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Review article

Influence of building direction on physical and mechanical properties of titanium implants: A systematic review

João Vicente Calazans Neto [a], Andréa Cândido dos Reis [b], Mariana Lima da Costa Valente [c,*]

[a] School of Dentistry of Ribeirão Preto, University of São Paulo, São Paulo, Brazil
[b] Department of Dental Materials and Prosthesis School of Dentistry of Ribeirão Preto, University of São Paulo, São Paulo, Brazil
[c] School of Dentistry of Ribeirão Preto University of São Paulo, São Paulo, Brazil

ABSTRACT

The objective of the systematic review is to find an answer to a question: "What is the influence of the building direction of titanium implants produced by additive manufacturing on their physical and mechanical properties?" This review followed the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA 2020) and was registered in the Open Science Framework (OSF) (osf.io/rdc84). Searches were performed in PubMed, Scopus, Science Direct, Embase, and Google Scholar databases on February 17th, 2024. Articles were chosen in 2 steps by 2 blinded reviewers based on previously selected inclusion criteria: In vitro studies that evaluated the influence of the impression direction of titanium implants produced by additive manufacturing on their physical and mechanical properties were selected. Articles were excluded that (1) did not use additive technology to obtain the implants, 2) used surfaces other than titanium, 3) did not evaluate the direction of impression, 4) Studies with only in vivo analyses, clinical studies, systematic reviews, book chapters, short communications, conference abstracts, case reports, and personal opinions.). In the initial search, 581 results were found. Of this total, 108 were excluded for duplication and, after applying the eligibility criteria, 16 articles were included in the present review. The risk of bias was analyzed using the RoBDEMAT. The risk of bias was analyzed using the RoBDEMAT. In addition, the coefficient of interagreement of the reviewers (Cohen's Kappa) and the certainty of evidence by GRADE were analyzed. In general, different impression angles showed variations in the physical and mechanical characteristics of the groups evaluated, including roughness, tensile strength, hardness, and modulus of elasticity. While some impression orientations resulted in greater strength or hardness, others showed greater elasticity or lower surface roughness. These findings suggest that print orientation plays a significant role in determining material properties. It can be concluded that printing directions influence the physical and mechanical properties of titanium implants and the studies included showed that the 0°, 45°, and 90° directions are the most evaluated as they present lower probabilities of structural anisotropies and provide better results in their roughness, hardness, tensile and compressive strength.

1. Introduction

Additive Manufacturing (AM) represents a 3D manufacturing technology that allows objects to be made layer by layer and enables the printing of implants with complex and individualized geometries, which provide a functional and aesthetic solution for replacing lost teeth [1–7]. 3D implants are created from a computer prototype that will be printed in successive layers with micrometric precision according to the patient's anatomy, optimal implant position, and occlusion, which can result in better integration with the bone and a higher long-term success rate [8–11]. In addition, this technique enables surface texturing with the creation of multipores in titanium that can enhance its resistance to corrosion, tensile, and compression [12–14].

The quality of the 3D implant is influenced by the printing parameters, such as beam current and size, layer thickness, number and

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* Corresponding author.
E-mail address: mariana.lima.valente@usp.br (M.L.C. Valente).

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speed of scans, and building direction, which should be selected according to material type, printer, and desired properties [15–20]. The current and beam size in processes such as Selective Laser Melting (SLM) or Electron Driven Energy Deposition (EBM) determine the amount of energy delivered to the material during its production and relates to the resolution and speed of the process, which affects the density of the molten material and porosity formation. The thickness of each layer impacts the accuracy and printing time, with smaller layers resulting in a more detailed surface finish. The number and speed of scans refer to the frequency and speed with which the beam strikes the part, and can affect the material density, adhesion between layers, modulus of elasticity, mechanical strength, and fatigue of the implant [2,16–19,21–26].

Building direction is characterized by the orientation in which the layers of the material are deposited during the manufacturing process and can affect the mechanical strength, fatigue, density, and surface characteristics of the part [2,25,27], being able to lead to decreased corrosion resistance, changes in tensile behavior and structural anisotropies [28–33]. Anisotropy is characterized by the presence of variations in the physical and mechanical properties of the implant in different directions and axes, resulting in distinct behaviors and implications for its clinical performance [34–36].

Although articles in the literature evaluate the properties of titanium surfaces to the angle of impression, the originality and relevance of this systematic review lie in evaluating the impact of different angles of impression on the physical and mechanical properties of titanium surfaces, specifically in the context of bone-implant contact. It should be noted that modifying a single parameter, such as the printing angle, can influence both the macro and final microstructure of the surfaces, affecting these properties and potentially impacting the success of implants. Among the most reported axes in the literature are X, Y, and Z, represented by horizontal (0°), vertical (90°), and diagonal (45°) positions, respectively [3,25,30,37–39]. Thus, the present systematic review started from the hypothesis that the direction of the impression angle of titanium implants influences their physical-mechanical properties. Thus, this systematic review aimed to foster discussion about the influence of the direction on the physical-mechanical properties of 3D titanium implants, since these can influence the clinical prognosis of rehabilitative treatment.

2. Material and methods

2.1. Protocol

The present study aimed to answer the question "What is the influence of the building direction of titanium implants produced by additive manufacturing on their physical and mechanical properties?" To this end, it was prepared according to Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA 2020) [40] standards, and its protocol was registered in the OSF (Open Science Framework) (osf.io/rdc84). The Population, Intervention, Comparison, Outcome, and Study Design (PICOS) strategy for this systematic review is shown in Table 1.

2.2. Eligibility criteria

Inclusion criteria: In vitro studies that evaluated the influence of the impression direction of titanium implants produced by additive manufacturing on their physical and mechanical properties were selected.

Exclusion criteria: Articles that did not use additive technology to obtain the implants, used surfaces other than titanium, and did not evaluate the direction of impression were excluded from this systematic review. Furthermore, in vivo studies, reviews, book chapters, conference abstracts, short communications, personal opinions, and case reports were excluded.

2.3. Search strategy

Customized search strategies, conducted in February 17th, 2024, were applied in the electronic databases: Pubmed, Scopus, Web of Science, Embase, and the grey literature, Google Scholar (Supplementary Table 1). All articles that fit the inclusion criteria were included and supplementary searches were performed, from the list of references and citations of the included articles, to find possible inclusions.

One author (J.V.C.N.) performed the initial search of the articles. The findings were attached to the Rayyan digital platform and then evaluated by 2 independent authors (J.V.C.N. and A.C.R.) who were responsible for analyzing the articles according to the pre-established inclusion and exclusion criteria. The other studies were read in full. Conflicting results were resolved by the third author

Table 1
Population/Animals, Intervention, Comparison, Outcome, and Study Design (PICOS) strategy for systematic review.

PICOS	Description
Population	Titanium surface produced by additive manufacturing
Intervention	Building direction
Comparison	Control Group
Outcome	Physical and mechanical properties
Study Design	In vitro

Legend: PICOS, participants, intervention, comparison, outcomes, study designs.

(M.L.C.V). Data extraction from the article was done through a table with the following topics: Author/year; objective; titanium alloy; evaluated direction; evaluation method; conclusion.

2.4. Risk of bias assessment

The risk of bias was assessed using the RoBDEMAT. The tool addresses four distinct areas: Bias in planning and allocation (D1), Bias in sample/specimen preparation (D2), Bias in outcome assessment (D3) and Bias in data treatment and outcome reporting (D4). Within these domains, nine items are considered that encompass various sources of bias [41].

2.5. Kappa de Cohen

Cohen's Kappa coefficient was used to assess the agreement between the reviewers to ensure greater consistency in the results. Kappa also helps to distinguish real agreement from that expected by chance and identifies areas of disagreement, allowing for revisions and ensuring validity and consistency in the final results of the review [42].

2.6. Certainty of the evidence

The reliability of the evidence for each outcome was determined using the GRADE (Grading of Recommendations Assessment, Development, and Evaluation) method. In this process, two independent authors (J.V·C.N. and M.L.C·V.) examined the robustness of the evidence. Initially, the results were considered to have a high-quality evidence base, and the reduction in the reliability of the evidence was determined by criteria including limitations, inconsistencies, lack of direct relationship, imprecision, and publication bias. Disagreements were resolved by consensus. According to these criteria, the reliability of each piece of evidence was classified as high, moderate, low, or very low [43].

3. Results

3.1. Search results

Fig. 1 addresses the strategy used to select the studies. In the initial search, 581 results were found. Of this total, 108 were excluded for duplication and, after applying the eligibility criteria, 16 articles were included in the present review.

Performing the statistical analysis through a meta-analysis was not possible because the articles had heterogeneous methodologies.

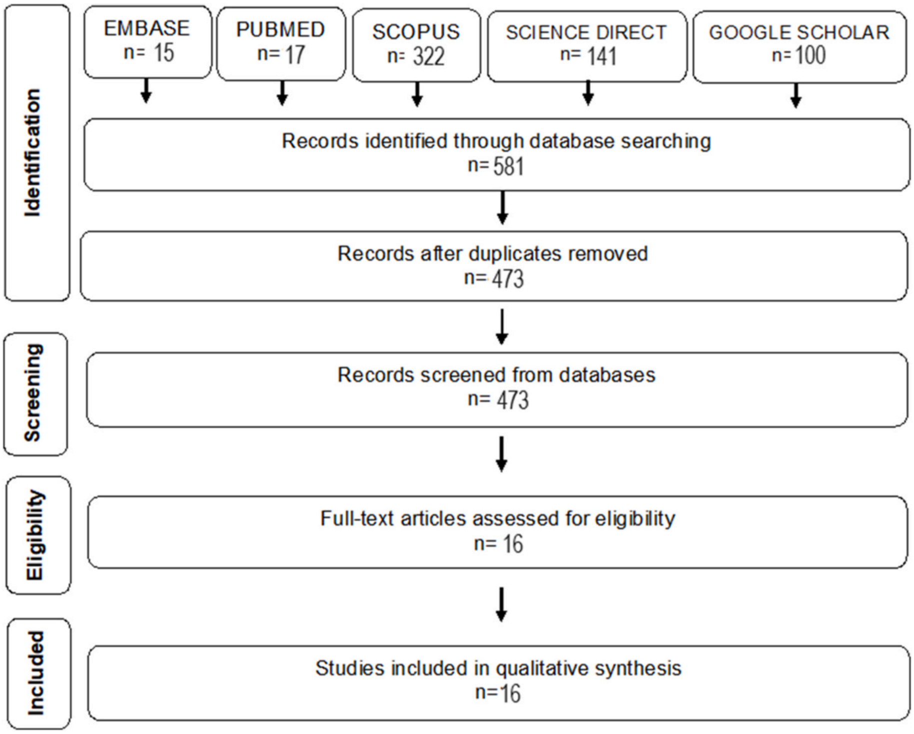

Fig. 1. Flow of information through the different phases of the systematic.

Table 2

Provides information on the studies in this paper. The articles used were published between 2011 and 2022.

AUTHOR, YEAR	OBJECTIVE	TITANIUM ALLOY	EVALUATED DIRECTION	EVALUATION METHOD	CONCLUSION
Murchio et al., 2021 [45]	Investigate tensile strength and fatigue behavior at different impression orientations.	Ti–6Al–4V	0°, 15°, 45°, and 90°	Tensile and fatigue testing; Surface fracture analysis; Microhardness.	The smaller the angle of the impression, the lower the fatigue resistance. The tensile showed independence of the angle.
Chen et al., 2017 [26]	Investigate anisotropy in terms of elasticity and hardness.	Ti–6Al–4V	0°, 45°, and 90°	MTS XP nanoindentation system, using continuous stiffness measurement mode (CSM).	Young's modulus was unchanged, while hardness was lower at 0°.
Todai et al., 2017 [5]	Control the microstructure of the titanium produced at different angles.	Ti–48Al–2Cr–2Nb	0°, 45°, and 90°	Tensile testing; Slip marks; Deformation microstructure; Nanoindentation hardness.	Yield and tensile limits varied depending on the angle used, being highest at 45°.
Simonelli et al., 2014 [6]	Evaluate the effect of impression orientation on mechanical properties and fracture modes.	Ti–6Al–4V	Xy, xz, and yz	Tensile and elasticity testing; Fracture analysis; Residual stress.	Building direction influences the tensile properties and especially the ductility.
Alsalla et al., 2018 [33]	Investigate mechanical properties in different directions of construction.	Ti–6Al–4V	xz, yx, and zx.	Tensile strength; Fracture toughness; Roughness; Vickers hardness.	The mechanical properties are altered with the change in microstructure promoted by the change in angle.
Huang et al., 2021 [20]	Measure the hardness and tensile properties of the parts built in different print directions.	Ti–6Al–4V	30°, 60°, and 90°	Hardness and tensile testing.	The angle changes the evaluated mechanical properties, and 60° gives the best results.
Hu et al., 2022 [27]	Evaluate the influence of microstructure on microhardness and wear at different impression angles.	Titanium (TA1)	XY, XZ, and YZ.	Wear resistance and microhardness.	XY shows higher microhardness and wears resistance than XZ and YZ.
Rans et al., 2018 [2]	Influence of orientation in the specimen on resistance to fatigue crack growth.	Ti–6Al–4V	0°, 30°, 45°, 60°, and 90°	Fatigue testing; crack growth measurement.	The building direction had a small but repeatable influence on crack propagation.
Liu et al., 2020 [44]	Investigate the mechanical properties of Ti6Al4V built up in different directions.	Ti–6Al–4V	xoz and xoy	Uniaxial tensile and push-pull fatigue testing; Roughness analysis.	Xoz offers better mechanical properties compared to xoy.
Zheng et al., 2022 [12]	Investigate the effect of building direction on mechanical properties.	Ti–6Al–4V	0°, 67,5°, and 90°	Vickers microhardness; Quasi-static compression experiments; Split Hopkinson pressure bar test.	Mechanical compression and microhardness properties below 67.5° exhibit the least anisotropy.
Harada et al., 2020 [3]	Investigate the effect of the printing direction on the sample properties.	Ti–6Al–4V e Ti.	0°, 45°, and 90°	Tensile testing; Surface roughness; Wettability; Vickers hardness; Corrosion discoloration test	Direction 90° showed higher tensile strength; 45° higher roughness.
Ginestra et al., 2020 [37]	Compare sample properties from different manufacturing directions.	Ti–6Al–4V	0°, 15°, 30°, and 45°	Scanning Electron Microscopy (SEM); Optical Microscopy; Surface wettability.	The directions showed similar surfaces, but 0° and 15° showed better results.
Wang et al., 2018 [38]	Characterize the influence of the printing direction on the mechanical properties, microporosity, and microstructure of the substrate.	Ti–6Al–4V	0°, 45°, and 90°	Tensile testing; Micro-CT; Microscopy (OM), Scanning electron microscopy (SEM), and electron backscatter diffraction (EBSD).	Samples printed in the 0° direction showed higher tensile strength.
Chlebus et al., 2011 [39]	Identify the influence of the impression direction on the mechanical and microstructural properties of titanium.	Ti–6Al–7Nb	0°, 45°, and 90°	Tensile and compression testing; Vickers hardness; Optical microscopy; Scanning electron microscopy; X-ray diffraction analysis.	The construction strategy generated more striking surface defects in the parallel direction (0 axes).
Szymczyk-Ziołkowska et al., 2022 [25]	Identify the effects of manufacturing directions on the microstructure and mechanical properties of implants.	Ti–6Al–4V	0°, 45°, and 90°	Confocal laser scanning microscope; Powder X-ray diffractometry (XRD); Analysis of mechanical properties.	The printing direction affects the properties, whereby 90° shows higher compressive strength, 45° tensile strength, and 0° elasticity.
Mengucci et al., 2017 [30]	Investigate the effects of the printing direction on the mechanical behavior of the alloy.	Ti–6Al–4V	0°, 45°, and 90°	Tensile, flexural, and hardness tests; X-ray diffraction (XRD); Scanning electron microscopy (SEM); Transmission electron microscopy (TEM).	Angle 0° showed higher tensile strength and hardness than the other samples.

The results were evaluated based on the descriptive analysis of the data found.

3.2. Risk of bias assessment

The risk of bias was assessed using the RoBDEMAT. Of the 8 included studies, most showed a low risk of bias [2,3,5,20,25,30,37,45]. Except for the criterion "Was adequate statistical analysis used?" to which 7 of the studies reported insufficiently [6,26,27,33,38,39,44] on D4 due to a lack of clarity regarding the statistical procedures or methods used and the results reported were neither complete nor aligned with what could be expected or whether they were defined as planned results by the researcher before conducting the study. In addition, 1 author [12] was classified as not adequate on the same topic for not reporting the statistical tests carried out or presenting results (Supplementary Table 2).

3.3. Kappa de Cohen

Cohen's Kappa coefficient was calculated as 0.53, indicating moderate agreement between the reviewers [42]. This suggests that there was consistency in the assessments of the studies included in the review, highlighting the methodological robustness of the agreement observed. The moderate inter-rater reliability demonstrated by the Kappa value reinforces the credibility of the results and the consistency of the systematic review process.

3.4. Certainty of the evidence

For the certainty of the evidence of the selected studies, the GRADE tool was applied [43]. The findings of the studies analyzed using this approach demonstrated a high certainty of the evidence. These results strengthen the conclusions drawn in this review, providing a solid basis for the recommendations and conclusions presented. This robustness is maintained since factors such as bias, inconsistencies, indirect evidence and inaccuracies in the results have been considered, keeping the certainty of the evidence at a high level (Supplementary Table 3).

3.5. Characteristics of the studies

Table 2 provides information regarding the included studies, based on the eligibility criteria. Murchio et al. [45] found higher hardness at 90° (408 ± 12 HV) compared to 15° (382 ± 14 HV), with no effect on Vickers microhardness [45]. Chen et al. [26] reported similar Young's modulus (0°: 127 ± 2 GPa, 90°: 128 ± 2 GPa, and 45°: 127 ± 4 GPa) but lower hardness at 0° (4.2 ± 0.5 GPa) compared to 90° and 45° (5.1 ± 0.5 GPa), affecting yield and strength [26]. Todai et al. [6] found lower yield strength at 45° (566 MPa) compared to 0° (605 MPa) and 90° (587 MPa), but higher elongation [6].

Simonelli et al. [6] noted differing surface fracture characteristics based on impression orientation [6]. Alsalla et al. [33] 90° samples exhibited lower elongation (7.1 ± 0.5 %), yield strength (7.1 ± 0.5 MPa), and hardness (376.5 ± 5.2 HV) [33]. Huang et al. [20] reported higher tensile strength at 60° (1235 MPa) with similar hardness values [20]. Hu et al. [27] observed higher Vickers microhardness in the parallel orientation (497.43 HV), resulting in reduced plastic deformation, and lower coefficient of friction (0.37) and wear [27].

Rans et al. [2] observed increased crack deviations at 30° and 45° angles, with 45° showing a 20 % greater deviation [2]. Liu et al. [44] found superior mechanical properties in the 90° impression direction (yield strength: 891 ± 14 MPa, ultimate tensile strength: 987 ± 8 MPa, elongation: 15.7 ± 1.9 %) compared to 0° (yield strength: 869 ± 11 MPa, ultimate tensile strength: 955 ± 7 MPa, elongation: 9.8 ± 2.3 %) [44]. Zheng et al. [12] noted a 30.14 % increase in microhardness at 0°, with lower elongation and greater yield strength compared to other angles [12].

Harada et al. [3] found that a 90° implant impression resulted in higher tensile strength (1118.17 MPa), while the 45° direction exhibited higher surface roughness (5.04 μm) and elongation (11.56 %) [3]. Ginestra et al. [37] observed increased surface roughness at 30° (24.4 μm) and noted optimized mineralization characteristics at 0° angulation [37]. Wang et al. [38] reported that 0° had the highest tensile strength (904 MPa) and yield strength (916 MPa), with the highest elongation (17.2 %), while 45° had the lowest values. Wang et al. [37] and Chlebus et al. [39], noted the presence of well-organized pores in the 90° and 0° directions [37,39].

Chlebus et al. [39] found lower tensile strength at 90° (1360 MPa) compared to 0° (1440 MPa) [39]. Szymczyk-Ziołkowska et al. [25] observed higher compressive strength at 90° (1792 MPa) and lower deformation, with higher hardness (334 AT) and tensile strength (1022 MPa) at 45° [25]. Mengucci et al. [30] noted higher hardness (12 AT) and tensile strength (1110 MPa) at 0° with no change in surface roughness, while 45° offered higher tensile strength (13 ÿb (%)) [30].

4. Discussion

The studies included in this review analyzed the influence of different printing angles on the physical and mechanical properties, such as roughness, wettability, microhardness, tensile, compressive and wear resistance, fatigue and crack growth measurement, of titanium implants produced by additive manufacturing, by means of optical microscopy analysis, Vickers microhardness, quasi-static compression experiments, Split Hopkinson pressure bar test, uniaxial tensile test and tensile fatigue., and supported the initial hypothesis that the angle direction influences the microstructural properties of the titanium implant and impacts its properties. Thus, the theme of this review is the knowledge of the mechanical and physical properties of titanium implants by changing the most commonly used angles in additive manufacturing.

Influence of the 0° angle.

In their study, Wang et al. [38] observed low values of type I porosity, characterized by small and well-distributed pores, which gives implants higher tensile strength [37]. The presence of uncontrolled porosity can weaken the connection between layers, which leads to structural anisotropies (variations in mechanical and physical properties in different directions) and decreased mechanical properties, such as tensile and compressive strength [38,39]. However, studies by Harada et al. [3] and Szymczyk-Ziołkowska et al. [25] reported that implants printed at 0° show roughness and lower tensile and compressive strength compared to implants at 90°, this is due to the position of the layers in the same direction as the tensile stress which acts to separate them under the action of tensile forces, resulting in lower mechanical strength [3,4]. Furthermore, implants at 0° tend to have lower stiffness than those produced vertically due to the dust distribution and different levels of residual stresses, which are due to the 3D printing process and can affect the mechanical properties of the implant, such as its stiffness [39]. Although Chen et al. [26] found similar elasticity values between 0° and 90° in their study, as they believe that this value is only altered by mutual atomic bonds and not by printing processes, the authors corroborate that the hardness of the device is lower in the 0° plane, so there are more processing defects in this direction because the implant is built concurrently with the irregular laser path, which weakens the local hardness and strength [12,26,46–49,50].

4.1. *Influence of the 45° angle*

The 45° angle presents structural anisotropy that reflects in the lower tensile strength and ductility values when compared to the implants printed at 90°. This is due to the diagonal positioning of the columnar grains (linear structures that form in a preferential direction along an axis during the printing process) constituting a sample that is not able to compensate for the directionality to which tensile stress is applied [38]. Plasticity refers to the ability of a material to undergo permanent deformation under stress without rupturing. In the case of implants printed at a 45° angle, less plasticity under applied stresses was observed, which can generate cracks and deformations due to the coincidence in the positioning of the shear stresses applied during loading with the columnar grains, making them aligned to the structure, resulting in stress concentration that compromises the structural integrity of the implant, reduces its tensile strength and ductility [25,51].

4.2. *Influence of the 90° angle*

Implants printed in this direction have higher stiffness, compressive strength, and tensile strength, since the tensile force is applied vertically to the direction in which it was printed, and thus there is no tendency for their layers to separate, as occurs at 0°, since they are positioned perpendicular to the loading direction [3,25,39]. Wang et al. [38] presented that due to the direction of the tensile axis being parallel to the junction of the columnar grains, implants at 90° have a greater capacity for plastic deformation without breaking, which is desirable in biomedical implants [51], Wang et al. [37] besides having better pore control, which influences implant osseointegration, allowing adequate bone tissue formation around the implant and improving its fixation at the implant site [37]. Todai et al. [5] observed that at this angle the propagation of cracks in the microstructure of the device does not lead it directly to fracture, due to the difference found in this axis in the geometry of the layered microstructural interface [5]. For Xu et al. [56] the fractures in these samples have the largest size 30–40 μm as the cyclic loading direction is similar to the construction direction, thus a larger defect area can be obtained [56].

4.3. *Influence of additive manufacturing processes*

Different additive manufacturing processes were used in the articles explored: 1. selective laser melting (SLM), which uses a laser to melt the powder into layers to obtain the desired shape of the implant [2], electron beam melting (EBM), which uses an electron beam to melt the metal powder to form the part [3], direct metal laser sintering (DMLS), a process in which the powder material is partially laser melted to create the layers of the part, with faster cooling and consolidation conditions that lead to better microstructural characteristics [33]. Among these processes, EBM stands out for performing the printing in a high vacuum chamber, which reduces hydrogen contamination, is responsible for problems such as brittleness and excessive porosity in printed parts, as well as allowing the printing of parts with high purity, and offers greater flexibility of choice in the size of the powder particles, which reflects on the density, mechanical strength, porosity, and surface roughness [16,25,38,52–56].

The fast-melting speed, high-temperature gradient, and thermal stress, together with the inclination of the parts, can cause deformations, warping, internal pores, melting failures, cracks, and impact on the density of the final object. These aspects not only influence the characteristics of the object produced but also affect the properties of the implant since they are determined by the manufacturing technique employed. Each additive manufacturing method has its particularities, such as melting rate, printing speed, material density, and surface quality, which can affect the physical, mechanical, chemical, and biological properties of the implant [7,25,55–57].

The scanning strategy also relates to the anisotropy of the device. With "CHESS" scanning, i.e. when the laser scans the surface in an interleaved fashion, the angle increment does not have a significant effect on the anisotropy, but in "STRIPES" mode, when it scans in parallel lines, the angle increment impacts the final printed part. When the scanning strategy and the direction of the crystal growth angle coincide in the second type, the anisotropy reaches maximum deformation, this occurs because the laser incurs more directly on the growing crystals, which results in a preferential orientation of the grains along the scan lines, which can have an impact on the physical-mechanical properties and other characteristics of the material produced by SLM. Thus, the scan angle used during the manufacturing process can affect the grain orientation of the produced material [20,58,59].

The studies included in this systematic review highlighted that different printing directions can result in different cooling and solidification rates of the material, leading to changes in the microstructure and consequently the mechanical and physical properties of the implants. In addition, other variables, such as the process used for printing, powder size, and columnar grain positioning, must also be considered when designing and fabricating dental implants by 3D printing. The relationship between printing parameters, surface quality, and implant properties still needs to be further investigated in dentistry.

This review and the articles included here have no financial or personal conflicts of interest that could influence the results of this work. During the preparation of this manuscript, some limitations were identified, including the lack of literature on the surface characteristics of titanium implants manufactured by additive manufacturing about different angles, excluding other processing. In addition, there was a limitation in the evidence of the experimental studies evaluated, due to the current nature of the subject. However, it is possible to infer and externally validate that modifying the angle in these parts can significantly impact the final properties, potentially resulting in better clinical responses, speeding up the treatment process, and increasing rehabilitative success, promoting greater patient satisfaction. Finally, there is a need for more clinical and experimental studies on the subject, with a better-standardized methodology, improved reproducibility, and greater control to ensure greater consistency in the results obtained.

5. Conclusions

Based on the results of this systematic review one can infer:

1. Among the angles evaluated, it is suggested that 0°, 45°, and 90° are the most suitable as they offer the best properties, such as stiffness, compressive strength, tensile strength, and ductility.
2. The physical and mechanical properties of implants are influenced by the chosen impression direction but are also influenced by variables such as the additive manufacturing process, the particle size of the powder, and the position of the columnar grains.
3. Further original research is needed to deepen the scientific community’s understanding of the correlation between changing the impression direction of titanium implants and their physical and mechanical properties

CRediT authorship contribution statement

João Vicente Calazans Neto: Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Andréa Cândido dos Reis:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Mariana Lima da Costa Valente:** Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing, Conceptualization, Formal analysis, Funding acquisition.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e30108.

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