Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Biomechanical Comparison of 3D-Printed Polylactic Acid Scaffold-Reinforced Hybrid Spacers and Conventional Polymethylmethacrylate Spacers for Advanced Femoral Bone Loss: An In Vitro Experimental Study

Mert Güler

dr.mertguler@gmail.com

Dokuz Eylül University

Vasfi Karatosun

Dokuz Eylül University

Bora Uzun

Dokuz Eylül University

Research Article

Keywords: Periprosthetic joint infection, two-stage revision, antibiotic spacer, 3D printing, polylactic acid, polymethylmethacrylate, biomechanics, bone defect, femoral reconstruction, hip arthroplasty

Posted Date: November 11th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11686933/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

Biomechanical Comparison of 3D-Printed Polylactic Acid Scaffold-Reinforced Hybrid Spacers and Conventional Polymethylmethacrylate Spacers for Advanced Femoral Bone Loss: An In Vitro Experimental Study

Mert Güler, MD[1] · Vasfi Karatosun, MD, Professor[2] · Bora Uzun[3]

[1] Department of Orthopaedics and Traumatology, Dokuz Eylül University Faculty of Medicine, İzmir, Turkey

[2] Department of Orthopaedics and Traumatology, Dokuz Eylül University Faculty of Medicine, İzmir, Turkey

[3] Department of Biomechanics, Institute of Health Sciences, Dokuz Eylül University, İzmir, Turkey

This study was conducted as the specialty thesis of Mert Güler, MD, at the Department of Orthopaedics and Traumatology, Dokuz Eylül University Faculty of Medicine, İzmir, Turkey.

Corresponding author:

Mert Güler, MD

Department of Orthopaedics and Traumatology

Dokuz Eylül University Faculty of Medicine

35340 Balçova, İzmir, Turkey

ORCID: 0000-0003-1113-5464

Abstract

Background: Two-stage exchange is widely regarded as the gold standard treatment for periprosthetic joint infection after total hip replacement . When patients have massive femoral bone loss, conventionally peroperatively hand-made polymethylmethacrylate (PMMA) spacers are more susceptible to instability and structural failure . In this study, we compared 3D-printed polylactic acid scaffold-reinforced hybrid spacers with conventional PMMA spacers designed for advanced femoral bone defects. We evaluated whether hybrid spacers provide suitable biomechanical performance in this patient group.

Methods: Twelve cylindrical specimens were fabricated and divided equally into two groups (n = 6 per group). For the 3D group, cylindrical polylactic acid (PLA) scaffolds (outer diameter, 18 mm; inner diameter, 8 mm; height, 70 mm) were printed using an UltiMaker 3 Extended printer and coated with a 5-mm layer of polymethylmethacrylate (PMMA; Simplex P, Stryker Bone Cement), resulting in an outer diameter of 28 mm. The conventional group comprised PMMA cylinders (outer diameter, 28 mm; inner diameter, 8 mm; height, 70 mm) fabricated using 3D-printed molds. Both groups underwent axial compression testing (target load, 4500 N) and three-point bending testing (target load, 4800 N) on a servo-hydraulic universal testing machine (Autograph AG-IS 5 kN, Shimadzu, Kyoto, Japan) at a crosshead speed of 20 mm/min. Maximum load and displacement at the target load were recorded during testing. Group comparisons were performed using the Mann–Whitney U test in IBM SPSS Statistics, version 26. Statistical significance was set at $p < 0.05$.

Results: All specimens of both groups met the axial compression limit of 4500 N. For the 3D group, the mean displacement value was 1.00 ± 0.23 mm; for the conventional group, it was 1.06 ± 0.21 mm ($p = 0.818$). For the three-point bending test, all six specimens of the 3D group reached the required 4800 N force threshold, while only five out of six did so among the conventional specimens. One conventional specimen failed at 1558 N. The mean bending force in the 3D group was 4800 ± 0 N, compared to 4259.69 ± 1323.49 N in the conventional test group ($p = 0.405$).

Conclusions: Under the tested axial compression and bending conditions, hybrid 3D-printed PLA–PMMA spacers showed no significant performance difference from conventional PMMA spacers. All hybrid specimens

reached the target load; one conventional specimen failed under bending (Table 1). The small sample size (n = 6 per group) limits the strength of these findings. These results support further evaluation of 3D-printed PLA–PMMA hybrid spacers in two-stage revision procedures for patients with advanced femoral bone defects.

Keywords: Periprosthetic joint infection; two-stage revision; antibiotic spacer; 3D printing; polylactic acid; polymethylmethacrylate; biomechanics; bone defect; femoral reconstruction; hip arthroplasty

Novelty statement: This is the first biomechanical study to evaluate a 3D-printed PLA scaffold–PMMA composite spacer designed specifically for advanced femoral bone defects in two-stage revision arthroplasty.

Background

Total joint arthroplasty has transformed the management of end-stage arthritis and remains one of the most successful surgical procedures of the modern era . With a globally ageing population, annual procedure volumes are projected to continue rising , placing increasing pressure on healthcare systems to manage related complications effectively . Among these, periprosthetic joint infection (PJI) is a major complication, carrying high morbidity and a substantial socioeconomic burden . The incidence of PJI ranges from 0.5% to 2% after primary arthroplasty and rises to approximately 20% after revision procedures . A single PJI episode in the United States has been estimated to cost approximately USD 50,000, exclusive of lost wages , with total annual expenditure on hip and knee PJI projected to exceed USD 1.85 billion by 2030 .

Two-stage revision arthroplasty remains the standard treatment for chronic PJI. It involves removing the infected prosthesis, placing an antibiotic-loaded cement spacer, and reimplanting a definitive prosthesis after the infection has been eradicated . Beyond their role as local antibiotic depots, spacers serve critical mechanical functions: they maintain limb length, preserve capsular and ligamentous tension, and prevent joint contracture, thereby facilitating the technical execution and functional outcome of second-stage reimplantation .

Spacers are integral to PJI management, but mechanical complications remain a clinical concern. Published studies have reported dislocation rates of up to 17% and fracture rates of approximately 10% . Mechanical failure is particularly consequential, as it may result in additional bone loss and require unplanned revision surgery . Manual mixing of intraoperative PMMA spacers can introduce porosity and compositional variability, potentially reducing compressive and bending strength . Although antibiotic loading is essential for local infection control, it may adversely affect the mechanical properties of PMMA; the magnitude of this effect depends on the antibiotic concentration .

Three-dimensional (3D) printing enables production of patient-specific implants and surgical planning aids with high-dimensional fidelity . In the context of PJI management, 3D-printed molds for spacer preparation and fully 3D-printed spacer constructs have been reported as cost-effective strategies that improve anatomical fit . Kong et al. reported that 3D-printing-assisted articulating spacers in two-stage revision total knee arthroplasty provided satisfactory range of motion, prevented bone loss and facilitated second stage reimplantation . Similarly, Tamarit-Martínez et al. showed that antibacterial-loaded 3D-printed PLA spacers released cloxacillin and vancomycin, with layer thickness influencing both drug release and mechanical strength .

Polylactic acid (PLA) is a biodegradable, biocompatible thermoplastic widely used in additive manufacturing with a well-established safety profile in biomedical applications . PLA has been described as a promising biomaterial with suitable mechanical properties for scaffolds and implants . PLA scaffolds have been combined with PMMA bone cement in a frame filling structure to provide load-bearing support in femoral bone defects . However, no prior in vitro biomechanical study has evaluated a 3D-printed PLA–PMMA composite spacer for advanced femoral bone defects under clinically representative axial and bending loads.

In our revision arthroplasty clinic, we have observed that both commercially available and manually prepared spacers are inadequate in patients with massive femoral bone loss. This study aimed to compare 3D-printed PLA scaffold-reinforced hybrid spacers with conventional PMMA spacers. We assessed biomechanical performance using axial compression and three-point bending tests. Both spacer types had identical external dimensions and were intended for advanced femoral bone loss. We assessed whether this design could withstand axial and bending loads during the interim period. We also evaluated its biomechanical suitability for implantation in patients undergoing two-stage revision for advanced femoral bone defects. Beyond the biomechanical considerations, a scaffold-reinforced hybrid design may offer practical advantages over conventional spacers. Additive manufacturing enables the scaffold's length and geometry to be tailored to the individual femoral defect. Its modular design may also allow the construct to be lengthened or shortened intraoperatively after the final defect geometry has been assessed. Applying a cement coating to the patient-specific scaffold may facilitate the fabrication of a more anatomical spacer that articulates with the acetabular component. Custom-made articulating spacers have been proposed as a promising approach to optimise the first stage of revision arthroplasty . A patient-specific 3D-printed spacer has previously been used in a patient with a segmental femoral defect, with satisfactory

hip function and no early postoperative complications . The scaffold also occupies part of the construct's volume, potentially reducing the amount of cement required and, consequently, material consumption. Moreover, CAD-based mold design allows the spacer to be adapted to individual bone gaps , and additive manufacturing has been described as a cost-effective approach in this context . Taken together, these features may enable implantation of a patient-specific hybrid spacer with a shorter operative time than that required for a manually prepared spacer while providing a more anatomical articulation.

Methods

Study Design

This was a prospective in vitro experimental biomechanical study. Ethics committee approval was obtained from Dokuz Eylül University Faculty of Medicine Non-Interventional Research Ethics Committee (EK: 2025/22-36). The study did not involve human participants or animals.

Specimen Fabrication

Twelve cylindrical spacer specimens were fabricated and divided into two groups (n = 6 per group). We fabricated all specimens in 3D-printed molds designed in SolidWorks 2018 to standardize geometry. The molds produced identical external shapes in both groups.

3D Group (Hybrid specimens).

Computer-aided design (CAD) models were created in SolidWorks 2018 (Dassault Systèmes, Vélizy-Villacoublay, France). The inner PLA scaffold was designed as a hollow cylinder (outer diameter 18 mm, inner diameter 8 mm, height 70 mm) with a roughened surface to enhance PMMA adhesion. Scaffolds were printed using an UltiMaker 3 Extended fused deposition modeling printer (Ultimaker B.V., Utrecht, the Netherlands) with medical-grade PLA filament. (Figure 1) We placed each scaffold in a custom 3D-printed cylindrical mold. The mold cavity centered the PLA scaffold within the cement mantle during setting. (Figure 2) We then coated the scaffold with PMMA (Simplex P Bone Cement, Stryker, Kalamazoo, MI, USA), mixed at the standard powder-to-liquid ratio according to the manufacturer's instructions. After setting, the outer diameter of the hybrid specimen was 28 mm, yielding a 5 mm circumferential PMMA mantle surrounding the PLA core. For potential clinical use, the scaffolds are intended to undergo ethylene oxide sterilization, a low-temperature process that may reduce the risk of thermally induced deformation of the printed PLA .

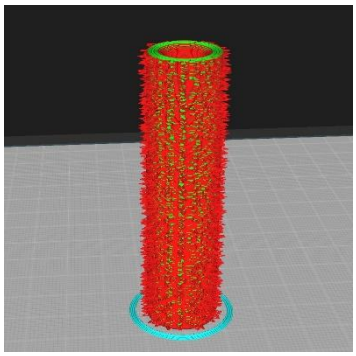


Figure 1: Computer-aided design (CAD) models illustrating the internal polylactic acid (PLA) scaffold with a roughened surface designed to enhance polymethylmethacrylate (PMMA) adhesion, alongside the custom 3D-printed cylindrical mold assembly used for specimen fabrication.



Figure 2: Fabrication process of the hybrid spacer. The 3D-printed PLA scaffold is positioned centrally within the custom 3D-printed mold cavity prior to the application of the PMMA mantle.

Conventional Group (PMMA-only specimens). Standard PMMA cylinders (outer diameter 28 mm, inner diameter 8 mm, height 70 mm) were fabricated using 3D-printed, SolidWorks-designed molds. PMMA was hand-mixed at the same powder-to-liquid ratio under identical ambient conditions and poured into the molds. In both groups, the cement was prepared with a first-generation manual cementing technique (hand mixing and manual application of the cement into the mold), without vacuum mixing or gun delivery. All specimens in both groups therefore had identical external dimensions (28 mm outer diameter, 8 mm inner diameter, 70 mm height). (Figure 3)

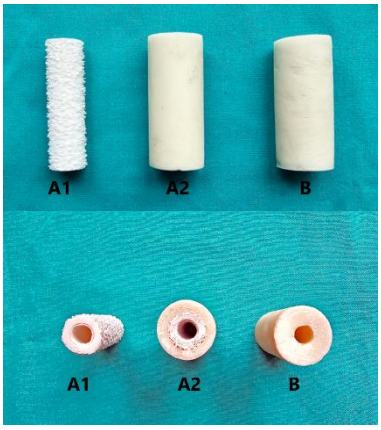


Figure 3: Macroscopic side and cross-sectional views of the fabricated specimens. (A1) 3D-printed PLA scaffold alone; (A2) PLA scaffold-reinforced hybrid spacer demonstrating the integration of the PLA core within the 5-mm PMMA mantle; and (B) Conventional PMMA-only spacer.

Biomechanical Testing

Specimens were tested at room temperature using a servo-hydraulic universal testing machine (Autograph AG-IS 5 kN, Shimadzu Corporation, Kyoto, Japan). Each specimen was first subjected to axial compression testing and then, in the same specimen, to three-point bending testing. We tested only these two modalities because our university lacked a system for other loading modes. For each test modality, the target load was defined as the maximum force that the testing machine could deliver in that loading configuration, which was 4500 N for axial compression and 4800 N for three-point bending. (Figure 4)

Axial compression test. Specimens were loaded uniaxially along their long axis. The target load was set at 4500 N, applied at a constant crosshead displacement rate of 20 mm/min. Maximum applied force (N) and maximum axial displacement (mm) at target load were recorded.

Three-point bending test. Specimens were positioned on two support points and loaded at the midpoint. The target load was set at 4800 N, applied at 20 mm/min. Maximum force (N) and maximum displacement (mm) were recorded. Structural failure was defined as a load drop before reaching the target force.

Statistical Analysis

Data normality was assessed prior to group comparison. Each group included six specimens, and normality assumptions were violated. We therefore used nonparametric Mann-Whitney U tests to compare maximum force and displacement between groups for each modality. Statistical analyses were performed using IBM SPSS Statistics version 26 (IBM Corporation, Armonk, NY, USA). Statistical significance was set at $p < 0.05$.

Results

Axial Compression

All 12 specimens (six per group) reached the target axial load of 4500 N without structural failure. Individual and group-level results are presented in Table 1.

The mean maximum axial compression force was 4500.00 ± 0.00 N in both the 3D and conventional groups (p = 1.000). Mean maximum axial displacement was 1.00 ± 0.23 mm in the 3D group and 1.06 ± 0.21 mm in the conventional group (p = 0.818). Neither axial compression measure differed significantly between groups (Table 2).

Three-Point Bending

All six specimens in the 3D group sustained the target three-point bending load of 4800 N without failure. In the conventional group, five of six specimens reached the target load; the remaining specimen failed prematurely at 1558.13 N (Table 1). (Figure 5)

Mean maximum bending force was 4800.00 ± 0.00 N in the 3D group and 4259.69 ± 1323.49 N in the conventional group (p = 0.405). Mean maximum bending displacement was 2.87 ± 0.25 mm and 2.45 ± 0.56 mm, respectively (p = 0.132). Neither outcome differed significantly between groups (Table 2). Conv-6 failed prematurely and produced a distinct force-displacement curve. The other conventional specimens and all 3D specimens showed reproducible, approximately linear loading profiles until reaching the target load.

Across both testing modalities, the 3D group showed consistent force-displacement responses. The conventional group showed greater variability between specimens, particularly in three-point bending displacement (SD 0.56 mm vs 0.25 mm in the 3D group).

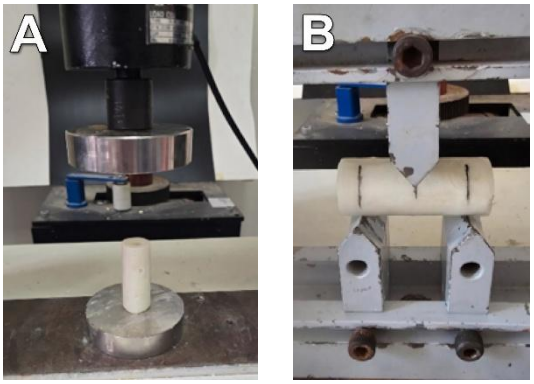


Figure 4: Biomechanical testing setups using a servo-hydraulic universal testing machine. (A) Axial compression test configuration evaluating the specimen along its longitudinal axis; (B) Three-point bending test configuration evaluating the specimen positioned horizontally on two support points.



Figure 5: Macroscopic appearance of a conventional PMMA-only specimen demonstrating complete structural failure and fracture following premature failure at 1558.13 N during the three-point bending test.

Discussion

This in vitro study found that 3D-printed PLA scaffold-reinforced hybrid spacers performed comparably to conventional PMMA spacers under axial compression and three-point bending. None of the between-group comparisons was statistically significant (axial compression, p = 0.818–1.000; three point bending, p = 0.132–0.405). All six hybrid specimens reached both target loads. By contrast, one conventional specimen failed during bending at 1558 N, about 33% of the target load. This result may reflect variability in manual PMMA preparation .

Tamarit-Martínez et al. reported that layer thickness affects the mechanical strength of 3D printed PLA spacers and that antibiotic-loaded constructs released antibiotics that inhibited *Staphylococcus aureus* . In finite element simulations, Milone and Spataro found that PEEK and PLA composite femoral implants may reduce stress shielding compared with conventional titanium stems . In the present design, the PLA core may reduce the

hybrid construct's stiffness relative to a solid PMMA block and could therefore reduce stress concentration at the implant-bone interface .

The hybrid group showed less variation in some test outcomes. Maximum force was identical across specimens in both loading modes, and bending displacement varied less than in the conventional group. This consistency may be clinically relevant, but the zero standard deviation in maximum force should be interpreted in light of the testing machine's load limits. Manual PMMA mixing can introduce air and compositional variation. These factors may affect mechanical properties . Vacuum mixing can reduce porosity , but it is not routinely used; manual mixing remains common in operating theatres . Antibiotic loading, which is standard practice in spacers used for PJI, can also reduce compressive and bending strength in a dose-dependent manner . For example, one study reported bending strengths of 57.6 MPa at 24 hours for low-dose vancomycin PMMA and 50.4 MPa for a high-dose formulation . The prefabricated PLA scaffold provides an internal load-bearing frame. This frame may reduce sensitivity to intraoperative PMMA mixing quality and improve mechanical consistency.

Articulating PMMA hip spacers are associated with mechanical complications in two-stage revision surgery . Some clinical series have reported fracture rates of 13%–24% , and spacer fracture may require unplanned revision surgery . A meta-analysis by Senthi et al. reported spacer dislocation and fracture rates of 17% and 10.2% . These estimates come from different study populations and should not be compared directly. In composite-femur testing, an endoskeleton-reinforced cement hip spacer tolerated approximately twice the load of a non-reinforced PMMA spacer . Finite element analysis has also shown that full stem reinforcement reduces the stress intensity factor associated with crack propagation in cement hip spacers . Together, these findings support the rationale for a hybrid construct with a reproducible, 3D-printed load-bearing scaffold. However, they do not show that the present design reduces clinical failure risk.

PLA filament is relatively inexpensive, and fused deposition modelling printers are increasingly used in academic medical centres . Preoperative CT, already used to plan revision arthroplasty, can help size a scaffold to the residual femoral canal and defect. This could allow the spacer to be manufactured before the first stage procedure. A separate clinical series of custom-made articulating hip spacers reported an overall mechanical complication rate of 4.2% .

The study has several limitations. First, laboratory tests applied constant loads and did not replicate in vivo cyclic loading. Second, each group included six specimens, precluding equivalence testing between spacer types. Larger studies should be undertaken. Third, the tests omitted antibiotics, which may affect spacer strength. Fourth, the specimens lacked surrounding cement and bone; therefore, failure at the bone interface could not be evaluated. Fifth, long-term in vivo effects of PLA and PMMA remain unknown. PLA degradation rate and particle-induced reactions require evaluation. Sixth, for the loads, the testing machinery had limits and did not take into account particular body load or earth-load. The tests therefore did not establish the hybrid spacer's failure load. We could not test cyclic loading or torsion because the required equipment was unavailable.

Future studies should address dynamic fatigue testing, antibiotic loading effects on the hybrid construct, and in vivo animal models to assess osseous integration, infection eradication, and spacer removal characteristics.

Conclusions

Three-dimensionally printed PLA scaffold-reinforced hybrid spacers showed biomechanical performance comparable to conventional PMMA spacers under axial compression (4500 N target) and three-point bending (4800 N target). Between-group differences were not statistically significant (all $p > 0.05$). All six hybrid specimens reached target loads in both loading modes. One conventional specimen failed during bending at approximately one-third of the target load. These findings support further study of 3D printed PLA-PMMA hybrid spacers for two-stage revision arthroplasty in patients with advanced femoral bone defects. Prospective clinical studies should assess antibiotic-loaded constructs under dynamic loading before clinical use.

Declarations

Ethics approval and consent to participate: This in vitro study involved no human participants, patient data, or animals. Ethical approval was obtained from the Dokuz Eylül University Faculty of Medicine Non-Interventional Research Ethics Committee (EK: 2025/22-36). Informed consent was not applicable.

Availability of data and materials: The datasets generated and analysed during this study are available from the corresponding author upon reasonable request.

Competing interests: The authors declare no competing interests.

Funding: This study received no external funding.

Authors' contributions: Mert Güler conceived the study, designed the specimens, conducted the biomechanical experiments, analysed the data, and drafted the manuscript. Vasfi Karatosun supervised the study design, provided methodological guidance, and critically revised the manuscript for important intellectual content. Bora Uzun provided biomechanical expertise and contributed to study design. He supervised specimen fabrication and contributed to data interpretation. All authors read and approved the final manuscript.

Acknowledgements: Not applicable.

Authors' information: Mert Güler is a resident physician in orthopaedics and traumatology at Dokuz Eylül University Faculty of Medicine, İzmir, Turkey. Vasfi Karatosun is a Professor of Orthopaedics and Traumatology at Dokuz Eylül University Faculty of Medicine, İzmir, Turkey. Bora Uzun is a faculty member at the Department of Biomechanics, Institute of Health Sciences, Dokuz Eylül University, İzmir, Turkey.

Table 1. Individual biomechanical test results for all specimens

Table 1.

Specimen	Axial compression: maximum force (N)	Axial compression: maximum displacement (mm)	Three-point bending: maximum force (N)	Three-point bending: maximum displacement (mm)
3D-1	4500	1.361	4800	3.112
3D-2	4500	1.159	4800	3.244
3D-3	4500	0.996	4800	2.724
3D-4	4500	0.877	4800	2.640
3D-5	4500	0.876	4800	2.811
3D-6	4500	0.724	4800	2.693
Conv-1	4500	1.350	4800	2.575
Conv-2	4500	0.875	4800	2.643
Conv-3	4500	1.292	4800	2.844
Conv-4	4500	0.943	4800	2.590
Conv-5	4500	0.909	4800	2.742
Conv-6	4500	0.993	1558.13*	1.324*

* Structural failure before reaching target load. Conv: conventional PMMA-only spacer; 3D: 3D-printed PLA scaffold-reinforced hybrid spacer.

Table 2. Statistical comparison of biomechanical parameters between the 3D hybrid and conventional spacer groups

Table 2.

Parameter	3D group (mean ± SD)	Conventional group (mean ± SD)	p value†

Axial compression			
Maximum force (N)	4500.00 ± 0.00	4500.00 ± 0.00	1.000
Maximum displacement (mm)	1.00 ± 0.23	1.06 ± 0.21	0.818
Three-point bending			
Maximum force (N)	4800.00 ± 0.00	4259.69 ± 1323.49	0.405
Maximum displacement (mm)	2.87 ± 0.25	2.45 ± 0.56	0.132

† Mann-Whitney U test. SD: standard deviation.

List of Abbreviations

3D: Three-dimensional

CAD: Computer-aided design

CT: Computed tomography

PEEK: Polyether ether ketone

PJI: Periprosthetic joint infection

PLA: Polylactic acid

PMMA: Polymethyl methacrylate

SD: Standard deviation

SPSS: Statistical Package for the Social Sciences

Figure Legends

Figure 1: Computer-aided design (CAD) models illustrating the internal polylactic acid (PLA) scaffold with a roughened surface designed to enhance polymethylmethacrylate (PMMA) adhesion, alongside the custom 3D-printed cylindrical mold assembly used for specimen fabrication.

Figure 2: Fabrication process of the hybrid spacer. The 3D-printed PLA scaffold is positioned centrally within the custom 3D-printed mold cavity prior to the application of the PMMA mantle.

Figure 3: Macroscopic side and cross-sectional views of the fabricated specimens. (A1) 3D-printed PLA scaffold alone; (A2) PLA scaffold-reinforced hybrid spacer demonstrating the integration of the PLA core within the 5-mm PMMA mantle; and (B) Conventional PMMA-only spacer.

Figure 4: Biomechanical testing setups using a servo-hydraulic universal testing machine. (A) Axial compression test configuration evaluating the specimen along its longitudinal axis; (B) Three-point bending test configuration evaluating the specimen positioned horizontally on two support points.

Figure 5: Macroscopic appearance of a conventional PMMA-only specimen demonstrating complete structural failure and fracture following premature failure at 1558.13 N during the three-point bending test.

References

1. Cooper HJ, Valle CJD. The two-stage standard in revision total hip replacement. Bone Joint J. 2013;95-B(11 Suppl A):84-87. doi: 10.1302/0301-620X.95B11.32906
2. Lunz A, Knappe K, Omlor GW, Schonhoff M, Renkawitz T, Jaeger S. Mechanical strength of antibiotic-loaded PMMA spacers in two-stage revision surgery. BMC Musculoskelet Disord. 2022;23(1):945. doi: 10.1186/s12891-022-05895-5

3. Lodge C, Adlan A, Nandra R, Kaur J, Jeys L, Stevenson J. Staged revision of the infected knee arthroplasty and endoprosthesis. Bone Joint J. 2024;106-B(10):1067-1073. doi: 10.1302/0301-620X.106B10.BJJ-2023-0432.R1

4. Marziani LD, Boffa A, Martino AD, et al. The reimbursement system can influence the treatment choice and favor joint replacement versus other less invasive solutions in patients affected by osteoarthritis. J Exp Orthop. 2023;10(1):146. doi: 10.1186/s40634-023-00699-5

5. Stubnya B, Schulz M, Váncsa S, Szilágyi GS, Szatmári A, Bejek Z. Global Trends in Joint Arthroplasty: A Systematic Review and Future Projections. J Clin Med. 2025;14(22):8214. doi: 10.3390/jcm14228214

6. Kurtz SM, Ong K, Lau E, Mowat F, Halpern MT. Projections of Primary and Revision Hip and Knee Arthroplasty in the United States from 2005 to 2030. J Bone Joint Surg Am. 2007;89(4):780-785. doi: 10.2106/00004623-200704000-00012

7. Alamanda VK, Springer BD. Perioperative and Modifiable Risk Factors for Periprosthetic Joint Infections (PJI) and Recommended Guidelines. Curr Rev Musculoskelet Med. 2018;11(3):325-331. doi: 10.1007/s12178-018-9494-z

8. Hoveidaei A, Hoveidaei A, Tavakoli Y, et al. Imaging in Periprosthetic Joint Infection Diagnosis: A Comprehensive Review. Microorganisms. 2024;13(1):10. doi: 10.3390/microorganisms13010010

9. Lentino JR. Prosthetic Joint Infections: Bane of Orthopedists, Challenge for Infectious Disease Specialists. Clin Infect Dis. 2003;36(9):1157-1161. doi: 10.1086/374554

10. Theil C, Bockholt S, Gosheger G, et al. Surgical Management of Periprosthetic Joint Infections in Hip and Knee Megaprostheses. Medicina (Kaunas). 2024;60(4):583. doi: 10.3390/medicina60040583

11. Siebel T, Kelm J, Porsch M, Regitz T, Neumann W. Two-stage exchange of infected knee arthroplasty with an prosthesis-like interim cement spacer. Acta Orthop Belg. 2002;68(2):150-156.

12. Liu X, Ding G, Zhou D, Xiang L. Antibiotic-loaded bone cement spacer usage combined with membrane induction in infected gap non-unions: A case series. Pak J Med Sci. 2018;34(5):1088-1093. doi: 10.12669/pjms.345.14569

13. Senthi S, Munro JT, Pitto RP. Infection in total hip replacement: meta-analysis. Int Orthop. 2010;35(2):253-260. doi: 10.1007/s00264-010-1144-z

14. Jabbal M, Simpson H, Walmsley P. Mechanisms of bone loss in revision total knee arthroplasty and current treatment options. Orthop Rev (Pavia). 2023;15:75359. doi: 10.52965/001c.75359

15. Lidgren L, Bodelind B, Möller J. Bone cement improved by vacuum mixing and chilling. Acta Orthop Scand. 1987;58(1):27-32. doi: 10.3109/17453678709146338

16. Gandomkarzadeh M, Moghimi HR, Mahboubi A. Evaluation of the Effect of Ciprofloxacin and Vancomycin on Mechanical Properties of PMMA Cement; a Preliminary Study on Molecular Weight. Sci Rep. 2020;10(1):3981. doi: 10.1038/s41598-020-60970-y

17. Hertzberg-Boelch SP von, Lüdemann M, Rudert M, Steinert AF. PMMA Bone Cement: Antibiotic Elution and Mechanical Properties in the Context of Clinical Use. Biomedicines. 2022;10(8):1830. doi: 10.3390/biomedicines10081830

18. Cong B, Zhang H. Innovative 3D printing technologies and advanced materials revolutionizing orthopedic surgery: current applications and future directions. Front Bioeng Biotechnol. 2025;13:1542179. doi: 10.3389/fbioe.2025.1542179

19. Li Z, Xu C, Chen J. Articulating spacers: what are available and how to utilize them? Arthroplasty. 2023;5(1):22. doi: 10.1186/s42836-023-00167-6

20. Kong L, Mei J, Ge W, et al. Application of 3D Printing-Assisted Articulating Spacer in Two-Stage Revision Surgery for Periprosthetic Infection after Total Knee Arthroplasty: A Retrospective Observational Study. Biomed Res Int. 2021;2021:3948638. doi: 10.1155/2021/3948638

21. Tamarit-Martínez C, Bernat-Just L, Bueno-López C, et al. An Antibacterial-Loaded PLA 3D-Printed Model for Temporary Prosthesis in Arthroplasty Infections: Evaluation of the Impact of Layer Thickness on the Mechanical Strength of a Construct and Drug Release. Pharmaceutics. 2024;16(9):1151. doi: 10.3390/pharmaceutics16091151

22. Pérez-Davila S, González-Rodríguez L, Lama R, et al. 3D-Printed PLA Medical Devices: Physicochemical Changes and Biological Response after Sterilisation Treatments. Polymers (Basel). 2022;14(19):4117. doi: 10.3390/polym14194117

23. Ranakoti L, Gangil B, Bhandari P, et al. Promising Role of Polylactic Acid as an Ingenious Biomaterial in Scaffolds, Drug Delivery, Tissue Engineering, and Medical Implants: Research Developments, and Prospective Applications. Molecules. 2023;28(2):485. doi: 10.3390/molecules28020485

24. Ding Y, Liu X, Zhang J, et al. 3D printing polylactic acid polymer-bioactive glass loaded with bone cement for bone defect in weight-bearing area. Front Bioeng Biotechnol. 2022;10:947521. doi: 10.3389/fbioe.2022.947521

25. Minasov BSh, Yakupov RR, Akbashev VN, et al. Optimizing revision arthroplasty: the role of customized articulating spacers. Genij Ortop. 2024;30(5):753-765. doi: 10.18019/1028-4427-2024-30-5-753-765

26. Liu Y, Pan H, Chen L, et al. Total hip revision with custom-made spacer and prosthesis: A case report. World J Clin Cases. 2021;9(25):7605-7613. doi: 10.12998/wjcc.v9.i25.7605

27. Harna B, Kumar R, Tomar S, Meena A, Maini L. A Cost-effective 3D Printed Antibiotic Spacer for Management of Periprosthetic Joint Infection of the Knee: A Case Report. Tech Orthop. 2021;37(1):52-55. doi: 10.1097/bto.0000000000000527

28. Slatinek T, Plohl O, Črešnar KP. Poly(ε-caprolactone) and poly(lactic acid) in implantable applications: From biodegradable polymers to emerging vitrimer nanocomposites. Biomater Adv. 2026;190:215179. doi: 10.1016/j.bioadv.2026.215179

29. Timofticiuc IA, Grigore AG, Tomescu ET, et al. Advances in 3D-Printed Drug Delivery and Screening Platforms for Bone Disease Therapy. Pharmaceutics. 2025;17(11):1372. doi: 10.3390/pharmaceutics17111372

30. Eyerer P, Jin R. Influence of mixing technique on some properties of PMMA bone cement. J Biomed Mater Res. 1986;20(8):1057-1094. doi: 10.1002/jbm.820200802

31. Milone D, Spataro M. Biomechanical Evaluation of PEEK and PLA Composite Femoral Implants for Stress Shielding Reduction: A Finite Element Simulation Study. Prosthesis. 2025;7(3):44. doi: 10.3390/prosthesis7030044

32. Peng L, Zhou S, Dong Y, et al. A Polymethyl Methacrylate Bone Cement With Reduced Stress Concentration. Electron. 2026;4(1). doi: 10.1002/elt2.70032

33. Hahn M, Engelbrecht E, Delling G. [A quantitative analysis for determining porosity of pre-compressed and vacuum-mixed bone cement]. Chirurg. 1990;61(7):512-517.

34. Wall V, Nguyen HT, Nguyen NTP, Tran PA. Controlling Antibiotic Release from Polymethylmethacrylate Bone Cement. Biomedicines. 2021;9(1):26. doi: 10.3390/biomedicines9010026

35. Loh KW, Haseeb A, Lee ZC, Soo YZ, Teh CSJ, Abbas AA. Elution, Porosity, and Mechanical Performance of Vancomycin-Loaded Polymethylmethacrylate (PMMA) Bone Cement. Ann Biomed Eng. 2026. doi: 10.1007/s10439-026-04081-1

36. Jaubert M, Baron ML, Jacquet C, et al. Failure analysis of articulating polymethyl methacrylate spacers in two-stage revision total hip arthroplasty. Bone Joint Open. 2022;3(6):485-494. doi: 10.1302/2633-1462.36.bjo-2022-0024.r1

37. Thielen T, Maas S, Zuerbes A, Waldmann D, Anagnostakos K, Kelm J. Mechanical behaviour of standardized, endoskeleton-including hip spacers implanted into composite femurs. Int J Med Sci. 2009;6(5):280-286. doi: 10.7150/ijms.6.280

38. Zengah S, Mankour A, Sahli A, Salah H, Mallek A, Bouziane MM. Numerical Analysis of the Crack Growth Path in the Cement of Hip Spacers. Frattura ed Integrità Strutturale. 2022;16(61):266-281. doi: 10.3221/igf-esis.61.18

39. Calvo-Haro JA, Pascau J, Asencio JM, et al. Point-of-care manufacturing: a single university hospital's initial experience. 3D Print Med. 2021;7(1):11. doi: 10.1186/s41205-021-00101-z

40. Liu A, Xue G, Sun M, et al. 3D Printing Surgical Implants at the clinic: A Experimental Study on Anterior Cruciate Ligament Reconstruction. Sci Rep. 2016;6(1):21704. doi: 10.1038/srep21704

41. Lunz A, Omlor GW, Schmidt G, Moradi B, Lehner B, Streit MR. Quality of life, infection control, and complication rates using a novel custom-made articulating hip spacer during two-stage revision for periprosthetic joint infection. Arch Orthop Trauma Surg. 2021;142(12):4041-4054. doi: 10.1007/s00402-021-04274-4