

Influence of Surface Roughness on the Adhesion of Hydroxyapatite Coatings to Titanium and Titanium Alloy Surfaces: A Systematic Review of *in vitro* Experimental Studies

Keywords

Adhesion
Titanium
Coating
Dental Implants
Hydroxyapatite

Authors

Victor de Melo-Soares *
(DDS)

Isadora Gazott-Simões §

Andréa Cândido dos Reis †
(PhD)

Mariana Lima da Costa Valente †
(PhD)

Address for Correspondence

Mariana L. D. C. Valente *

Email: mariana.lima.valente@usp.br

* Master's student, Department of Dental Materials and Prosthodontics, Ribeirão Preto, Dental School, University of São Paulo (USP), Ribeirão Preto, Brazil

§ Graduate student, Ribeirão Preto Dental School, University of São Paulo, (USP), Ribeirão Preto, São Paulo, Brazil

† Professor, Department of Dental Materials and Prosthodontics, Ribeirão Preto Dental School, University of São Paulo (USP), Ribeirão Preto, Brazil.

ABSTRACT

This systematic review gathered evidence to identify the influence of roughness on titanium surfaces on the adhesion of hydroxyapatite coatings. This research followed the PRISMA guidelines and was registered on the Open Science Framework (osf.io/cxrsf). In vitro studies were searched on Science Direct, PubMed, Embase, Scopus, Google Scholar and in the references of the articles included. Two independent reviewers selected the studies based on the inclusion and exclusion criteria. The risk of bias analysis was carried out using the adapted Joanna Briggs Institute quasi-experimental study tool. 2890 articles were found and after applying the selection criteria 22 were chosen to be read in full. 9 studies were excluded because they did not evaluate substrate roughness or coating adhesion. Finally, 13 studies composed this systematic review. Of these, 4 indicated that greater titanium roughness provides better adhesion of the hydroxyapatite coating; 7 that in addition to roughness, other factors play a role in this process, and 2 other studies presented divergent results. Surface roughness has influence on the adhesion of hydroxyapatite coatings to titanium. However, the type of titanium alloy, the thickness of the coating and other characteristics also affect the adhesion process and should be considered.

INTRODUCTION

Commercially pure titanium (TiCP) and titanium alloys (Ti) are widely used in implant-supported oral rehabilitation due to its mechanical properties, biocompatibility, good strength-to-weight ratio and corrosion resistance.¹⁻⁹ The absence of bioactivity is a limitation of Ti10 that can be reversed by combining it with bioactive materials. Furthermore, hydroxyapatite (HAp) may enhance cell adhesion, proliferation and differentiation and induce the formation of bone similar to biological apatite along the titanium surface. The improved biological performance, the ability to integrate with the surrounding bone tissue^{8,11-16} and the functionalization of the physicochemical properties provided justify the application of surface coatings.^{4,6,9,10,12,16}

Received: 01.08.2024

Accepted: 19.11.2024

doi: 10.1922/EJPRD_2776Melo-Soares11

The bond between Ti surfaces and bone tissue is made possible by the formation of a layer of apatite on the metal surface.¹⁵ HAp consists of a calcium phosphate similar to the inorganic bone matrix and its use as a bioactive coating allows for better bone formation and attachment to adjacent bone.¹⁰ Despite the clinical benefits provided, the clinical application of this coating is challenged by uncertainties about microbial adhesion, bone degradation and failure due to mechanical limitations,¹⁷ low adhesion strength on metal substrates,^{3,10,15,18–21} detachment of debris^{3,8,12,22–27} which can dissolve due to the presence of amorphous phases resulting from exposure to the high temperatures of physical deposition.¹⁰

Metal implants with intact HAp coatings have a survival rate of over 90%²⁸ but the fragmentation of the film reduces its mechanical capacity. With the high mechanical properties of the metal substrate, delamination²⁹ and absorption are favored, as well as the loss of biocompatibility, biofunctionality and the release of material residues into the biological environment³⁰ reducing the implant survival by approximately 40%.^{28,31}

The clinical failure of an HAp-coated implant may be related to an irregular, thick, porous film with low cohesive and adhesive strength,³² the ideal being the formation of thin layers of HAp (<1 µm) with a homogeneous composition and nanocrystalline character.^{29,32} Of these, adhesion strength is identified as the main factor in the long-term stability of HAp coatings.²⁹ Thus, in addition to the efforts to develop a film with satisfactory characteristics,^{29,32} modifications to the metal substrate are indicated to enhance the coating-surface bond, promote cell adhesion, proliferation and differentiation.³³

There are different techniques for depositing HAp on the metal surface, such as the sol-gel method,^{24,25,34–36} incorporation of apatite cores,⁵ radiofrequency magnetron-assisted sputtering,^{3,37} hydrothermal treatment,³⁸ metal organic chemical vapor deposition,³⁹ chemical deposition,¹⁶ electrochemical deposition,^{8,15} plasma spraying,²³ and other methods.^{6,10,26,40}

Performing prior procedures on the titanium surface such as laser treatment,^{25,41–43} acid attack,^{5,27,39} sandblasting²⁷ and anodizing²⁴ may induce better adhesive resistance by varying surface textures,^{25,27,41,42} as well as influencing the rate of osseointegration by enabling bone growth on surface irregularities,^{44,45} the greater surface roughness provides an important mechanical imbrication for the adhesion of HAp coatings to metals.^{5,25} However, roughness is not the only factor involved, as the following have been presented 26 different adhesion forces for the same surface finish, which also made it possible to attribute the influence of chemical bond on the adhesion of HAp. Other results found in the same year³⁵ corroborate that the chemical composition of the coating itself is capable of altering its adhesion.

The adhesive tensile strength of HAp coatings should not be less than 15 MPa, although HAp deposited by plasma spraying achieves tensile strengths of approximately 28 MPa,⁴⁶ other methods of obtaining the coating, such as electrophoresis deposition, achieve a strength limited to around 8 MPa.⁴⁷ In

addition to tensile strength, the scratch test can be used to measure the adhesion of the coating to the substrate.^{8,25,27,34,35,48}

The success of surface coatings with HAp on Ti is consequence of adhesion with the metal. Since surface properties influence this process, it is important to investigate the effect of roughness on adhesive strength to develop more suitable surfaces. Therefore, this Systematic Review (SR) aimed to gather evidence to answer the question “What is the influence of surface roughness on the adhesion of hydroxyapatite coatings to titanium surfaces and their alloys?”. The null hypothesis was that roughness had no direct relationship with the adhesion of coatings to the titanium surface.

MATERIAL AND METHODS

PROTOCOL

This review was structured according to the PRISMA guidelines⁴⁹ for systematic reviews and meta-analyses and registered on the Open Science Framework platform (osf.io/cxrsf). The PICOS strategy for this review was defined as follows: Population - surface roughness of titanium implants and its alloys (Ti with biomedical application); Intervention - application of HAp coating; Outcome - adhesion or resistance of the coating; Study Design - *in vitro* studies.

ELEGIBILITY CRITERIA

The inclusion criteria were research articles that dealt with the influence of surface roughness on the adhesion or resistance of hydroxyapatite coatings formed on the surface. And the exclusion criteria were articles that did not evaluate surface roughness; that did not observe the adhesion or resistance of the HAp coating deposited on Ti or cp Ti; that used surfaces other than Ti and its alloys; articles that did not evaluate the surface to apply it to dental or biomedical implants. Finally, *in vivo* and clinical studies, systematic reviews, book chapters, short communications, conference abstracts, case reports and personal opinions were also excluded.

SEARCH STRATEGY

The articles were searched in 4 databases: Science Direct, PubMed, Embase and Scopus. The keywords used in the search strategy for each database and the number of results found are described in Supplementary Table 1. Manual search was also carried out using the reference lists of the selected articles.

SELECTION PROCESS

The articles were selected by two reviewers (VMS e IGS) and a third reviewer (MLCV) was consulted in cases of disagreement. The manual selection of peer-reviewed articles was carried out using the web software Rayyan⁵⁰ (Qatar Computing Research Institute, Doha, Qatar) by the two reviewers. The initial selection was made according to the title and abstract, and for studies with

insufficient data, the manuscript was read in full. A second selection was made based on the complete reading of the articles. The studies found were assessed for eligibility using the previously established inclusion and exclusion criteria and were finally selected for this systematic review.

DATA TABULATION

The data from the studies that remained after applying the exclusion and inclusion criteria were extracted into a table with the following information: (1) authors and year of publication; (2) titanium alloy evaluated; (3) method used to form the hydroxyapatite coating; (4) roughness evaluated and means of obtaining this roughness; (5) method of evaluating coating adhesion; (6) main results. The data are shown in Table 1.

RISK OF BIAS ANALYSIS

The methodological quality of the studies was assessed using the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Quasi-Experimental Studies (non-randomized experimental studies), which was based on the results that this systematic review sought to assess.

It was not possible to carry out a meta-analysis due to the heterogeneity of the studies concerning the methods used to form the hydroxyapatite coating, evaluate the adhesion of the coatings, produce the different roughnesses and the different titanium alloys evaluated. Thus, a descriptive analysis of the data was used to present the results.

RESULTS

The initial search found 2890 results: 2253 in Science Direct, 520 in PubMed, 33 in Embase and 84 in Scopus. The gray literature was accessed via Google Scholar, and the first 100 results were included. After removing duplicate studies, 2614 remained, of which 2673 were excluded after reading the title and abstract. The 22 articles were read in full and 9 were excluded because they did not in any way evaluate the roughness or adhesion of HAp coatings on the titanium surface. At the end of this selection process, 13 articles were selected to make up this systematic review. The details of the selection process can be seen in Figure 1.

The articles included used different methods to form HAP on the Ti surface, most of them using the sol-gel deposition method,^{24,25,34–36} but other methods have also been used such as the incorporation of apatite cores,⁵¹ radiofrequency magnetron-assisted sputtering,^{27,37} hydrothermal treatment,³⁸ organic chemical vapor deposition of metal,³⁹ chemical deposition,⁴⁸ electrochemical deposition,⁸ plasma spraying.²³

Regarding the method used to evaluate the adhesion of HAP coatings on the surface, from the 13 articles included, 6 used the scratch test,^{8,25,27,34,35,48} 5 used the tensile test,^{23,36,37,39,51} 1 used the microtensile test,²⁴ 1 used the nano-identification test³⁸ and 1 used the flexion test.³⁶

When evaluating the influence of different roughness on the adhesion of HAp coatings, from the 13 studies included in the systematic review, 4 of them obtained results indicating that increasing roughness provided better adhesion of the coatings on the titanium surface,^{23,25,27,51} 7 that greater roughness may be related to improved adhesion of coatings but that it is not a determining factor and that adhesion of coatings is also influenced by other factors,^{8,34,36–39,48} 1 did not observe relation between roughness and increased adhesion, but rather that the composition of the coating could influence³⁵ and 1 evaluated two different Ti alloys and observed that for the first, the adhesion was greater on rougher surfaces, while for the second there was no direct relation between the roughness and adhesion of the coatings, and also observed that one of the alloys provided greater adhesion than the other.²⁴ The main results observed for each of the included studies can be seen in Table 2.

Among the 6 studies that carried out the scratch test,^{8,25,27,34,35,48} just one³⁵ showed no interaction between roughness and greater adhesion of the coating to the metal surface, the other^{8,25,27,34,48} reported that greater substrate roughness leads to greater coating adhesion. The influence of roughness on adhesion was also attested to by 5 studies^{23,36,37,39,51} who performed the tensile test, although 2 of these^{39,51} have an adhesive tensile strength of less than 15 MPa.⁴⁶

The risk of bias assessment is summarized in Figure 2 and presented in Figure 3, where it can be seen that all the articles presented a low risk of bias for questions 1 and 7. For questions 2, 4, and 8, over 80% of the included studies presented a low risk of bias. For the 2nd question, from 13 articles included, 2 presented a high risk of bias because they compared different Ti alloys. As for question 3, around 60% of the included articles presented a low risk of bias, while 5 articles presented a high risk of bias because they compared samples that had undergone different surface treatments. Questions 5 and 6 were marked as not applicable for all articles. Question 5 was not applicable, as it assesses whether measurements were taken before and after the intervention, however the adhesion test is only carried out after the intervention which is the HAp treatment. Question 6 concerns follow-up, as this review only assesses *in vitro* studies this question was also excluded.

DISCUSSION

The initial hypothesis of this review, that the surface roughness of Ti and cp Ti would not influence the adhesion of HAP coatings, was rejected. In addition to the surface roughness of the substrate affecting the adhesion process of the HAP coating,^{5,23,25,36} it was possible to see that other factors also influence this process, such as the Ti alloy used,²⁴ the chemical composition of the surface,⁴⁸ the size and morphology of surface asperities,³⁹ thickness³⁶ and the composition of the coating.³⁵

The two methods most commonly used to assess the adhesion of coatings to the surface were tensile methods^{5,23,36,37,39} and scratches.^{8,25,27,34,35,48} The first is done by fixing pins to the

Table 1. Characteristics of studies that evaluated the influence of surface roughness on the adhesion or resistance of hydroxyapatite coatings formed on the surface.

First Author and Year of Publication	Titanium Alloy (Ti) Evaluated	Method used to form the hydroxyapatite (HAp) coating	Method for assessing coating adhesion	Roughnesses evaluated and means of obtaining these roughnesses
Yabutsuka et al., 2020	Ti6Al4V Ti-15Mo-5Zr-3Al Ti-12Ta-9Nb-6Zr-3Al-O (Gummetal®)	Incorporation of apatite cores	Tensile test	Roughness of the surfaces evaluated after acid etching: 0,70 µm (Ti6Al4V) 11,68 µm (Ti-15Mo-5Zr-3Al) 0,57 µm (Ti-12Ta-9Nb-6Zr-3Al-O (Gummetal®))
Stango et al., 2018	Ti-6Al-4V	Sol-gel	Scratch test	Polished and laser-treated surfaces were evaluated: ~ 0,1 µm (polished) 1,183 µm (laser treatment)
Grubova et al., 2017	Ticp	Radiofrequency magnetron-assisted cathodic spraying	Scratch test	Roughness obtained after sandblasting + acid etching: 1.8 ± 0.1 (blasting with 250-320 µm) 0.96 ± 0.04 (blasting with 50 µm)
Baptista et al., 2016	Ticp	Sol-gel	Scratch test	Roughness obtained from surface polishing with silicon carbide sandpaper: 0,51 µm (polished to grain 240) 0,44 µm (polished to grain 400) 0,15 µm (polished to grain 800) ~ 0,09 µm (polished to grain 1200)
Charitidis et al., 2013	Did not specify the alloy used	Hydrothermal treatment A coating of hydroxyapatite combined with dendrimer was formed.	Nanoidentification test	Roughness obtained from surface polishing with silicon carbide sandpaper): 0,28 ± 0,09 µm (polished to grain 220) 0,22 ± 0,05 µm (polished to grain 400) 0,11 ± 0,05 µm (polished to grain 600) 0,10 ± 0,04 µm (polished to grain 800) 0,09 ± 0,05 µm (polished to grain 1000)
Hieda et al., 2013	Ti-29Nb-13Ta-4.6Zr (TNTZ)	Organic chemical vapor deposition of metal	Tensile test	The author evaluated surface roughness with acid treatments using HF and H2SO4 solutions and with mechanical polishing using grit sandpaper #1000, #1500 and #2400 and a mirrored surface. The roughness values obtained for the acid-treated surfaces were presented graphically, so the values are reported here in approximate form. 19,1±3,2 nm (Mirrored surface) ~ 20 nm (Treatment solution H2SO4 60s) ~ 40 nm (Treatment solution HF 60s) 68,4±11,0 nm (Mechanical polishing with grit sandpaper #2400) 122,1±0,5 nm (Mechanical polishing with grit sandpaper #1500) ~ 210 nm (Treatment solution HF 600s) 254,4±36,1 nm (Mechanical polishing with grit sandpaper #1000) ~ 320 nm (Treatment solution H2SO4 600s) ~ 450nm (Treatment solution HF 3600s) ~ 650 nm (H2SO4 solution treatment 3600s)
Roest et al., 2011	Ticp Ti-6Al-4V	Sol-gel	Microtraction test	The samples were anodized at different voltages, producing surfaces with the following roughnesses: 5,3 ± 0,2 nm (Ticp polished) 17,1 ± 0,6 nm (Ticp anodized 25V) 28,6 ± 3,6 nm (Ticp anodized 50 V) 17,2 ± 1,4 nm (Ticp anodized 75 V) 5,5 ± 0,5 nm (Ti-6Al-4V polished) 16,2 ± 0,8 nm (Ti-6Al-4V anodizado 25 V) 27,8 ± 3,4 nm (Ti-6Al-4V anodized 50 V) 17,6 ± 2,4 nm (Ti-6Al-4V anodized 75 V)
Zavgorodniy et al., 2011	Ticp	Chemical deposition	Scratch test	Roughness obtained with heat treatment, alkaline treatment and acid treatment: 0,426 ± 0,049 µm (polished without other surface treatments) 0,434 ± 0,052µm (alkaline treatment) 0,453 ± 0,061 µm (acid treatment) 0,595 ± 0,049 µm (heat treatment) 1,121 ± 0,092 µm (blasted surface) 1,421 ± 0,034 µm (blasted surface + heat treatment)
Blackwood et al., 2010	Ti	Electrochemical deposition	Scratch test	Roughness obtained from surface polishing with silicon carbide sandpaper and alumina powder: 323 nm (to the grain 120) 95,51 nm (to the grain 600) 3,16 nm (alumina powder)
Gonzalez-mcquire et al., 2008	Ticp	Sol-gel The study evaluated the adhesion of hydroxyapatite coatings added with L-arginine or L-lysine precursors.	Scratch test	Roughness obtained from surface polishing, acid/peroxide treatment and NaOH treatment: 2,88 µm (without modification) 0,53 µm (polished) 2 µm (acid/peroxide treatment) 2,90 µm (treatment with NaOH)
Oh et al., 2005	Ticp	Plasma spraying	Tensile test	Porous and non-porous substrates were used: 3,7 mm (non-porous titanium substrate) 9,3 mm (porous titanium substrate) 33,7 mm (porous titanium substrate)
Piveteau et al., 2000	Ticp	Sol-gel	Rotary flexural test Tensile test	The author did not report the roughness in numerical form but only defined which surfaces were rougher. The following surfaces were evaluated from smoothest to roughest: Mirror polishing Mechanical polishing Alumina blasting
Ding et al., 1999	Ti-6Al-4V	Radiofrequency magnetron-assisted cathodic spraying	Tensile test	Polished and acid etched surfaces were evaluated: 0,06 µm (mechanically polished) 0,7 µm (acid attack)

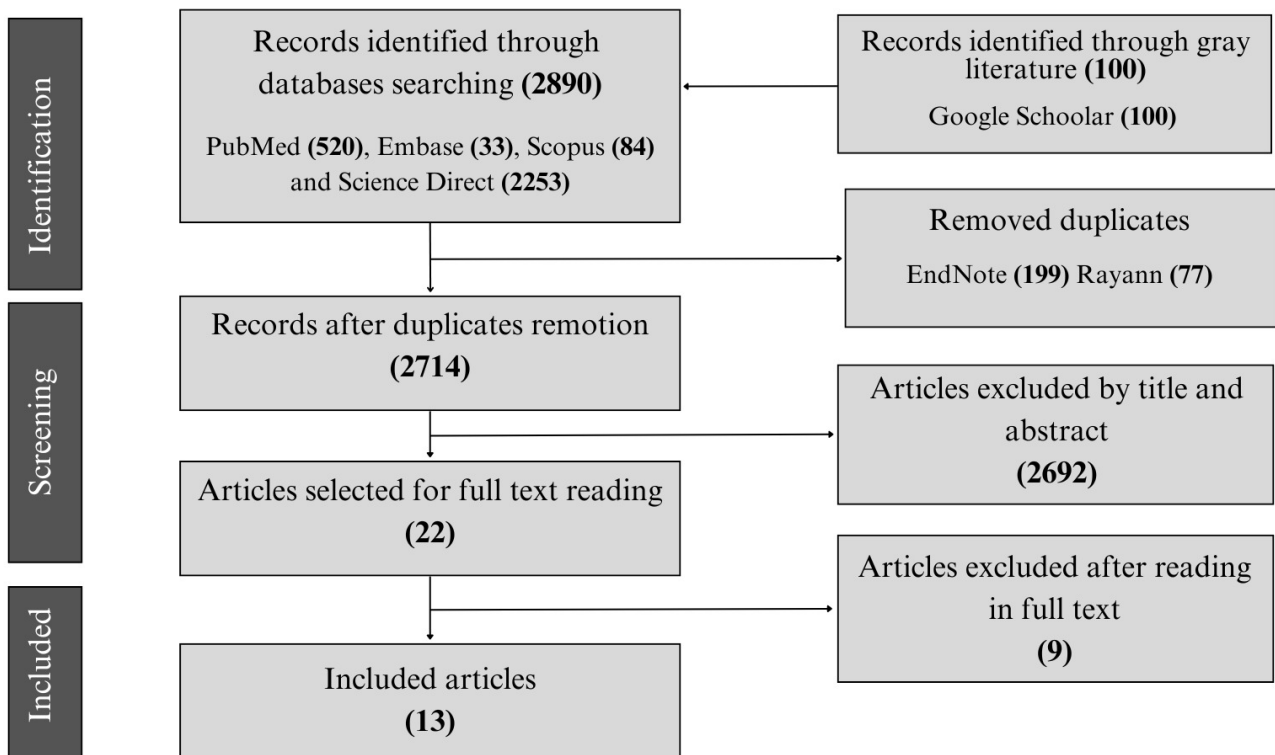


Figure 1: Flowchart of the studies selection process through the different phases of the systematic review.

surface using epoxy resin and applying a tensile load until fracture occurs and the maximum stress is measured.^{36,51} The scratch test, on the other hand, can be carried out using a scratch tester, in which the tip comes into contact with the surface and tensile force is applied at a constant load and speed to obtain scratches which are then analyzed using optical microscopes and characterized in terms of the different types of defects formed, such as cracks, flaking and chipping.^{25,34}

The adhesion of coatings to the metallic substrate is decisive in inhibiting its degradation and favoring its stability.⁵² The action of forces during implant installation may cause delamination of HAp coatings due to frictional wear and generate inflammatory reactions induced by detached particles, which can lead to loosening of the implant and subsequent failure.^{53,54} Therefore, adhesive conditions that ensure the stability of the metal-coating interface in the face of mechanical stress and contact pressure are pertinent⁵⁴ to avoid corrosive fatigue and ensure effective osseointegration and predictability.^{53,55}

Different types of stresses arise depending on the origin of the forces applied and the shape of the implant, such as tensile, shear, and compressive stresses.⁵⁶ The interface between materials with different moduli of elasticity generates mechanical limitations in the face of implant installation forces²⁹ and cyclical occlusal loads (500 N in the canine region, 600 N in premolars, and 800 N in molars).⁵⁶ This increases the risk of corrosion due to delamination of the coating, inflammation in the surrounding tissues, and impaired bone remodeling.⁵⁶

The adhesion between coatings and metallic surfaces benefits from satisfactory covalent interactions,⁵⁷ poor adhesion to the metallic substrate or the inability to resist the mechanical

stresses on the implants make coatings ineffective, even if they have high biological performance.⁵² In this sense, improving covalent bonds by increasing the contact area can favor adhesion between the ceramic coating and the metallic substrate.^{58,59}

Ticp and Ti surfaces are modified to alter their chemical properties, surface topography and wetting capacity.⁴² Moderately rough surfaces (1-2 μm) are described as favorable for cell adhesion, proliferation and viability,⁴² in addition to favoring the adhesion of the HAp coating.²⁵ The articles included involved different methods of modifying the surface before to coating deposition, including chemical methods (acid attack⁶⁰⁻⁶⁴ and alkaline attack),^{62,63} physical (heat treatment,⁶² mechanical polishing,^{8,25,36,38,64,65} laser treatment,²⁵ alumina blasting,³⁶ sandblasting plus acid attack²⁷ and sintering of Ti⁶⁶) and electrochemical (anodizing²⁴).

Among the studies included in this review, authors⁶² which carried out the chemical deposition of the coating on the previously heat-treated surface ($0,595 \pm 0,049 \mu\text{m}$) reached the lowest critical load (1,14 N) necessary to delaminate the coating. While the study⁶³ which had the highest critical load (19 N) had a HAp coating with l-arginine deposited by sol-gel technique on previously polished Ticp surface ($0,53 \mu\text{m}$). Despite similar values for surface roughness on the same alloy with different pre-treatments, different loads were required to break the coatings. This analysis suggests that besides roughness, other factors can affect the adhesion of coatings and indicates that in addition to the surface treatment technique, the coating deposition technique and the coating composition can impact surface-coating adhesion.

Table 2. The main results of the included studies.

First Author and Year of Publication	Main results
Yabutsuka et al., 2020	<p>The results showed that the adhesion force for each of the surfaces Ti6Al4V, Ti-15Mo-5Zr-3Al e (Ti-12Ta-9Nb-6Zr-3Al-O (Gummetal®)) were 9,2 MPa, 22 MPa and 4,4 MPa respectively.</p> <p>In other words, the greater the roughness, the greater the adhesion force obtained.</p> <p>This suggests that the increase in surface roughness was related to improved adhesion of the hydroxyapatite film formed in the biological environment.</p>
Stango et al., 2018	<p>The adhesion of the coatings was better on the laser-treated surfaces. According to the authors, this improved adhesion is related to the increased roughness that keeps the coating more adherent to the surface when compared to an uncoated surface.</p>
Grubova et al., 2017	<p>The load required to delaminate the substrate coating along the scratch path was greater for the rougher surface (~ 3.14 N) compared to the surface with less roughness (~ 2.60 N).</p>
Baptista et al., 2016	<p>According to the authors, the results observed suggest that hydroxyapatite coatings produced on Ti substrates with surface finishes up to 400 grain and particularly up to 800 grain are the most resistant coatings. The least resistant coating was the one deposited on the smoothest surface.</p>
Charitidis et al., 2013	<p>The authors reported that the greatest adhesion was observed on the surface polished to 400 grit, which had an intermediate roughness between the roughnesses evaluated. The surface with the lowest adhesion was polished to 1000 grain and had the lowest surface roughness.</p> <p>The results suggest that roughness may be related to coating adhesion, but that it is not the only factor influencing roughness.</p>
Hieda et al., 2013	<p>When comparing adhesive resistance only between surfaces that have been mechanically polished and the mirror surface, it can be seen that the rougher surfaces have greater adhesive resistance.</p> <p>However, when comparing the adhesive strength of these samples with those treated with acidic solutions, it was observed that greater adhesive strength is not directly related to roughness, since surfaces that have undergone mechanical polishing, which showed lower roughness than surfaces treated with acids (H2SO4 3600s and H2SO4 600s), at the same time showed greater adhesive strength than these surfaces.</p> <p>Adhesive strength was highest for the sample treated with HF 3600s solution (~ 21 MPa), followed by the samples Mechanical polishing with ~1000 grit sandpaper (~ 15 MPa), Mechanical polishing with #1500 grit sandpaper (~ 15 MPa), Mechanical polishing with #2400 grit sandpaper (~ 12.5 MPa), 60s H2SO4 solution (~ 12 MPa), Mirrored surface (~ 10 MPa), H2SO4 3600s solution (~10 MPa), HF 60s solution (~ 9 MPa), HF 600s solution (~ 8 MPa), H2SO4 600s solution (~ 5 MPa).</p> <p>These results indicate that although the general increase in roughness is important because it promotes mechanical anchorage to the coating, this anchorage may also be related to other factors.</p> <p>The author reports that surface morphologies and the sizes of surface asperities are more important for the adhesive strength of hydroxyapatite films than the surface roughness of the substrates.</p>
Roest et al., 2011	<p>For the Ticp alloy, the highest adhesion forces were observed in the roughest samples, with the following adhesion force values: 652 ± 12 MPa for the roughness sample 28,6 ± 3,6 nm; 614 ± 22 MPa for the roughness sample 17,1 ± 0,6 nm; 564 ± 50 MPa for the roughness sample 17,2 ± 1,4 nm; e 538 ± 40 MPa for the roughness sample 5,3 ± 0,2 nm.</p> <p>For the Ti-6Al-4V alloy, similar bond strengths were observed for roughnesses of 5.5 ± 0.5 nm, 16.2 ± 0.8 nm and 27.8 ± 3.4 nm (1073 ± 30 MPa, 1083 ± 25 and 1086 ± 40, respectively). For the 17.6 ± 2.4 nm roughness, the adhesion force was 868 ± 93 MPa.</p> <p>When comparing the adhesion force between the two polished surfaces, it was observed that the Ti-6Al-4V alloy had twice the adhesion force compared to the Ticp alloy, and that both had similar roughness.</p> <p>For the Ticp alloy, adhesion was greater on rougher surfaces, but for the Ti-6Al-4V alloy there was no direct relationship with roughness, which suggests that the adhesion of coatings is also influenced by factors other than roughness.</p>
Zavgorodniy et al., 2011	<p>The critical load required to cause the coatings to fail was highest for the roughest surfaces - sandblasted (13.13 N) and sandblasted + heat treated (10.34). The third roughest sample, the polished sample, had a critical load of 5.89 N, followed by the acid-treated (4.89 N), alkaline-treated (4.17 N) and heat-treated (1.14 N) samples.</p> <p>It can therefore be seen that roughness influenced coating adhesion, as the sandblasted and sandblasted + heat-treated surfaces had more than double the roughness of the other surfaces and a considerably higher critical load than the others. However, this roughness may also be related to other surface characteristics, as the sandblasted + heat-treated surface had greater roughness (1.421) than the sandblasted surface (1.121), and even so had a lower critical load than the latter.</p>
Blackwood et al., 2010	<p>The average critical load to delaminate the coating formed was higher for the rougher surface (323 nm) indicating that stronger adhesion is achieved with a rough surface, which implies that interfacial adhesion between the Ca-P coating and the titanium substrate involves mechanical interlocking.</p> <p>However, when comparing the other two surfaces with smoother roughness (95.51 nm and 3.16nm), the critical load was similar, suggesting that adhesion in this case occurred independently of surface roughness and that roughness is not the only factor influencing adhesion.</p>
Gonzalez-mcquire et al., 2008	<p>When comparing the adhesion of the coatings between the different roughnesses, it was observed that roughness had no direct relationship with adhesion strength, which was more influenced by the composition of the coating.</p> <p>The hydroxyapatite + l-arginine coating showed the highest critical load value (19 N) for the polished samples, while for the other roughnesses the critical load value was similar (13 N/14 N).</p> <p>On the other hand, the hydroxyapatite + l-lysine coating showed the highest critical load value (11 N) for the samples with acid/peroxide treatment, while the critical load values were the same (4 N) for the other roughnesses.</p> <p>Thus, no direct relationship was observed between roughness and coating adhesion.</p>
Oh et al., 2005	<p>The bond strength obtained by the tensile test showed that the bond strength was greater for the more porous surfaces compared to the smooth surfaces. However, when comparing two porous surfaces, the surface with the lowest porosity promoted the greatest bond strength of the coating.</p>
Piveteau et al., 2000	<p>Greater coating adhesion was observed for the rougher surface. However, the increase in adhesion may also be related to the increase in coating thickness, since the mechanically polished surfaces showed less adhesion than the mirror-polished surfaces, which were smoother.</p>
Ding et al., 1999	<p>Coatings with different concentrations of hydroxyapatite were evaluated, with the pure hydroxyapatite coating showing greater adhesion to the rougher surface.</p> <p>However, for coatings with hydroxyapatite concentrations >100%, the roughnesses evaluated had no significant effect on coating adhesion, but in these cases the other component of the coating, which in this case was titanium, may have contributed to improving coating adhesion, making the results of the adhesive tests similar between the different roughnesses.</p>

Legends: D1 (Is it clear in the study what is the “cause” and what is the “effect” (i.e. there is no confusion about which variable comes first?); D2 (Were the participants included in any comparisons similar?); D3 (Did the participants included in any comparisons receive similar treatment/care, in addition to the exposure or intervention of interest?); D4 (Was there a control group?); D5 (Were there several measurements of the outcome before and after the intervention/exposure?); D6 (Was the follow-up complete and, if not, were the differences between the groups in terms of follow-up adequately described and analyzed?); D7 (Were the outcomes of the participants included in any comparisons measured in the same way?); D8 (Were the outcomes measured reliably?); and D9 (Was adequate statistical analysis used?).

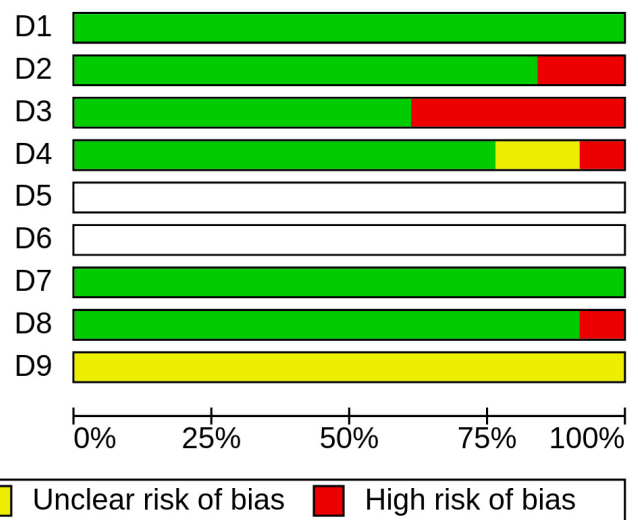


Figure 2: Qualitative analysis with adapted the quasi-experimental studies appraisal tool by the Joanna Briggs Institute.

	D1	D2	D3	D4	D5	D6	D7	D8	D9
Baptista et al., 2016	+	+	+	+			+	+	?
Blackwood et al., 2010	+	+	+	+			+	+	?
Charitidis et al., 2013	+	+	+	?			+	+	?
Ding et al., 1999	+	+	-	+			+	+	?
Gonzalez-mcquire et al., 2008	+	+	-	+			+	+	?
Grubova et al., 2017	+	+	+	-			+	+	?
Hieda et al., 2013	+	+	-	+			+	+	?
Oh et al., 2005	+	+	+	+			+	+	?
Piveteau et al., 2000	+	+	+	+			+	-	?
Roest et al., 2011	+	-	+	+			+	+	?
Stango et al., 2018	+	+	-	+			+	+	?
Yabutsuka et al., 2020	+	-	+	?			+	+	?
Zavgorodniy et al., 2011	+	+	-	+			+	+	?

Figure 3: Qualitative analysis with adapted the quasi-experimental studies appraisal tool by the Joanna Briggs Institute per studies. The white bars correspond to questions D5 and D6, which were not applied to the articles. Question 5 was not applied, as it evaluates measurements before and after the intervention, however, adherence analysis is only carried out after the intervention. Question 6 concerns follow-up; as this review only evaluates in vitro studies, this question was also excluded.

The low adhesion of HAp coatings represented by the low critical load required for delamination can lead to implant failure by compromising the bond with the bone tissue.⁶⁷ The detachment of particles that form debris and trigger inflammatory responses can result in bone resorption and loosening⁶⁸ and even the exposure of metallic areas that favor the attachment and proliferation of bacteria.⁶⁹ It was observed⁵¹ that increasing roughness was the most important factor in improving the coating’s adhesion strength through bonding

with the pores formed and not through chemical bonding. The increase in roughness favors the occupation of HAp in the cavities generated to create mechanical interlocking between the coating and the substrate.²⁵ Another systematic review carried out⁴² corroborates these results by observing that laser treatment of the Ti surface with higher powers and lower scanning speeds not only produces greater roughness, but also provides better adhesion of the coating to the surface.

The failure of the coating-surface adhesion force and the failure of coating-coating cohesion were evaluated by a study²³ which made it possible to observe greater adhesion with rough surfaces than with smooth ones. However, when evaluating two rough substrates, they found that the less rough substrate had a higher cohesive force and more adhesive failures. In this way, it is understood that the adhesion force with the rougher substrate is greater, since the lower cohesion force is related to the coating itself and not to the surface.

Despite a study⁵¹ indicate predominant influence of roughness on adhesion strength, the majority of the articles included^{8,34,36–39,48} indicated that this is not a determining factor for adhesion strength, and that other characteristics may also have an influence, since in some situations less rough surfaces show better adhesion.^{8,34,36–39,48} After analysis it was reported³⁶ that the adhesion force is related to both the surface roughness and the thickness of the coating, other authors⁴⁸ stated that the adhesion strength of HAp coatings derives from a combination of chemical bonding and mechanical imbrication between the coating and the substrate.

Authors found³⁹ similar adhesive strengths for surfaces with different surface roughness, and that treatments that did not provide greater surface area did not improve adhesion strength, even if there was an increase in roughness. Another study⁸ also observed that unlike rough surfaces, those with smoother roughness do not affect adhesion strength. These results indicate that the morphologies and level of roughness are more important for the adhesive strength of HAp films than the roughness of the substrates themselves.

In addition to microtextures and roughness, it was possible to observe that the composition of the coating also has a major influence on its adhesion. Studies^{18,19,21} reported that coatings composed of HAp and titanium dioxide (TiO₂) have improved adhesive properties. In addition, the presence of TiO₂ on the titanium surface itself can also contribute to improving the adhesion of the coating.²⁴ Since previous authors³⁷ evaluated HAp coatings associated with different levels of incorporated Ti and observed that in addition to greater roughness, the incorporation of Ti into the coating contributed to greater adhesion to the substrate. Other authors³⁵ found that HAp coatings with gelation facilitated by l-arginine and l-lysine could also influence the adhesion of the coating. Another study²⁶ observed that fluorinated HAp coatings enhance adhesion when compared to conventional coatings.

Authors²⁴ who evaluated the Ticp alloy and the Ti-6Al-4V alloy with similar roughness, observed that the latter showed better adhesive properties. According to them, the lower values of intrinsic interfacial bonding in Ticp would be related to the deformation and yield stress of the substrate, which play an important role in the evolution of coating damage. In addition, the mixture of anatase and rutile phases could also have caused worse adhesion to Ticp, suggesting that a predominantly anatase structure could bind better to Ti,²⁴ which was confirmed by another study,⁷⁰ by reporting that crystalline anatase provides more effective bonding to bone.³⁸

As limitations of this systematic review, the authors highlight the heterogeneity of the included studies, especially in deposition methods, coating adhesion analysis and the different Ti alloys evaluated. In addition, the primary studies included in this review did not explore in detail the chemical interactions between the HAp coatings and the Ti substrate, nor the surface characteristics of the coated implant, such as morphology and roughness after deposition. Therefore, further studies focusing on these factors in greater detail could provide more effective answers on the influence of roughness on the adhesion of HAp substrates to the surface of Ti and its alloys.

As observed, this review presented evidence that there is an influence between the surface roughness of Ti and cp Ti on the adhesion of HAp coatings as a result of the mechanical imbrication between surface-coating and the greater cohesive force provided between coating-coating. As seen previously, the thickness of the coating itself also influences its ability to adhere to the Ti substrate, as do the stress and deformation of this substrate, which are related to the evolution of damage to the coating and consequent failure. Thus, in addition to the need to evaluate how these factors act on the adhesion capacity between coating and surface, it is important to investigate how resistant the coatings must be to withstand the loads related to implant installation. This information will contribute to the development of coatings with adhesive properties that work better clinically.

FINAL CONSIDERATIONS

From the *in vitro* results gathered in this systematic review, it was possible to conclude that surface roughness is an important factor in the adhesion of HAp coatings on Ti. However, other characteristics also have influence and need to be considered, such as the composition and thickness of the coating, the morphology and composition of the surface, the Ti alloy used, and the pre-treatment method used.

REFERENCES

1. Pierre, C., Bertrand, G., Rey, C., Benhamou, O. and Combes, C. Calcium phosphate coatings elaborated by the soaking process on titanium dental implants: Surface preparation, processing and physical-chemical characterization. *Dent Mater.* 2019; **35**:e25–35.
2. Zavgorodniy, A.V., Borrero-López, O., Hoffman, M., Legeros, R.Z. and Rohanzadeh, R. Mechanical stability of two-step chemically deposited hydroxyapatite coating on Ti substrate: Effects of various surface pre-treatments. *J Biomed Mater Res B Appl Biomater.* 2011; **99B**:58–69.
3. Safi, I.N., Hussein, B.M.A., Al Shammari, A.M. and Tawfiq, T.A. Implementation and characterization of coating pure titanium dental implant with sintered β -TCP by using Nd:YAG laser. *Saudi Dental Journal.* 2019; **31**:242–250.
4. Wang, L., Xu, C., Meng, K., Xia, Y., Zhang, Y., Lian, J., et al. Biomimetic hydroxyapatite composite coatings with a variable morphology mediated by silk fibroin and its derived peptides enhance the bioactivity on titanium. *ACS Biomater Sci Eng.* 2023; **9**:165–181.

5. Yabutsuka, T., Kidokoro, Y. and Takai, S. Improvement of hydroxyapatite formation ability of titanium-based alloys by combination of acid etching and apatite nuclei precipitation. *IET Nanobiotechnol.* 2020; **14**:688–694.
6. Zhu, G., Peng, Q., Luo, T., Pan, H., Wang, Y. and Peng, Z. Synthesis of Ti6Al4V/SrFHA Composites by microwave-assisted liquid phase deposition and calcination. *Materials.* 2022; **15**:6206.
7. Souza, J.C.M., Sordi, M.B., Kanazawa, M., Ravindran, S., Henriques, B., Silva, F.S., et al. Nano-scale modification of titanium implant surfaces to enhance osseointegration. Vol. 94, *Acta Biomaterialia. Acta Materialia Inc*; 2019. p.112–31.
8. Blackwood, D.J. and Seah, K.H.W. Influence of anodization on the adhesion of calcium phosphate coatings on titanium substrates. *J Biomed Mater Res A.* 2010; **93**:1551–1556.
9. Mohseni, E., Zalnezhad, E. and Bushroa, A.R. Comparative investigation on the adhesion of hydroxyapatite coating on Ti-6Al-4V implant: A review paper. *Int J Adhes Adhes.* 2014; **48**:238–257.
10. Guillem-Marti, J., Cinca, N., Punset, M., Cano, I.G., Gil, F.J., Guilemany, J.M., et al. Porous titanium-hydroxyapatite composite coating obtained on titanium by cold gas spray with high bond strength for biomedical applications. *Colloids Surf B Biointerfaces.* 2019; **180**:245–253.
11. Ghadami, F., Amani Hamedani, M., Rouhi, G., Saber-Samandari, S., Mehdi Dehghan, M., Farzad-Mohajeri, S., et al. The correlation between osseointegration and bonding strength at the bone-implant interface: *In-vivo* & *ex-vivo* investigations on hydroxyapatite and hydroxyapatite/titanium coatings. *J Biomech.* 2022; **144**:111310.
12. Heimann, R.B. Structure, properties, and biomedical performance of osteoconductive bioceramic coatings. *Surf Coat Technol.* 2013; **233**:27–38.
13. Khalili, V. and Naji, H. Developing a mechanochemical surface pretreatment to increase the adhesion strength of hydroxyapatite electrophoretic coating on the NiTi alloy as a bone implant. *Surf Coat Technol.* 2020; **397**:125985.
14. Mohseni, E., Zalnezhad, E. and Bushroa, A.R. Comparative investigation on the adhesion of hydroxyapatite coating on Ti-6Al-4V implant: A review paper. *Int J Adhes Adhes.* 2014; **48**:238–257.
15. Yılmaz, E., Çakıroğlu, B., Gökçe, A., Fındık, F., Gulsoy, H.O., Gulsoy, N., et al. Novel hydroxyapatite/graphene oxide/collagen bioactive composite coating on Ti16Nb alloys by electrodeposition. *Mater Sci Eng C.* 2019; **101**:292–305.
16. Zavgorodniy, A.V., Borrero-López, O., Hoffman, M., Legeros, R.Z. and Rohanizadeh, R. Mechanical stability of two-step chemically deposited hydroxyapatite coating on Ti substrate: Effects of various surface pretreatments. *J Biomed Mater Res B Appl Biomater.* 2011; **99B**:58–69.
17. Barfeie, A., Wilson, J. and Rees, J. Implant surface characteristics and their effect on osseointegration. *Br Dent J.* 2015; **218**:E9
18. Araghi, A. and Hadianfard, M.J. Fabrication and characterization of functionally graded hydroxyapatite/TiO₂ multilayer coating on Ti-6Al-4V titanium alloy for biomedical applications. *Ceram Int.* 2015; **41**:12668–12679.
19. Mohan, L., Durgalakshmi, D., Geetha, M., Sankara Narayanan, T.S.N. and Asokamani, R. Electrophoretic deposition of nanocomposite (HAP + TiO₂) on titanium alloy for biomedical applications. *Ceram Int.* 2012; **38**:3435–3443.
20. Rath, P.C., Besra, L., Singh, B.P. and Bhattacharjee, S. Titania/hydroxyapatite bi-layer coating on Ti metal by electrophoretic deposition: Characterization and corrosion studies. *Ceram Int.* 2012; **38**:3209–3216.
21. Rocha, R.C., de Sousa Galdino, A.G., da Silva, S.N. and Machado, M.L.P. Surface, microstructural, and adhesion strength investigations of a bioactive hydroxyapatite-titanium oxide ceramic coating applied to Ti-6Al-4V alloys by plasma thermal spraying. *Materials Research.* 2018;**21**(4).
22. Li, H., Khor, K.A. and Cheang, P. Adhesive and bending failure of thermal sprayed hydroxyapatite coatings: Effect of nanostructures at interface and crack propagation phenomenon during bending. *Eng Fract Mech.* 2007; **74**:1894–1903.
23. Oh, I.H., Nomura, N., Chiba, A., Murayama, Y., Masahashi, N., Lee, B.T., et al. Microstructures and bond strengths of plasma-sprayed hydroxyapatite coatings on porous titanium substrates. *J Mater Sci Mater Med* 2005; **16**:635–640.
24. Roest, R., Latella, B.A., Heness, G. and Ben-Nissan, B. Adhesion of sol-gel derived hydroxyapatite nanocoatings on anodised pure titanium and titanium (Ti6Al4V) alloy substrates. *Surf Coat Technol.* 2011; **205**:3520–3529.
25. Stango, S.A.X., Karthick, D., Swaroop, S., Mudali, U.K. and Vijayalakshmi, U. Development of hydroxyapatite coatings on laser textured 316 LSS and Ti-6Al-4V and its electrochemical behavior in SBF solution for orthopedic applications. *Ceram Int.* 2018; **44**:3149–3160.
26. Zhang, S., Wang, Y.S., Zeng, X.T., Khor, K.A., Weng, W. and Sun, D.E. Evaluation of adhesion strength and toughness of fluoridated hydroxyapatite coatings. *Thin Solid Films.* 2008; **516**:5162–5167.
27. Grubova, I., Priamushko, T., Surmeneva, M., Korneva, O., Epple, M., Prymak, O., et al. Sand-blasting treatment as a way to improve the adhesion strength of hydroxyapatite coating on titanium implant. *J Phys Conf Ser.* 2017; **830**:012109.
28. Ko, Y.C., Lee, D., Koo, K.T., Seol, Y.J., Lee, Y.M. and Lee, J. A randomized controlled trial of immediate implant placement comparing hydroxyapatite nano-coated and uncoated sandblasted/acid-etched implants using a digital surgical guide. *Int J Implant Dent.* 2024; **10**:29
29. Schönweger, F., Sprecher, C.M., Milz, S., Dommann-Scherrer, C., Meier, C., Dommann, A., et al. New insights into osteointegration and delamination from a multidisciplinary investigation of a failed hydroxyapatite-coated hip joint replacement. *Materials.* 2020; **13**:1–17.
30. Silva-Bermudez, P. and Rodil, S.E. An overview of protein adsorption on metal oxide coatings for biomedical implants. *Surface and Coatings Technology.* 2013; **233**:147–158
31. Lee, J.J., Rouhfar, L. and Beirne, O.R. Survival of hydroxyapatite-coated implants: A meta-analytic review. *J Oral Maxillofac Surg.* 2000; **58**:1372–1379.
32. Almeida, D., Sartoretto, S.C., Calasans-Maia, J.A., Ghiraldini, B., Bezerra, F.J.B., Granjeiro, J.M., et al. *In vivo* osseointegration evaluation of implants coated with nanostructured hydroxyapatite in low density bone. *PLoS One.* 2023; **18**:e0282067.
33. Leonardi de Oliveira Rigotti, R., Dias Corpa Tardelli, J. and Cândido Dos Reis, A. Influence of antibacterial surface treatment on dental implants on cell viability: A systematic review. *Heliyon.* 2023; **9**:e13693.
34. Baptista, R., Gadelha, D., Bandeira, M., Arteiro, D., Delgado, M.I., Ferro, A.C., et al. Characterization of titanium-hydroxyapatite biocomposites processed by dip coating. *Bull Mater Sci.* 2016; **39**:263–272.
35. Gonzalez-McQuire, R. and Tsetsekou, A. Hydroxyapatite-biomolecule coatings onto titanium surfaces. *Surf Coat Technol.* 2008; **203**:186–190.
36. Piveteau, L.D., Gasser, B. and Schlapbach, L. Evaluating mechanical adhesion of sol-gel titanium dioxide coatings containing calcium phosphate for metal implant application. *Biomaterials.* 2000; **21**:2193–2201.
37. Ding, S.J., Ju, C.P. and Lin, J.H.C. Characterization of hydroxyapatite and titanium coatings sputtered on Ti-6Al-4V substrate. *J Biomed Mater Res.* 1999; **44**:266–279.
38. Charitidis, C.A., Skarmoutsou, A., Tsetsekou, A., Brasinika, D. and Tsiourvas, D. Nanomechanical properties of hydroxyapatite (HAP) with DAB dendrimers (poly-propylene imine) coatings onto titanium surfaces. *Materials Science and Engineering: B.* 2013; **178**:391–399.

39. Hieda, J., Niinomi, M., Nakai, M., Cho, K., Gozawa, T., Katsui, H., et al. Enhancement of adhesive strength of hydroxyapatite films on Ti-29Nb-13Ta-4.6Zr by surface morphology control. *J Mech Behav Biomed Mater.* 2013; **18**:232–239.
40. Behera, R.R., Hasan, A., Sankar, M.R. and Pandey, L.M. Laser cladding with HA and functionally graded TiO₂-HA precursors on Ti-6Al-4V alloy for enhancing bioactivity and cyto-compatibility. *Surf Coat Technol.* 2018; **352**:420–436.
41. Simões, I.G., Kreve, S., Cruz, M.A.E., Botelho, A.L., Ramos, A.P., dos Reis, A.C., et al. Influence of Er:YAG laser irradiation on surface properties of Ti-6Al-4V machined and hydroxyapatite coated. *Lasers Med Sci.* 2023; **38**:48.
42. Simões, I.G., Dos Reis, A.C. and da Costa Valente, M.L. Analysis of the influence of surface treatment by high-power laser irradiation on the surface properties of titanium dental implants: A systematic review. *J Prosthet Dent.* 2023; **129**:863–870.
43. Calazans Neto, J.V., Kreve, S., Valente, M.L.D.C. and Reis, A.C.D. Protein absorption on titanium surfaces treated with a high-power laser: A systematic review. *J Prosthet Dent.* 2024; **131**:591–597.
44. Eom, T.G., Jeon, G.R., Jeong, C.M., Kim, Y.K., Kim, S.G., Cho, I.H., et al. Experimental study of bone response to hydroxyapatite coating implants: Bone-implant contact and removal torque test. *Oral Surg Oral Med Oral Pathol Oral Radiol.* 2012; **114**:411–418.
45. Jemat, A., Ghazali, M.J., Razali, M. and Otsuka, Y. *Surface modifications and their effects on titanium dental implants.* Vol. 2015, BioMed Research International. Hindawi Publishing Corporation; 2015.
46. McManamon, C., de Silva, J.P., Power, J., Ramirez-Garcia, S., Morris, M.A. and Cross, G.L.W. Interfacial characteristics and determination of cohesive and adhesive strength of plasma-coated hydroxyapatite via nanoindentation and microscratch techniques. *Langmuir.* 2014; **30**:11412–11420.
47. Raihan, M.M., Otsuka, Y., Tsuchida, K., Manonukul, A., Ohnuma, K. and Miyashita, Y. Damage evaluation of HAP-coated porous titanium foam in simulated body fluid based on compression fatigue behavior. *J Mech Behav Biomed Mater* 2021; **117**:104383.
48. Zavgorodniy, A.V., Borrero-López, O., Hoffman, M., Legeros, R.Z. and Rohanizadeh, R. Mechanical stability of two-step chemically deposited hydroxyapatite coating on ti substrate: effects of various surface pretreatments. *J Biomed Mater Res B Appl Biomater.* 2011; **99B**:58–69.
49. Page, M.J., Moher, D., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., et al. PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *BMJ.* 2021; **372**:n160.
50. Ouzzani, M., Hammady, H., Fedorowicz, Z. and Elmagarmid, A. Rayyan-a web and mobile app for systematic reviews. *Syst Rev.* 2016; **5**:210.
51. Yabutsuka, T., Kidokoro, Y. and Takai, S. Improvement of hydroxyapatite formation ability of titanium-based alloys by combination of acid etching and apatite nuclei precipitation. *IET Nanobiotechnol.* 2020; **14**:688–694.
52. Tardelli, J.D.C., Schiavon, M.A. and dos Reis, A.C. Chitosan coatings on titanium-based implants - From development to characterization and behavior: A systematic review. *Carbohydr Polym* 2024; **344**:122496.
53. Nagentrau, M., Mohd Tobi, A.L., Jamian, S., Otsuka, Y. and Hussin, R. Delamination-fretting wear failure evaluation at HAP-Ti-6Al-4V interface of uncemented artificial hip implant. *J Mech Behav Biomed Mater.* 2021; **122**:104657.
54. Otsuka, Y., Kawaguchi, H. and Mutoh, Y. Cyclic delamination behavior of plasma-sprayed hydroxyapatite coating on Ti-6Al-4V substrates in simulated body fluid. *Mater Sci Eng C Mater Biol Appl* 2016; **67**:533–541.
55. Raihan, M.M., Otsuka, Y., Tsuchida, K., Manonukul, A., Ohnuma, K. and Miyashita, Y. Damage evaluation of HAP-coated porous titanium foam in simulated body fluid based on compression fatigue behavior. *J Mech Behav Biomed Mater.* 2021 May 1; **117**:104383.
56. Li, J., Jansen, J.A., Walboomers, X.F. and van den Beucken, J.J. Mechanical aspects of dental implants and osseointegration: A narrative review. *J Mech Behav Biomed Mater.* 2020; **103**:103574.
57. Rashed, A.A., Misnan, N.M. and Nawi, M.N.M. Chitosan-based formulation for bone health: A review. *Carbohydrate Polymer Technologies and Applications.* 2023; **6**:100359.
58. Terek, P., Kovačević, L., Terek, V., Bobić, Z., Miletić, A., Škorić, B., et al. Surface roughness and its effect on adhesion and tribological performance of magnetron sputtered nitride coatings. *Coatings.* 2024; **14**:1010.
59. Imbriglio, S.I. and Chromik, R.R. Factors affecting adhesion in metal/ceramic interfaces created by cold spray. *Journal of Thermal Spray Technology.* 2021; **30**:1703–1723.
60. Yabutsuka, T., Kidokoro, Y. and Takai, S. Improvement of hydroxyapatite formation ability of titanium-based alloys by combination of acid etching and apatite nuclei precipitation. *IET Nanobiotechnol.* 2020; **14**:688–694.
61. Hieda, J., Niinomi, M., Nakai, M., Cho, K., Gozawa, T., Katsui, H., et al. Enhancement of adhesive strength of hydroxyapatite films on Ti-29Nb-13Ta-4.6Zr by surface morphology control. *J Mech Behav Biomed Mater.* 2013; **18**:232–239.
62. Zavgorodniy, A.V., Borrero-López, O., Hoffman, M., Legeros, R.Z. and Rohanizadeh, R. Mechanical stability of two-step chemically deposited hydroxyapatite coating on Ti substrate: Effects of various surface pretreatments. *J Biomed Mater Res B Appl Biomater.* 2011; **99B**:58–69.
63. Gonzalez-McQuire, R, Tsetsekou, A. Hydroxyapatite-biomolecule coatings onto titanium surfaces. *Surf Coat Technol.* 2008; **203**:186–190.
64. Ding, S.J., Ju, C.P. and Lin, J.H.C. Characterization of hydroxyapatite and titanium coatings sputtered on Ti-6Al-4V substrate. *J Biomed Mater Res.* 1999; **44**:266–279.
65. Baptista, R., Gadelha, D., Bandeira, M., Arteiro, D., Delgado, M.I., Ferro, A.C., et al. Characterization of titanium-hydroxyapatite biocomposites processed by dip coating. *Bull Mater Sci.* 2016; **39**:263–272.
66. Oh, I.H., Nomura, N., Chiba, A., Murayama, Y., Masahashi, N., Lee, B.T., et al. Microstructures and bond strengths of plasma-sprayed hydroxyapatite coatings on porous titanium substrates. *J Mater Sci Mater Med.* 2005; **16**:635–640.
67. Gardon, M., Concustell, A., Dosta, S., Cinca, N., Cano, I.G. and Guilemany, J.M. Improved bonding strength of bioactive cermet cold gas spray coatings. *Mater Sci Eng C Mater Biol Appl.* 2014; **45**:117–121.
68. Mestres, G., Espanol, M., Xia, W., Persson, C., Ginebra, M.P. and Ott, M.K. Inflammatory response to nano- and microstructured hydroxyapatite. *PLoS One.* 2015; **10**:e0120381.
69. Lakshmi Mounika, K., Lanke, R.B., Mudaliyar, M.C., Khandelwal, S., Gaddam, B. and Boyapati, R. Comprehensive evaluation of novel biomaterials for dental implant surfaces: an *in vitro* comparative study. *Cureus.* 2024; **16**:e61175.
70. Liang, B., Fujibayashi, S., Neo, M., Tamura, J., Kim, H.M., Uchida, M., et al. Histological and mechanical investigation of the bone-bonding ability of anodically oxidized titanium in rabbits. *Biomaterials.* 2003; **24**:4959–4966.

SUPPLEMENTARY TABLES

Supplementary Table 1. Database search strategies.

Database	Search strategy	Found
Science Direct May 25th, 2024	("titanium" OR "dental implant") AND ("surface roughness" OR "roughness") AND ("hydroxyapatite coating" OR "hydroxyapatite") AND ("coating strength" OR "scratch resistance" OR "toughness")	2253
PubMed May 25th, 2024	("titanium"[Mesh Terms] OR "titanium"[All Fields] OR "dental implants"[Mesh Terms] OR "dental implants"[All Fields] OR "implants"[All Fields]) AND ("surface roughness"[All Fields] OR "roughness"[All Fields]) AND ("hydroxyapatite coating"[All Fields] OR "hydroxyapatite"[All Fields] OR "coating"[All Fields]) AND ("coating adhesion"[All Fields] OR "coating strength"[All Fields] OR "scratch resistance"[All Fields] OR "toughness"[All Fields] OR "strength"[All Fields] OR "resistance" [All Fields] OR "adhesion"[All Fields])	520
Embase May 25th, 2024	('titanium'/exp OR 'titanium' OR 'dental implant'/exp OR 'dental implant' OR 'implant'/exp OR 'implant') AND ('surface roughness'/exp OR 'surface roughness' OR 'roughness'/exp OR 'roughness') AND ('hydroxyapatite coating' OR 'hydroxyapatite'/exp OR 'hydroxyapatite' OR 'coating'/exp OR 'coating') AND ('coating adhesion' OR 'coating strength' OR 'scratch resistance'/exp OR 'scratch resistance' OR 'toughness'/exp OR 'toughness')	33
Scopus May 25th, 2024	('titanium' OR 'dental implant' OR 'implant') ('surface roughness' OR 'roughness') AND ('hydroxyapatite coating' OR 'hydroxyapatite' OR 'coating') AND ('coating adhesion' OR 'coating strength' OR 'scratch resistance' OR 'toughness' OR 'adhesion' OR 'strenght' OR 'scratch' OR 'resistance')	84