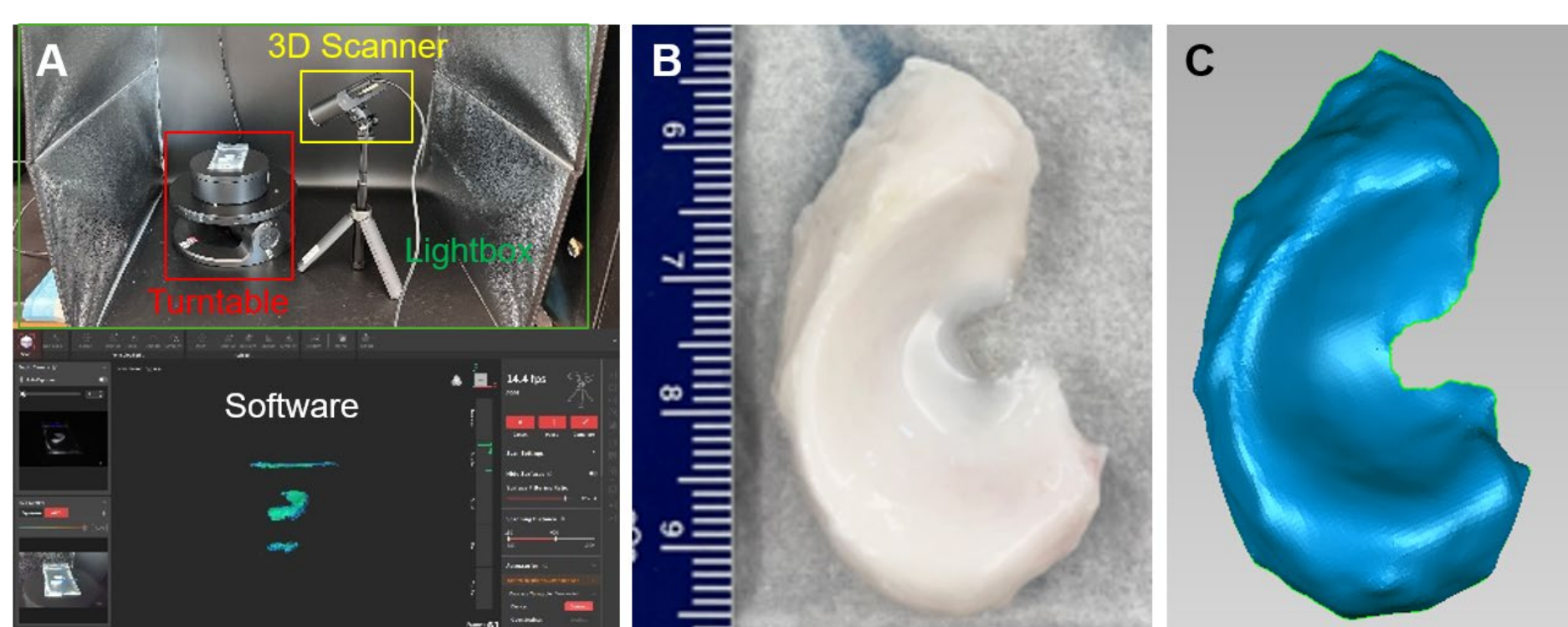


Fig. 3. 3D scanning hardware and software system. (A) The 3D scanning setup for a meniscus in the PBS solution within a transparent bag (top) and the software (bottom). A porcine meniscus sample (B) and its 3D scanned geometry (C).

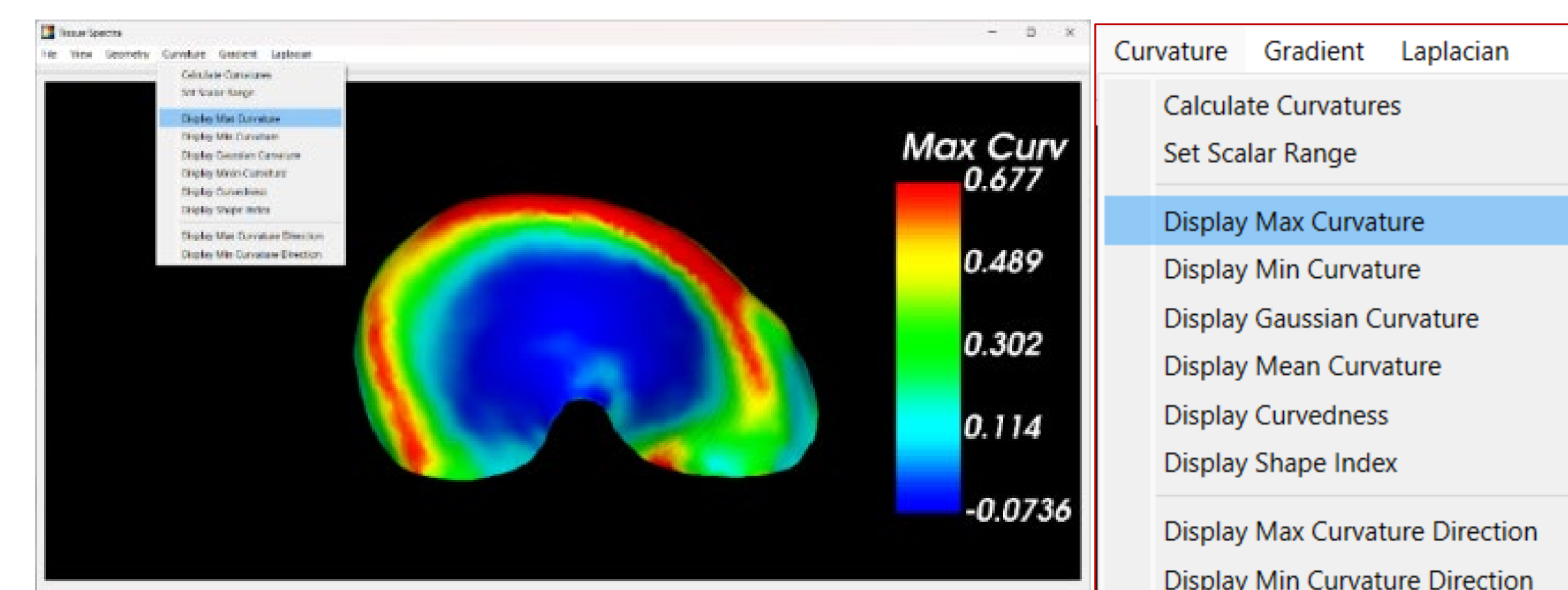


Fig. 4. Graphical user interface (GUI)

Scanning Accuracy Validation

- To validate 3D scanning accuracy, porcine menisci were scanned using both the 3D optical system and high-resolution μ CT as the reference standard (**Fig. 5**). The two datasets were compared in terms of volumetric equivalence and surface deviation after best-fit alignment.
- Accuracy was further tested under tissue bank-relevant preservation conditions by scanning samples in air and within transparent PBS-filled storage bags. This allowed assessment of whether the bag material or immersion affected scan fidelity.

Tissue Viability Validation

- The effect of scanning on tissue viability was assessed using fresh porcine menisci exposed to scanning conditions either in air or immersed in PBS. Samples were evaluated at 0, 2, 5, 10, 15, and 20 minutes.
- Tissue slices were stained with Calcein AM and Ethidium Homodimer-1 and imaged with fluorescence microscopy. Cell viability was quantified as the ratio of live to total cells, thereby defining a safe scanning time window for tissue banks.

Structural Integrity Assessment Validation

- To examine defect detection, standardized defects were introduced in porcine menisci, including 5 mm diameter wear, 10 mm longitudinal tears, and 5 mm radial tears (**Fig. 6**). Stereomicroscopy measurements of these defects served as the ground truth.
- The scanned 3D geometries were analyzed using the curvature-based software, which highlighted regions of abnormal curvature and allowed interactive measurement of defect size.
- Two measurement approaches were implemented: a two-point method for longitudinal and surface defects, and a three-point method for radial tears. Detection results were compared against ground truth to evaluate accuracy and robustness (**Fig. 6**).

Statistical Analysis

- Cell viability differences between groups and time points were analyzed using one-way ANOVA.
- Equivalence between μ CT and 3D scanning volumes was tested using two one-sided tests (TOST) with equivalence bounds of $\pm 10\%$. For defect size detection, TOST bounds were set at $\pm 20\%$.

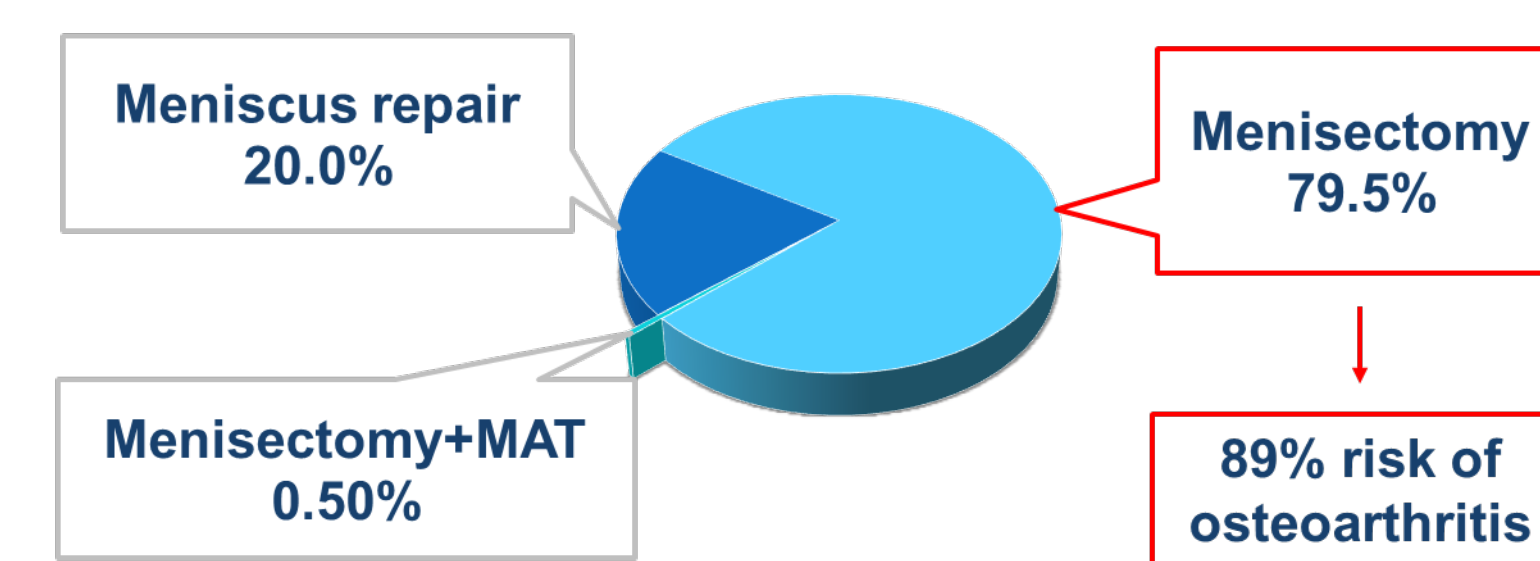


Fig. 1. Current treatment methods for meniscus injuries.

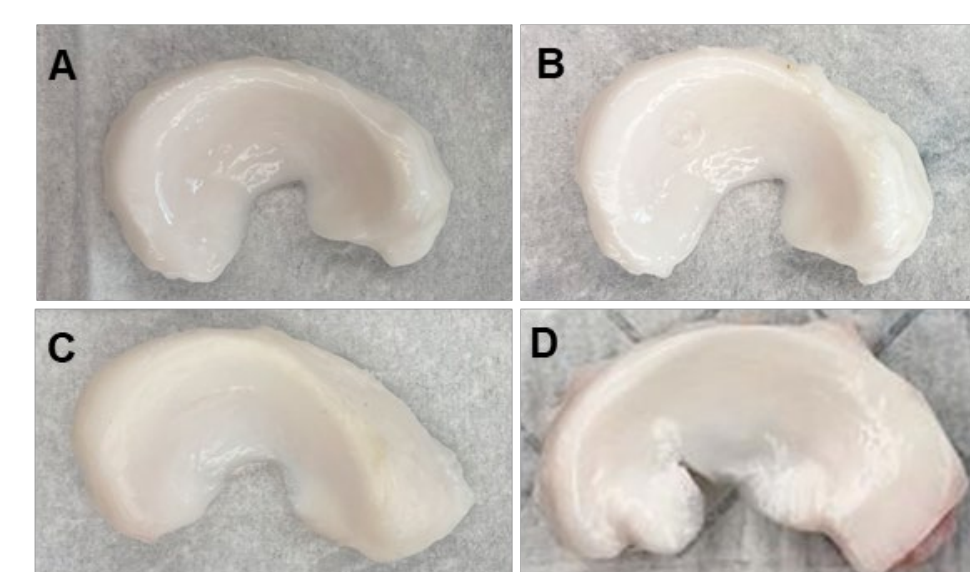


Fig. 2. Challenges in detecting and quantifying the subtle meniscal surface defects using the naked eye. (A) Intact meniscus; (B) menisci with various defects including 5-mm wear (B), a 5-mm radial tear (C), and a 10-mm longitudinal tear (D).

RESULTS

3D Geometry Scanning Accuracy

- Each scan was completed in ~2 minutes, compared to ~60 minutes required for μ CT.
- The 3D scanner achieved a mean relative volume error of 6.9% and a mean surface deviation of 8.3% when compared with μ CT models, with TOST confirming volumetric equivalence.
- 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 mean surface deviation was 12.5%.

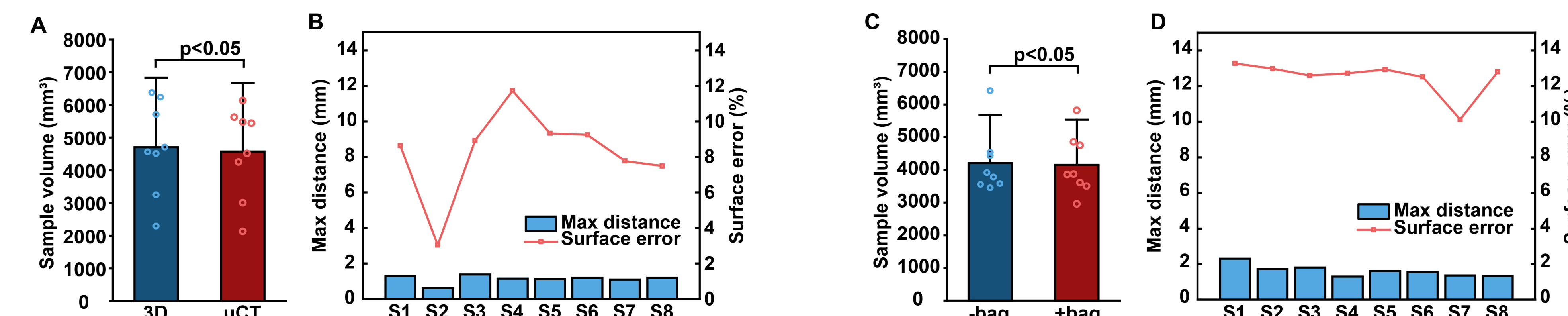


Fig. 7. Accuracy validation for volume and surface measurements. Comparison of volumes (A) and surface (B) obtained for the same samples using μ CT and the 3D scanning system. Comparison of volumes (C) and surface (D) obtained for the same samples under air and preserved conditions using the 3D scanning system.

Tissue Viability

- Live/dead imaging showed a rapid loss of viability in air-exposed menisci, dropping below the 70% clinical threshold after 10 minutes ($63.1 \pm 8.1\%$).
- In contrast, menisci stored in PBS retained >94% viability across 20 minutes, with no significant difference compared to freshly harvested tissue.
- These findings indicate that PBS immersion substantially prolongs the safe scanning window, whereas scanning in air is feasible only for very short durations.

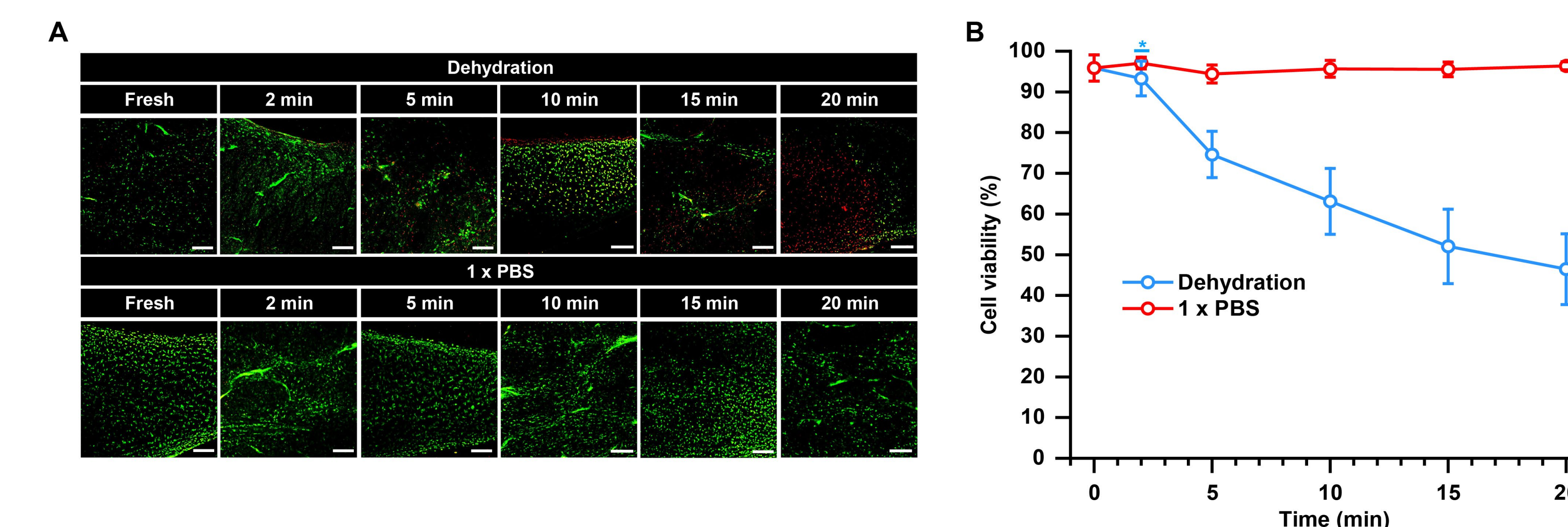


Fig. 8. Cell viability of meniscal tissues under air-exposed and PBS-immersed conditions, assessed by fluorescence live/dead imaging. (A) Representative fluorescence images of tissues at defined time intervals. Green: Living cells; Red: Dead cells. Scale bar is 200 μ m. (B) Quantitative analysis of cell viability based on image data.

Structural Integrity Detection

- Three clinically relevant defect types (surface wear, longitudinal tears, radial tear) were consistently detected using curvature-based software.
- Optimal indicators were identified for each defect: maximum curvature for surface wear, and minimum curvature for both longitudinal tears and radial tears.
- Surface wear and longitudinal tears achieved statistical equivalence with stereomicroscopy within $\pm 20\%$ bounds, while radial tears showed the largest deviations from ground truth.
- Overall, the system enabled accurate, reproducible defect detection and measurement with minimal user input, demonstrating strong potential for integration into tissue bank workflows.

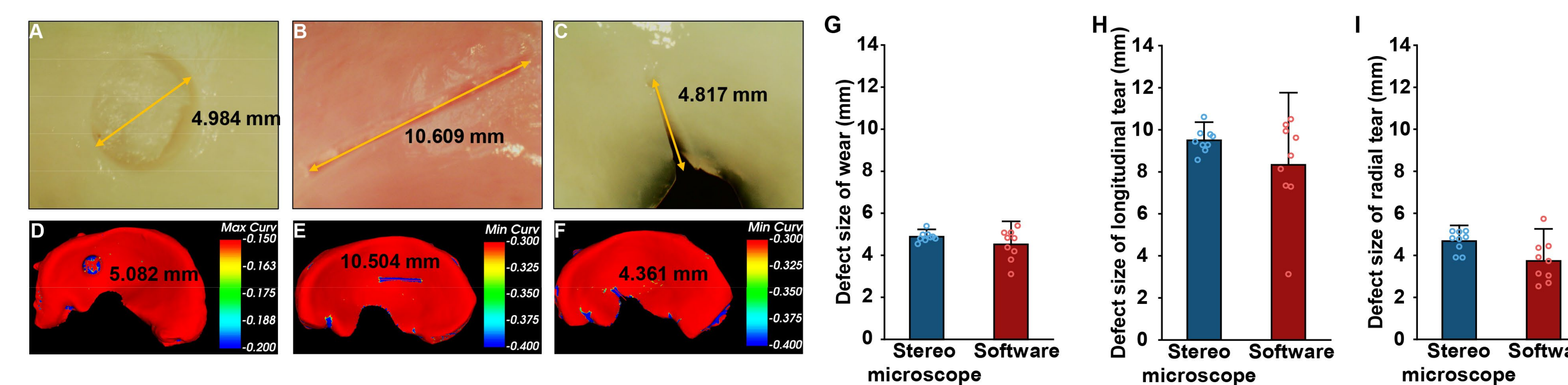


Fig. 9. Comparison of defect size measurements between stereomicroscope and algorithm-based curvature software. (A-C) Representative measurements of three defects under the stereomicroscope. (D-F) Corresponding measurements of the same samples using our software. (G-I) Comparison in size measurements between the two methods across three defect modes.

DISCUSSION

- Our system enables rapid (~2 min) 3D optical scanning with μ CT-comparable accuracy, and it functions effectively under preservation conditions in PBS-filled sterile bags. These allows it to be integrated into current tissue bank workflows.
- Rapid acquisition preserves tissue quality: viability drops below 70% after 10 minutes in air but remains >94% for 20 minutes in PBS, allowing reliable scanning within tissue bank workflows.
- Curvature-based analysis reliably detects surface wear, longitudinal tears, and radial tears with quantitative defect measurements. This supports objective screening of donor tissues for clinical usability.
- Accurate 3D geometry scanning facilitates precise donor–recipient shape matching, while defect screening enables graded allocation: intact grafts for transplantation, and those with minor defects redirected for research.
- The user-friendly interface reduces variability and training needs, and future work will extend validation to human tissues, naturally occurring defects, and AI-assisted automated classification.

ACKNOWLEDGMENTS

This work was supported by the American Association of Tissue Banks (AATB), NIH P20GM121342, NIH R01DE021134, NIH T32DE017551, NIH F30DE033914.