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A novel digital workflow for fabricating artificial periodontal ligament using three-dimensional printing flexible resin: A dental technique

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ABSTRACT

The fabrication of periodontal ligament (PDL) models for in vitro dental studies has seen a wide range of techniques and materials being utilized. This paper introduces a novel dental technique that employs a digital workflow for the fabrication of artificial PDL using three-dimensional printing of flexible resin. This innovative approach offers several advantages, including enhanced accuracy and realism in simulating PDL. The digital workflow facilitates a streamlined fabrication process, ensuring efficiency and precision. By presenting this novel technique, this digital approach contributes to the advancement of in vitro dental research, providing researchers with a reliable and realistic model for studying various dental phenomena.

1. Introduction

The periodontal ligament (PDL) is a connective tissue that provides a distinctive connection between the alveolar bone and cementum layer encompassing the tooth root structure (Miletich and Sharpe, 2004; Jong et al., 2017). The primary function is to confer crucial mechanical properties to the tooth, serving as a stabilizing element that mitigates the impact of occlusal forces (Miletich and Sharpe, 2004; Jong et al., 2017). Under its viscoelastic properties, the PDL efficiently absorbs and dissipates occlusal forces, thus minimizing their transmission to the underlying alveolar bone (Miletich and Sharpe, 2004; Jong et al., 2017). Furthermore, the PDL acts as a barrier along with the gingival cuff to protect against pathogen infiltration originating from the oral cavity (Jong et al., 2017; Beertsen et al., 2000). The PDL originates from type I and III collagen, which provides strength by forming cross-banded fibrils approximately 54–59 nm in diameter (Beertsen et al., 2000). The PDL occupies space between the cementum and the bone, which ranges from 0.15 to 0.21 mm in thickness. This thickness varies slightly depending on the type of tooth, location, and age of the person (Beertsen et al., 2000). Various areas of dental research utilize PDL stimulation such as biomechanics, implant dentistry, orthodontics, dental material testing, and occlusion and temporomandibular joint (TMJ) research. A variety of materials, including polyether and polyvinyl siloxane (PVS) impressions, have been commonly employed to replicate the PDL in studies conducted in vitro (Rathi et al., 2018; Jamani et al., 1989). These materials are selected for their ability to effectively simulate the properties of the PDL, particularly in terms of their capacity to absorb external stress due to their similar viscous characteristics (Rathi et al., 2018; Jamani et al., 1989). By utilizing polyether and PVS impressions, researchers aim to accurately mimic the mechanical behavior of the PDL, allowing for reliable investigations and analyses in controlled laboratory settings (Rathi et al., 2018; Jamani et al., 1989). These materials serve as valuable tools in studying the biomechanical aspects and response of the PDL under various experimental conditions (Rathi et al., 2018; Jamani

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Abbreviations: PDL, Periodontal ligament; TMJ, Temporomandibular joint; PVS, Polyvinyl siloxane; CAD, Computer-aided design; STL, Standard tessellation language; CEJ, Cementoenamel junction; CBCT, Cone-beam computed tomography.

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et al., 1989). The utilization of materials such as polyether and PVS impressions to simulate the PDL in studies conducted in vitro is not without drawbacks (Rathi et al., 2018). These materials have certain limitations that need to be taken into consideration, such as the lack of biological complexity of natural PDL, potential for degradation of these materials over time, and reproduction of the anatomical variability of the PDL using these materials, which can be challenging (Rathi et al., 2018). Computer-aided design (CAD) technology has gained significant traction in studies conducted in vitro (Nawafleh et al., 2020; Van Noort R., 2012). The integration of CAD systems in this domain presents a range of benefits, such as enhanced precision and accuracy, time efficiency, improved communication and collaboration, and standardization and reproducibility (Huang et al., 2022). The technique presented in this study utilizes CAD to establish a novel digital workflow for the fabrication of three-dimensional (3-D) printed flexible resin, aimed at stimulating the PDL. This innovative approach demonstrates the potential to replicate the complex characteristics of the PDL using advanced digital technologies and additive manufacturing techniques.

Fig. 1. Close-up frontal view of the mandibular first premolar ready for scanning.

2. Technique

1. The remaining soft tissue from the root surface of an extracted tooth, which is similar to the morphology intended for this study, should be cleaned and removed using a periodontal curette and scalpel, and the tooth should be disinfected using 5 % sodium hypochlorite (Rathi et al., 2018).
2. The tooth is scanned using a desktop scanner (D9000L, 3Shape®, Copenhagen, Denmark), and then the data are exported and saved as a standard tessellation language (STL) file (Fig. 1).
3. The STL file is imported to an open-source CAD software program (Meshmixer, Autodesk Inc., San Rafael, CA) (Fig. 2, a).
4. The "select" button is clicked, and then from the brush mode, "unwrap brush" is selected to outline the root surface (Fig. 2, b).
5. An outline of a cementoenamel junction (CEJ) is drawn using "select tools" and "smooth boundary" as needed, and then "group borders" are preserved, and the "accept" button is clicked (Fig. 2, c).

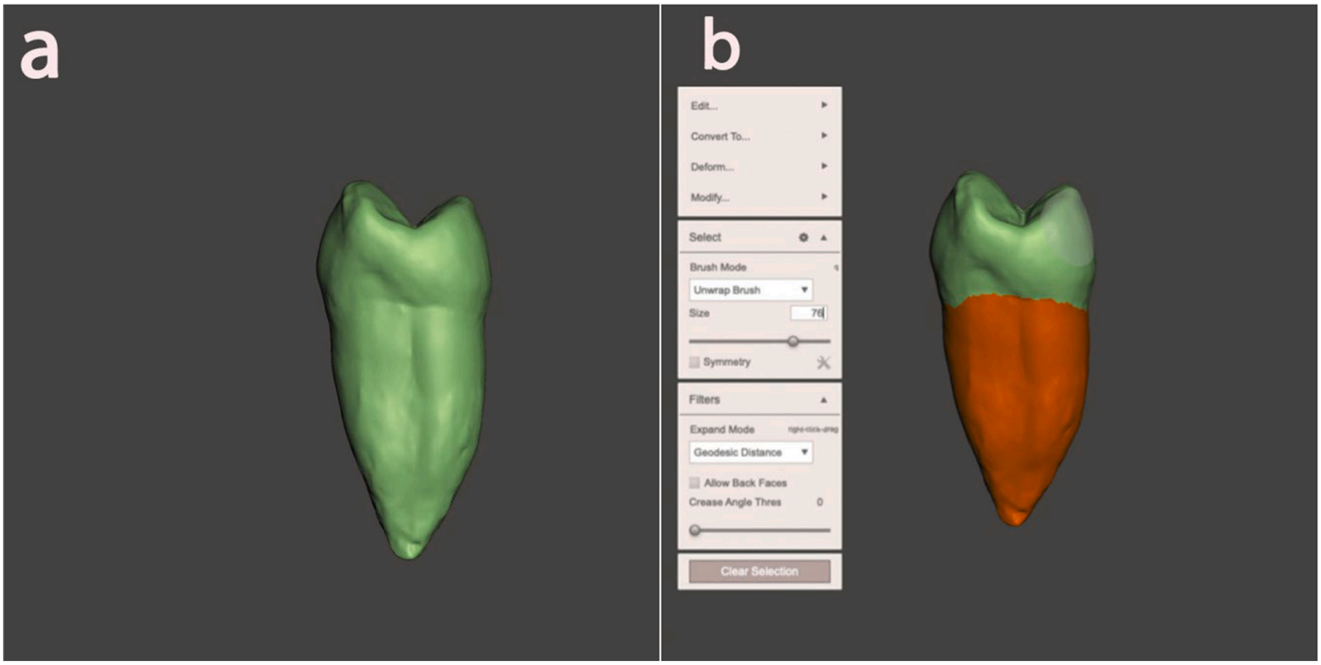
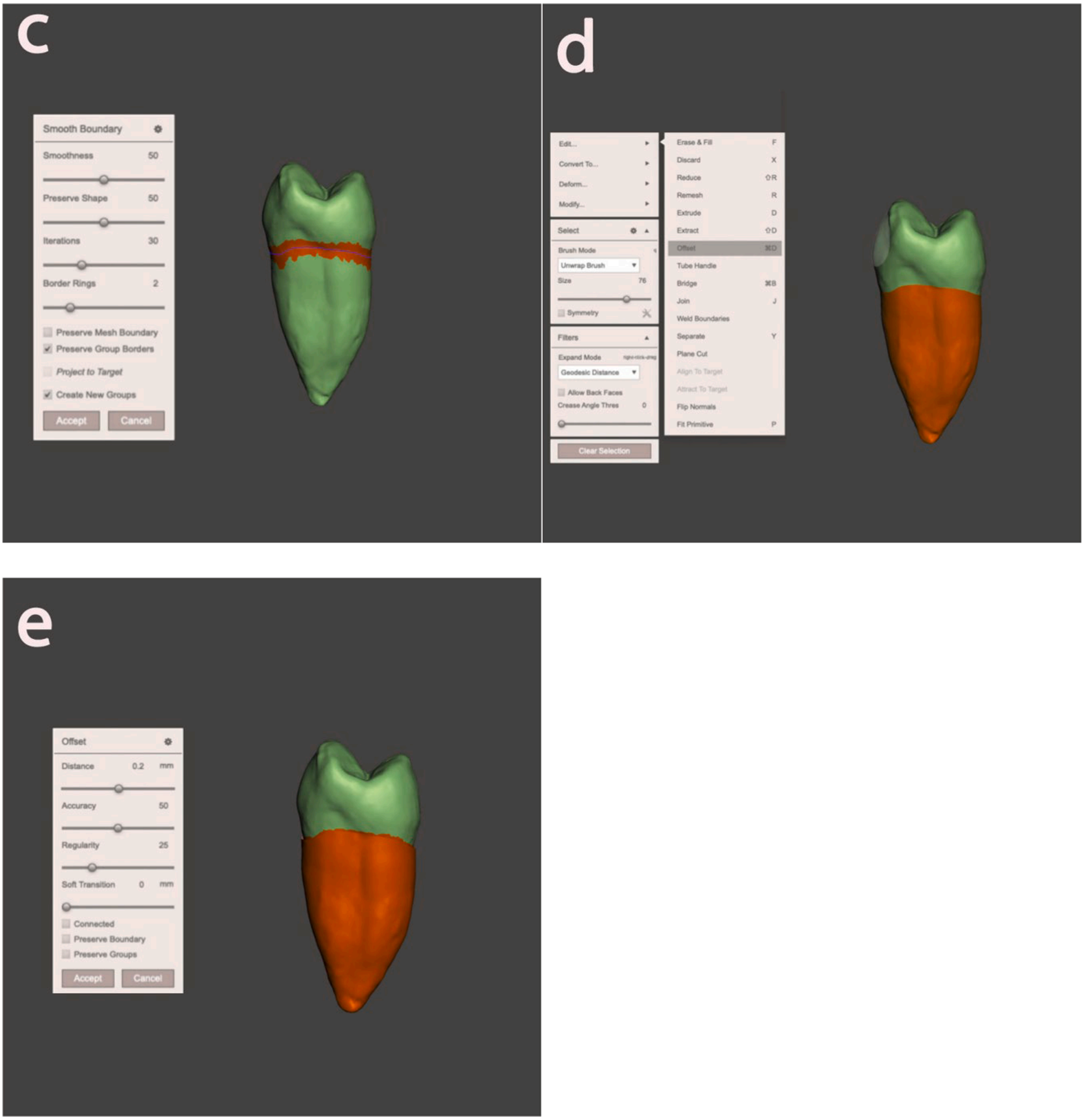


Fig. 2. The design process with a non-dental open-source software program. a, Software view of the cross-section of maxillary first premolar. b, Software view of the outline of the root surface. c, Software view of the outline of cementoenamel junction (CEJ). d, Software view of the outline of the root surface. e, Software view of the offset to set the thickness of periodontal ligament (PDL) to the desired thickness of 0.2 mm.



Smoothness 50
Preserve Shape 50
Iterations 30
Border Rings 2
☐ Preserve Mesh Boundary
☑ Preserve Group Borders
☐ Project to Target
☑ Create New Groups

Brush Mode Unwrap Brush
Size 76
☐ Symmetry
Expand Mode Geodesic Distance
☐ Allow Back Faces
Crease Angle Thres 0

Distance 0.2 mm
Accuracy 50
Regularity 25
Soft Transition 0 mm
☐ Connected
☐ Preserve Boundary
☐ Preserve Groups

Fig. 2. (*continued*).

6. The “select” and then “offset” buttons are clicked to set the thickness of PDL to the desired thickness of 0.2 mm (Fig. 2, d, e).
7. The “extrude” option is selected, then the “offset,” “separate,” and “accept” is selected to separate the tooth crown from the root surface (Fig. 3, a).
8. The original file is named for the separate root shell according to the tooth name, for example, “premolar original,” then a duplicate is made, and “separate” is selected (Fig. 3, b,c).
9. The root shell offset is modified as needed, and “analysis” option followed by “inspector” is selected to fill the hole and differentiate between the PDL and root surface. (Fig. 3, d).
10. Following this, “make solid” is selected from the edit list, and the “customize dimension between the PDL and root surface” option will appear; then the “accept” button is clicked to make a solid object. (Fig. 4, a).
11. The “sculpt” is selected, then “brushes,” “robust smooth,” and “secondary brush” are clicked to smooth the PDL surface, and the file is named “premolar solid” (Fig. 4, b).
12. Merge the two files to check the fitting of the PDL by selecting the “premolar original” and “premolar root” solid (Fig. 4, c).
13. The design is previewed before exporting the STL file, the edit is selected, and “solution mode” is clicked followed by “preserve group borders,” “auto-reduce result,” and accept (Fig. 4, d).
14. The exported data are sent as STL files to 3D printer formlabs 3D printer V2 (Formlabs Inc) for printing the artificial PDL with flexible resin V2 (Formlabs, Somerville, MA) in vertical orientation (Fig. 5).

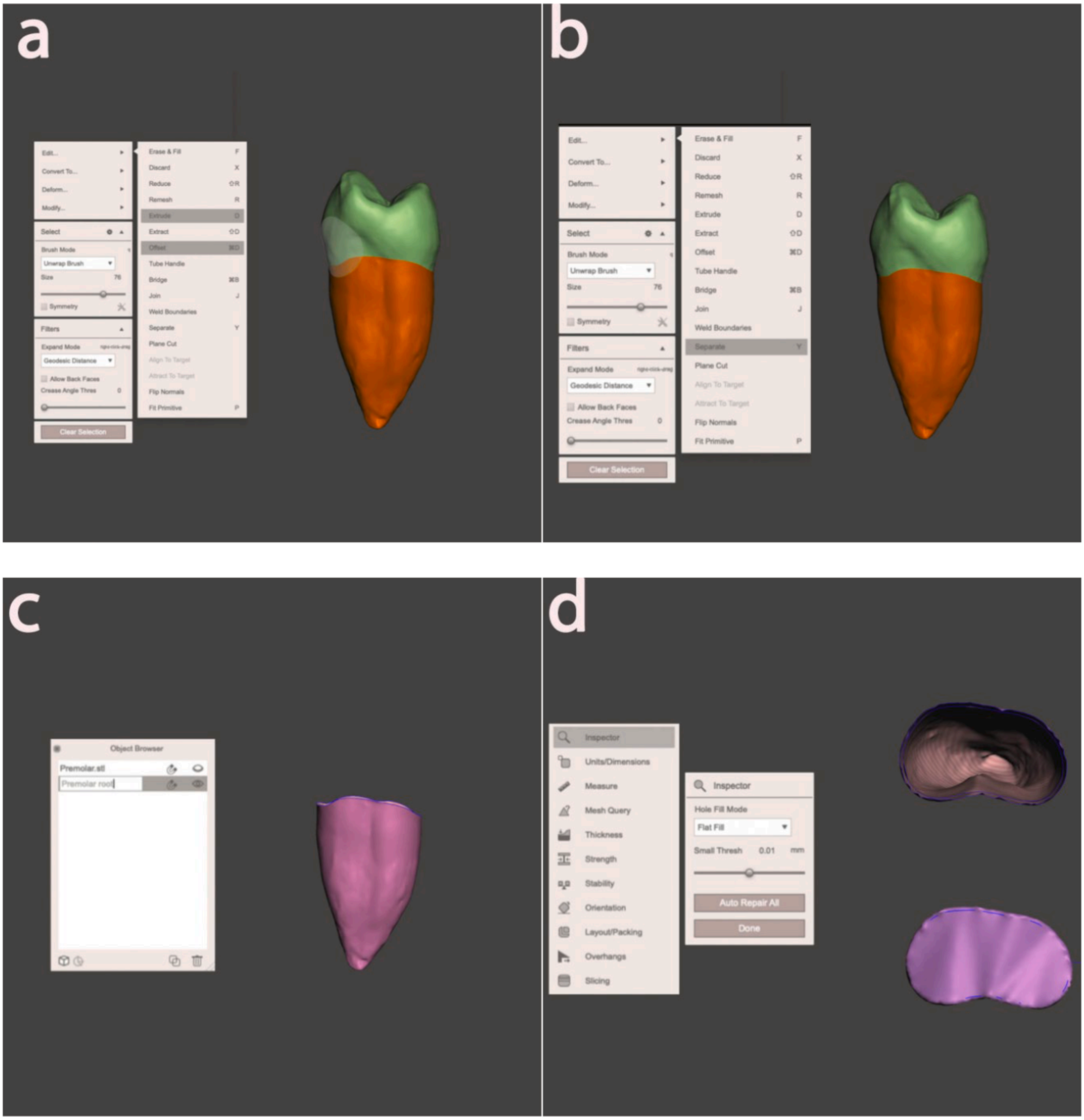
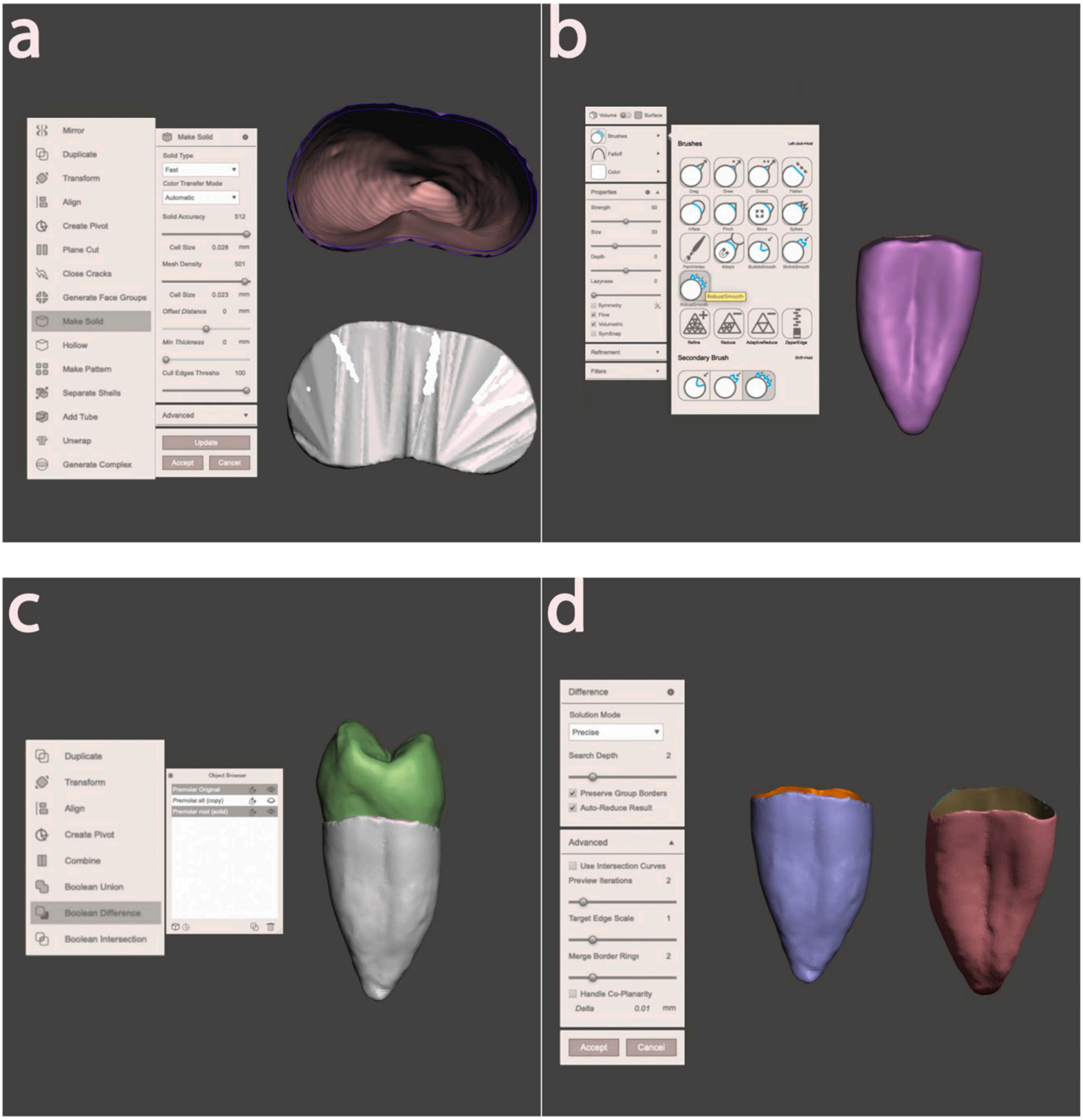


Fig. 3. The design process with a non-dental open-source software program. a, Software view of the tooth crown separate from the root surface. b, Software view of the original file for the separate root shell according to the tooth name. c, Software view of the outline of making a duplicate root surface. d, Software view of the outline of the filled root surface.

15. The printed PDL is cleaned using isopropanol for 5 min in an ultrasonic cleaner and then cured using a polymerization chamber curing machine for 30 min; the sprue is dissected, and then the artificial PDL is seated to the root (Fig. 5).

3. Discussion

Accurately reproducing the intricate architecture of the PDL to withstand applied forces poses a significant challenge in laboratory research studies (Ho et al., 2010; Fill et al., 2011). The use of viscoelastic materials to establish standardized PDL thickness further compounds the complexity of this endeavor, demanding considerable time and effort (Rathi et al., 2018; Jamani et al., 1989). The elastic modulus of approximately 850 MPa of the PDL exhibits variations corresponding to the applied load, with Young's moduli ranging from 0 to 2.0 N in 0.5 N increments (Fill et al., 2011). The stiffness or rigidity of the PDL, which is a connective tissue that surrounds and supports teeth within their sockets in the arch, can change depending on how much force or pressure is exerted on it (Yoshida et al., 2001). This property is crucial for the proper functioning and health of the teeth, as it allows the PDL to absorb and distribute forces during activities like chewing or biting. Different loads can result in varying levels of stiffness within the PDL, and Young's moduli are used to quantify and understand these changes in stiffness (Fill et al., 2011).



Make Solid
Solid Type: Fast
Color Transfer Mode: Automatic
Solid Accuracy 512
Cell Size 0.028 mm
Mesh Density 501
Cell Size 0.023 mm
Offset Distance 0 mm
Min Thickness 0 mm
Cull Edges Thresho 100

Strength 50
Size 33
Depth 0
Lazyness 0
☐ Symmetry
☑ Flow
☑ Volumetric
☐ SymSnap

Premolar Original
Premolar.stl (copy)
Premolar root (solid)

Difference
Solution Mode: Precise
Search Depth 2
☑ Preserve Group Borders
☑ Auto-Reduce Result
Advanced
☐ Use Intersection Curves
Preview Iterations 2
Target Edge Scale 1
Merge Border Ring: 2
☐ Handle Co-Planarity
Delta 0.01 mm

Fig. 4. The design process with a non-dental open-source software program. a, Software view of the outline of a solid root object. b, Software view of the smooth surface of the three-dimensional (3D) periodontal ligament (PDL) surface. c, Software view of the superimposition of the fitting of the 3D PDL with 3D tooth object. d, Software view of the 3D root surface design before exporting the STL file.

Additionally, considering non-uniform PDL thickness and dimensions vary depending on the type of tooth, location, and age of the person (Beertsen et al., 2000; Rathi et al., 2018), this approach proves to be a valuable method to replicate PDL in clinical scenarios and achieve suitable biomechanical characteristics relevant to in vitro studies (Rathi et al., 2018). The integration of digital dentistry in studies conducted in vitro offers numerous benefits, including enhanced efficiency, precision, standardization, and opportunities for advanced data analysis while minimizing potential errors (Van Noort R., 2012; Huang et al., 2022). Furthermore, the integration of CAD technology and additive manufacturing methods offers significant advantages for designing and simulating the PDL. By employing CAD software, researchers can digitally recreate the complex architecture of the PDL, incorporating precise dimensions and anatomical features. Subsequently, additive manufacturing techniques enable the fabrication of physical models that accurately mimic the properties of the PDL such as elasticity and thickness. This advanced approach provides researchers with realistic and standardized PDL models, facilitating comprehensive investigations of various dental phenomena in controlled laboratory settings. This novel workflow can be utilized across a spectrum of dental research domains such as biomechanics, implant dentistry, orthodontics, dental material testing, and occlusion and TMJ research.

The additive manufacturing material, such as 3D flexible resin, offers practical advantages in streamlining the workflow for fabricating

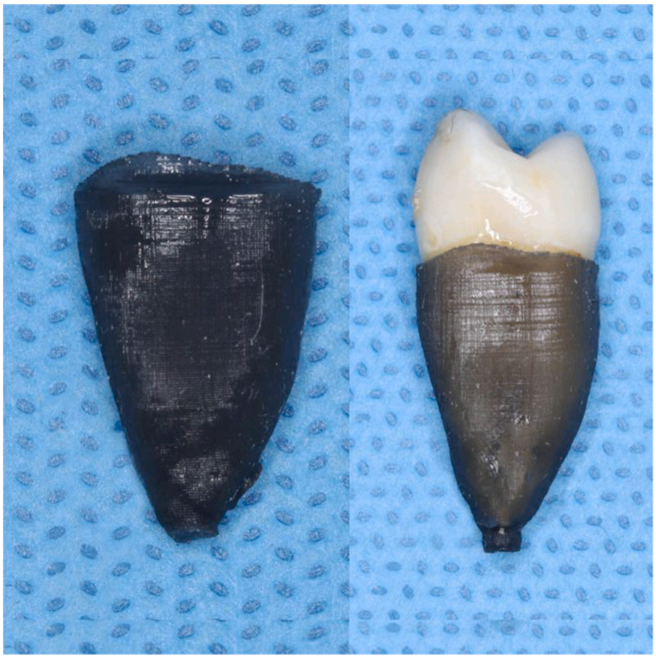


Fig. 5. Three-dimensional (3D)-printed periodontal ligament Without and the tooth is inserted inside the flexible resin periodontal ligament.

artificial PDL models, such as realistic mechanical properties, customizability, enhanced accuracy and reproducibility, ease of fabrication and manipulation, and cost-effectiveness.

This approach enables efficient manufacturing of PDL simulations using a 3D printable flexible resin that possesses suitable elasticity and standardized thickness. By employing these digital technologies, researchers can achieve precise replication of the PDL structure, ensuring an accurate representation of its mechanical properties. The utilization of 3D printable resin in a digital workflow or CAD technology has limitations. These include the potential mismatch in material properties with natural tissues, resolution limitations, post-processing requirements, and the need for specialized skills and expertise (Resende et al., 2021; Tian, Y et al., 2021).

Furthermore, it is imperative to acknowledge the limitation of the non-uniformity within the PDL while accounting for variables such as age, ethnicity, and other relevant factors when conducting research using this novel method. The PDL is a crucial component of the dental structure, influencing the stability and function of individual teeth. However, its specific properties for individual teeth can be challenging to determine due to its heterogeneity. To address this, researchers can conduct extensive literature analysis, examining the characteristics of the PDL, considering factors like age, ethnicity, and tooth type. A diverse sample of teeth, including various age groups, ethnicities, and tooth types, can be assembled to capture desired variations. Using imaging methods like cone-beam computed tomography (CBCT) or micro-CT scans, researchers can visualize and quantify PDL dimensions and properties. Statistical analysis can identify significant disparities in PDL characteristics, allowing for the establishment of normative data or reference ranges. Validating existing normative data through collaboration with other research groups ensures the reliability and replicability of study findings. Establishing protocols and reporting standards for researchers can enhance the comparability and comprehensibility of findings across different studies.

To ascertain and authenticate the performance and elasticity of the materials described in this technique, additional research is imperative to assess the effectiveness and capacity of 3D flexible resin in withstanding the applied loading during laboratory testing. In dentistry, flexible resin can be used to fabricate flexible dentures, clear aligners, and TMJ splints, enhancing patient comfort.

4. Conclusion

The utilization of a novel digital workflow in the fabrication process offers streamlined efficiency and enhanced precision. By introducing this novel technique, the digital approach contributes to the progression of in vitro dental research, providing researchers with a dependable and authentic model for investigating diverse dental phenomena.

CRediT authorship contribution statement

Hatem Alqarni: Conceptualization, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Mohammed A. Alfaifi:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Majed S. Altoman:** Resources, Writing – original draft, Writing – review & editing, Project administration. **Abdulaziz A. AlHelal:** Resources, Project administration. **Walaa Magdy Ahmed:** Writing – review & editing, Visualization, Supervision. **Amr Ahmed Azhari:** Writing – review & editing, Visualization. **Mathew T. Kattadiyil:** Writing – review & editing, Visualization, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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