Summary

Meniscal injuries represent a significant clinical challenge due to the intrinsic avascularity and complex biomechanical functions of the meniscus in load-bearing joints, including the knee and temporomandibular joint (TMJ). Traditional surgical interventions often lead to long-term complications such as osteoarthritis. Recent breakthroughs in additive manufacturing, 3D bioprinting, and emerging 4D printing techniques—have revolutionized tissue engineering by enabling the fabrication of customized, biomimetic scaffolds. It is essential that researchers in TMJ yissue engineering appreciate the practical challenges faced by clinicians treating TMJ disorders so that the solutions developed are both beneficial for patients and demonstrate long-term safety and effectiveness.

One major limitation to using bioengineered tissues is the presence of underlying TMJ pathologies—such as osteoarthritis—where their value remains uncertain. Because engineered tissues are vulnerable to the same disease processes as natural TMJ structures, a thorough understanding of disease etiology and pathology is mandatory before considering bioengineered options. Certain conditions may contraindicate bioengineered TMJ devices, including parafunctional oral habits, active local infection, joint ankylosis, end-stage diseases like rheumatoid arthritis, multiple prior surgeries, and previous failures of alloplastic implantsAs the field advances toward clinical translation, appropriate preclinical animal models and human trials are crucial. Although TMJ tissue engineering has not yet entered clinical trials, animal studies, initially favoring pigs,have been explored; concerns over continued porcine skeletal growth have led to consideration of goats, sheep, and other species.

The research part of the thesis addresses the limitation of developing patient-specific tissue scaffolds, specifically focusing on replicating a real patient's articular meniscus using non-invasive methods. We aimed to create an accurate replica of a TMJ meniscus from a living patient using 3D radiological images and a PCL/ATZ composite material. The goal was to demonstrate the feasibility of 3D printing accurate, patient-specific scaffolds with a tested material.

While Cone Beam Computed Tomography (CBCT) is a benchmark for 3D dental imaging, offering superior spatial detail and geometric precision for craniofacial analysis, it involves higher X-ray radiation exposure and difficulty representing soft tissues. Magnetic Resonance Imaging (MRI) is explored as a radiation-free alternative, capable of visualizing both soft and hard tissues with improving resolution and reduced artifacts. An in vivo study showed promising geometric precision and repeatability for 3D cephalometric analyses using MRI, supporting its potential to provide 3D data comparable to CBCT, crucial for radiation-vulnerable younger patients.

The methodology involved acquiring a 3T MRI scan from a patient. DICOM files were segmented using open-source 3D Slicer software by two expert operators who reconstructed the

temporomandibular meniscus in five replicates each, using a brush selection tool and thresholding to isolate the meniscus. Resulting 3D models were checked and refined, then exported as STL files.

Mesh analysis was performed using CloudCompare. Surface (S) and volume (V) measurements were recorded. Models were compared pairwise to a reference using distance computation, generating histograms and heatmaps to visualize discrepancies. Statistical analysis included Mann–Whitney–Wilcoxon, Bland–Altmann analysis for inter-operator reproducibility, and Kruskal–Wallis with Bonferroni correction for intraclass variability.

Results showed high similarity between models with random errors for V and S not exceeding 2% and mean linear deviations below 47 μm, indicating accuracy and repeatability.

For the scaffold material, a composite of Poly(ε-caprolactone) (PCL) matrix filled with Alumina-Toughened Zirconia (ATZ) (PCL/ATZ 85/15) was prepared via solvent casting to combine the biological properties of PCL with enhanced mechanical resistance from ATZ. Planar samples were 3D printed using a thermoplastic pneumatic printer with specific parameters (print-bed temperature 30°C, printhead temperature 115/130°C, 0.4 mm nozzle, 195 kPa pressure, 2 mm/s speed). Cylindrical discs were prepared for testing.

Material characterization included Scanning Electron Microscopy (SEM) and EDX to study microstructure and verify filler dispersion. Biological compatibility was assessed via protein adsorption (using BSA), cell adhesion, and cell viability using ASC52hTert adipose stem cells.

Biological tests demonstrated that all samples allowed cell proliferation and growth, indicating non-cytotoxic behavior. Both neat PCL and the PCL/ATZ composite showed an increase in viable cells over time. The comparable biological performance suggests the composite is a good starting point for further investigation