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Multiresin Additive Manufacturing Process for Printing a Complete Denture and an Analysis of Accuracy

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Abstract

A complete denture, consisting of teeth and a gum base, is a standard device used to restore masticatory and esthetic functions in patients with complete edentulism. The different colors and mechanical properties for teeth and the gum base mean a complete denture is manufactured using two materials with different mechanical properties. This study proposes a method to make a complete denture using a laboratory-developed, multiresin additive manufacturing (MRAM) system with two resins and different mechanical properties. A tenon joint is used to create the bottom of the teeth that fit into the gum base, ensuring automatic alignment and higher bending strength. The mechanical properties, material waste, fabrication time, and effect of the tenon joint on the bending strength of a complete denture printed using the MRAM system are compared with the values for a computer-aided design and computer-aided manufacturing (CAD/CAM) system. Experimental results show that the printed denture is manufactured 3 times faster and produces 14 times less material waste, but is 35.08% less inaccurate than one produced using a CAD/CAM system. The proposed tenon joint increases the bending strength by 31.94%. The MRAM system is applicable for printing a complete denture.

Keywords: additive manufacturing, multiresin, complete denture, tenon joint, stereolithography, accuracy

Introduction

Edentulism or toothlessness is the final result of aging or improper tooth maintenance after teeth are usually exposed to dynamic mechanical forces during the mastication process. When teeth are ground by a material harder than themselves, they are traumatized or injured, affecting mouth function. Despite advances in preventive dentistry, edentulism is still a significant public health problem worldwide. The prevalence of edentulism in adults over 60 years of age is 25% in the United States and 21.7% in Canada.[1] A complete denture is generally used as a restoration device for edentulism patients because it restores occlusal, masticatory, esthetic, physiognomic, phonetic, and psychosocial functions.[2,3]

The conventional method for complete denture fabrication uses complex laboratory techniques, including two impression sessions (preliminary and definitive impressions) and a facebow transfer. It provides satisfactory clinical results, but sophisticated manual procedures lead to extended delivery times (usually 3 weeks) and high costs.[4] Therefore, much dentistry work uses computer-aided design/computer-aided manufacturing (CAD/CAM) to mill artificial teeth and the gum base separately,[5,6] after which a complete denture is constructed by gluing together the teeth and gum base. This decreases the delivery time to 1 week and gives repeatable accuracy, but its drawbacks are high equipment cost, risk of tooth mispositioning during gluing, and material waste. Additive manufacturing for dental applications is replacing CAD/CAM.

Additive manufacturing, also known as three-dimensional (3D) printing, is used to print dental restoration devices such as dental models, temporary crowns, surgical stents,[7] and occlusal splints.[8] Vat photopolymerization (VP),[9] material jetting (MJ),[10] binder jetting,[11] and material extrusion (ME)[12] are used to produce dental restoration devices with acceptable accuracy. VP is the primary method because it is faster than ME, the equipment cost is lower than that for MJ,

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and many resins are commercially available. Notably, the restoration devices mentioned can use only a single resin in the process. A complete denture requires two resins, so multiresin printing technology is necessary to obtain complete dentures using one printing process.

Multimaterial additive manufacturing (MMAM) increases the performance of printed parts because it allows greater complexity and functionality. It is also possible to improve performance by varying the material composition or type within layers.[13–16] The two-resin additive manufacturing system shows that a suitably clean method can avoid interstaining in the junction layer when one layer requires two resins to be fabricated.[17] The air pressure-assisted solvent spraying method is promising because it eliminates interstaining. This method sprays the solvent on the cured layer, and then pressurized air is used to dry the printed object completely. Several methods use MMAM in a microactive scaffold,[18] a biohybrid actuator,[19] a functionally graded biopolymer composite,[20] simultaneous food printing,[21] and a microfluid.[22] However, there are no studies showing how MMAM can be used to fabricate a complete denture.

This study proposes a process to print complete dentures using multiresin additive manufacturing (MRAM). A machining system, CAD/CAM, is then also used to mill the same model, and the fabrication time, material waste, and accuracy of the printed parts are compared. A tenon joint structure is proposed to increase the bending strength between the teeth and gum base and ensure high accuracy of the fabricated complete denture.

Materials and Methods

Complete denture model

A standard edentulous model is used for the reverse scan with a dental scanner (3Shape TRIOS, Denmark), and scanned data can be exported into STereoLithography (STL) files to design and obtain STL files of the complete denture model using dental software (ExoCAD, Germany). These files can be converted into different storage sizes based on the changing triangle element size, using free software (Autodesk Meshmixer). STL files are used for complete denture fabrication with an MRAM system and a machining system. Figure 1A shows a standard, adult complete denture with 28 teeth, 14 each for the upper and lower jaws. The tooth model's bottom is a smooth surface with no structure to assist self-positioning, so tooth misalignment can occur during gluing. The tenon joint is 1.5 mm in diameter and 1.8 mm high, and the designs are created on the upper surface of the gum base, and the bottom surface of each tooth is extruded to form a hole to fit the tenon joint, as shown in Figure 1B.

MRAM system

Figure 2 shows a laboratory-developed MRAM system using two vats and one novel clean module to print a complete denture. Figure 2A shows that the platform can be rotated to vat A, vat B, and the clean vat. A light engine is set up beneath the vat to emit radiation at a wavelength of 405 nm with a power intensity of 700 mW. The projected pixel size is 50 μm. Resin colors for the gum base and tooth are pink in vat A and A2 white in vat B. The reaction wavelength for both resins is 405 nm. Figure 2B shows the building of complete denture bonds on the platform, which is rotated to clean the vat by removing the residual resin before the platform switches to another vat. The viscosity coefficient for the gum base resin (Enlighten Materials Co., Taiwan) is 1180 cps, higher than that for the tooth resin, at 498 cps. Both resins are acrylate polymers and comply with ISO 10993. Since the resin's high viscosity reduces flowability, the MRAM system's clean module, as shown in Figure 2C, uses pressurized

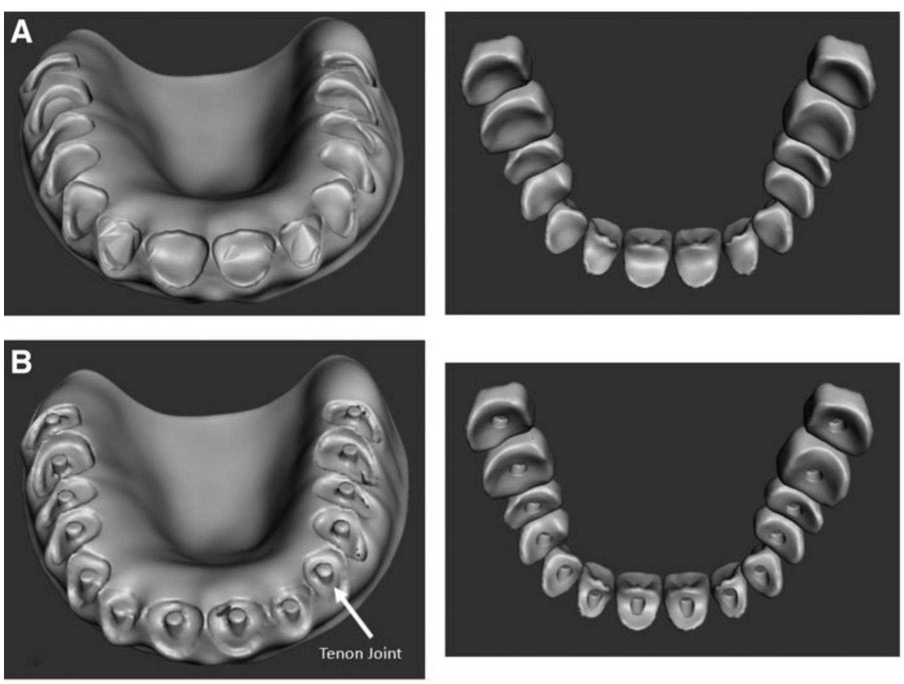

FIG. 1. Illustration of a standard, adult, complete denture model **(A)** and modified model with tenon joints **(B)**.

air in the solvent to generate bubbles, as shown in Figure 2D, quickly removing residual resin on the surface of the printed part. The minimum thickness for a layer using this system is 5 μm.

Dual resin slicer software is developed to carry out the layer slicing process, importing two CAD models, for teeth and gum base, and exporting the layer pattern for the MRAM system. The sliced layers are shown in Figure 3, which shows different codes for each layer. Code A and code B, respectively, represent material A and material B. If the number in the file name has two codes, the sliced layer is constructed using two resins, so two different slicing patterns must be used. Cleaning is also necessary before the platform is transferred to another vat to avoid interstaining. This dual resin slicer is a critical process for the MRAM system. Both models require the same reference coordinates.

Effect of the diameter of the tenon joint on bending and compressive strength

The teeth and gum base are designed separately if a CAD/CAM system is used because the CAD/CAM system must mill two different materials with a white A2 color blank and a pink color blank. The traditional design does not use a tenon joint, as shown in Figure 1A, so misalignment is possible when the milled teeth and the gum base are glued manually. This study uses the tenon joint to resolve this problem. Modified models with tenon joints allow self-positioning of the teeth on the gum base for high positional accuracy and reduced risk of tooth misalignment.

Figure 4 shows how teeth experience a pull force when tearing food using incisions or a compressive strength when grinding food with molars during mastication. A bending test using ASTM D7264 and a compressive test using ASTM 695 are performed. For this study, the tenon joint diameters used are 1.5, 2, 2.5, 3, and 3.5 mm to determine the effect of the tenon joint's diameter on bending strength and to optimize tenon joint diameters for various teeth. A standard model is subjected to the same tests to compare results with those for the modified model.

Curing test

Curing characteristics of the resin depend on specifications of the light engine used. This study's light engine has a focal length of 92 mm, wavelength of 405 nm, and light energy of 700 mW. The active working field is $65.6 \times 41\ mm^2$. To create Jacob's working curve, two vats are filled with the gum base and tooth resin. Filled resin in the vat is 3 mm deep. The curing test specimen dimensions are $5 \times 5\ mm^2$ with a 1 mm diameter at the center. All samples are solidified using different exposure times at the same intensity ($20\ mW/cm^2$). After printing, the specimen is removed from the vat, cleaned with methanol, and dried using a compressed air spray, and the thickness of the sample is measured.

CAD/CAM system

A CAD/CAM system is also used to mill the proposed model to compare the fabrication time, material waste, and accuracy with those for the printed object. The Imes-core CORiTEC 250i is widely used in dental laboratories. It allows 4-axis simultaneous machining with 2-μm precision in tool length. Dental CAD/CAM software (SUM3D; CIMsystem, Italy) is used to generate the tool path for milling. Polymethyl methacrylate of different colors, supplied by Bilkim Co., is used for the teeth and gum base. The diameter and thickness are 98 and 18 mm, respectively. The milled tool's diameters are 0.5 and 1 mm for high precision and standard milling.

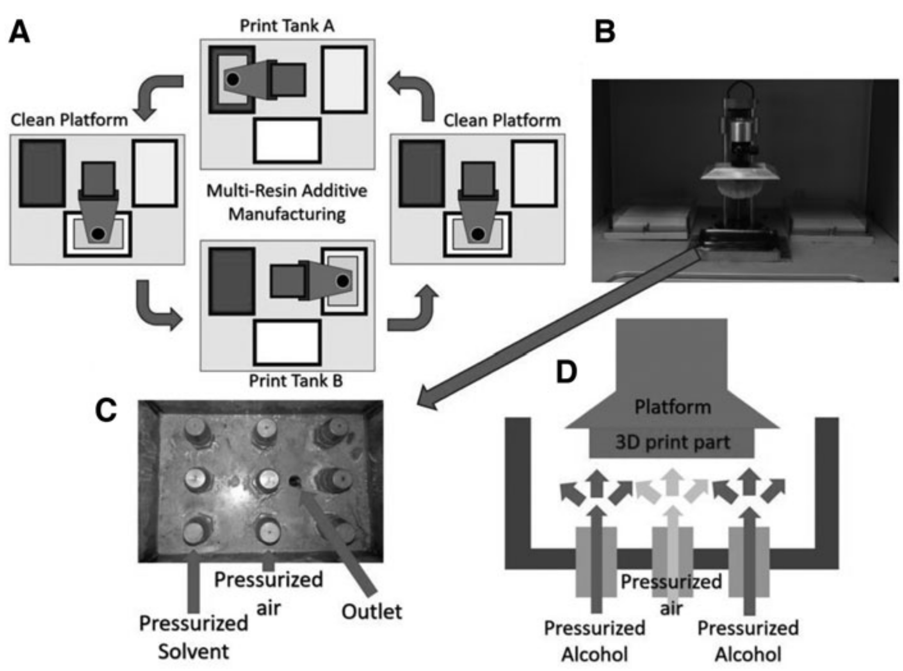

FIG. 2. Printing process for an MRAM system **(A)** with the clean module **(B)** using pressurized air in the solvent **(C)** to remove residual resin on building part **(D)**.

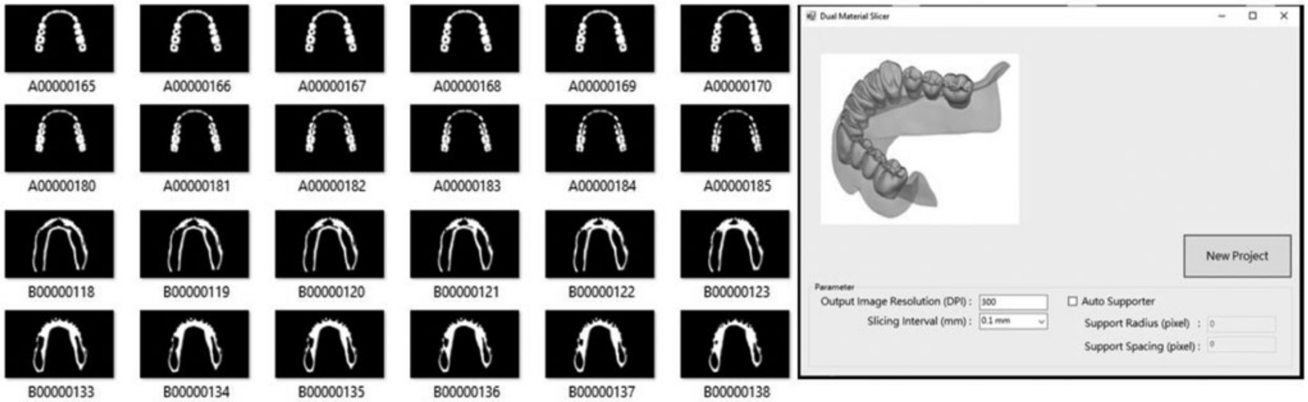

FIG. 3. Dual resin slicer software.

The milling parameters for a CAD/CAM system affect the surface appearance, dimensional accuracy, and processing time. The triangle elements comprise the gum base model and the milling thickness for each layer. The smaller triangle elements result in larger output model storage data, smoother milled surface,[23] and longer milling time. The tooth model's curved surfaces and lower jaw are more complicated than that of the gum base without the upper jaw's tooth model, so the effect of the triangle element size on surface roughness cannot be determined. This study uses the gum base model of the upper jaw without the tooth model as the experimental object, and the triangle element sizes are 0.2, 0.4, and 0.8 mm.

Accuracy analysis

A reverse scanner system, ATOS 3D, is used to evaluate the dimensional accuracy of printed and milled specimens. This 3D scanner has two cameras with 8-megapixel resolution and a laser pointer with distance adjustment. The scan speed is 1 s, with an accuracy of 29 μm. The scanning result is compared with that for the original dental model, in STL format, to determine the accuracy of 3D printed and milled products using inspection software (GOM Company).

Statistical analyses

All statistical analyses were performed using the Excel Analysis ToolPak. ANOVA was conducted for study of each parameter. The difference of means was compared using the Tukey post-test, which is considered significant at 5%.

Results and Discussion

Curing test and printing parameters for the MRAM system

Figure 5 displays the cured thickness for different exposure times for the resins. Both resins are highly active photopolymers because a 1-s exposure generates a cured layer at least 0.4 mm thick and a longer exposure time increases the thickness of the cured layer. The A2 white resin has a slightly thicker cured layer than the gum base resin. To increase the accuracy of the printed complete denture, the thickness of the sliced layer is 25 μm. Figure 5 also shows that an exposure time of 2 s ensures a cured thickness more significant than 50 μm for both resins. This is twice the thickness of the sliced layer, so an exposure time of 2 s is used for both resins.

Milling parameters for the CAD/CAM system

The STL format is an open file describing the surface in terms of a 3D object's triangular facets. It is the import format for a CAD/CAM system and 3D printer. The triangular element size affects the data storage, milling time, and surface roughness of the milled object.

Figure 6 shows the result for the milled gum base using three sizes of triangle elements. The processing time for a gum base with a triangle element of 0.8 mm is 45 min, but a step effect is seen in the 3D scan, with inaccuracy ranging from –0.5 to 0.57 mm. The longest processing time of 354 min applies to a gum base model with a 0.2 mm

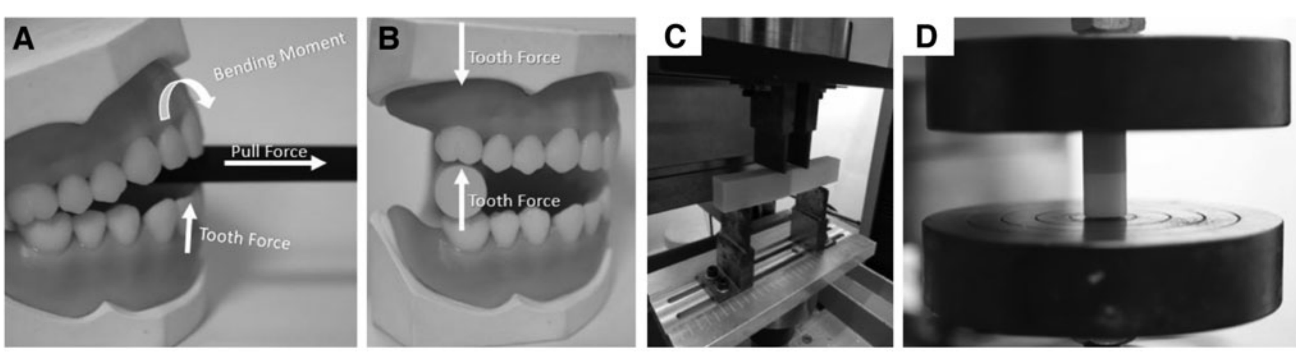

FIG. 4. An incisor and molar are subjected to a pull (**A**) and compressive force (**B**) using a three-point bending test (**C**) and compressive test three-point bending test (**D**) to simulate the pull force and compressive force.

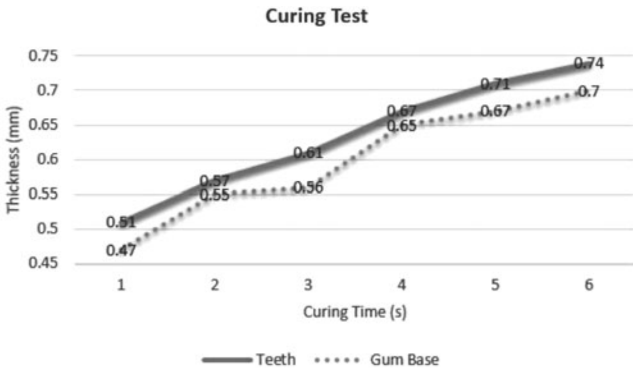

FIG. 5. Cured thickness versus exposure time.

triangular element size, and this inaccuracy decreases to –0.31 to 0.35 mm. Using a 0.4 mm triangle element to construct a gum base object requires 259 min of processing time, but the surface roughness and inaccuracy are comparable with those for a 0.2 mm triangle element. Notably, the greatest inaccuracy occurs in the tooth cavities of the gums. In this study, a 0.4 mm triangle element is determined to construct the tooth and gum base models and to print the models using the MRAM system for comparison with milled parts.

Complete denture fabrication

The fabrication results for MRAM printing and CAD/CAM milling are shown in Figure 7A and B. Both methods fabricate a complete denture. The colors differ slightly because the resins and blank composition are different, but the size and shape are comparable. The surface brightness for a CAD/CAM part is better than that for a component produced using multimaterial printing. This may be caused by the different manufacturer using different filler compositions, although both materials are acrylate-based polymers. The material also uses two different manufacturing processes, with the CAD/CAM dental blank formed by the traditional polymerization process and the 3D printed part made by photopolymerization. The milled result is sharper than the printed product at the interface between the tooth and the gum because the teeth are milled separately and then glued to the gum base. The molars and premolars of a printed complete denture have deeper grooves than a milled denture. The milling tool's minimal diameter is 0.5 mm, which is greater than the projected pixel size for an MRAM printer.

Total manufacturing time

The total manufacturing time includes preprocessing time (also known as machine setup time), processing time, and postprocessing time. The preprocessing time for a CAD/CAM system involves setting up the mill tools and blanks and importing the NC-code for milling. For MRAM, the preprocessing time includes the time required to pour resins into two vats and import the sliced layer data. The processing time for CAD/CAM is the sum of the time necessary to mill the teeth and the gum base, and for MRAM, it is the total printing time.

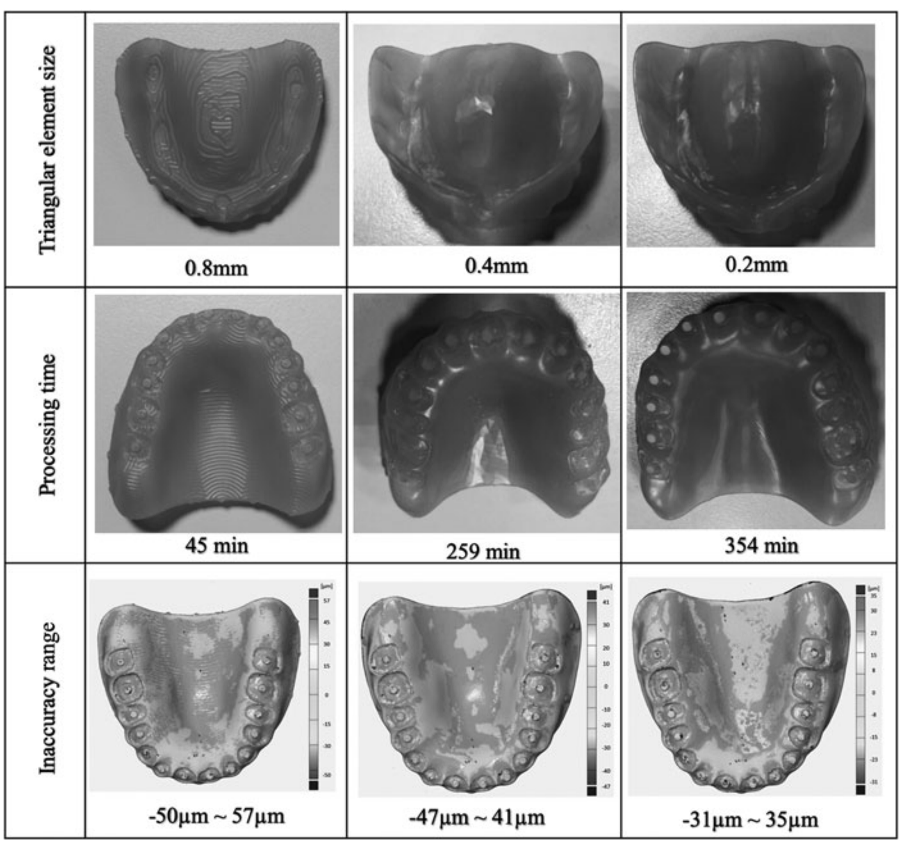

FIG. 6. Surface appearance, processing time, and inaccuracy range of the milled gum bases using different triangular element sizes.

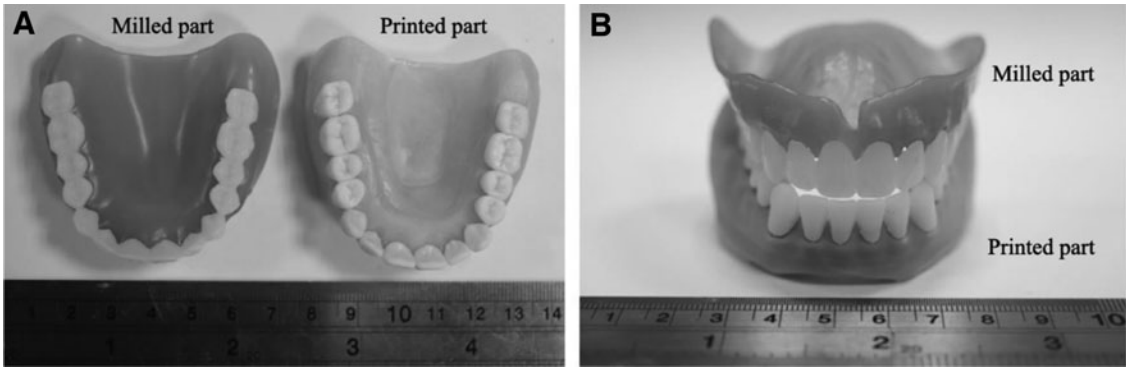

FIG. 7. Results for fabricating a complete denture using **(A)** a CAD/CAM system and **(B)** an MRAM system. CAD/CAM, computer-aided design and computer-aided manufacturing; MRAM, multiresin additive manufacturing.

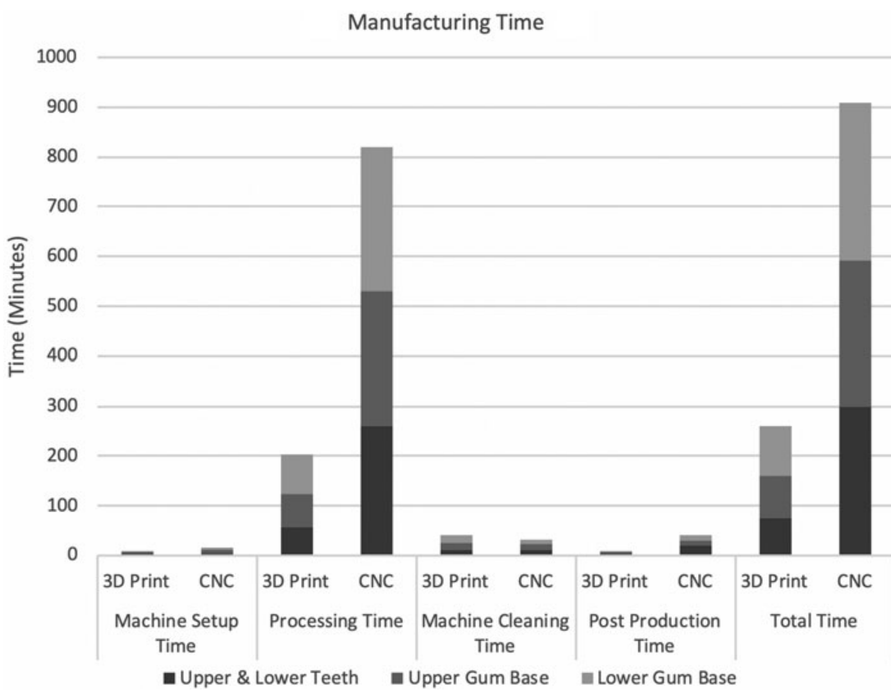

FIG. 8. Comparison of the time required for preprocessing, processing, and postprocessing using a CAD/CAM system and an MRAM system. CAD/CAM, computer-aided design and computer-aided manufacturing; MRAM, multiresin additive manufacturing.

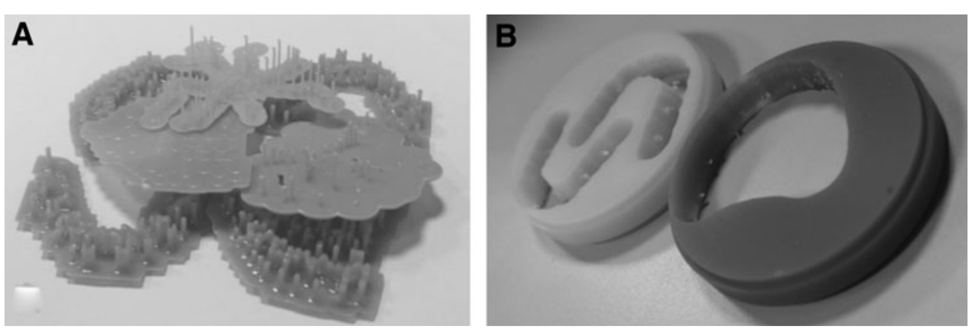

FIG. 9. Material waste for **(A)** the MRAM system and **(B)** CAD/CAM system. CAD/CAM, computer-aided design and computer-aided manufacturing; MRAM, multiresin additive manufacturing.

TABLE 1. WEIGHT OF THE RAW PRODUCT AND WASTE GENERATED IN THE PROCESS

	Raw weight (g)		*Product weight (g)*		*Waste weight (g)*	
	MRAM	*CAD/CAM*	*MRAM*	*CAD/CAM*	*MRAM*	*CAD/CAM*
Upper and lower teeth	9.92	155.55	9.92	6.72	5.96	148.83
Upper gum base	19.76	156.11	8.99	10.22	10.77	145.89
Lower gum base	23.97	156.03	14.62	16.62	9.35	139.41
Total weight	55.41	467.69	33.53	33.56	20.12	434.13

CAD/CAM, computer-aided design and computer-aided manufacturing; MRAM, multiresin additive manufacturing.

Postprocessing, it is necessary to obtain complete dentures. If a CAD/CAM system is used, the milled teeth and gum base parts must be trimmed and glued using cement. For the MRAM system, the printed complete denture must be immersed in methanol as a solvent. An ultrasonic machine removes the residual resin and removes the printed part's support after the postcuring process, using a 90-s exposure time. The total manufacturing time is the sum of these individual times.

Figure 8 shows the result for each time. The preprocessing time and postprocessing time for CAD/CAM and MRAM are comparable. More processing time is required for CAD/CAM than for printing. The total manufacturing time for CAD/CAM is 908 min, but it is 261 min for MRAM. Notably, the time cost of vat cleaning for the MRAM system depends on the resin's viscosity since a resin with higher viscosity increases the vat cleaning time. Water-washable resin products are commercially available, and if these meet the requirements for biocompatibility, they can be used to print complete dentures with reduced cleaning time.

Material cost and waste

More waste is produced by the CAD/CAM system than by the MRAM system, as shown in Figure 9. The CAD/CAM system uses two blanks to mill two objects, but the remaining portion cannot be reused and becomes waste, as shown in Figure 9B. For the MRAM system, only the support portion becomes waste. The total debris and waste weight for the CAD/CAM system is 434.13 g, and 20.12 g of waste is produced by the MRAM system, as shown in Table 1. Printing of the upper and lower teeth produces no waste because they are printed and embedded with the upper and lower gum bases at the same time. The final weights of both complete dentures are similar. Some studies report that the waste produced by a CAM system is recyclable, but the cost is high.[24] MRAM is a promising tool for making complete dentures with sustainable development because it produces less material waste than the CAD/CAM system.

Bending strength and compressive strength

The bending test shows the effect of the tenon joint's diameter on the bending strength, the glued crown's compressive strength, and the gum base, indicating that the proposed modified model with tenon joints has greater bending strength. Figure 10 shows that the bending strength of a standard complete denture is 13.46 MPa. The bending strength for the modified model with a 1.5-mm diameter tenon joint increases to 17.76 MPa, and this value increases as the tenon joint diameter increases. The tenon joint design produces a larger bonding surface.

There is no significant difference in compressive strength. The compressive strength for the standard model and modified model is 61.1 and 62.3 MPa, respectively. This result shows that an appropriate tenon joint design increases the bending strength by 31.94% over that for a no-tenon joint, but has no effect on compressive strength.

Accuracy analysis

An accurate complete denture is necessary because inaccuracy results in discomfort for the patient and reduced willingness to wear the denture. Figure 11 shows the reverse scanning results for gum bases with teeth constructed using CAM milling and MRAM printing. The color bar represents

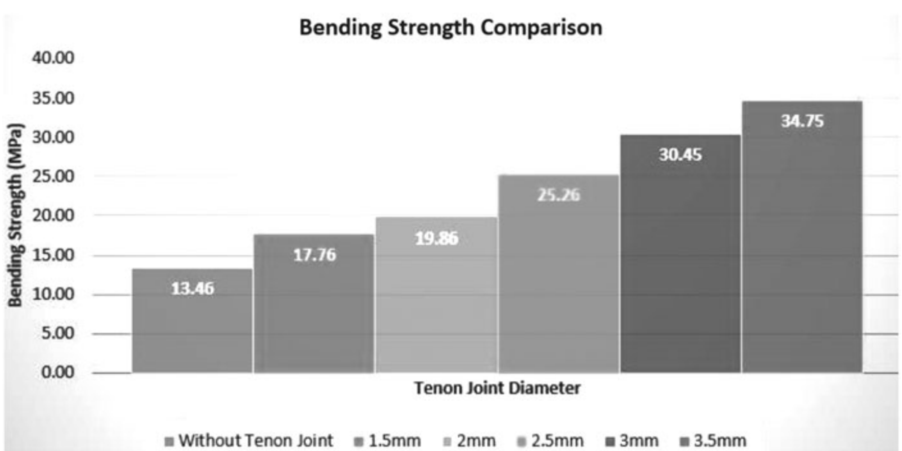

FIG. 10. Comparison of the bending strength for tenon joints with different diameters.

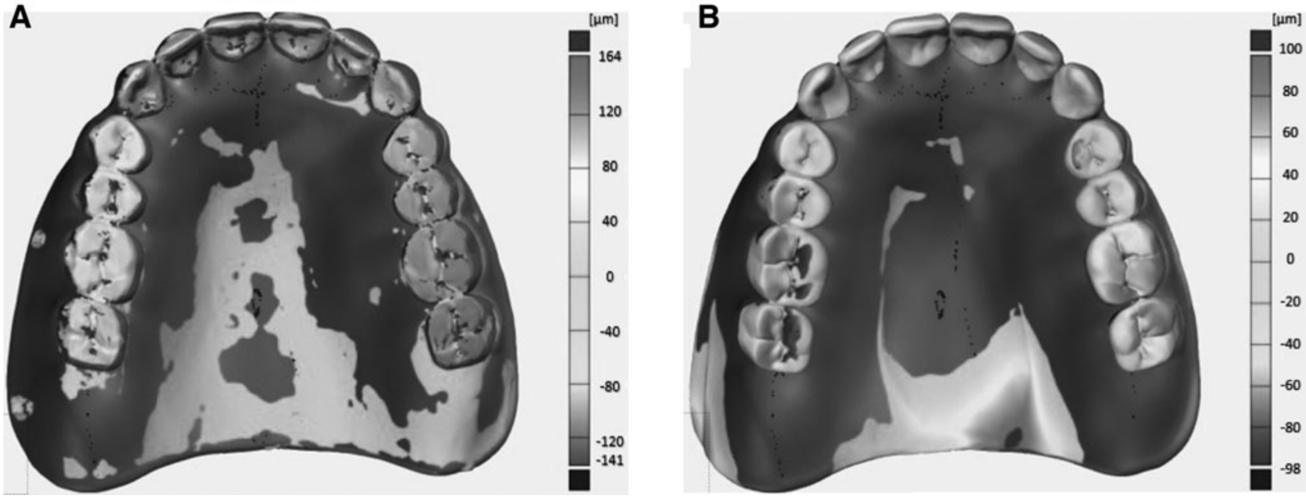

FIG. 11. Inaccuracy of **(A)** the CAM milled part and **(B)** MRAM printed part. CAD/CAM, computer-aided design and computer-aided manufacturing; MRAM, multiresin additive manufacturing.

the inaccuracy compared with the original model. Figure 11A shows that a milled gum base is accurate to +164 to −141 μm, but a printed part is accurate to +100 to −98 μm with about 35.08% less inaccuracy. Notably, milled parts' inaccuracy is more uniform than the inaccuracy of printed pieces because the printed part experiences shrinkage. Therefore, dental technicians must adjust both parts using a dental stone model before applying them in clinical practice.

Previous studies used an inkjet 3D printer to construct a dental model and compared the accuracy with that for a milled part using a 5-axis CAM system[25] and found that milled parts are more accurate than printed pieces. This study does not agree with results of previous studies, but different CAM and printing methods are used. This study uses a 4-axis milling system and MRAM to make the complete denture. The STL file's triangle element size is optimized, so the comparison is based on the same initial condition, and the result is more reliable. An MRAM system makes the tooth and gum base simultaneously, so there is no requirement for postprocessing or tooth adjustment.

Study limitation

It is still early to confirm the success of multiresin, additive manufactured complete dentures since the current printed parts could not compete with products prepared by the classic subtractive process due to concerns over FDA (Food and Drug Administration) approval and the economy. However, the future potential of multiresin, additive manufactured complete dentures is clear due to the advantages and potentials of this technology such as manufacturing by adding materials and providing customized manufacturing.

Conclusions

This study fabricates a complete denture using MRAM and a CAD/CAM system. The triangle element size is optimized using a CAD/CAM system, which is then compared with the MRAM system printed parts for the same model. Experimental results show that the proposed tenon joint structure increases the bending strength of the complete denture. Comparison of a complete denture produced using the MRAM system with one produced using the CAD/CAM system shows that the MRAM system creates more accurate parts, produces less material waste, and requires less processing time.

Author Contributions

R.L. offered the measurement system and helped in polishing the draft manuscript. All authors contributed to manuscript revision and read and approved the submitted version. C.-P.J. is the corresponding author and he conducted this study together with his PhD student M.F.R.M. S.-Y.L. is a DDS and DScD. He offered the complete denture model, resins, and opinions about how to compare the difference between the milled object and printed part. R. L. offers the measurement system and help to polish the draft manuscript.

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