THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Fracture resistance of additive manufactured and milled implant-supported interim crowns

Nuria Martín-Ortega, DDS,[a] Alessandro Sallorenzo, DDS,[b] Javier Casajús, PhD,[c] Alberto Cervera, DDS, MD,[d] Marta Revilla-León, DDS, MSD,[e] and Miguel Gómez-Polo, DDS, PhD[f]

ABSTRACT

Statement of problem. Interim dental prostheses can be fabricated by using subtractive or additive manufacturing technologies. However, the fracture resistance of implant-supported interim crowns fabricated by using vat-polymerization additive manufacturing methods remains unclear.

Purpose. The purpose of this in vitro study was to evaluate the fracture resistance of anterior and posterior screw-retained implant-supported interim crowns fabricated by using subtractive and vat-polymerization direct light processing (DLP) additive manufacturing procedures.

Material and methods. An implant (Zinic Implant RP ∅4.0×10 mm) was placed in a 15×15-mm polymethylmethacrylate block. An implant abutment (ZiaCam, nonrotatory RP) was positioned on each implant. The virtual implant abutment standard tessellation language (STL) file provided by the manufacturer was imported into a software program (Exocad v2.2 Valletta) to design 2 anatomic contour crowns, a maxillary right central incisor (anterior group) and a maxillary right premolar (posterior group). Each group was subdivided into 2 subgroups depending on the manufacturing method: milled (milled subgroup) and additive manufacturing (additive manufacturing subgroup). For the milled subgroup, an interim material (Vivodent CAD Multi) and a milling machine were used to fabricate all the specimens (N=40, n=10). For the additive manufacturing subgroup, a polymer interim material (SHERAprint-cb) and a DLP printer (SHERAprint 30) were used to manufacture all the specimens at a 50-μm layer thickness and 45-degree build orientation as per the manufacturer's instructions. Then, each specimen was cemented to an implant abutment by using composite resin cement (Multilink Hybrid Abutment HO) as per the manufacturer's instructions. A universal testing machine was used for fracture resistance analysis, and the failure mode was recorded. The Shapiro-Wilk test revealed that data were normally distributed. One-way ANOVA and Tukey multiple comparison were selected (α=.05).

Results. One-way ANOVA revealed significant differences among the groups (P<.05). The anterior milled subgroup obtained a significantly higher fracture resistance mean ±standard deviation value of 988.4 ±54.8 N compared with the anterior additive manufacturing subgroup of 636.5 ±277.1 N (P<.001), and the posterior milled subgroup obtained significantly higher mean ±standard deviation of 423.8 ±68 N than the additive manufacturing subgroup of 321.3 ±128.6 N (P=.048). All groups presented crown fracture without abutment fracture.

Conclusions. Manufacturing procedures and tooth type influenced the fracture resistance of screw-retained implant-supported interim crowns. Milled specimens obtained higher fracture resistance compared with the DLP additive manufacturing groups. The anterior group was higher than the posterior group. (J Prosthet Dent 2020;■:■-■)

Interim restorations are used to restore implants during and after osseointegration, providing esthetics, soft-tissue modeling, and restoring occlusion and function.[1-5] Implant-supported interim restorations should offer adequate mechanical and biocompatibility properties to facilitate the diagnosis and

[a]Graduate student, Advanced in Implant Prosthodontics, Department of Conservative Dentistry and Prosthodontics, School of Dentistry, Complutense University of Madrid, Madrid, Spain.
[b]Graduate student, Advanced in Implant Prosthodontics, Department of Conservative Dentistry and Prosthodontics, School of Dentistry, Complutense University of Madrid, Madrid, Spain.
[c]Assistant Professor of Signal Processing Applications Group, Department of Signals, Systems, and Telecommunications, Politécnica University of Madrid, Madrid, Spain.
[d]Guest Lecturer, Materials Engineering Department, Carlos III University of Madrid, Madrid, Spain.
[e]Assistant Professor and Assistant Program Director, AEGD Residency, Department of Comprehensive Dentistry, College of Dentistry, Texas A&M University, Dallas, Texas; and Affiliate Faculty Graduate Prosthodontics, Department of Restorative Dentistry, School of Dentistry, University of Washington, Seattle, Wash; and Researcher at Revilla Research Center, Madrid, Spain.
[f]Associate Professor and Program Director of Graduate in Advanced Implant Prosthodontics, Department of Conservative Dentistry and Prosthodontics, School of Dentistry, Complutense University of Madrid, Madrid, Spain.

Clinical Implications

Anterior implant-supported interim crowns can be manufactured either by using subtractive or additive manufacturing procedures; however, milling procedures produced stronger implant-supported interim crowns than the additively manufactured methods tested.

functional evaluation of the future definitive restoration.[6-8]

Different computer-aided manufacturing (CAM) methods have been developed to fabricate resin-based implant-supported interim prostheses, including subtractive and additive manufacturing (AM) technologies.[9-12] Vat-polymerization AM technologies for dental interim restorations include stereolithography (SLA), direct light processing (DLP), liquid-crystal display based (LCD), also called daylight polymer printing (DPP), and continuous liquid interface (CLIP).[9,10,13,14]

Manufacturing variables, including milling strategy,[15] computer numerical control (CNC) machine,[16] AM technology,[17,18] slicing procedures,[17,19] geometry[20,21] and color of the device,[22,23] build orientation,[17,19,21,24,25] position in the build platform,[17,26] layer thickness,[17,27] and postprocessing procedures,[19,26,28] influence the surface roughness,[27] manufacturing accuracy,[18,20,21,24] marginal and internal discrepancy,[25] and mechanical properties of the dental restoration.[17,19,26,28] Studies have analyzed the mechanical properties, including the fracture resistance of interim protheses fabricated by using milling and AM methods[19,25,29-34]; however, studies on the fracture resistance of an AM implant-supported interim crown are lacking.

The physiologic occlusal forces of natural dentition have been reported to range from 200 N to 900 N, with the maximum occlusal force in the anterior teeth ranging from 50 N to 223 N in women and from 190 N to 244 N in men.[35,36] In the posterior teeth, forces have been reported to range from 402 N to 650 N in women and from 490 N to 807 N in men.[35,37-41] The authors are aware of only 1 study analyzing forces in the premolar area, which reported a force ranging from 424 N to 583 N for men with a mean age of 31.1 years.[42] However, physiologic forces can be greater in patients with implant-supported restorations who have reduced proprioception[43,44] and in patients with parafunctional habits such as bruxism, where nocturnal forces may be as much as 790 N, a mean of 53.1% higher than the maximum diurnal forces considered habitual.[45] Therefore, interim implant-supported restorations should be able to withstand such increased forces.

Screw-retained implant-supported restorations enhance retrievability compared with cement-retained restorations, which facilitates the provision of interim restorations.[46-50] Furthermore, by using intraoral scanning devices, an implant-supported interim crown can be manufactured with a completely digital workflow.[51]

The purpose of this in vitro study was to compare the fracture resistance of screw-retained implant-supported interim anterior and posterior crowns manufactured by subtractive and DLP AM methods. The null hypotheses were that no significant difference would be found in fracture resistance between milled and AM screw-retained implant-supported interim crowns and that no significant differences would be found in fracture resistance between anterior and posterior screw-retained implant-supported interim crowns manufactured either by milling or DLP AM methods.

MATERIAL AND METHODS

Forty internal hexagonal connection implants (Zinic Implant RP ∅4.0×10 mm; Ziacom) were placed in custom 15×15-mm polymethylmethacrylate blocks with the implant shoulders located at the same level of the acrylic resin material to simulate the clinical bone level placement. An implant abutment (ZiaCam, nonrotatory RP; Ziacom) of 5 mm in height and with a 0.5-mm shoulder was positioned on each implant and tightened to 30 Ncm with a torque wrench (Tork70; Ziacom) as per the manufacturer's recommendations.

The virtual standard implant abutment (ZiaCam, nonrotatory RP; Ziacom) standard tessellation language (STL) file was provided by the manufacturer and imported into a CAD dental software program (Exocad v2.2 Valletta; Exocad GmbH) to design 2 different anatomic contour crowns, a maxillary right central incisor (anterior group) crown and a maxillary right premolar (posterior group) crown (Fig. 1).

In the anterior group, the virtual crown design included the ideal dimensions of a maxillary central incisor with a cervicoincisal dimension of 11 mm and a mesiodistal width of 9 mm. The screw-access hole was positioned in the center of the lingual surface without extending to the incisal edge of the crown. In the posterior group, the maxillary premolar crown had a cervico-occlusal dimension of 9 mm and a mesiodistal width of 7 mm. The screw-access hole was positioned in the center of the occlusal surface of the crown. In both groups, the virtual design of the crowns included a uniform die space of 50 μm, and the screw access holes had a standard diameter of 2.33 mm.

When the virtual crown designs were completed, 2 STL files were exported (STL_A and STL_P files). Each group was further subdivided into 2 subgroups

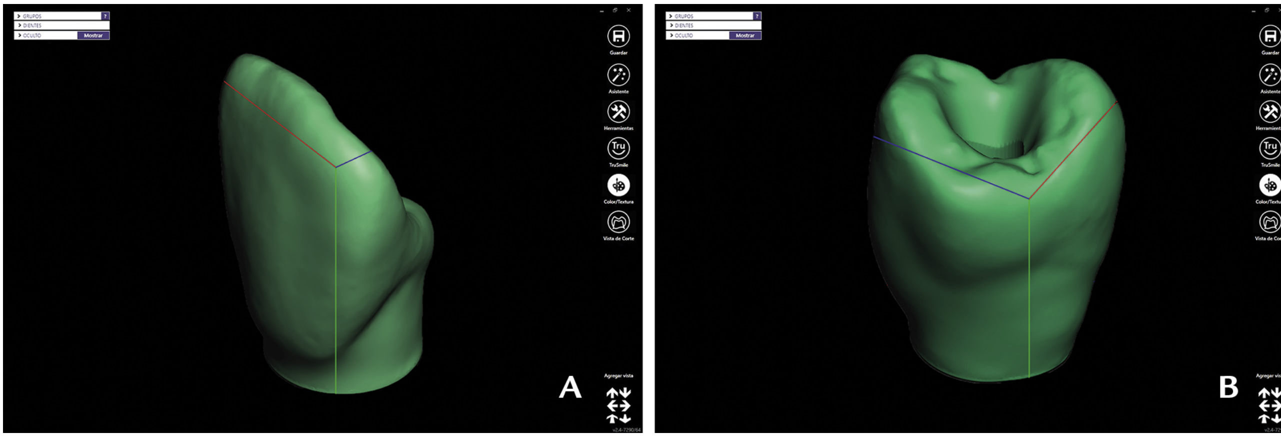

Figure 1. Anatomic contour crown virtual design. A, Anterior group. B, Posterior group.

Table 1. Manufacturing procedures completed for specimens

Group; Subgroup		Material	Manufacturing Method	Anatomic Contour Design
Anterior group	Milled subgroup	PMMA-based interim dental material (Vivodent CAD Multi; Ivoclar Vivadent AG)	5-axis milling machine (PrograMill CAM V4; Ivoclar Vivadent AG)	Maxillary right central incisor crown
	AM subgroup	Photopolymer interim dental resin (SHERAprint-cb; Shera)	Vat-polymerization DLP 3D printer (SHERAprint30; Shera)	Maxillary right premolar crown
Posterior group	Milled subgroup	PMMA-based interim dental material (Vivodent CAD Multi; Ivoclar Vivadent AG)	5-axis milling machine (PrograMill CAM V4; Ivoclar Vivadent AG)	Maxillary right central incisor crown
	AM subgroup	Photopolymer interim dental resin (SHERAprint-cb; Shera)	Vat-polymerization DLP 3D printer (SHERAprint30; Shera)	Maxillary right premolar crown

AM, additive manufacturing; DLP, direct light processing.

depending on the manufacturing method used to fabricate the specimens: milled (milled subgroup) and AM (AM subgroup) technologies (Table 1).

For the milled subgroup, the STL_A and STL_P files were imported into the milling machine software program (PrograMill CAM V4; Ivoclar Vivadent AG) to define the milling strategy, as well as the positions and supports of the specimens on the interim dental material block. A total of 10 PMMA-based interim (Vivodent CAD Multi; Ivoclar Vivadent AG) specimens for each group (anterior and posterior groups) were manufactured by using a 5-axis milling machine (PrograMill CAM V4; Ivoclar Vivadent AG). Subsequently, the specimens were trimmed from their supports and polished with low-speed polishing burs and disks (Kit ref. 4409; Komet) marketed for finishing interim dental restorations (Fig. 2).

For the AM subgroup, the STL_A and STL_P files were imported into the printer software program (Autodesk Netfabb Standard 2019.1; Autodesk) to slice the virtual designs and determine the printing parameters. A total of 10 virtual crown designs for each group (anterior and posterior groups) were positioned on the build platform by using the printer software program. A layer thickness of 50 μm and a 45-degree print orientation were determined. To standardize the manufacturing procedure, the printing parameters were adjusted as per the manufacturer's instructions, and all the specimens were fabricated at the same time. A polymer interim dental material (SHERAprint-cb; Shera) and a vat-polymerization DLP printer (SHERAprint 30; Shera) were used to manufacture the specimens of the AM subgroup. After printing, all the specimens were washed in an ultrasonic bath (Biosonic UC300; Coltène) of a 98% isopropyl alcohol solution (Shera Ultra-P; Shera), followed by a second bath in a clean isopropyl alcohol 98% solution. Subsequently, the specimens were placed inside a UV polymerizing unit (Shera Flash-Light Plus; Shera) for 25 minutes at 220 W for final polymerization as per the manufacturer's instructions. Then, the support material was trimmed, and the specimens were polished with the same protocols as for the milled subgroup (Fig. 2B, 2D).

A total of 40 screw-retained implant-supported interim crowns were fabricated (n=10). Each specimen was randomly assigned (by using a shuffled deck of cards) to a standard implant abutment-implant system prepared at the start of the experiment. Each specimen was evaluated for good adjustment to the implant abutment by using a profile projector with ×4 magnification (Xenoplan; Schneider). Successively, each specimen was cemented to the corresponding implant abutment (ZiaCam, nonrotatory RP; Ziacom) with an

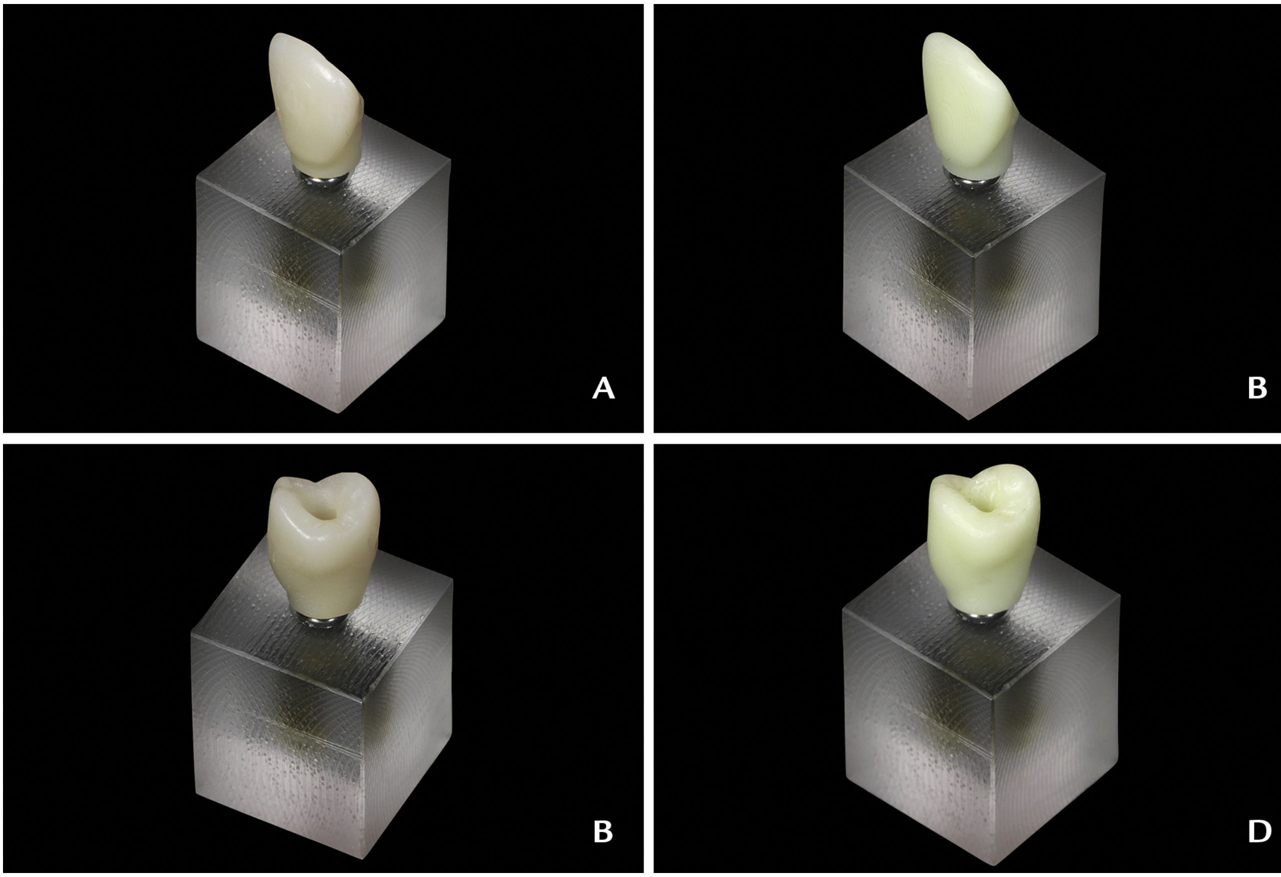

Figure 2. A, Milled specimen of anterior group. B, Additive manufactured specimen of anterior group. C, Milled specimen of posterior group. B, Additive manufactured specimen of posterior group.

autopolymerizing composite resin cement (Multilink Hybrid Abutment HO; Ivoclar Vivadent AG) as per the manufacturer's instructions. Previously, the implant abutment had been airborne-particle abraded at 0.2 MPa air pressure (Basic Quatro IS Renfert Neumatic Sandblaster; Renfert) with 50-µm aluminum oxide particles for 10 seconds at a 10-cm distance and cleaned with a steam jet cleaner (Steam Cleaner Model i702C Ea; Zhan Henry Schein). After the cementation procedures, the specimens were stored at 37 °C for 24 hours.

To simulate aging, the specimens were subjected to a thermocycling process (Thermocycler THE-1100; D-Sat) by following the International Organization for Standardization (ISO) 10477 standard: 52 5000 cycles (5 °C to 55 °C, 5 seconds for transfer and 30 seconds for dwell time) were run automatically.[52] All specimens completed the thermocycling procedures without observable cracks or debonding from the implant abutment.

A universal testing machine (BT1-FR2.5TS.D14; Zwick Roell) was used for the fracture resistance analysis. Force was applied with a 3-mm-diameter round tip at a specific point and load angle for each sample group: on the lingual face at 30 degrees from the implant axis in the anterior group and perpendicular to the implant axis in the posterior group (Fig. 3). A 0.2-mm sheet of tinfoil was placed between the specimens and the punch.[31,53] The load was applied at a speed of 1 mm/min until fracture occurred. The fracture loads were automatically registered in newtons (N) by the software program (TestXpert 2.1; Zwick Roell). After testing, the specimens were photographed for fracture mode and location analysis with classifications as follows: crown fracture without abutment fracture, crown fracture with abutment fracture, fracture of both crown and abutment, and screw fracture.

A Shapiro-Wilk test revealed that the data were normally distributed. One-way ANOVA and Tukey multiple comparison tests were selected to analyze the data (α=.05) by using a statistical software program (Matlab R2019b; MathWorks). An analysis of power for the 4 groups (n=10) ANOVA (F-statistics) was performed (G*power v.3.1; Universität Düsseldorf) for a normalized size of the effect of 0.5 (Cohen effect size), a power of 0.8, and 0.1 significance level.

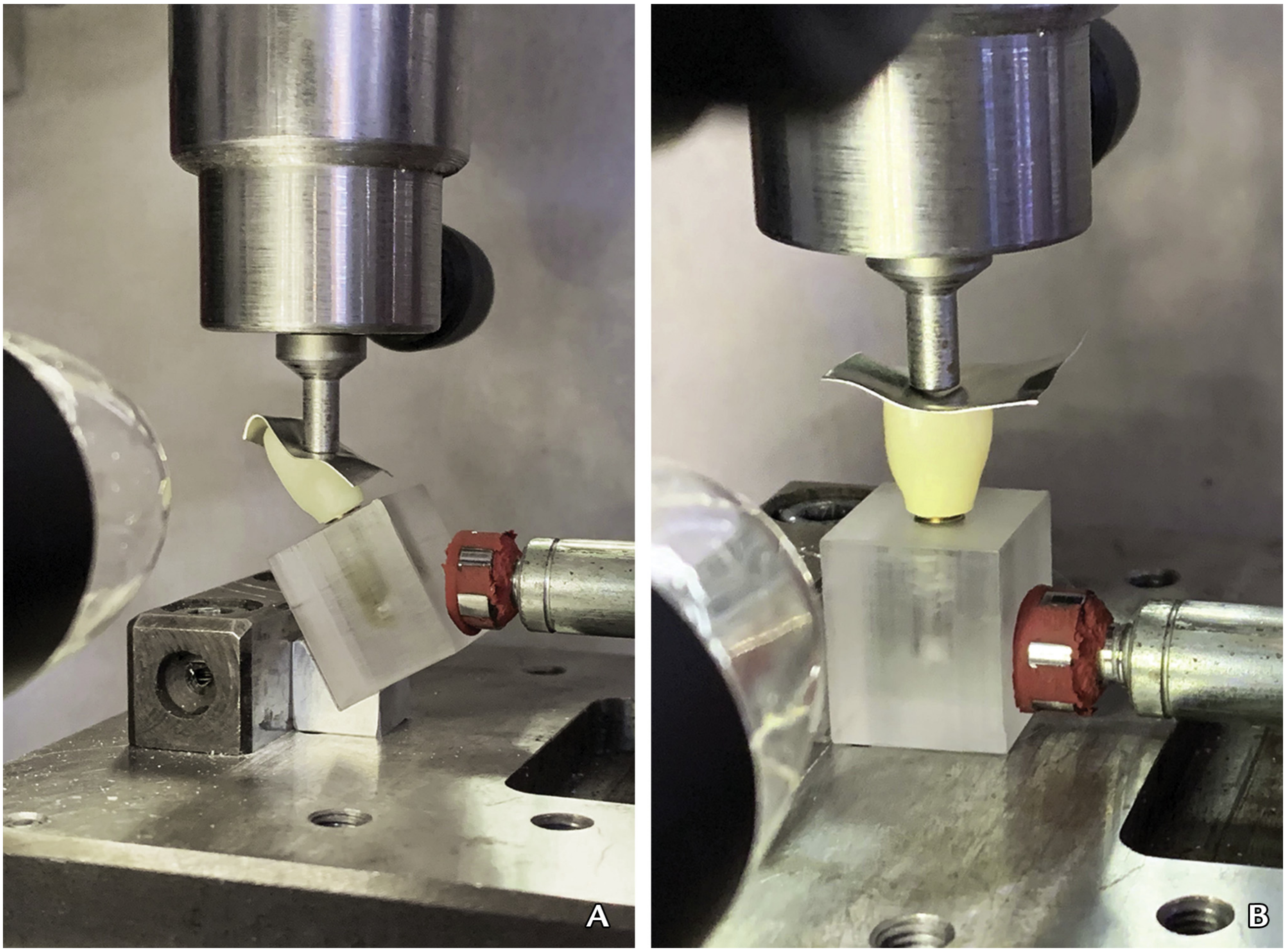

Figure 3. A, Anterior specimen under fracture load testing by using universal testing machine with load applied test application of force at angle of 30 degrees to implant axis. B, Posterior specimen with load force applied to central fossa of occlusal surface at angle of 90 degrees to implant axis.

RESULTS

For the anterior group, the milled subgroup had a fracture resistance mean ±standard deviation of 988.4 ±54.8 N and the AM subgroup had 636.5 ±277.1 N. For the posterior group, the milled subgroup obtained a fracture resistance mean ±standard deviation of 423.8 ±68.0 N and the AM subgroup obtained 321.3 ±128.6 N (Table 2).

One-way ANOVA test revealed significant mean value differences for fracture resistance among the groups ($P<.05$). The Tukey multiple comparison test showed that the anterior milled subgroup had a significantly higher fracture resistance mean value compared with the anterior AM subgroup ($P<.001$) and that the posterior milled subgroup had a significantly higher mean value compared with the AM subgroup ($P=.048$). The Tukey multiple comparison test showed that the anterior AM subgroup presented a significantly higher fracture resistance mean value than the posterior AM subgroup ($P<.001$) and that the anterior milled subgroup obtained a significantly higher mean value than the posterior milled subgroup ($P<.001$) (Fig. 4).

In both the anterior and posterior groups, all specimens had a crown fracture without abutment fracture. Furthermore, in all specimens, the screw or implant abutment were not fractured. The failure mode in the anterior group consisted of multiple fractures, splitting the crown into fragments (Fig. 5A). However, in the posterior group, the predominant failure pattern was a single longitudinal fracture from the central fossa, splitting the crown into 2 pieces (Fig. 5B).

DISCUSSION

Based on the results obtained in the present investigation, both null hypotheses were rejected, as significant differences in fracture resistance were found between the milled and AM specimens and for both manufacturing

Table 2. Fracture resistance values (N) for studied groups

Tooth Type	Subgroup	Mean	SD	Difference	CI (95%)	*P*
Anterior group	Milled	988.4	54.8	351.9	164.2-539.6	<.001*
	AM	636.5	277.1			
Posterior group	Milled	423.8	68.0	102.5	5.8-199.2	.048*
	AM	321.3				

Processing	Tooth type	Mean	SD	Difference	CI (95%)	*P*
AM	Anterior group	636.5	277.1	315.2	112.2-518.2	<.001*
	Posterior group	321.3	128.6			
Milled	Anterior group	988.4	54.8	564.6	506.6-622.6	<.001*
	Posterior group	423.8	68.0			

AM, additive manufacturing; CI, confidence interval; SD, standard deviation. *Significant difference (*P*<.05) using 1-way ANOVA and Tukey multiple comparison tests.

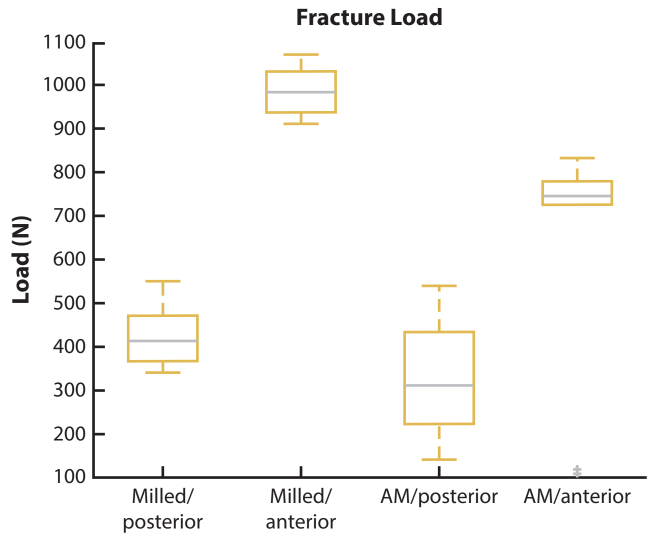

Figure 4. Box plot of fracture loads computed among groups tested. AM, Additive manufacturing.

methods. Significant differences in fracture resistance were also found between the anterior and posterior groups.

In the present study, the manufacturing procedures tested influenced the fracture resistance of screw-retained implant-supported interim crowns. The subtractive technique demonstrated significantly higher mean values for fracture resistance than the vat-polymerization AM method tested. The authors are unaware of a previous study evaluating the fracture resistance of AM implant-supported interim crowns; therefore, comparisons with previous data were not feasible.

Previous studies have demonstrated the influence of build orientation on the mechanical properties of an AM device.[33] Vertically printed specimens with the layers oriented perpendicular to the load direction have shown improved mechanical properties compared with those of horizontally printed specimens with the layers oriented parallel to the load direction. In the present study, all the specimens were manufactured at a 45-degree build orientation as per the manufacturer's recommendations. Further studies are needed to evaluate the mechanical properties, including fracture resistance, different printing parameters, and postprocessing procedures.

The anterior milled specimens had a fracture resistance 351.9 N higher than that of the anterior AM crowns, and the posterior group had lower fracture resistance differences between both manufacturing methods than for the anterior group. Similarly, the posterior milled specimens showed a fracture load 102.5 N higher than that of the posterior AM crowns. Establishing whether such fracture resistance differences are clinically significant is complex. Nevertheless, except for the AM posterior group, mean fracture load values were in the physiological clinical range.[35-44] Therefore, the AM implant-supported interim crowns for the anterior region might be expected to withstand physiological forces, but AM crowns in the posterior region could pose a higher risk of fracture. These results can be partly explained by the area and direction in which force was applied. In the present study, a different direction of the loading force was applied to replicate the clinical setting. The distance between the loading area and the underlying metal of the implant abutment might differ among the groups, and the use of tinfoil might have created variations on the loading area among the specimens. However, studies that evaluated the influence of the direction of force and the thickness of the material on the fracture resistance of interim implant-supported fixed dental prostheses are lacking. More studies evaluating this variable would therefore be advisable.

Differences in the fracture resistance of screw- and cement-retained implant-supported crowns have been reported.[48-51] In addition, different parameters have been identified as an influencing factor on the fracture resistance of dental crowns, for example, the mechanical properties of the selected restorative material, design and characteristics of the implant abutment interface, fracture load parameters, cement thickness, and cement type selected.[29,31,54-58] As the majority of those studies were performed on definitive restorative materials,[31,48-51,53-58] extrapolation of those results to both definitive and interim implant-supported restorations should be performed carefully. In the present study, only interim dental materials were tested, and the screw-access hole was designed with a standardized diameter. Moreover, the cement space provided in the digital restoration designs and the bonding technique was similar in the groups.

Limitations of the present investigation included the in vitro design, which might not reflect clinical conditions, the limited number of interim dental materials

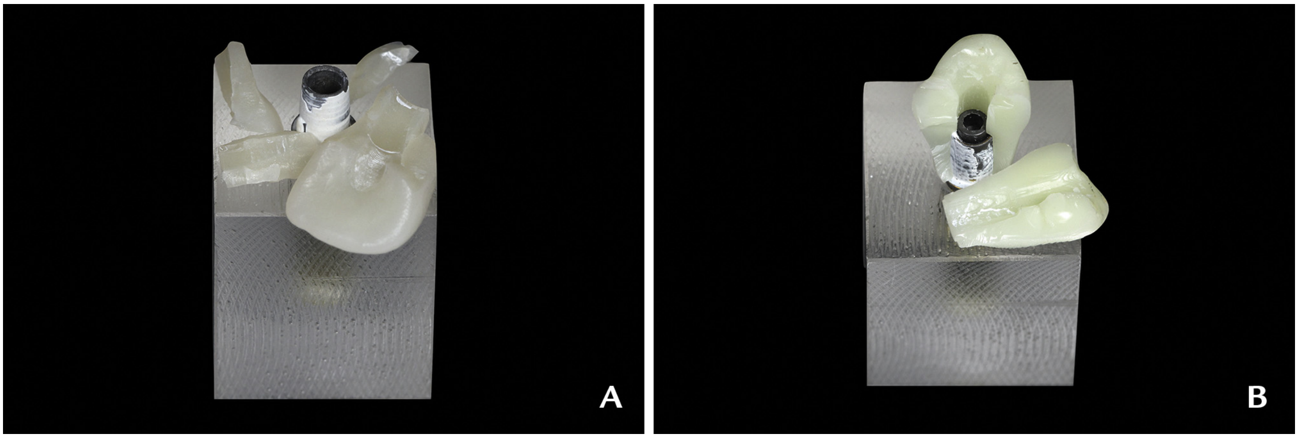

Figure 5. Failure mode that included fracture of interim crown with integrity of screw and implant abutment. A, Anterior specimen. B, Posterior specimen.

and manufacturing procedures tested, the restricted printing parameters and postprocessing procedures evaluated in the AM group, and the constrained implant restoration design. Further in vitro and clinical trials are recommended to broaden the analysis of the mechanical properties and include biocompatibility, color stability, and the repairability of implant-supported interim restorations manufactured by using AM procedures.

CONCLUSIONS

Based on the findings of this in vitro investigation, the following conclusions were drawn:

1. Manufacturing procedures and tooth type influenced the fracture resistance of screw-retained implant-supported interim crowns on internal-hexagonal connection implants.
2. Screw-retained implant-supported interim crowns manufactured with subtractive methods presented higher fracture resistance than those manufactured with vat-polymerized DLP AM methods.
3. The anterior group showed higher fracture resistance than the posterior specimens.

REFERENCES

1. Lewis S, Parel S, Faulkner R. Provisional implant-supported fixed restorations. Int J Oral Maxillofac Implants 1995;10:319-25.
2. Tarnow DP, Eskow RN. Preservation of implant esthetics: soft tissue and restorative considerations. J Esthet Dent 1996;8:12-9.
3. Gallucci GO, Belser UC, Bernard J-P, Magne P. Modeling and characterization of the CEJ for optimization of esthetic implant design. Int J Periodontics Restorative Dent 2004;24:19-29.
4. Priest G. Esthetic potential of single-implant provisional restorations: selection criteria of available alternatives. J Esthet Restor Dent 2006;18:326-38.
5. Gratton DG, Aquilino SA. Interim restorations. Dent Clin North Am 2004;48:487-97.
6. Krug RS. Temporary resin crowns and bridges. Dent Clin North Am 1975;19:313-20.
7. Miller SD. The anterior fixed provisional restoration: a direct method. J Prosthet Dent 1983;50:516-9.
8. Lowe RA. The art and science of provisionalization. Int J Periodontics Restorative Dent 1987;7:64-73.
9. Revilla-León M, Özcan M. Additive manufacturing technologies used for processing polymers: current status and potential application in prosthetic dentistry. J Prosthodont 2019;28:146-58.
10. Revilla-León M, Sadeghpour M, Özcan M. An update on applications of 3D printing technologies used for processing polymers used in implant dentistry. Odontology 2020;108:331-8.
11. Mainjot AK, Dupont NM, Oudkerk JC, Dewael TY, Sadoun MJ. From artisanal to CAD-CAM blocks: state of the art of indirect composites. J Dent Res 2016;95:487-95.
12. Beuer F, Schweiger J, Edelhoff D. Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. Br Dent J 2008;204:505-11.
13. Revilla-León M, Meyers MJ, Zandinejad A, Özcan M. A review on chemical composition, mechanical properties, and manufacturing work flow of additively manufactured current polymers for interim dental restorations. J Esthet Restor Dent 2019;31:51-7.
14. Alghazzawi TF. Advancements in CAD/CAM technology: options for practical implementation. J Prosthodont Res 2016;60:72-84.
15. Lebon N, Tapie L, Duret F, Attal JP. Understanding dental CAD/CAM for restorations-dental milling machines from a mechanical engineering viewpoint. Part A: chairside milling machines. Int J Comput Dent 2016;19:45-62.
16. Lebon N, Tapie L, Duret F, Attal JP. Understanding dental CAD/CAM for restorations-dental milling machines from a mechanical engineering viewpoint. Part B: labside milling machines. Int J Comput Dent 2016;19:115-34.
17. Puebla K, Arcaute K, Quintana R, Wicker RB. Effects of environmental conditions, aging, and build orientations on the mechanical properties of ASTM type I specimens manufactured via stereolithography. Rapid Prototyp J 2012;18:374-88.
18. Braian M, Jimbo R, Wennerberg A. Production tolerance of additive manufactured polymeric objects for clinical applications. Dent Mater 2016;32:853-61.
19. Reymus M, Fabritius R, Keßler A, Hickel R, Edelhoff D, Stawarczyk B. Fracture load of 3D-printed fixed dental prostheses compared with milled and conventionally fabricated ones: the impact of resin material, build direction, post-curing, and artificial aging-an in vitro study. Clin Oral Investig 2020;24:701-10.
20. Ide Y, Nayar S, Logan H, Gallagher B, Wolfaardt J. The effect of the angle of acuteness of additive manufactured models and the direction of printing on the dimensional fidelity: clinical implications. Odontology 2017;105:108-15.
21. Wu D, Zhao Z, Zhang Q, Qi HJ, Fang D. Mechanics of shape distortion of DLP 3D printed structures during UV post-curing. Soft Matter 2019;15:6151-9.
22. Ambosio L. Biomedical composites. Oxford Cambridge, New Delhi: Woodhead Publishing Limited; 2010. p. 33-5.
23. Revilla-León M, Umorin M, Özcan M, Piedra-Cascón W. Color dimensions of additive manufactured interim restorative dental material. J Prosthet Dent 2020;123:754-60.

24. Alharbi N, Osman RB, Wismeijer D. Factors influencing the dimensional accuracy of 3D-printed full-coverage dental restorations using stereolithography technology. Int J Prosthodont 2016;29:503-10.
25. Park GS, Kim SK, Heo SJ, Koak JY, Seo DG. Effects of printing parameters on the fit of implant-supported 3D printing resin prosthetics. Materials (Basel) 2019;12:25-33.
26. Unkovskiy A, Bui PH-B, Schille C, Geis-Gerstorfer J, Huettig F, Spintzyk S. Objects build orientation, positioning, and curing influence dimensional accuracy and flexural properties of stereolithographically printed resin. Dent Mater 2018;34:e324-33.
27. Arnold C, Monsees D, Hey J, Schweyen R. Surface quality of 3D-printed models as a function of various printing parameters. Materials (Basel) 2019;19:12.
28. Tahayeri A, Morgan M, Fugolin AP, Bompolaki D, Athirasala A, Pfeifer CS, et al. 3D printed versus conventionally cured provisional crown and bridge dental materials. Dent Mater 2018;34:192-200.
29. Zimmermann M, Ender A, Egli G, Özcan M, Mehl A. Fracture load of CAD/CAM-fabricated and 3D-printed composite crowns as a function of material thickness. Clin Oral Investig 2019;23:2777-84.
30. Alharbi N, Alharbi S, Cuijpers VMJI, Osman RB, Wismeijer D. Three-dimensional evaluation of marginal and internal fit of 3D-printed interim restorations fabricated on different finish line designs. J Prosthodont Res 2018;62:218-26.
31. Rosentritt M, Raab P, Hahnel S, Stöckle M, Preis V. In-vitro performance of CAD/CAM-fabricated implant-supported temporary crowns. Clin Oral Investig 2017;21:2581-7.
32. Digholkar S, Madhav VNV, Palaskar J. Evaluation of the flexural strength and microhardness of provisional crown and bridge materials fabricated by different methods. J Indian Prosthodont Soc 2016;16:328-34.
33. Alharbi N, Osman R, Wismeijer D. Effects of build direction on the mechanical properties of 3D-printed complete coverage interim dental restorations. J Prosthet Dent 2016;115:760-7.
34. Rayyan MM, Aboushelib M, Sayed NM, Ibrahim A, Jimbo R. Comparison of interim restorations fabricated by CAD/CAM with those fabricated manually. J Prosthet Dent 2015;114:414-9.
35. Kiliaridis S, Kjellberg H, Wenneberg B, Engström C. The relationship between maximal bite force, bite force endurance, and facial morphology during growth. A cross-sectional study. Acta Odontol Scand 1993;51:323-31.
36. Mao J, Osborn JW. Direction of a bite force determines the pattern of activity in jaw-closing muscles. J Dent Res 1994;73:1112-20.
37. Dean JS, Throckmorton GS, Ellis E 3rd, Sinn DP. A preliminary study of maximum voluntary bite force and jaw muscle efficiency in pre-orthognathic surgery patients. J Oral Maxillofac Surg 1992;50:1284-8.
38. Bakke M, Holm B, Jensen BL, Michler L, Möller E. Unilateral, isometric bite force in 8-68-year-old women and men related to occlusal factors. Scand J Dent Res 1990;98:149-58.
39. Varga S, Spalj S, Lapter Varga M, Anic Milosevic S, Mestrovic S, Slaj M. Maximum voluntary molar bite force in subjects with normal occlusion. Eur J Orthod 2011;33:427-33.
40. Ferrario VF, Sforza C, Zanotti G, Tartaglia GM. Maximal bite forces in healthy young adults as predicted by surface electromyography. J Dent 2004;32:451-7.
41. Braun S, Bantleon HP, Hnat WP, Freudenthaler JW, Marcotte MR, Johnson BE. A study of bite force, part 1: relationship to various physical characteristics. Angle Orthod 1995;65:367-72.
42. Van Eijden TM. Three-dimensional analyses of human bite-force magnitude and moment. Arch Oral Biol 1991;36:535-9.
43. Trulsson M, Gunne HS. Food-holding and -biting behavior in human subjects lacking periodontal receptors. J Dent Res 1998;77:574-82.
44. Fontijn-Tekamp FA, Slagter AP, Van Der Bilt A, Van 'T Hof MA, Witter DJ, Kalk W, et al. Biting and chewing in overdentures, full dentures, and natural dentitions. J Dent Res 2000;79:1519-24.
45. Nishigawa K, Bando E, Nakano M. Quantitative study of bite force during sleep associated bruxism. J Oral Rehabil 2001;28:485-91.
46. Silva GC, Cornacchia TM, de Magalhães CS, Bueno AC, Moreira AN. Biomechanical evaluation of screw- and cement-retained implant-supported prostheses: a nonlinear finite element analysis. J Prosthet Dent 2014;112:1479-88.
47. Wittneben J, Millen C, Bern U. Clinical performance of screw- versus cement-retained reconstructions - a systematic review. Int J Oral Maxillofac Implants 2014;29:84-98.
48. Kim WD, Jacobson Z, Nathanson D. In vitro stress analyses of dental implants supporting screw-retained and cement- retained prostheses. Implant Dent 1999;8:141-51.
49. Pietrabissa R, Gionso L, Quaglini V, Di Martino E, Simion M. An in vitro study on compensation of mismatch of screw versus cement-retained implant supported fixed prostheses. Clin Oral Implants Res 2000;11:448-57.
50. Kelly JR. Perspectives on strength. Dent Mater 1995;11:103-10.
51. McGlumphy EA, Papazoglou E, Riley RL. The combination implant crown: a cement- and screw-retained restoration. Compendium 1992;13. 34, 36, 38 passim.
52. International Organization for Standardization. ISO 10477:2018. Dentistry. Polymer-based crown and veneering materials. Geneva: International Organization for Standardization; 2018. Available at: https://www.iso.org/standard/68235.html.
53. Albrecht T, Kirsten A, Kappert HF, Fischer H. Fracture load of different crown systems on zirconia implant abutments. Dent Mater 2011;27:298-303.
54. Krejci I, Reich T, Lutz F, Albertoni M. An in vitro test procedure for evaluating dental restoration systems. A computer-controlled mastication simulator. Schweiz Monatsschr Zahnmed 1990;100:953-60.
55. Guess PC, Schultheis S, Wolkewitz M, Zhang Y, Strub JR. Influence of preparation design and ceramic thicknesses on fracture resistance and failure modes of premolar partial coverage restorations. J Prosthet Dent 2013;110:264-73.
56. De Kok P, Kleverlaan CJ, De Jager N, Kuijs R, Feilzer AJ. Mechanical performance of implant-supported posterior crowns. J Prosthet Dent 2015;114:59-66.
57. Keul C, Müller-Hahl M, Eichberger M, Liebermann A, Roos M, Edelhoff D, et al. Impact of different adhesives on work of adhesion between CAD/CAM polymers and resin composite cements. J Dent 2014;42:1105-14.
58. Bähr N, Keul C, Edelhoff D, Eichberger M, Roos M, Gernet W, et al. Effect of different adhesives combined with two resin composite cements on shear bond strength to polymeric CAD/CAM materials. Dent Mater J 2013;32:492-501.

Corresponding author:
Dr Marta Revilla-León
3302 Gaston Ave, Room 713
Dallas, TX 75246
Email: revillaleon@tamu.edu

Acknowledgments
The authors thank Mr Lorenzo del Río for help and support with the design and manufacturing of the specimens.

https://doi.org/10.1016/j.prosdent.2020.11.017