European Journal of Prosthodontics and Restorative Dentistry (2024) **32**, 9–19

Zirconia Implants Produced by Additive Manufacturing - A Scoping Review

Keywords

3D Printing
Additive Manufacturing (AM)
Rapid Prototyping
Dental Zirconia

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Received: 19.01.2023
Accepted: 18.06.2023

doi: 10.1922/EJPRD_2513Kreve11

ABSTRACT

Introduction: Additive manufacturing is a tool with potential use in medicine and dentistry. The manufacture of metals and composites is already advanced, however, concerns about titanium hypersensitivity, tissue staining, and corrosion caused by gradual material degradation encourage research into more biocompatible alternatives. Objective: This systematic scoping review aimed to gather studies that evaluated zirconia implants produced by additive manufacturing to describe the current stage of the printing technique and the final product. Methods: Searches in Embase, PubMed, SCOPUS, Web of Science, and Google Scholar databases were enriched with manual searches between February and March 2021 and updated in June 2022 using keywords: zirconium implants, zirconium oxide, additive manufacturing, rapid prototyping, 3D printing, selective laser melting, and electron beam melting. The criteria included studies that evaluated or described zirconia implants obtained by 3D printing, with a direct relationship to dentistry or orthopedics. Results: The database search resulted in 671 articles. Eight articles were selected for full reading and remained in this systematic review. Conclusion: The printing technique for zirconia implants is promising. However, further studies are required before implants produced by the printing technique can be tested clinically. The literature with results regarding the impression product is still limited.

INTRODUCTION

The first generation of ceramic implants was developed to overcome the problems of metallic implants, such as ion release, allergy, color, and oxidation.[1-4] However, these ceramics implants, consisting mainly of systems containing aluminum oxide, showed unsatisfactory mechanical properties.[3] Thus, they were replaced by tetragonal zirconia polycrystals containing aluminum oxide (Al_2O_3) and some additives such as yttria and ceria.[1,5-8] These additives enable the generation of a multiphase material with molecular stability and improved mechanical performance. In other words, zirconia has excellent properties thanks to a phenomenon called phase transformation hardening.[3,9] This phenomenon prevents the propagation of cracks resulting from the transformation of zirconia from a tetragonal to a monoclinic phase. Such phase transformation generates 3-5% volume expansion and induction of compressive stresses.[9] Zirconia has three crystallographic forms, monoclinic (reduced mechanical performance), cubic (moderate mechanical properties), and tetragonal (improved mechanical properties).[3,8] Stabilization of the monoclinic phase occurs at room temperature, and the cubic and tetragonal phases occur at elevated temperatures.[8,9] Whereas pure zirconia is monoclinic at room temperature, by mixing it with additives such as yttria and ceria, it is possible to stabilize the tetragonal or cubic phase at room temperature and achieve better mechanical

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properties.[3,8] Alumina-hardened zirconia combines the high wear resistance and hardness of alumina with the high mechanical strength of zirconia.[6]

Zirconia has high mechanical properties, making it an acceptable material for implant manufacturing.[1,3,5,9-11] In addition, it is a bioinert material and has chemical stability and optical properties that allow it to mimic the color and translucency of natural teeth.[1,8] Currently, zirconia implants are produced by milling, and these offer limited options regarding design, length, diameter, and emergence profile.[12] Moreover, failures such as pores and microcracks are often reported, which can be of chemical or mechanical origin.[9,12,13] Such failures can be the result of imperfections in the manufacturing process since the subtractive methodology hinders the production of parts with complex internal details.[10] In addition, the presence of concentration stress areas can increase the probability of crack propagation, and also low-temperature degradation (LTD), which occurs due to a slow transformation of the crystal surface from the tetragonal phase to the monoclinic phase in the presence of water or water vapor.[9,12]

The zirconia implants are fabricated by injection molding technique, and it needs additional surface treatments.[14,15] However, Branco *et al.*,[10] states the conventional subtractive manufacturing technique has milling units with restrictions on angulations making it difficult to produce details.[10] It has waste of raw material, high energy consumption, delays in manufacturing complex parts, design changes that can only be implemented and performed in a labor-intensive and time-consuming way, and high cost.[10,16,17] In addition, micro-cracks are present in zirconia milling.[18]

In order to overcome these drawbacks, a tool with great potential for use in medicine and dentistry is additive manufacturing, which has become popular in different segments such as aeronautics, automotive industry, electronics, and arts.[19-22] Its main advantages include mass production, easy reproduction of complex geometries, reduced manufacturing time, and less raw material waste.[10,18]

In dentistry, additive manufacturing of metals and composites including casts,[23] prosthetic crowns,[24] copings,[2] surgical guide,[26] prosthetic frameworks, and components is advanced and even commercially available.[27] However, additive manufacturing of implants, especially zirconia implants, is still in its infancy.[28,29]

Different zirconia products were successfully printed as specimens,[6,10,16,19] dental prosthetics,[30,31] and among others, teeth or crowns.[10,22,32-35] The literature shows that the impression of dental implants[2,11,28-30] and orthopedics[36] has been realized, but remains in the testing phase raising the need for continued scientific development.

Custom implants can reduce some of these failures due to the difference in the manufacturing process. And also, they allow the solution of clinical cases that present anatomical conditions of bone height and thickness unfavorable to the use of conventional subtractive manufacturing implants.[28]

Considering the above, the aim of this scoping review was to gather studies that evaluated zirconia implants produced by additive manufacturing in order to describe the current state-of-the-art and the final product.

MATERIALS AND METHODS

PROTOCOL

This scoping review was structured according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist and the JBI Briggs Reviewers Manual in order to answer the following question: What is the current status of additive manufacturing techniques for zirconia implants? The protocol was registered in the Open Science Framework (https://osf.io/4zv5w/).

ELECTRONIC SEARCH

Five databases (SCOPUS, PubMed/Medline, EMBASE, Web of Science, and Google Scholar) were searched using the following keywords: “zirconium implants,” “zirconium oxide,” “additive manufacturing,” “rapid prototyping,” “3D printing,” “selective laser fusion,” and “electron beam fusion.” The literature review was conducted between February and March 2021 and updated in Jun 2022. It was included all relevant papers published from 1900 to 2022.

The population, intervention, comparison, outcomes, and study designs (PICOS) for this scoping review are defined in Table 1.

Table 1. PICOS

PICOS	Description
Participants	Zirconium implants
Interventions	Produced by additive manufacture
Comparisons	Not applicable
Outcomes	Current state-of-the-art
Study designs	In vitro studies

DATA CHARTING PROCESS AND SCREENING PROCESS

The articles found in the initial literature search were uploaded to the Rayyan software and screened separately by two independent reviewers (S.K and I.F), responsible for reading the titles and abstracts and discarding the studies unrelated to the subject according to the established inclusion and exclusion criteria. The remaining studies were completely read.

Possible disagreements were solved by a discussion with the third reviewer (A.C.R). Data extracted from included papers were registered independently by two researchers (S.K and I.F), tabulating data of interest in a Microsoft Excel.

ELIGIBILITY

We included articles written in English that evaluated or described zirconia implants obtained by 3D printing, with a direct relationship to dentistry or orthopedics.

Articles that described only a particular additive manufacturing technique or tested characteristics of the powders used for printing, who printed specimens instead of implants, literature reviews, unpublished data, reviews, letters to the editor, and personal communications were excluded.

RISK OF BIAS WITHIN STUDIES

The quality and risk for bias of the included studies were assessed by the quasi-experimental studies appraisal tool by the Joanna Briggs Institute.[37] Each study was classified as low risk (bias, if present, is unlikely to alter the results seriously), unclear risk (a risk of bias that raises some doubt about the results, or high risk (bias may alter the results seriously).

RESULTS

SEARCH AND SELECTION

Figure 1 shows the procedure for the study selection. A total of 671 studies were identified in the initial screening. Following the PRISMA statement for scoping reviews, all abstracts were reviewed. After duplicates exclusion and applying the inclusion criteria, 8 articles were selected for a full-text reading and included in the qualitative synthesis.[2,11,28,29,36,38-40]

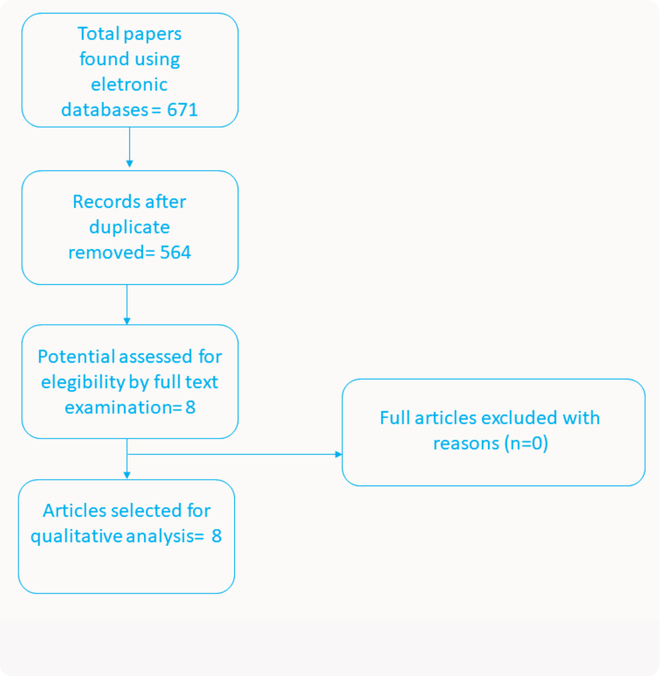


Figure 1: Flow diagram of literature search and selection criteria.

STUDY CHARACTERISTICS

Table 2 provides information about the included studies. Their publication years ranged from 2015 to 2022.

Regarding the type of specimens, of the 8 articles included, 6 of them produced zirconia dental implants.[11,28,29,38-40] Anssari Moin *et al.*,[2] produced a zirconia root analogue implant, and Zhu *et al.*,[36] printed a zirconia rabbit's femur.

PRINTING TECHNIQUES

Different 3D printing techniques were observed in the selected studies. Digital light processing (DLP) consists of a photochemical reaction in which a photosensitive liquid polymer is cured while the model is built layer by layer. This method that was used by Osman *et al.*,[28] Anssari Moin *et al.*,[2] and Zhang *et al.*[39] Three-dimensional Slurry Printing (3DSP) uses a digital light projector to project the pattern of layers onto the photocurable paste to form the green parts. This method was used by Cheng *et al.*[11] and Lee & Jiang.[29] Liytography-based method was used by Kim *et al.*,[38] Zhang *et al.*,[40] meanwhile, performed the Nano-particle ink-jetting method that consists of selective deposition of droplets employing small diameter injectors at 0° angulation. And Zhu *et al.*,[36] did not specify which technique was used to print the implants.

IMPLANT TYPES, MATERIAL USED AND SINTERING

Implants were printed with different types of zirconia depending on the study, with TZ-3YS used by Osman *et al.*;[28] EZU3YA-1 by Cheng *et al.*,[11] and Lee & Jiang;[29] 3Y-ZrO$_2$ by Zhu *et al.*;[36] ZrO$_2$ by Anssari Moin *et al.*,[2] 3Y-TZP by Kim *et al.*,[38] ZrO$_2$(3Y)Al$_2$O$_3$ by Zhang *et al.*,[39] and 45 wt.% zirconia powder and 31 wt.% sodium carbonate by Zhang *et al.*[40] The implants printed by Osman *et al.*,[28] Cheng *et al.*,[11] Lee & Jiang,[29] Kim *et al.*,[38] Zhang *et al.*,[39] and Zhang *et al.*,[40] were dental implants. Anssari Moin *et al.*[2] printed a tooth root analogue, and Zhu *et al.*[36] performed hip joint implant printing.

The sintering methods of the ceramics were divergent among the studies, so that Cheng *et al.*,[11] Zhu *et al.*,[36] and Lee & Jiang[29] perform the sintering in two stages, aiming to avoid microcracks formation, with stable microstructure in tetragonal phase and better mechanical properties. Osman *et al.*,[28] in turn, carried out the sintering process in one step with a maximum temperature of 1500°C. Zhang *et al.*[39] tested different sintering times and temperatures, being 20ºC -1200ºC (3ºC/min) for 2.5h, 1200ºC -1550ºC (1ºC/min) for 3h, 1600ºC - 1650ºC (1ºC/min) for 3h and 1600ºC - 1650ºC (1ºC/min) for 1.5h. Kim *et al.*[38] and Anssari Moin *et al.*[2] do not report which sintering process was used in their study. Zhang *et al.*[40] carried out the Archimedes sintering method which consists of the absence of atmospheric pressure at 1450ºC for 2h and a cooling rate of 5ºC/min in a chamber furnace.

Table 2. Summary of studies included.

Study/ Year	Objective	Specimen type	Tests performed	Main conclusions
Osman et al.,	To evaluate dimensional accuracy, surface topography of a custom-designed, 3D-printed zirconia dental implant and mechanical properties of printed zirconia discs	Zirconia dental implant; zirconia discs	Dimensional accuracy; Biaxial flexure strength; SEM and surface roughness; X-ray diffractometer	DLP proved to be efficient for printing customized zirconia dental implants with sufficient dimensional accuracy; The mechanical properties showed flexure strength close to those of conventionally produced ceramics.
Cheng et al.,	To propose a 3-dimensional printing fabrication of zirconia ceramic implant, and the mechanical properties and microstructure of sintered implant were evaluated.	Zirconia dental implant	Three-point bending test; Hardness; Scanning electron microscopy	A 3DSP is successfully applied to fabricate the green body of the obtained model, but the accuracy of the sintered part still needs to be improved.
Zhu et al.,	To get a zirconia ceramic joint implant with precise 3D structure and effective antibacterial properties	Zirconia rabbits' femur	Tensile tests; bending tests; compression tests; antibacterial properties; histological analysis; Cytotoxicity assay; biocompatibility	The ceramic 3D printing technology combined with antibacterial nano-modification can quickly customize the ideal implant material with precise structure, wear-resistant and effective antibacterial properties.
Anssari et al.,	To explore the feasibility of fabrication of three-dimensional (3D)-printed zirconia root analog implant (RAI) through digital light processing (DLP) technology.	Zirconia root analog implant	Optical scanning	With the use of currently available technology, it is feasible to 3D print in zirconia a custom RAI.
Lee & Jiang	Develop a 3D printing system slurry printing (3DSP) in the printing of zirconia implants through two steps of a sintering process.	Zirconia dental implant and simple benchmark.	Flexural strength, micro-hardnes, density, emission scanning electron microscope (SEM), and energy dispersive spectrometer (EDS).	Success has been achieved in the production of zirconia implants by the 3DSP system, and these implants consist of fine features and good mechanical properties.
Kim et al.,	To evaluate the in vivo bone response to an additively manufactured zirconia surface	Zirconia dental implant	Scanning electron microscopy; electron spectroscopy for chemical analysis; confocal laser scanning microscopy (roughness).	Additively manufactured zirconia ceramic implants are biocompatible. However, the surface was inferior to that of the SLA titanium implants.
Zhang et al.,	To evaluate the effects of different heat treatment processes on the forming quality, precision, and mechanical properties of ZrO_2 (3Y)/ Al_2O_3. Additionally, to evaluate the tribological and biological properties.	Zirconium sample and dental implant	Flexural strength; fracture toughness; hardness; Wear resistence	The sintering temperature and holding time at 1600°C and 3h promoted higher hardness, flexural strength, and Vickers fracture toughness due to the particles being in close contact and relative density at 98.79%.
Zhang et al.,	To analyze 3D printed zirconia implants for mechanical properties, relationship to structures, aging and cellular response.	Zirconia dental implant	X-ray micro-computed tomography, SEM, load-to-failure test, thermcycling, mechanical cycling loading, fatigue test.	The zirconia implants obtained by additive manufacturing showed high long-term mechanical strength thanks to the dense core along with the compressive stress.

MECHANICAL AND PHYSICAL TESTS

The selected studies performed different mechanical and physical tests in order to verify the behavior of the printed implants. Osman *et al.*[28] performed the impression of implants with angulations of 0° (horizontal), 45° and 90° (*Figure 2*). The authors found that flexural strength was greatest at the 0° angulation and SEM revealed the presence of microcracks, pores and interconnected pores. The microporosities of the specimens ranged in size from 196 nm to 3.3 µm.

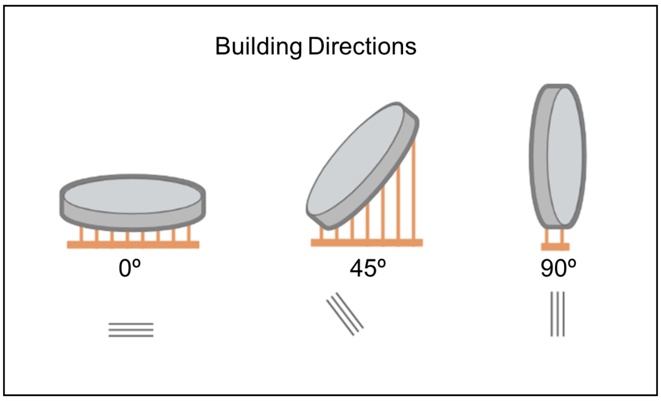


Figure 2: Graphical abstract representing specimen building directions.

Cheng *et al.*,[11] evaluated the flexural strength, Vickers hardness and performed SEM. The authors observed high flexural strength and low hardness values in the green parts. The tetragonal phase of the sintered portion showed high hardness. SEM demonstrated that the zirconia grains have an average diameter of 110 nm, which represents a typical microstructure in the tetragonal phase. This indicates that the 2-stage sintering process can produce a stable microstructure without microcracks. These analyses were also performed by Lee & Jiang[29] who obtained high flexural strength and hardness. SEM showed that zirconia particles and green part binder can be clearly observed. However, no binder is seen after two-stage sintering. The EDS test revealed only the zirconia and oxygen elements, which indicates that the binder has been completely burned out.

Zhu *et al.*[36] evaluated the mechanical properties and found that OZn addition to zirconia for additive manufacturing implants did not affect the compressive, flexural, and tensile properties.

Anssari Moin *et al.*,[2] developed analogues of printed tooth roots and performed optical scanning to compare the analog, the natural tooth, and the CAD-CAM printed model. The authors observed greater disparity for the 3D DLP printed analog compared to the original tooth, with a maximum deviation (Hausdorff distance) of 0.86 mm.

Kim *et al.*[38] performed a surface characterization of zirconia implants obtained by additive manufacturing and compared them to titanium (Ti) implants obtained by SLA or turned. The authors observed microcracks, porosities, and the interconnection of pores on the zirconia surface, diverging from Ti, which had a smooth and polished surface. Higher surface roughness values were seen for zirconia (0.54 µm) and Ti-SLA (0.65 µm) implants compared to Ti-turned (0.27 µm).

Zhang *et al.*[39] analyzed sintered implants with different times and temperatures and observed that the combination 1600ºC for 3 h showed higher Vickers hardness (13.5 GPa) and higher compressive strength values (1935 MPa). When they evaluated the flexural and fracture strengths, it was seen that for the 1220ºC-1600ºC groups and times of 1.5 h and 3 h, as the temperature increased, the flexural and fracture strengths increased. However, very high temperatures (1650ºC) caused a flexural and fracture strength drop.

Zhang *et al.*[40] performed a microstructure analysis and confirmed the presence of a porous layer on the implant surface but no imperfections below this layer. The microstructure of the zirconia implant obtained by 3D printing was similar to that found in typical zirconia, with micrometric grains in equal axes. It showed fracture loading strength of 516±39 N and flexural strength of 284±39 Ncm fitting the prerequisites for clinical application. After fatigue, the flexural strength was unchanged, suggesting high long-term mechanical strength.

RISK OF BIAS

The results of the quality evaluation of the studies are summarized in figures 3 and 4. The risk of bias was evaluated with the use of an adapted quasi-experimental studies appraisal tool by the Joanna Briggs Institute. Of the eight studies included in this scoping review, most showed a low risk of bias. The exception was for the criterion “Were outcomes measured in a reliable way?” where approximately 75% of the studies showed a high risk of bias. This result can be explained as these studies did not mention the number of raters, training of raters, the intra-rater reliability, and the inter-rater reliability within the study, so they were classified as high risk of bias.

Some studies[11,28] presented a high risk of bias in the criterion “Was there a control group?” because they had no control group, just compared groups.

DISCUSSION

This scoping review aimed to describe the current stage of the zirconia implant printing technique. In this regard, it is worth discussing impression techniques, the surface quality of the printed implant, dimensional accuracy, and mechanical properties of the final product.

IMPRESSION TECHNIQUES

The studies selected for this scoping review have used different printing techniques Osman *et al.*,[28] Anssari Moin *et al.*,[2] Kim *et al.*,[38] Zhang *et al.*,[39] Lee & Jiang[29] and Cheng *et al.*,[11] used vat photopolymerization (VPP) technology in one of its different forms, such as digital light processing (DLP),[2,28] StereoLithogrAphy

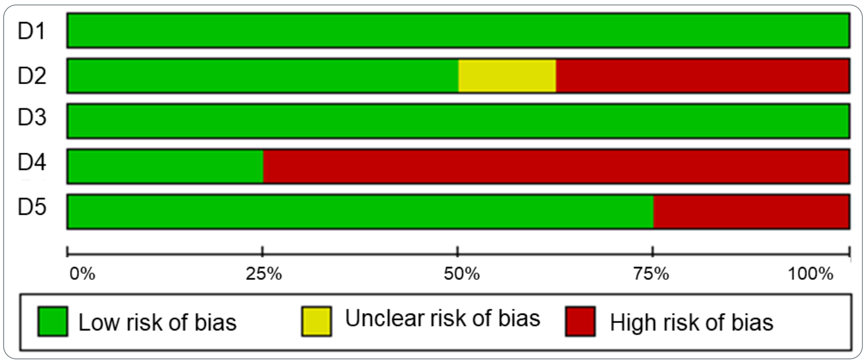
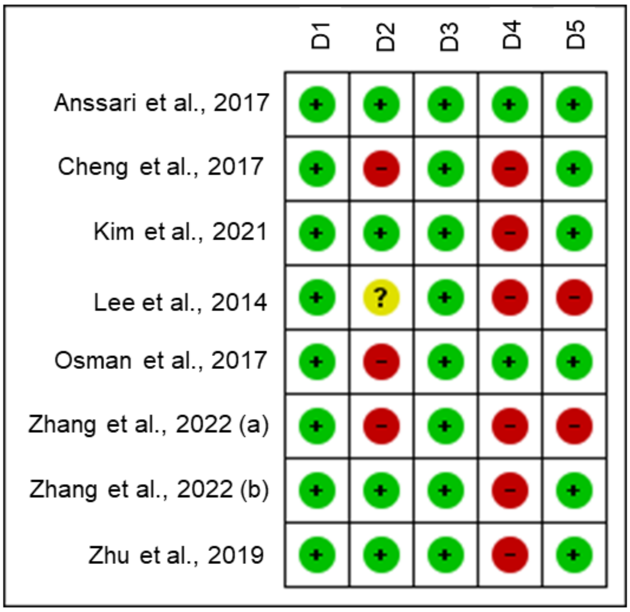


Figure 3: Qualitative analysis with adapted the quasi-experimental studies appraisal tool by the Joanna Briggs Institute. Legend: D1-Is it clear in the study what is the 'cause' and what is the 'effect'; D2- Was there a control group?; D3- Were the outcomes of participants included in any comparisons measured in the same way?; D4- Were outcomes measured in a reliable way?; D5- Was appropriate statistical analysis used?



	D1	D2	D3	D4	D5
Anssari et al., 2017	+	+	+	+	+
Cheng et al., 2017	+	−	+	−	+
Kim et al., 2021	+	+	+	−	+
Lee et al., 2014	+	?	+	−	−
Osman et al., 2017	+	−	+	+	+
Zhang et al., 2022 (a)	+	−	+	−	−
Zhang et al., 2022 (b)	+	+	+	−	+
Zhu et al., 2019	+	+	+	−	+

Figure 4: Quantitative analysis with adapted the quasi-experimental studies appraisal tool by the Joanna Briggs Institute per studies. Legend: D1-Is it clear in the study what is the 'cause' and what is the 'effect'; D2- Was there a control group?; D3- Were the outcomes of participants included in any comparisons measured in the same way?; D4- Were outcomes measured in a reliable way?; D5- Was appropriate statistical analysis used?

(SLA),[38] and a 3-dimensional slurry printing system (3DSP).[11,29] VPP is one of the first forms of 3D printing and consists of light-curing a liquid resin inside a vat. This resin can be filled with ceramic particles.[11,16,39] In this technology, formed parts made using photosensitive polymer slurry are cured by light projection layer by layer, and then the organic components are removed by a degreasing treatment.[39] Each of the forms of VPP has been developed due to the introduction of new materials and improvements in material properties. The DLP system allows the fabrication of ceramics with high levels of detail and precision and provides a good surface finish.[16,41] It is also faster compared to SLA, as the entire layer is exposed to light at once, unlike SLA where only one laser spot is used. The disadvantages of DLP are the long manufacturing time and the high volumetric shrinkage rate resulting from the firing of the binder during sintering.[11] Osman *et al.*,[28] observed difficulty in attaching subsequent layers when fabricating 45° angled specimens, however, the authors do not address the reason for this. Zirconia manufactured by this method has added polymeric particles, and it is a common consensus that all layer impressions feature pre-curing of the subsequent layer, thus the adhesion of the future layer may be compromised.[42,43] Further studies are needed to justify this phenomenon. Lee & Jiang,[29] and Cheng *et al.*,[11] used the 3-dimensional slurry printing system (3DSP). This system uses a digital light projector to project the layers onto the light-curing slurry to form the green parts. This technique provides higher precision and faster manufacturing speed compared to an SLA system, as it uses the layer exposure method instead of laser scanning.[11] According to Lee & Jiang[29] the main advantage of this method is that the total green block fabrication time is much shorter than for laser scanning.

Zhang *et al.*,[40] used the material jetting technique. This technology uses a ceramic suspension to build structures by the successive deposition of individual drops of a ceramic dispersed in a thermoplastic material, delivered through a piezoelectric nozzle/printing head.[45,46] The printing heads pass over the build area in the XY plane and deposit particles containing zirconium ink in small droplets.[40] According to Zhang *et al.*,[40] this technique requires a low viscosity for printing, and the printing directions influence the success rate. Also, it offers the possibility to generate dense green bodies, is economical with minimal material waste, and has high flexibility and a short lead time.[31] However, it still faces the problem of nozzle clogging, breakage and thinning of the printed filament.[41]

The ASTM[44] has classified seven different technologies for additive manufacturing, however, not all of them can be used for printing ceramics.[33] The main techniques available for zirconia printing are stereolithography/digital light processing (SLA/DLP), material extrusion, selective laser sintering (SLS), and selective laser melting (SLM) technologies from the powder bed fusion technologies family, like direct deposition printing/jetting.[2,29,33,40,45,46] Not all available techniques for zirconia impression were found in the studies included in this scoping review.

SURFACE QUALITY OF THE PRINTED IMPLANT

Regarding the surface quality of the printed implant, Cheng *et al.*,[11] found no cracks and defects and could observe the screw and taper of the implant. It was seen that the accuracy of the smaller features is good, but the volumetric shrinkage is high. Zhang *et al.*,[40] observed a limited amount of very small pores at some grain boundaries, and the implant thickness was not homogeneous. These were considered processing defects. Imprecisions related to implant size were also observed by Kim *et al.*,[38] Zhu *et al.*,[36] and Anssari & Moin.[2] Lee & Jiang[29] conversely, successfully fabricated the implant threads, and the roundness of the implant platform was acceptable. Osman *et al.*,[28] observed micro-cracks on the surface of the printed implant and attributed these to shrinkage of the structure during the sintering process. A possible reason for these cracks is the solvent evaporation contained in the ceramic slurry used for printing. Before the next layer is added, the evaporation of the solvent generated porosities or micro-cracks which are responsible for volumetric shrinkage.[28] Other possible explanations for the micro-cracks are the insufficient amount of ceramic particles in the dispersion, the light source used, the amount of irradiation, the wavelength, or even the type of resin used.[28] The light source must be suitable and compatible with the composition of the powder since low irradiance or inadequate wavelength can result in partial polymerization of the printed layers.[28] As for the number of ceramic particles in the dispersion, the greater the amount, the lower the shrinkage, and consequently the lower the probability of micro-cracking.[32] Also, the quality of the printed implant may depend on inherent characteristics of the printing system, such as the resolution of the digital mirroring device and the composition of the ceramic photopolymer.[2]

DIMENSIONAL ACCURACY

Five studies[2,11,29,36,39] included in this scoping review reported some change in the size of the printed material. Zhang *et al.*,[39] observed linear shrinkage in the length and width of the implant, with the width being slightly smaller than the height. According to the authors, this is due to the low bond strength and significant porosity of the green ceramic body in the height direction compared to the horizontal direction. Lee & Jiang[29] observed that the volumetric shrinkage increased with increasing sintering temperature. It was also an inhomogeneity between the layers of the green printed product. The adjacent layers had fewer zirconia particles than the average content. The authors suggested that this may be a consequence of zirconia segregation at the bottom of each layer during the solvent vaporization time, thus the upper portion of the polymerized layer contained less zirconia. This resulted in a more critical shrinkage and less efficient sintering. Anssari Moin *et al.*,[2] found that the printed model was larger than the cad model. The authors related the volumetric change observed in the root apex area to the scannability, as well as the difficulty in delimiting the separation between the root apex and the bone at the time of scanning. Another explanation for this volumetric change was the model's position on the printing platform. When the impression initializes in the apex region, there is the possibility of overprinting material in this area. Cheng *et al.*,[11] observed a greater volumetric shrinkage and need for improvements in the precision of the sintered implant. The shrinkage was higher on the implant portions that comprise the body size and the tapered angle. However, they observed that it is possible to reduce the volumetric shrinkage by increasing the proportion of zirconia particles in the slurry.[11] It is known that the incorporation of ceramic particles into curable resins modifies their rheological behavior.[7,46] As the slurry viscosity is linked to the confidence of the structures, in this sense, the slurry rheology must be adjusted in order to allow the reliability of the printed structures.[7,46] In general, a higher solid filler could ensure a lower shrinkage and a higher relative density of the sintered samples. This would reduce cracking caused by deformation and shrinkage. However, the higher the solid filler, the higher the viscosity, and the decrease in fluidity could cause defects in the printing process and affect the final properties of the ceramic.[32] Zhu *et al.*,[36] verified compatibility in the anatomical size of the part (rabbit hip joint) after sintering. The authors produced green parts with 15% magnification in the central region and 20% in specific areas, and the piece was polymerized under 50% humidity. Thus the 50% fixed humidity method and selective inverse area compensation effectively resolved the issue of brittleness and irregular shrinkage produced after sintering. And Osman *et al.*,[28] printed implants with dimensional accuracy close to the dimensions of the reference model.

Dimensional accuracy can be influenced by factors inherent to all types of printers or even specific to a particular system. The powder particle size and the manufacturing parameters, such as the laser beam spot diameter and scanning speed, strongly influence the product accuracy.[11] Also, high sintering temperature can cause severe volumetric shrinkage, which results in uncontrollable distortions and deformations.[29] However, increasing the sintering temperature up to 1500°C makes it possible to obtain the microstructure stability of zirconia oxide, i.e., it prevents the transformation from the stable tetragonal phase to the monoclinic phase, which is brittle, promotes volumetric increase and occurrence of cracks.[11,47,48]

MECHANICAL PROPERTIES

Six studies included in this scoping review[11,28,29,36,39,40] described the mechanical properties of the printed product. Osman *et al.*,[28] observed higher flexural strength values when the specimen was fabricated in the vertical direction at an angle of 0° on the build platform because in this position the layers are placed perpendicular to the load direction. The same was seen in the study by Nakai *et al.*,[15] Zhang *et al.*,[40] and Miura *et al.*[42] And further, Miura *et al.*,[42] reported lower flexural strength of additive manufacturing products compared to subtractive manufacturing, regardless of the construction angle. Possible explanations are the higher incidence and size of pores between the layers of printed zirconia compared to that obtained by subtractive manufacturing, differences in sintering shrinkage, or the presence of structural defects.[28,49] In the study by Osman *et al.*[28] printed zirconia showed a flexural strength value (943 MPa) comparable to that of machined zirconia (800-1000 MPa). Nakai *et al.*,[15] found similar flexural strength between additive and subtractive manufacturing when using zirconia 3Y-TZP. However, according to the authors, the flexural strength depends on the zirconia type. Regarding the composition of zirconia materials, Cheng *et al.*,[11] described that increasing the yttria content and adjustments in sintering temperature can increase the flexural strength. Zhu *et al.*,[36] on the other hand, observed no changes in the tensile, flexural, and compressive mechanical properties of printed zirconia when incorporating ZnO into the composition. Lee & Jiang[29] found that the mechanical properties were better after sintering, and the density was under recommended values for dental restorative devices. Cheng *et al.*,[11] observed that the flexural strength and Vickers hardness of AM zirconia increased significantly after sintering, however, they were below the values reported for machined zirconia. Zhang *et al.*,[39] observed that microhardness, flexural strength, and fracture toughness are dependent on sintering temperature. According to Mei *et al.*,[50] the Vickers hardness of AM specimens (DLP technique) is 5% lower than those manufactured by subtraction. One explanation is that the pores in AM zirconia are mainly concentrated on the surface, while those in subtractive manufacturing throughout the volume. The pores on the surface tend to decrease the hardness.[50] In the study by Zhang *et al.*,[40] sintered implants (AM) showed fracture load and bending moment compatible with clinical application, with the bending moment reaching the level of commercially available implants. The fracture load was lower than that measured for conventionally fabricated implants but without a porous surface layer. The lower strength of zirconia AM implants was due to the porous surface layer on the implant surface. Zirconia stands out from other ceramics mainly due to its high fracture toughness.[50] When it is under a high load, the tetragonal phase (stabilized at room temperature) transforms into a monoclinic phase.[3,8] This phase transformation causes 3 to 5% volumetric expansion generating compressive stress to prevent crack propagation.[3,8] Thus, it is essential that additively manufactured zirconia has the same microstructural characteristics as additively manufactured zirconia. Zhang *et al.*,[40] and Nakai *et al.*,[15] observed typical zirconia microstructure similar to conventionally fabricated. Cheng *et al.*,[11] observed stable microstructure (tetragonal phase) after sintering. Mei *et al.*,[50] found no statistical difference in fracture toughness values when comparing zirconia produced by additive and subtractive manufacturing. Both zirconias had the same phase composition, including the grain size and grain boundary, which are critical as they determine the energy required for crack extension.

As mentioned, green parts sintering is critical to achieving satisfactory mechanical properties. Zhang *et al.*,[39] tested different sintering temperatures and observed changes in porosity and grain size. The authors concluded that temperature and holding time are crucial factors in determining the density of samples. When the temperature is too high or the holding time is too long, secondary abnormal grain growth occurs and a certain spatial resistance is generated between larger/larger grains, which reduces the density. Thus, changes in grain size can influence the microstructure and mechanical properties of the sintered piece.[28]

Zhang *et al.*,[39] Osman *et al.*,[28] and Kim *et al.*,[38] reported the presence of pores and porosities in the printed material. According to Osman *et al.*,[28] these can be generated by solvent evaporation in the polymer-loaded printed ceramic slurry on the exposed surface during the printing. Pores can also be caused by the trapping of air bubbles during the manufacturing process due to the high viscosity of the ceramic slurry,[10,38] or they can originate depending on the purity and particle size distribution of the powder particles.[38] Printed ceramics have the disadvantage of producing green bodies which have a porous surface finish.[11,29,39] Thus there is a need for sintering to obtain dense bodies[28] as the particles are in close contact eliminating almost all residual pores.[39]

The included studies used 1-stage[28,36,39,40] and two-stage sintering,[11,29,36] and to avoid flaws that include porosity, grain size, and micro-cracks, two-stage sintering or slow-temperature ramps have been suggested.[11,28,29] The studies showed no consensus on the temperature of sintering which ranged from 1200°C[36] to 1650°C.[39] Cheng *et al.*,[11] reported the need to adjust the sintering step, however, they observed that the temperature at 1500°C produced good density and compressive strength. In contrast, Osman *et al.*,[28] found micro-cracks, porosities, and interconnected pores at this same temperature. Lee & Jiang[29] observed uncontrollable distortions and deformations at the temperature of 1550°C. And finally, Zhang *et al.*,[39] found better Vickers hardness, compressive strength, flexural strength, and fracture toughness at 1600°C temperature.

One limitation of this study is that few articles were found that evaluated zirconia printed implants. In addition, there was a variation in sintering stages and temperature as well as printing techniques. Thus, there is a gap in the development and complete understanding of the technique, which makes it worth exploring the different technologies.

Future research seeks solutions to improve the precision of the printed implant, control porosity formation, compensate for distortion resulting from sintering, and improve production speed by maturing AM technologies given the long post-processing time (part cleaning, degreasing, and sintering). Regarding the standardization of manufacturing processes, research tends to improve the preparation of the raw material, for example, by adjusting the particle size distribution of the ceramic powders[49,50] since this can affect the thickness of the printed layer. AM technology is another field of research under development since the levels of maturity/advance between the techniques are different. Already denser parts can be produced (by selective laser melting or directed energy deposition),[51] while others manufacture green bodies (e.g. DLP)[9,50] and require sintering to achieve mechanical properties.[51] Therefore, process optimization is needed to find the best combination of process parameters so that optimal mechanical properties can be achieved.

This review presented recent advances and knowledge on three-dimensional printing of dental and orthopedic implants using zirconium oxide as a material. The literature containing results regarding the printing product is still limited, however, the technique is promising. More studies are needed before this technique can be tested clinically.

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Appendix 1. Database search strategy.

Database	Search	Found
PubMed **Jun 24th 2022**	(‘zirconium implants’ OR ‘zirconium oxide’) AND (‘three dimensional printing’ OR ‘rapid prototyping’) (((“zirconium”[MeSH Terms] OR “zirconium”[All Fields]) AND (“embryo implantation”[MeSH Terms] OR (“embryo”[All Fields] AND “implantation”[All Fields]) OR “embryo implantation”[All Fields] OR “implantation”[All Fields] OR “implant”[All Fields] OR “implant s”[All Fields] OR “implantability”[All Fields] OR “implantable”[All Fields] OR “implantables”[All Fields] OR “implantate”[All Fields] OR “implantated”[All Fields] OR “implantates”[All Fields] OR “implantations”[All Fields] OR “implanted”[All Fields] OR “implanter”[All Fields] OR “implanters”[All Fields] OR “implanting”[All Fields] OR “implantion”[All Fields] OR “implantitis”[All Fields] OR “implants”[All Fields])) OR (“zirconium oxide”[Supplementary Concept] OR “zirconium oxide”[All Fields])) AND (“printing, three dimensional”[MeSH Terms] OR (“printing”[All Fields] AND “three dimensional”[All Fields]) OR “three-dimensional printing”[All Fields] OR (“three”[All Fields] AND “dimensional”[All Fields] AND “printing”[All Fields]) OR “three dimensional printing”[All Fields] OR ((“rapid”[All Fields] OR “rapidities”[All Fields] OR “rapidity”[All Fields] OR “rapidness”[All Fields]) AND (“prototypal”[All Fields] OR “prototype”[All Fields] OR “prototype s”[All Fields] OR “prototyped”[All Fields] OR “prototypes”[All Fields] OR “prototypic”[All Fields] OR “prototypical”[All Fields] OR “prototypicality”[All Fields] OR “prototypically”[All Fields] OR “prototyping”[All Fields])))	46
Scopus **Jun 24th 2022**	((ALL (“zirconium implants”) OR ALL (“zirconium oxide”))) AND ((ALL (“additive manufacturing”) OR ALL (“rapid prototyping”) OR ALL (“3D printing”) OR ALL (“selective laser melting”) OR ALL (“electron beam melting”)))	450
Web of Science **Jun 24th 2022**	“zirconium implants” (All Fields) or “zirconium oxide” (All Fields) AND “additive manufacturing” (All Fields) or “rapid prototyping” (All Fields) or “3D printing” (All Fields) or “selective laser melting” (All Fields) or “electron beam melting” (All Fields)	15
Embase **Jun 24th 2022**	(‘zirconium implants’ OR ‘zirconium oxide’) AND (‘three dimensional printing’ OR ‘rapid prototyping’)	60
Google Scholar **Jun 28th 2022**	zirconium; implants; printing; additive (with all of the words)	100