



UNIVERSIDADE
FERNANDO
PESSOA

ANALYSIS OF DENTAL IMPLANT FIXTURES FRACTURES: INCIDENCE, FACTORS AND CHARACTERISTICS

[Análise de Fraturas de Implantes Dentários: Incidência, Fatores e Características]

Dissertação de Mestrado

[Mestrado Integrado em Medicina Dentária]

Karim Oumalou

Orientador:

Professor Doutor Pedro Jorge Gonçalves Pereira

August 2024

ANALYSIS OF DENTAL IMPLANT FIXTURES FRACTURES: INCIDENCE, FACTORS AND CHARACTERISTICS

[Análise de Fraturas de Implantes Dentários: Incidência, Fatores e Características]

Dissertação de Mestrado

[Mestrado Integrado em Medicina Dentária]

Karim Oumalou

Orientador:

Professor Doutor Jorge Augusto Martins Pereira

August 2024

First and foremost, I give thanks to God, the source of all wisdom and discernment, for guiding me throughout this journey.

To my mother, whose unconditional love and unwavering support have been an anchor in my life. Thank you for always being by my side, through moments of doubt and moments of success. Your patience, wisdom, and constant encouragement have given me the strength to persevere. You are and will always be a model of dedication and kindness to me.

To my wife, my companion and my pillar, who has patiently and devotedly managed our household responsibilities in my absence. Your love and understanding have been a constant source of comfort and motivation. Thank you for always believing in me.

To my daughter, whose bright presence and smiles have been a constant source of motivation and joy. Your zest for life and innocence inspires me to be a better person every day.

To my uncle and aunts, whose paths I have followed and whose guidance and examples have helped shape my journey. Your achievements and support have been a source of inspiration and direction.

To my sisters and cousins for their unwavering support and encouragement. Your constant motivation, understanding, and love have been invaluable to me, and I am truly thankful for everything you have done to help me reach this milestone.

Finally, to my grandparents, who are no longer with us but whose benevolent influence continues to accompany me each day. Their memory is a precious legacy that inspires and comforts me.

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to all those who contributed to the completion of this thesis.

First and foremost, I sincerely thank my thesis advisor, Professor Doutor Pedro Jorge Gonçalves Pereira, for their guidance, insightful advice, and unwavering support throughout this endeavor. Your expertise, scientific rigor, and patience have been crucial to the success of this project. Thank you for your availability, immense kindness, and for creating a calm and supportive work environment. Your compassionate approach has made this experience enriching and enjoyable. Additionally, I am grateful for your prompt responses to emails, which facilitated efficient communication and progress.

I also extend my gratitude to all the professors for their quality teaching and dedication to their students. Your lectures, guidance, and passion for the discipline have been a constant source of inspiration and motivation throughout my academic journey.

A special thank you to the dental assistants at the school, whose invaluable assistance and logistical support were essential to the smooth progress of my practical work. Your professionalism and kindness greatly facilitated my learning.

I would also like to express my appreciation to all the staff in the administration. Your efficiency and administrative support were crucial in overcoming the logistical and administrative challenges of this project. Thank you for your diligence and constant dedication.

Finally, I warmly thank everyone who has contributed, directly or indirectly, to the completion of this thesis. Your support, encouragement, and belief in me have been invaluable throughout this journey.

ABSTRACT

Implant fracture is one of the rare complications in Implant Dentistry that leads to implants failure.

Such complications pose important problems to both the patient and the dental surgeon.

The objective of this comprehensive review was to examine how particular implant characteristics, such as diameter, length, design, connection type, position, and type of implants materials can lead to various complications encompassing both biological and mechanical issues, that may contribute to fractures or cracks in the implant fixture

Methods: The bibliographic research was conducted in PubMed/Medline database, Cochrane Library, ScienceDirect, IEEE Xplore and Google Scholar from which 16 studies published were selected.

Results: This review also highlights the location of fractures, while reporting a 0.65% incidence of implant fixture fracture. Most implants functioned for 3 to 5 years before fracturing. However, the studies did not provide sufficient information to establish a correlation between different implant parameters and the incidence of fractures.

Conclusion: Based on the reviewed studies, the design, particularly the type of connection, diameter, and composition of dental implants, significantly influence fracture risk and determine the type, position, and direction of fixture fractures. The proposed detailed fracture classification can aid in identifying various fixture fractures, enhancing understanding of fracture mechanisms and predicting potential failure points.

Key words: "dental implant fixture", "crack", "fatigue", "mechanical stress", "fractography".

RESUMO

A fratura de implante é uma das complicações raras na implantodontia que leva à falha dos implantes. Tais complicações apresentam problemas importantes tanto para o paciente quanto para o cirurgião dentista. O objetivo desta revisão abrangente foi examinar como determinadas características dos implantes, como diâmetro, comprimento, design, tipo de conexão, posição e tipo de materiais dos implantes, podem levar a várias complicações abrangendo questões biológicas e mecânicas, que podem contribuir para fraturas ou fissuras no corpo do implante.

Métodos: A pesquisa bibliográfica foi conduzida nas bases de dados PubMed/Medline database, Cochrane Library, ScienceDirect, IEEE Xplore and Google Scholar, das quais 16 estudos publicados foram selecionados.

Resultados: Esta revisão também destaca a localização das fraturas, ao mesmo tempo em que relata uma incidência de 0,65% de fratura do corpo do implante. A maioria dos implantes funcionou por 3 a 5 anos antes de fraturar. No entanto, os estudos não forneceram informações suficientes para estabelecer uma correlação entre os diferentes parâmetros dos implantes e a incidência de fraturas.

Conclusão: Com base nos estudos revisados, o design, particularmente o tipo de conexão, diâmetro e composição dos implantes dentários, influencia significativamente o risco de fratura e determina o tipo, a posição e a direção das fraturas da fixação. A proposta detalhada de classificação das fraturas pode ajudar a identificar várias fraturas de corpo, melhorando a compreensão dos mecanismos de fratura e prevenindo pontos potenciais de falha.

Palavras-chave: "fractura de implante dentário", "fissura", "fadiga", "stress mecânico", "fractografia".

TABLE OF CONTENTS

1 INTRODUCTION	1
1.1. Mechanical properties	2
1.2. Mechanical complications - Fatigue	3
1.3. Risk factors associated with implant fixture fracture	6
1.4. Biomechanical behavior of implants	7
1.4.1 Diameter	7
1.4.2 Length.....	8
1.4.3 Position and alignment	8
1.4.4 Implant design and Connection	8
1.4.5 Materials.....	13
1.4.6 Surface treatment.....	18
1.5. Management of implant fracture	18
2 MATERIALS AND METHODS	21
2.1. Focused question and study objective:	21
2.2. Search strategy	21
2.3. Selection process of articles	22
2.4. Synthesis of the results	23
2.5. Selection of studies.....	23
2.6. General description of the included studies.....	25
2.7. Risk of bias	25
3 RESULTS	29
3.1. Rates.....	29
3.2. Diameter	30
3.3. Length.....	31
3.4. Position and alignment	31
3.5. Implant Fracture location	32
4 DISCUSSION	35
4.1. Diameter	35
4.2. Length.....	38
4.3. Installation Region (Maxilla/Mandible)	39
4.4. Design Connection	39
4.5. Fixture fracture classification proposal.....	40
5 CONCLUSION	51
6 BIBLIOGRAPHY	53

TABLE OF FIGURES

Figure 1: Identification of studies via databases and registers	23
Figure 2: Classification of fixture fractures in selected studies.....	43

TABLE OF TABLES

Table 1: Mechanical Properties of Titanium Used in Dental Implants	15
Table 2: Performance of Ultrafine Grained Titanium.....	15
Table 3: List of Retrospective Selected Studies.....	24
Table 4: List of in vitro Selected Studies.....	24
Table 5: The Cochrane Collaboration's tool for assessing the risk of bias.....	26
Table 6: Rates and times to fractures.....	29
Table 7: Fracture incidence according to implant diameter	30
Table 8: Fracture rate according to implant length.....	31
Table 9: Position of fractured dental implant.....	32
Table 10: Location of fractured dental implant.....	32

TABLE OF ABBREVIATIONS

Alloy – Titanium–aluminum–vanadium (Ti-6Al-4V)

CP4 – Commercially pure titanium

Dcp – (direction of crack propagation)

ELI – *Extra-Low Interstitial*

ECAP – Equal channel angular pressing

FEA – Finite Element Analysis

TiZr: Titanium-zirconium alloys

Zr – Zirconia

NR – Not Reported

Hex – Hexagonal

PEEK – *Polyether-ether-ketone*

PICO – *Population, Intervention, Comparison, Outcome*

PRISMA statement – *Preferred Reporting Items for Systematic Reviews and Meta Analyses*

SEM – *scanning electron microscopy*

Ti – Titanium

TiZr – Titanium-zirconium alloys

Zr – Zirconia

1 INTRODUCTION

Dental implants are one of the most common treatment options for the rehabilitation of patients with partial or total edentulism, providing the patient with a functional and aesthetic solution. Although the long-term maintenance of osseointegration has been confirmed by several studies (Gargallo et al., 2008), as well as a high success and survival rate (Moraschini et al., 2015), dental implants and the prostheses they support can be subject to complications, in particular implant loss, which is a major problem for both patient and practitioner.

There are many reasons for implant failure, including osseointegration failure, infectious complications leading to loss of implant-supporting tissue, and mechanical complications resulting in fractures of prosthetic restorations, abutments, screws or implant fixture (Esposito et al., 1998).

Fractures of the implant fixture remain an exceptional complication that may occur during implant placement, or a mechanical complication following loading of the prosthesis, the incidence of which is estimated at between 0.2% and 1.5%. Gargallo et al. (2008) identifies the 3rd and 4th years as a high-risk period (Berglundh et al., 2002; Goodacre et al., 2003; Gargallo et al., 2008).

The management of this complication is difficult, and may involve additional surgery requiring modification of the existing implant or insertion of a new one (Goodacre et al., 2003), with the main aim of being as conservative as possible in terms of bone volume, so as to allow re-implantation.

Moreover, if implant fracture is not noticed in time, it may lead to other biomechanical complications, including failure or fracture of other implants, implant components or implant-supported prostheses (Esposito et al., 1998).

Consideration of risk factors, which can be classified into four categories, is essential to ensure the longevity of this treatment:

- Materials (implant design, nature and chemical composition, etc.) (Eckert et al., 2015)
- Biomechanical factors (implant position, diameter, length, type of connection, cantilever) (Shemtov-Yona et al., 2012)

- patient-related factors: biomechanical overload, bruxism) (De Carvalho et al., 2012; Kochar et al., 2022; Kong et al., 2009) or bone loss around the implant (Gargallo et al., 2008).
- iatrogenic factors (poor treatment planning and prosthesis design, errors during insertion) (Chang et al., 2013; Kochar et al., 2022; Yokoyama et al., 2002)

The objective of this review was to examine how particular implant characteristics, such as diameter, length, connection type, position, angle placement and type of implants materials can lead to various complications encompassing both biological and mechanical issues, that may contribute to fractures or cracks in the implant fixture.

This thesis is divided into three sections:

- The first section consists in a Review of the Literature with a review of background knowledge and current understanding of dental Implant, implant fracture and related risk indicators, mechanical behaviour, fatigue and fractography analysis.
- A second section based on the study objectives, material and methods, results.
- The last section consists of discussing about the findings of our study compared to previous research/articles done previously and **propose a classification of dental implant fractures based on the fracture pattern of the fixture.**

1.1. Mechanical properties

The mechanical properties of dental implants are crucial to their stability, durability and long-term success. They relate to the implant's behaviour within the bone under axial or lateral pressure, to the forces within it and to the stress induced by its material, which may be ductile or brittle. In short, it can be defined as the resistance to deformation, crack formation or fracture of a material subjected to an applied force or pressure and the stress induced over a long period of time (Anusavice, 2013).

An important parameter is the Strength that characterizes the maximum stress a material can withstand before fracturing (Anusavice, 2013). It's referring to the capacity of a material to withstand applied stress without undergoing fracture or enduring permanent deformation. Plastic deformation becomes evident when the elastic stress threshold is exceeded.

The fracture potential of implants is linked to the mechanical properties and microstructure of the implant material (Moraschini et al., 2015; Tey et al., 2016). Mechanical properties encompass the observed behaviours of materials when subjected to an external force, distribution of forces, or pressure, including both elastic and plastic responses. These properties are commonly quantified in terms of stress and/or strain units. They serve as indicators (Moraschini et al., 2015; Tey et al., 2016) of various aspects such as:

- elastic behaviour (resilience, elasticity),
- plastic behaviour (elongation and hardness);
- or a combination of both elastic and plastic deformation (toughness and yield strength).

Understanding these concepts involves examining the relationship between stress and strain: stress induced by external forces or pressure leads to deformation or strain (Anusavice, 2013).

1.2. Mechanical complications - Fatigue

Following Shemtov-Yona & Rittel (Shemtov-Yona & Rittel, 2015b), mechanical complications are a generic term for mechanical damage of the implant, its components, or to the superstructure supported by the implant. Implant loss, in the context of mechanical complications, includes of course implant fracture.

Dental implant failures can be classified into two categories (Tribst et al., 2023): biological and mechanical. Biological failures primarily involve issues related to osseointegration, peri-implantitis, and soft tissue complications. Conversely, mechanical failures are related to fractures and other structural problems directly associated with the implant components (Lee et al., 2019; Yi et al., 2018; Chrcanovic et al., 2017; Yu & Qiu, 2022).

A series of recent reviews, based on clinical studies, reported a high incidence of such mechanical complications (Moraschini et al., 2015; Tey et al., 2016).

Dhima et al., (2013) carried out a comprehensive retrospective investigation covering a 29-year period, examining the condition of 1325 implants. Their results unveiled a prevalence of mechanical complications surpassing that of biological ones. Notably, over

half (58%) of the implants experienced at least one mechanical challenge. Furthermore, their study indicated a notable time gap between the onset of mechanical and biological complications, with mechanical issues emerging significantly later.

Fatigue can be resulting from repeated stresses and/or or cyclic loading, ultimately leading to failure under a significantly lower stress than that required for a single application rupture. In which cracks are generated (crack initiation) and then propagate steadily until the final catastrophic result (Shemtov-Yona & Rittel, 2016b).

Several studies examined the fracture surfaces of dental implants fractured *in vivo* using a scanning electron microscopy (SEM). These studies showed the classic fatigue marking (striation) on the implants' fracture surfaces, which indicates metal fatigue as a probable cause of the implants fractured intraorally (Shemtov-Yona & Rittel, 2016b).

Shemtov-Yona et al. (2016b) introduced the concept of implant fracture attributed to fatigue rather than overload. The fracture surfaces of dental implants fractured *in vivo* was examined using a scanning electron microscopy (SEM) showed two distinct zones (Overload and Fatigue zones) with striation in the fatigue zone which indicates metal fatigue and secondary cracks. SEM analysis of the fractured implant surface reveals a contrast between the crack growth region (corresponding to fatigue) and the critical overload region with smooth dimples that can be seen.

The notion of implant fracture due to fatigue rather than overload was also introduced by the study of Morgan *et al* (Morgan et al., 1993) reported on five Brandmark fixtures which fractured clinically. The retrieved specimens were examined using a scanning electron microscope (SEM) and it was maintained that fatigue striations from cyclic loading were found.

The study done by Lee *et al* (Lee et al., 2009) provides further clarification, distinguishing three stages in fatigue fracture:

- Crack initiation and cessation: derived from areas of stress concentration such as a change in cross section, an internal crack, or an irregularity caused by machining
- Fatigue crack growth (fatigue striae): fatigue crack tends to propagate along atomic planes but once the crack reaches discontinuities, it can change directions

- Ductile failure: When the crack reaches sufficient length, and the remaining cross section is unable to support the applied load, a ductile mechanism predominates involving processes such as dimple rupture or cleavage

Shemtov-Yona et al. (2015a) also conducted a comparative analysis by examining the surfaces of implants fractured *in vivo* with those fractured in laboratory settings under controlled monotonic and cyclic loads. Scanning electron microscopy (SEM) examination revealed striking similarities in the surface characteristics of both *in vivo* and *in vitro* fractured implants. Their experimental findings indicated that implants fractured *in vitro* due to fatigue under physiological loads, correlates with the repetitive nature of mastication loads.

Further research conducted by Shemtov-Yona *et al* (Shemtov-Yona et al., 2015a), involved a surface analysis that report secondary cracks near the primary crack (fracture plane). Although these secondary cracks did not directly contribute to the final fracture, they provided insights into their association with surface topography (roughness).

Mechanical corrosion (Yokoyama et al., 2002; Shemtov-Yona & Rittel, 2016a) is a specific type of corrosion that occurs in environments where materials are subjected to both mechanical stress and corrosive environments; this can lead to an acceleration of the corrosion process.

Corrosion can severely limit the fatigue life and ultimate strength of the material leading to mechanical failure of the implant. Yokoyama *et al* (Yokoyama et al., 2002) studied the delayed fracture of titanium dental implant. It was concluded that titanium in a biological environment absorbs hydrogen and this may be the reason for delayed fracture of a titanium implant. Stress corrosion occurs because of fatigue of metal when it is associated with a corrosive environment. Differential surface of a metallic restoration may have small pits / crevices. Consequently, stress and pit corrosion occurs. Time plays a crucial role in the process of mechanical fatigue and corrosion, as it influences the length of time stress is applied to the implant. The longer the stress is applied, the greater the likelihood of cracks developing and fracture occurring (Yokoyama et al., 2002).

1.3. Risk factors associated with implant fixture fracture

The rate at which cracks propagate, and consequently, the distance between striations, can be influenced or result from various risk factors that can be divided into two categories (Sánchez-Pérez et al., 2010):

- elevated forces being transmitted to the implant:
 - ✓ Bruxism or heavy occlusal forces (Balshi, 1996; Gargallo et al., 2008).
 - ✓ Design of the prosthesis (fixed vs screwed) may influence the load and stress that are transmitted to the implant body (Eckert et al., 2015; Gargallo et al., 2008).
 - ✓ The presence of a cantilever leads to increased forces being transmitted to the supporting implants compared to situations where cantilevers are not present (Gargallo et al., 2008)
 - ✓ Dental implant location (anterior vs posterior) (Eckert et al., 2015 ; Moraschini et al., 2015 ; Tey et al., 2016)
 - ✓ Prosthesis-to-implant ratio (Goodacre et al., 2003)
 - ✓ The inadequate fit of the superstructure (Goodacre et al., 2003; Yu & Kim, 2020)
- reduced ability of the implant(s) :
 - ✓ Implant composition (Moraschini et al., 2015 ; Tey et al., 2016 ; Eckert et al., 2015)
 - ✓ Design or production flaws (Goodacre et al., 2003)
 - ✓ Implant size (diameter, length) (Moraschini et al., 2015 ; Tey et al., 2016 ; Esposito et al., 1998 ; Berglundh et al., 2002 ; Goodacre et al., 2003 ; Eckert et al., 2015)
 - ✓ Bone resorption around the implant (Eckert et al., 2015)
 - ✓ Presence of micro thread (Oh et al., 2023)

Other mechanical complications such loading condition, screw loosening or fracture, framework fracture and environmental factors such as temperature and exposure to corrosive or embrittling gases and fluids has also been proposed as a risk factor for implant fracture (Eckert et al., 2015).

Consequently, the occurrence and nature of mechanical issues are anticipated to vary among implant systems. This disparity stems from distinct manufacturing techniques, structural design, and material choices inherent to each system (Eckert et al., 2015).

In the next section, we will describe the factors that influence on the incidence of fractures.

1.4. Biomechanical behavior of implants

The type of implant chosen depends on the available bone volume, the prosthetic space, and existing mechanical constraints. A surgical and prosthetic analysis would therefore appear to be essential. The parameters characterizing an implant are: morphology, neck, body diameter, implant length, type of connection and mechanical strength. The morphology of an implant is defined by the shape of the body (cylindrical or conical), the shape of the neck (cylindrical or flared), and its architecture (one or two parts) (Chang et al., 2013 ; Koyano et Esaki, 2014).

1.4.1 Diameter

Diameter is an important factor influencing the amount of load it can support and consequently the incidence of fractures (Shemtov-Yona et al., 2014b).

In fact, diameter is directly related to the moment of inertia $I = \frac{1}{4} \times \pi \times (\text{radius})^4$. And the stress (σ) induced is indirectly proportional to the system's moment of inertia (I) calculated as follows (Sanivarapu et al., 2016):

$$\sigma = My / I$$

- ✓ M = Moment load caused by eccentric loading
- ✓ y = Point in the center of the part
- ✓ I = Moment of inertia.

The ability of implants and components to resist bending loads is directly proportional to the component's moment of inertia. So, from a theoretical point of view, if an implant or its component is 2 times wider, it is 16 times more resistant to fracture (Misch et al., 2015).

1.4.2 Length

In the study done by Koyano et Esaki (Koyano et Esaki, 2014), the crown-to-implant ratio is defined as a risk factor for implant overload. This ratio depends on the length of the implant and the prosthetic design.

1.4.3 Position and alignment

Depending on whether the implant is positioned anteriorly or posteriorly, the forces exerted on it will differ. In the molar and premolar regions, masticatory forces and lateral movements generate undesirable forces. Occlusal loads in the posterior region are three times stronger than those in the anterior region (Tabrizi et al., 2017).

According to Eckert *et al* (Eckert et al., 2015); it is prudent to consider single implant systems in molar positions at a higher risk of fracture. The proximity of the molar to the temporomandibular joint creates a mechanically unfavorable situation due to the significant transmission of forces. Additionally, the molar has a larger occlusal table compared to premolars or anterior teeth. A wider occlusal surface supported by a single implant generates forces that are not aligned with the long axis of the implant. These tipping forces can lead to chronically elevated complex force structures, contributing to implant fracture.

Following Balshi (Balshi, 1996), all of the fractured implants exhibited a straight alignment. Thus, suggest staggering implants to prevent them from being in a straight line, as this alignment, especially when coupled with overload factors, seems to elevate the risk of fracture.

1.4.4 Implant design and Connection

Implant design is a critical aspect within the realm of dental implants, encompassing the intricate three-dimensional structure of the implant along with its various components and features (Jansen et al., 1997; Tang et al., 2012).

There's a rich diversity in design (Tang et al., 2012), with each configuration meticulously tailored to ensure the long-term success of the osseointegrated interface (Jansen et al., 1997), the pivotal point where the implant fuses with the surrounding bone. Among the myriad factors shaping implant design, considerations include the

configuration of the prosthetic interface, the threading characteristics, and the overall contour of the implant (Pita et al., 2011; Jansen et al., 1997).

In the realm of dental implants, the concept of connection interfaces plays a crucial role in determining the success and longevity of the implant restoration. These interfaces refer to how the implant fixture connects with the superstructure or abutment (Bozkaya et al., 2004).

According to Bozkaya *et al* (Bozkaya et al., 2004), the design and configuration of the abutment connection play a significant role in preserving osseointegration. This factor influences how load is distributed within the peri-implant bone, particularly at the interface between the implant and abutment.

Assunção *et al* (Assunção et al., 2008) found that elevated stress levels detected in the implant's apical region may be attributed to its design. Adjusting the design could potentially enhance stress distribution across the trabecular bone. So, the design of implants can impact bone stress and contribute to bone crest loss (Huang et al., 2008).

The connections should aim to minimize tension on both the prosthetic components and the bone-implant interface, thereby ensuring sufficient stability for the prosthesis (Jansen et al., 1997). The external hexagon, internal hexagon, and Morse taper are the most frequently utilized types of implantology connections.

Following Gehrke (Gehrke, 2013), assess the static fatigue resistance of implants with different connections at varying crown heights based on ISO 14801 recommendations. According to this study, there is no difference between implants with internal and external connections, although each type of connection results in specific fractures. However, Morse taper implants are more resistant to fracture and appear to be a better choice in cases of high crown-to-implant ratio.

Baggi *et al* (Baggi et al., 2008) reported lower level of stress on the cancellous bone of the internal hexagonal system compared to that of the external hexagon.

▪ **External connection:**

External connections, involve a design where the connection between the implant fixture and abutment occurs externally (Goiato et al., 2015). This type of connection is the oldest and typically achieved through features like hexagonal or octagonal platforms on the

implant fixture and corresponding components on the abutment. While external connections may be easier to manufacture and restore, they can sometimes be less stable than internal connections, particularly in situations where rotational forces are involved, and presents certain limitations as it transmits significant bending forces to the abutment screw, leading in some cases to its fracture or unscrewing and lost. The most common external connection is the hexagonal (“hex”) type; variations in height and width affect tactile perception and the anti-rotational stability of the prosthesis (Tsuge & Hagiwara, 2009).

The limitations of the hexagonal platform became increasingly evident as its usage expanded to partially edentulous arches or single-unit prostheses. In such cases, anti-rotational internal connections have proven to be more suitable (Tsuge & Hagiwara, 2009).

This platform is capable of withstanding vertical loads; however, it’s important to note that the abutment screw is the sole component responsible for absorbing lateral loads that depends only on the contact angle between the hexagonal abutment and the implant (Pessoa et al., 2010) that results in a smaller distribution area compared to an internal connection system.

Following the study of Manda *et al* (Manda et al., 2008), that focus on the failure on a Titanium Ti-6Al-4V implant with external connection, Ca/P formation was identified within the wake of an unstable crack, previously initiated within the implant main body. The fracture took place along the direction of the external first thread.

▪ **Internal connection:**

Internal connections that appeared with the development of Ti grade 4 or 5 involve a design with where an internal junction at the neck level where the implant fixture and abutment connect internally, usually through a screw-retained mechanism (Goiato et al., 2015).

This type of connection is characterized for its ability to provide a more stable and aesthetic outcome and it is now more widely used (Davarpanah et al., 2000). This offers advantages such as a reduced incidence of abutment screw loosening and fracture, along with greater load absorption.

The lateral wall of the abutment serves to facilitate the dissipation of lateral loads, while the abutment screw acts to shield it from excessive stress (Pessoa et al., 2010) that is favorable for its use in a one-step surgical procedure and with single implants. Additionally, internal connections can offer better protection against bacterial invasion, reducing the risk of complications such as peri-implantitis, better protection and resistance to bending forces, and minimize micromovements between the abutment and the implant, especially when subjected to bending forces. The category of internal connection includes the Morse Taper interface, the internal hexagon, and internal octagon, triangular, ...

Pessoa *et al* (Pessoa et al., 2010) demonstrated that the internal connection exhibited lower shear stress in the cervical region.

According to Lee *et al* (Lee et al., 2019), implants with an internal connection are more stable than implants with an external connection, which reduces marginal alveolysis of the implants and provide better joint stability.

Following Nam *et al* (Nam et al., 2024), some internal-type implants experienced fixture tearing. These internal bone level implants, which are mechanically stable and have a self-locking interface, improve the centralization of occlusal forces and offer better stability against lateral forces compared to the external type (İplikçioğlu & Akça, 2002). However, a drawback is the potential for the upper part of the fixture to fracture under high occlusal forces. To mitigate this risk, it is advised to use an implant with a sufficiently thick diameter.

Following Yi *et al* (Yi et al., 2018), when an implant is subjected to force, external and internal types exhibit different structural force distributions. In the external type, external force is transferred to the screw, which is the most vulnerable part, thus preventing fixture fracture. On the other hand, in the internal type, a mechanical interface exists between the abutment and the fixture. Consequently, when external force is applied, stress transmitted to the abutment is subsequently transferred to the fixture. If this stress surpasses the fixture's fracture resistance, fixture fracture may occur. That can explain the overall fracture rate greater in internal type (1%), but the conclusion on this review is that there was no significant difference according to implant connection type. however, all fixture fractures occurred at the posterior region in regular platform.

▪ **Threads**

Dental implants can be categorized into two main types based on their design: threaded implants and non-threaded (press-fit) implants (Carlsson et al., 1986).

Threaded implants feature spiral grooves or ridges along the surface of the implant fixture provide mechanical stability by engaging with the surrounding bone tissue, offering primary stability during the initial placement of the implant maximizing initial contact (Brunski, 1988). Threaded implants are often preferred in situations where the bone density is lower or compromised, as the threads help to anchor the implant securely in place. They are also beneficial in cases where immediate or early loading of the implant is desired, as the threads enhance the implant's ability to withstand occlusal forces and dissipation of interfacial stress (Brunski, 1988).

Geometric parameters such as thread depth, thickness, pitch, face angle, and helix angle vary and collectively shape the functional surface of threads on dental implants. These parameters play a crucial role in determining how loads are distributed biomechanically across the implant (Strong et al., 1998).

There are various types of threads used in dental implant designs, each with its own characteristics and benefits. These include V-shape, square, acme threads, buttress and reverse buttress threads are dental implant thread forms with a long history of successful use. These threads serve to dissipate occlusal loads into the bone surrounding the implant; however, they differ in form, inherent strength and in how they transmit forces (Strong et al., 1998).

Some implants feature multiple threads with different profiles along their length. These implants are designed to provide optimal stability and load distribution in various bone types and clinical scenarios, especially for Type IV (cancellous) bone (Sykaras et al., 2000). A plethora of additional features have been employed by implant companies to accentuate or replace the effect of threads. These include perforations of various shapes and dimensions, vents, ledges, grooves, flutes, and indentations. The implant can be solid or hollow, with a parallel, tapered/conical, or stepped shape/outline and a flat, round, or pointed apical end (Sykaras et al., 2000).

Following Ji-Hwan Oh *et al* (Ji-Hwan Oh et al., 2023) revealed that implants possessing both micro-threads and a rough surface exhibited notably lower MBL compared to those with a polished surface. However, when implants had a rough surface, the presence or

absence of micro-threads did not yield a significant difference in MBL. Van de Velde et al., (2010) similarly found no notable distinction in MBL between rough-surface implants equipped with micro-threads and those without micro-threads.

Following Lee *et al* (Lee et al., 2019), the fracture rate on dental implant fracture is 0.83 % with micro-thread vs 0.98 % without micro-thread.

▪ **Screwed vs cemented**

However, the literature is still controversial concerning the choice of connection and/or crown-retaining system. The advantages of using cement-retained restorations, as given by several authors, were primarily aesthetics, passive fit of the crown, and the potentially improved load distribution during function (Tey et al., 2016; Esposito et al., 1998). On the other hand, previous studies (Berglundh et al., 2002; Goodacre et al., 2003) also highlighted the advantages of screw-retained restorations, such as their retrievability, making the evaluation of oral hygiene and peri-implant probing easier.

Following Freitas *et al* (Freitas et al., 2011), in step-stress accelerated life testing, tests were done on fourth type of implant (cemented or screwed for internal and external connection). Regarding the fixture only the internal cemented implant presents a longitudinal fracture at the implants neck area.

Following Anchieta *et al* (Anchieta et al., 2015), cemented and screwed implant have been tested using different implant-abutment horizontal matching configurations (regular vs switching platforms). The fixture fracture for cemented presented abutment and implant fracture more often than other groups.

1.4.5 Materials

Dental implants can be manufactured mainly from (Saini et al., 2015):

- metallic biomaterials that have biomechanical and biocompatibility properties and are easy to process and sterilize:
 - ✓ Commercially pure titanium (Ti CP, grade 1 à 4)
 - ✓ Titanium alloys
 - ✓ Titanium-zirconium alloys (TiZr)

- Zircon (dioxide de Zirconium)
- PEEK or Niobium

a) Titanium

Titanium (Ti) and its alloys have become the main choice for the manufacture of dental implants due to their good mechanical properties, their low density (4.5 g/cm³) which makes them extremely light, their good biocompatibility in contact with bone and their resistance to corrosion induced by the passivation process (Nicholson, 2020).

Passivation is a natural process that forms a protective layer of titanium oxide on the surface when titanium is exposed to atmospheric oxygen. This extremely thin passive layer, typically measuring just a few nanometers in thickness, plays a crucial role in protecting titanium dental implants from corrosion, enhancing biocompatibility and promoting osseointegration (Nicholson, 2020; McCracken, 1999).

b) Grade

Commercially pure titanium (CPTi) consists of at least 99% elemental titanium, with 1% mixtures of other elements (oxygen, hydrogen, carbon, iron and nitrogen) not removed during material processing and dental implant manufacture (McCracken, 1999).

It is classified into 4 grades numbered from 1 to 4, depending on purity and processing oxygen content (Liu et al., 2017). These grades differ in terms of corrosion resistance, ductility and strength, and cp-Ti grade 4 has the highest oxygen content (around 0.4%) and the best overall mechanical strength. Grade 1, on the other hand, has the lowest oxygen content (0.18%) (Liu et al., 2017; Zhang & Chen, 2019). The presence of impurities enhances titanium's mechanical properties. Thus, the breaking strength of grade 2 titanium is lower than that of grade 3, etc. (Table 1).

Table 1*Mechanical Properties of Titanium Used in Dental Implants*

Material	Modulus (GPa)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Density (g/cc)	Type of Alloy
Cp Ti grade I	102	240	170	24	4.5	α
Cp Ti grade II	102	345	275	20	4.5	α
Cp Ti grade III	102	450	380	18	4.5	α
Cp Ti grade IV	104	550	483	15	4.5	α
Ti-6Al-4V- ELI	113	860	795	10	4.4	$\alpha + \beta$
Ti-6Al-4V	113	930	860	10	4.4	$\alpha + \beta$
Ti-6Al-7Nb	114	900–1050	880–950	8–15	4.4	$\alpha + \beta$
Ti-5Al-2.5Fe	112	1020	895	15	4.4	$\alpha + \beta$
Ti-15Zr-4Nb-2Ta-0.2Pd	94–99	715–919	693–806	18–28	4.4	$\alpha + \beta$
Ti-29Nb-13Ta-4.6Zr	80	911	864	13.2	4.4	β

Note: adapted from A critical review of dental implant materials with an emphasis on titanium versus zirconia. Copyright 2015 by MDPI. (Osman & Swain, 2015)

It should also be noted that certain surface treatments help to increase their mechanical strength (Fernandes et al., 2015; Table 2). This is the case, for example, with Ultrafine-Grained Titanium pure titanium (UFG-Ti) implants with improved mechanical properties can be obtained by the equal channel angular pressing (ECAP) method using CP-Ti without introducing other elements.

Table 2*Performance of Ultrafine Grained Titanium*

UFG Ti grade 2 4 XH + CR (70) ⁽¹⁾	796	877	18	Estrin et al. ²⁰ , Handtrack et al. ²¹
UFG Ti grade 4 TMT + A (6h) ⁽²⁾	1110	1250	13	Truong et al. ¹⁹
UFG Ti grade 4 TMT + A (1h) + W ⁽³⁾	1200	1430	12	Truong et al. ¹⁹

Note: a dapted from Properties and Performance of Ultra fine Grained Titanium for Biomedical applications, by (Fernandes et al., 2015).

This results in more uniform stress distribution and improved fatigue strength, which in turn contributes to longer implant life. It should be noted that research into ultra-fine-grain titanium dental implants (Fernandes et al., 2015) is still in progress, and further studies are needed to fully assess their efficacy, safety and long-term durability in a clinical context.

Following the study of Velasco-Ortega *et al* (Velasco-Ortega et al., 2019), focused on CP-Ti grade 4 implant, the SEM images provide a comprehensive depiction of both the origins of cracks and their subsequent paths of expansion with longitudinal cracks spanning across virtually all junctures between the inner hexagonal connection's walls.

c) Alloys

In order to improve the mechanical properties of implants, which pave the way for new implant therapies such as the use of short implants limiting the indications for bone grafts, new alloys are being proposed such as grade 5 titanium or TA6V4 (Sykaras et al., 2000).

Titanium alloys are obtained by adding elements such as silver, aluminium (Al), argon (Ar), copper (Cu), iron (Fe), iridium (Ir), vanadium (Va) and zinc (Zn) which, depending on their nature, modify the relative stability of the α and β phases (Sykaras et al., 2000). The alloy's various constituents therefore play a very important role in modifying its mechanical, physical and corrosive properties. The solid substitution atoms below are not present on Ti-CP. This is what differentiates the alloy (Sykaras et al., 2000):

- Aluminum, an alphasgenic element, which hardens the α phase. This improves strength and reduces the alloy's weight. Its concentration is limited to 7% by weight;
- Vanadium, a betagenic element, improves ductility and acts as an aluminum scavenger, forming intermetallic compounds with aluminum and improving its corrosion resistance.
- Iron (Fe): The addition of iron can improve the mechanical strength and corrosion resistance of titanium alloys. However, high concentrations of iron can adversely affect the biocompatibility of alloys.)

The alloys most commonly used for dental implants are mixed alpha-beta types (Sykaras et al., 2000).

Note that there are two different grades of Ti-6Al-4V: TA6V and TA6V-ELI (for Extra-Low Interstitial). In both cases, the addition or reduction of interstitial elements is used as an adjustment variable to adapt alloy properties to the desired standards. The ELI grade thus increases ductility at the cost of a slight reduction in mechanical strength. In addition, the reduced interstitial content of TA6V increases the material's toughness by 30% (from 75 to 100 MPa - m^{1/2}), considerably simplifying the machining of implants (Sykaras et al., 2000).

d) Zirconium alloys

Recently, titanium-zirconium alloys containing 13 to 17% zirconium (TiZr1317) have been introduced, providing improved mechanical properties, but its mechanical strength

or corrosion resistance is insufficient in some cases, where reduced-dimension implants are required. Although its yield strength is much lower than that of TA6V-ELI (690 MPa), it offers equivalent mechanical strength and is made exclusively of alloying elements considered biocompatible and inert with respect to the environment (Chiapasco et al., 2011). The enhancement occurred because the substitution of titanium with zirconium atoms induced distortion in the crystalline structure, hindering the movement of dislocations.

e) Zirconia

Zirconia dental implants, made from zirconium dioxide (ZrO_2), have emerged as a promising alternative to traditional titanium (Ti) implants. One of the main advantages of zirconia implants is their aesthetic benefit, especially in patients with thin gingival biotypes, where the underlying metal color of titanium implants might otherwise be visible through the tissue. In addition to their superior aesthetic properties, zirconia implants also demonstrate excellent biocompatibility, comparable to that of titanium. Studies have shown that zirconia implants are associated with reduced plaque accumulation, which can contribute to better periodontal health and potentially lower the risk of peri-implant diseases. These characteristics make zirconia implants a valuable option in contemporary implantology, offering both functional and aesthetic benefits to patients (Osman & Swain, 2015). Zirconia dental implants are available in both one-piece and two-piece designs, each offering distinct advantages that cater to various clinical needs and patient preferences.

f) PEEK is a polyether-ether-ketone

PEEK has many advantages like Flexibility, Radiolucency, Aesthetic features, Thermal resistance, Cost-Efficient and its Biocompatibility. It has long life and it is insoluble having low moisture absorption, low density (1.32 g/cm^3), and low elastic modulus. They will not be developed further in this thesis (Rahmitasari et al., 2017).

g) Niobium

Recently, beta titanium–niobium (β -Ti-Nb) (Chézeau et al., 2022), thanks to its strong mechanical properties (e.g., shape memory effect, super elasticity, and low elastic modulus) and non-cytotoxic constructing elements, has been extensively studied for biomedical applications. Binary β -Ti-Nb alloys have been recently proposed as an alternative to TA6V due to the biocompatibility of both constituents originating from the ability of both metals to form protective surface oxides. They will not be developed further in this thesis.

1.4.6 Surface treatment

Various studies have investigated the impact of grit blasting treatments, a prevalent surface modification technique in biomedical applications, on the fatigue behavior of CP-Ti and titanium alloys. For instance, Baleani et al. (2000) examined the influence of grit blasting treatments using alumina particles on the fatigue endurance strength of Ti-6Al-4V. Their findings revealed that grit blasting decreased the endurance limit of Ti-6Al-4V by 35–40%. This decrease was attributed to stress concentration effects and surface roughness concerns.

On the other hand, Gil *et al* (Gil et al., 2014), analyzed the impact of surface treatments on the fatigue performance of commercial dental implants. They specifically investigated the fatigue behavior of grit-blasted implants. Their research demonstrated that grit blasting CP-Ti dental implants enhances their fatigue resistance, attributed to the formation of a layer of compressive residual stresses.

Following Shemtov-Yona & Rittel (Shemtov-Yona & Rittel, 2016a) saline solution medium accelerates the fatigue rate reducing the fracture toughness of Ti-6Al-4V.

1.5. Management of implant fracture

Managing fractures of dental implant fixtures poses a significant challenge in clinical practice. Clinicians are faced with decisions regarding either removing the implant, preferably to mitigate peri-implant bone loss and prevent infectious complications, or modifying the existing implant based on the specific prosthodontic treatment plan (Adell

et al., 1990). Common treatment options include (Gargallo et al., 2008; Oh & Barnes, 2016):

1. Complete removal of the fractured implant, employing techniques tailored to the implant's situation, intra-osseous length, and availability of internal threading:
 - When internal threading is unavailable, options include using a trephine to remove the implant by drilling the bone around it or using piezoelectric ultrasonic surgery to enhance precision and control bone loss.
 - When internal threading is present, tools like the Implant Removal Tool are employed to disengage the implant from surrounding bone tissue, allowing for its safe extraction.

Following implant removal, placement of a new implant may occur either at the same surgical site or an alternative location.

2. Removal of the coronal portion of the fractured implant, followed by the utilization of the remaining portion to support a new abutment and crown. Specialized kits containing rotary instruments for smoothing fracture edges and tools for creating new internal threading may be employed for this purpose.
3. Removal of the coronal portion of the fractured implant, leaving the apical portion integrated within the bone without immediate utilization. Depending on prosthetic requirements, placement of a new implant at a different location may be considered. Complications may arise in certain scenarios, such as implant removal in sinus-grafted areas, leading to buccal-sinus communication and associated challenges.

Critical considerations for appropriate prosthetic management include:

- Identification of fracture location (coronal, mid, or apical thirds).
- Evaluation of the number, position, and distribution of remaining implants, if applicable.
- Selection of prosthesis design (fixed or removable), considering the number of units and specific characteristics.
- Determination of the preferred prosthesis retention method (screw-retained or cemented).
- Understanding and addressing patient preferences and expectations.

2 MATERIALS AND METHODS

2.1. Focused question and study objective:

The objective of this Comprehensive review was to examine how particular implant characteristics, such as diameter, length, connection type, position, angle placement and type of implants materials can lead to various complications encompassing both biological and mechanical issues, that may contribute to fractures or cracks in the implant fixture and determine the related position.

This review was carried out in accordance with the steps of practice based on scientific evidence and the methodology was adapted to the PRISMA statement (Preferred Reporting Items for Systematic Reviews and Meta Analyses) (Page et al., 2021). To carry out this review, the research question was formulated using the method defined by the acronym PICO as recommended by PRISMA, we established specific criteria for questioning to structure a concise clinical inquiry and to devise a suitable inclusion. The analysis performed using the PICO index is:

1. "Population": patients rehabilitated with dental implants.
2. "Intervention": occurrence of fractures and the different characteristics of fractured implants.
3. "Comparison" dental implants without fixture fracture” “.
4. "Outcome" is the influence of the dental implant characteristics on fracture incidence of dental implant fixture.

2.2. Search strategy

The bibliographic research was conducted in PubMed/Medline database, Cochrane Library, ScienceDirect, IEEE Xplore and Google Scholar.

We conducted an exhaustive literature search on "Dental implant fixture fracture" up to the present date. The selection of articles adhered to specific inclusion and exclusion criteria:

- Inclusion criteria:
 - publication till date, language (English), and articles with full text availability.

- Studies with quantitative outcomes including the survival rate of RCTs, CCTs, prospective or retrospective cohort studies.
- At least 6 months of follow-up after implant placement.
- Studies, which evaluated the clinical outcome of Dental implant fixture, Ti, Ttcp (grau 4), Ti6Al4V (grau 5), TiZr, Zr dental implants.
- Exclusion criteria consisted of:
 - Duplicated, isolated case reports,
 - Reviews, and studies that reported no cases of implant fractures
 - Abstracts lacking full text

The search strategy was implemented using the following key words:

dental implant fixture ("fracture" OR "crack" OR "fatigue" OR "failure" OR "mechanical" OR "stress" OR "fractography").

Additional search strategies included the terms: the following keywords were used in combination: "titanium-zirconium versus titanium dental implants" AND "zirconia versus titanium implants "AND "zirconia dental implants "AND "titanium-zirconium implant".

2.3. Selection process of articles

Randomized controlled clinical trials, retrospective study, clinical trials, and case studies were included, leading to the examination of 385 articles for classifying implant fixtures fractures

The exclusion criteria were duplicates, reviews and studies that did not include cases of implant fractures.

After full-text analysis, publications were further assessed for relevance and compliance with the selection criteria. Eligible publications were included in this review.

The selection of studies was initially based on the title of the articles and an analysis of the abstract giving priority to cases with details of fracture aetiologies.

To achieve this goal, we have selected retrospective studies to obtain the maximum amount of data, as well as *in vitro* studies to examine the positions of fractures.

2.4. Synthesis of the results

Appropriate data of interest on the previously stated data items were collected and organized into the following fields of tables: year of publication, number of patients, study design, type of implant used, total patients dropout, implant system and implant lost, position of fracture, clinical data outcomes.

2.5. Selection of studies

The search delivered 385 search results (Figure 1).

Preliminary exclusion was made by the title and its relevancy and later by abstract relevancy. After title checking and removal of duplicates, 200 articles remained. Of the 200 articles, 184 were filtered out because they did not meet the inclusion.

An in-depth selection of articles according to study type and clinical protocols resulted in the selection of 16 articles (Figure 1; Table 3; Table 4), the others will be retained for the following sections.

Figure 1

Identification of studies via databases and registers

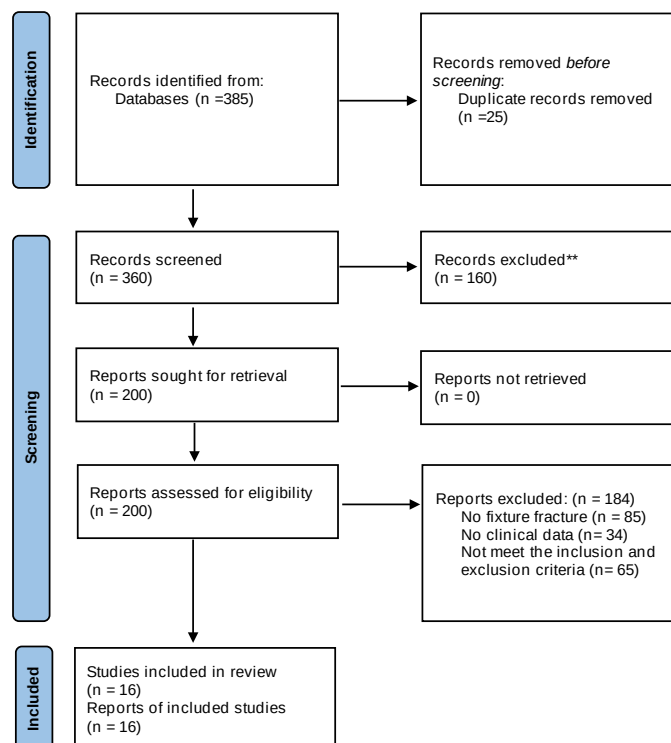


Table 3*List of Retrospective Selected Studies*

Study	Study type	Implant material	Number of patients	Number of implants	Number of fractured implants	Follow-up (years)
Lee et al. (2019)	Retrospective	Ti-6Al-4V / CP4	5 124	19 006	174	12
Yi et al. (2018)	Retrospective	CP1, CP3, CP4	406	1289	53	12
Chrcanovic et al. (2017)	Retrospective	CP1, CP3, CP4	2 670	10 099	44	34
Shemtov-Yona & Rittel (2015b)	Retrospective	CP-Ti / Ti-6Al-4V	NR	NR	100	NR
Gargallo et al. (2007)	Retrospective	NR	NR	1500	21	NR
Yu & Qiu (2022)	Retrospective	CP4	2810	7 502	37	6.9
Nam et al. (2024)	Retrospective	Titanium	151	490	10	10
Tabrizi et al. (2017)	Retrospective	Titanium	NR	18 700	37	16
Gahlert et al. (2013)	Retrospective	Zirconia	79	119	13	NR
Total (retrospective)			11240	58 705	389	

Note: Alloy: titanium–aluminum–vanadium (Ti-6Al-4V); CP1, CP2, CP3 & CP4: commercially pure titanium Grade 1, 2, 3, &4; "NR" (Not Reported)

Table 4*List of in vitro Selected Studies*

Study	Study type	Implant material	Implants characteristics	Number of implants	Type of test	Fractography analyses
Zhang et al. (2022)	<i>In vitro</i> study	Zirconia	One piece Two pieces	16	Fracture analysis	Yes
Scherrer et al. (2019)	Translational research	Zirconia	One piece Two pieces	15	Occlusal contact wear location	Yes
On et al. (2023)	<i>In vitro</i> study	CP4 / Ti–Zr	Torx & Internal hex design	45	Static Compression to Fracture Test and Dynamic Cyclic Fatigue Test	Yes
Shemtov-Yona et al. (2014b)	<i>In vitro</i> study	Ti-6Al-4V	Conical with three diameters	112 (8 fractured)	Fatigue performance	SEM and images
Yamaguchi et al. (2018)	<i>In vitro</i> study	CP4	Internal and external connection	12	Dynamic Cyclic Fatigue Test	Micro-CT images

					FEA analysis	
Choi et al. (2019)	<i>In vitro</i> study	CP4	TX and EV design	30	Single and Dynamic Cyclic Fatigue Test	Yes
Kim et al. (2020)	<i>In vitro</i> study	Ti-6Al-4V	Internal connection	20	Static and Dynamic Shear-Compression Tests. Single and multi-directional	Yes

Note: FEA: Finite Element Analysis

2.6. General description of the included studies

Of the studies selected, there were:

- 9 Retrospective *in vivo* studies were carried out on patients, both female and male. The time of follow-up is ranged from 6.9 years to 34 years. Data included at least 11240 patients with 58705 dental implants and 389 fractured dental implants.
- 6 *in vitro* studies including a constant stress fatigue test, fracture position and fracture load test
- 1 translational research

Table 3 and Table 4, present data on implants placed and implants fractured for each selected study: number of patients, number of implants and failure, time of follow-up. It can be seen that not all studies provided complete information, which was designated "NR" (Not Reported).

Given the complexity of comparison due to the use of different implant models in the various studies, we will also rely on *in vitro* studies where tests have been carried out with different inputs, which also provide more precise details of fracture position.

2.7. Risk of bias

Studies on dentals implants fracture are complex because of the large number of existing variables, such as surgical techniques, the heterogeneity of the implants, whether in terms of composition (grade of titanium), connectors, brand, etc. and duration of follow-up. The absence of international standardization makes comparison between studies difficult. Thus, the analysis of these different studies will not be able to take into account all the factors that may influence the choice of implants.

The risk of bias that can affect the cumulative evidence was independently by two reviewers using the Cochrane Collaboration's tool for assessing the risk of bias including the following domains: allocation concealment, random sequence generation, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting, and other bias. The assessment was not centered on the outcomes of the paper but the ones of the present review. Each domain was considered at low, unclear, or high risk of bias agreeing to the evaluation criteria as reported in the Cochrane Handbook for Systematic Reviews of Interventions (Cumpston et al., 2022).

After judgment was given for each of the domains mentioned above, studies were divided into the following groups: studies with low risk of bias, if all domains were considered at low risk of bias; unclear risk of bias, if one or more domains were considered at unclear risk of bias; and high risk of bias, if one or more domains were reported at high risk of bias. Cases of disagreement were resolved by discussion.

Table 5

The Cochrane Collaboration's tool for assessing the risk of bias

Study	Random sequence generation	Allocation concealment	Blinding (participants and personnel)	Blinding (outcome assessment)	Incomplete outcome data	Selective reporting
Lee et al. (2019)						
Yi et al. (2018)						
Chrcanovic et al. (2017)						
Shemtov-Yona & Rittel (2015b)						
Gargallo et al. (2007)						
Yu & Qiu (2022)						
Nam et al. (2024)						
Tabrizi et al. (2017)						

Analysis of Dental Implant Fixtures Fractures: Incidence, factors and characteristics

Zhang et al. (2022)						
Gahlert et al. (2013)						
Scherrer et al. (2019)						
On et al. (2023)						
Shemtov-Yona et al. (2014b)						
Yamaguchi et al. (2018)						
Choi et al. (2019)						
Kim et al. (2020)						
Note:  High risk of bias  Some concerns  Low risk						

3 RESULTS

3.1. Rates

Table 6

Rates and times to fractures

Study	Number of patients	Number of implants	Number of fractured implants	Fixture fracture	Time to fracture High Risk (years)
Lee et al. (2019)	5 124	19 006	174	0,91%	4-5 y. (20,65%)
Yi et al. (2018)	406	1289	53	0,54 %	NR
Chrcanovic et al. (2017)	2 670	10 099	44	0.43 %	7.9 y. $\pm$ 4.9
Yu & Qiu (2022)	2810	7 502	37	0.49 %	7.16 y.
Nam et al. (2024)	151	490	10	0.8 %	6.85 y.
Tabrizi et al. (2017)	NR	18 700	37	0.02 %	3.75 y. $\pm$ 2.6
Gargallo et al. (2007)	NR	1500	21	1,4 %	3-4 y. (76%)
Gahlert et al. (2013)	79	119	13	10,92 %	NR
Total / average	11240	58705	389	0,65 % Ti 10,92% Zi	

Note: Ti for titanium and Zi for zirconia

The average incidence across these various studies is 0.65 % for the fixture dental implant fracture, which is lower than that found Berglundh *et al* (Berglundh et al., 2002) that reviewed 159 articles on dental implant complications during a 5-year period and reported that the prevalence of fixture fracture to be less than 1 % (0.08 to 0.74%) and are often associated with inflammatory reactions at the site of fracture.

The implant loading period until fracture was reported by 6 studies (Table 6). Fractures were observed between 3 to 8 years of implants in function.

3.2. Diameter

Diameter of the fixture is classified into 3 categories (Al-Johany et al., 2016):

- Extra-narrow < 3 mm
- 3 mm<Narrow < 3.75
- 3.75<regular<4
- wide >4

Five studies provided information about diameters of both the installed and fractured implants. Thus, 868 implants were reported with seven different diameters. The narrow diameter presented a higher incidence of fracture compared to the other diameters (Table 7).

Below, you will find the fixture fracture rates for each diameter based on the selected studies, along with their conclusions.

Table 7

Fracture incidence according to implant diameter

Study	Fracture according Diameter	Findings
Lee et al. (2019)	1,7 % narrow <3.75 mm / 0,87 % regular 3.75 to <5.0 mm / 0,45 % $\geq$ 5.0 mm	Wide-diameter implants had a reduced fracture risk within 90 months, after which the diameter did not correlate with fractures.
Chrcanovic et al. (2017)	1,35 % narrow <3.5 mm / 0.34 % regular: 3.7 to 4.1 mm / 0 % wide > 4.2 mm	The highest implant fracture rate occurred among implants of narrow diameter. Every 1 mm increase in diameter decreases the probability of fracture by 96.9%
Yu & Qiu (2022)	Narrow: 1% / regular: 0,4 %	Implants with a reduced diameter may be more prone to fracture due to a high stress concentration or excess load.
Gargallo et al. (2007)	Ratio: 95 % regular 3.75 mm / 5% wide: 4 mm	NR
Shemtov-Yona & Rittel (2015b)	33% narrow <3.5 mm / 30% regular 3.6 to 4.4 mm / 11% wide > 4.5 mm	No correlation between the implants' width and defect occurrence

Note: based on the studies that reported data on both installed and fractured diameters.

3.3. Length

There's a wide range of views in the literature regarding the survival rates associated with different implant lengths, along with varying interpretations of what constitutes a "short" implant. In our study, the length of the fixture was classified into 3 categories (Nam et al., 2024):

- short [6 to <10 mm]
- standard [10 to <13 mm]
- long [$\geq$ 13 mm]

Below, you will find the fixture fracture rates for each length based on the selected studies, along with their conclusions.

From the 16 selected studies, only 3 provided the lengths of both installed and fractured implants (Table 8). In these 3 studies, longer implants exhibit a less favourable stress distribution.

Table 8

Fracture rate according to implant length

Study	Fracture according Length	Findings
Lee et al. 2019	0,32%: short <10 mm / 0,87%: standard 10 to 13 mm / 1,4%: long $\geq$ 13 mm	Longer implants exhibit a less favourable stress distribution
Chrcanovic et al. 2017	every 1 mm increase in length increases the probability of fracture by 22.3%	Considering the statistically significant influence of implant length on implant fracture
Nam et al. 2024	3% short < 10 mm / 1.88 %: 10 mm / 1.5 %: 11.5 mm / 6 %: 13 mm	Length was significantly associated with the survival rate.

Note: from the 16 selected studies, only 3 provided the lengths of both installed and fractured implants. In these three studies, length was significantly associated with the survival rate.

3.4. Position and alignment

Analysis of six studies enabled the comparison of installation and fracture regions (Table 9). The majority of implants were placed in the mandible. Notably, implants in the posterior region (83,5 %) and mandible exhibited the highest fracture rate.

Table 9*Position of fractured dental implant*

Study	Fracture: Maxilla / Mandible	Fracture: Anterior / Posterior
Lee et al. (2019)	Maxilla: Installed 9722 / Fractured 88 (0,9 %) Mandible: Installed 9284 / Fractured 86 (0,92 %)	7.5 % anterior / 92.5 % posterior
Yi et al. (2018)	Maxilla: Installed 780 / Fractured 5 (0,65 %) Mandible: Installed 499 / Fractured 86 (4,6 %)	100 % posterior
Chrcanovic et al. (2017)	0.5 % Maxilla / 0.40 % Mandible	0.4 % anterior / 0.5 % posterior
Yu & Qiu, (2022)	50 % maxilla / 50 % Mandible	22% anterior / 78% posterior
Nam et al. (2024)	Maxilla 1.63 % / 2.7 % Mandible	100 % posterior
Gargallo et al. (2007)	NC	19.4 % anterior / 80.9 % posterior

3.5. Implant Fracture location

Table 10*Location of fractured dental implant*

Study	Implant material	Implants characteristics	Fixture fracture position	Type of fracture
Lee et al. (2019)	Ti-6Al-4V / CP4	Butt joint and Conical joint With and without platform switching	NR	NR
Yi et al. (2018)	CP1, CP3, CP4	Internal and external connection	NR	NR
Chrcanovic et al. (2017)	CP1, CP3, CP4	NR	Thread	Transversal
Shemtov-Yona & Rittel (2015b)	CP-Ti / Ti-6Al-4V	NR	Thread Platform	NR
Gargallo et al. (2007)	Titanium	NR	Platform	Vertical Complex

Analysis of Dental Implant Fixtures Fractures: Incidence, factors and characteristics

Yu & Qiu (2022)	Titanium	NR	End of the screw Thread Platform	Horizontal Vertical
Nam et al. (2024)	Titanium	Internal and external connection	NR	NR
Tabrizi et al. (2017)	Titanium	Conical implants with cemented and screw retained	Thread Platform	Vertical
Zhang et al. 2022	Zirconia	One piece Two piece cemented and self- tapping	Thread Screw level Platform Abutment	Horizontal Vertical (upwards and downwards)
Gahlert et al. (2013)	Zirconia	One piece Two pieces	Thread	Horizontal
Scherrer et al. (2019)	Zirconia	Torx & Internal hex design	Thread	Horizontal
On et al. (2023)	CP4 / Ti-Zr	Conical with three diameters	Microthread Thread Platform	Horizontal Vertical
Shemtov-Yona et al. (2014b)	Ti6Al4V	Internal and external connection	In 3.3-mm implants: at second or third thread In 3.75 mm implants: at the platform or second thread In 5 mm implants: abutment platform or screw	Horizontal Vertical
Yamaguchi et al. (2018)	CP4	Internal and external connection	Thread, Joint and Platform area	Horizontal Vertical (downward)
Choi et al. (2019)	CP4	TX and EV design	Thread	Horizontal Complex
Kim et al. (2020)	Ti-6Al-4V	Internal connection	Thread	Horizontal Complex

4 DISCUSSION

Fractures of the implant body remain an exceptional complication that may occur during implant placement, or a mechanical complication following loading of the prosthesis, the incidence of which is estimated at between 0.2% and 1.5% (Goodacre et al., 2003; Gargallo et al., 2008).

Berglundh *et al* (Berglundh et al., 2002), reviewed 159 articles on dental implant complications over a 5-year period and reported a prevalence of fixture fractures to be less than 1%, ranging from 0.08 to 0.74%. These fractures are often associated with inflammatory reactions at the site of the fracture (Berglundh et al., 2002).

This review reported a Titanium fracture incidence of **0,65 %** in the studies selected based on **58705** dentals implants and **389** fractures (Table 3; Table 4) a value that fits the range demonstrated in the literature (Berglundh et al., 2002).

Regarding zirconia implants, Gahlert *et al* (Gahlert et al., 2013), evaluated 119 implants and reported that **13 (10.9%)** were lost due to fractures. Macroscopic and microscopic analyses of these fractures revealed that overload, implant design, and surface microcracks from the manufacturing process were the main causes of zirconia implant fractures.

Following the meta-analysis conducted by Pommer *et al* (Pommer et al., 2014), which examined the average time before fracture for specific implants, the average time before a fracture occurred was 4.1 years, with a standard deviation of 3.5 years. Additionally, detailed information on the time before fracture was available for 165 implants out of the 827 included in the study, representing approximately 20.2% of the total sample.

However, in this review, the largest number of fractures was reported in a range of 3–5 years (Table 6).

4.1. Diameter

In this review, the highest incidence of fractures in terms of diameter occurred in narrow implants (Table 7).

The appropriate selection of the implant diameter is generally based on the amount of available bone (Bayraktar et al., 2013). So, implants with a narrow diameter can be employed for specific patients who have a thin alveolar crest, eliminating the necessity for bone grafts (Davarpanah et al., 2000; Tallarico et al., 2017). This approach helps to avoid the expenses and potential hardships associated with bone grafting procedures. Additionally, these smaller implants are utilized in cases where there is limited prosthetic space available (Tallarico et al., 2017). When the height is limited, the use of larger implants might increase the bone–implant interface. Consequently, the diameter of the implant could be considered the most effective factor when compared with the length. (Okumura et al., 2010).

Indeed, the size of the implant diameter significantly affects its ability to withstand forces. Research indicates that smaller implant diameters have less surface area for osseointegration and can compromise the mechanical integrity of the implant fixture, abutment, and screws (Shemtov-Yona & Rittel, 2015b). Additionally, narrow diameter implants are more susceptible to mechanical failure due to reduced fatigue strength, especially when subjected to unfavorable force magnitudes and angles (Eckert et al., 2015).

Expanding the diameter of the implant while maintaining the same load results in reduced stress on both the implant and the surrounding bone (Baggi et al., 2008; Okumura et al., 2010) particularly in the cortical bone. Implants with larger diameters exhibit lower stress levels in both the bone and the implant due to improved distribution facilitated by increased contact area between the implant and the surrounding bone (Baggi et al., 2008).

According to our selected studies, Shemtov-Yona *et al* (Shemtov-Yona *et al.*, 2014b), fracture mode analysis showed that fractures occurred at the second (52%) or third thread (48%) in 3.3-mm implants and at the body-neck (44.5%) or second thread (55.5%) in 3.75-mm implants, whereas fractures in 5-mm implants occurred at the abutment neck and screw (100%). The Implants metallographic sections revealed that the two fracture were:

- Body-neck located where thin metal cross sections
- Implant body-thread located opposite the place where the inner thread creates a sharp notch.

Shemtov-Yona *et al* (Shemtov-Yona *et al.*, 2014b) conclude that the diameter has a direct influence on the position of the fracture, which can occur either at the dental implant neck, second thread or third thread and does not always occur in the thinnest part of the implant. The fractographic analysis provided in this study (Shemtov-Yona *et al.*, 2014b) indicated that pinpointing a fatigue failure mechanism, especially for analyzing *in vivo* failures where fatigue striations between transgranular fractures indicate fatigue fracture, with possible secondary parallel cracks perpendicular to the local crack-front propagation. A recent retrospective analysis by Tabrizi *et al* (Tabrizi *et al.*, 2017), found that standard or narrow diameter implants were sometimes used in the area to avoid bone augmentation, which in turn increases the risk of implant fracture.

According to Nagasawa *et al.*, the use of narrow (<3.3 mm) implants diameter increased the magnitude of the stress applied to the abutment head. The limitation of this study is that it takes threads into account.

Following Lee *et al* (Lee *et al.*, 2019) wide-diameter implants demonstrated a notably reduced risk of fracture compared to narrow-diameter and regular implants within 90 months, after which the diameter did not correlate with fractures. This finding is important as it confirms previous laboratory research outcomes, suggesting that the impact of diameter aligns closely with observations in clinical studies done by Shemtov-Yona *et al.*, (2014b, 2015a).

Following Gahlert *et al* (Gahlert *et al.*, 2013), Ninety-two percent of the fractured zircon implants were categorized as diameter-reduced implants, with a diameter of 3.25 mm. Due to this high incidence of fracture, the author says that it is not advisable to continue using these diameter-reduced implants in clinical practice.

However, even with contemporary design and materials (titanium alloys) that enhanced designs aimed at better stress dissipation across the implant interface, achieved through innovations like double-threaded or triple-threaded designs that increase the implant's surface area, a narrow diameter implant may still exhibit lower resistance to forces when compared to regular and wide diameter implants and should be use in specific cases (Kim *et al.*, 2023).

In contrast to what is described, a long survival period might be expected for reduced diameter implants, as long as the number of implants used is sufficient to support well planned prostheses (Kim *et al.*, 2023).

4.2. Length

The length of the implant presents a contentious topic in the literature, with diverging viewpoints on survival rates and offers different definitions for short implants. Some researchers (Goodacre et al., 2003) suggest that implant failure risks increase with shorter lengths, while others (Tada et al., 2003) argue that shorter implants result in higher stress and strain on the bone due to reduced contact area at the implant-bone interface and less uniform stress distribution.

Indeed, Petrie & Williams (Petrie & Williams, 2005) found that extending the implant length could potentially decrease bone deformation and maximum stress when compared to shorter implants. However, if the length increase surpasses 60% of the available cancellous bone height, the reduction in stress is not significant. Additionally, several authors (Pierrisnard et al., 2003; De Carvalho et al., 2012) have stated that under axial loads, stress variation among different lengths is not substantial.

Renouard & Nisand, (2006), emphasized that failures cannot solely be attributed to the length of the implant. It seems that regardless of the length of the implant within the cancellous bone, stress consistently concentrates at the level of the implant neck, with minimal impact on peri-implant bone stress values (Pierrisnard et al., 2003). Geng et al. (2004) suggest that in cases of type I bone quality (Lekholm and Zarb, 1985), the length of the implant does not significantly affect treatment success.

Consequently, in biomechanical literature, there isn't a unanimous agreement regarding clear linear relationship between the length and implant survival (Baleani et al., 2000).

Regarding our selected studies, the results have shown that longer implants have a less favorable stress distribution.

Chrcanovic et al. (2017) find that the increased fracture risk associated with length implants might be attributed to the trend of wider diameters (wider implant are related to short implant that presented lower probability of fracture).

According to Lee *et al* (Lee et al., 2019), previous research has suggested that implant length does not impact implant survival. However, few studies have explored the relationship between implant length and fractures.

The others authors find significant influence of implant length on implant fracture (Nam et al., 2024; Oh et al., 2023).

4.3. Installation Region (Maxilla/Mandible)

In this review, failures were notably more common in the mandible than in the maxilla (Table 9). Adell et al. (1990), reported a cumulative implant fracture rate of less than 5% in both the maxilla and mandible in a period of 10 to 15 days, except for one study group where fracture rate reached 16% in the maxilla. It can be explained by the fact that shape and bone density are important factors for implants survival. The mandible is a cortical bone, while the maxillary bone is trabecular and less mineralized, which might compromise primary implant stability and lead to future failures (Tada et al., 2003).

The two prospective studies indicate a difference in implant fractures between the maxilla and mandible, whereas the five retrospective studies found no significant differences. According to Pommer et al.'s meta-analysis, the positioning of implants was evaluated for 656 cases (Pommer et al., 2014). Among these, 426 implants fractured in the maxilla (64.9%) compared to 230 in the mandible (35.1%). Nevertheless, these findings do not provide sufficient evidence to conclusively assert an increased risk of fracture in the maxilla compared to the mandible.

4.4. Design Connection

The literature review did not allow for a definitive conclusion or comparison between internal and external connection implants. To better understand the biomechanical behavior of these implants, a retrospective study and an *in vitro* study is detailed.

The retrospective study done by Yi *et al* (Yi et al., 2018), conducted over 12 years, specifically analyzes the incidence of fractures by comparing external and internal connection implants. A total of 1289 implants were placed in 406 patients: 799 implants had an external connection (62%), and 490 had an internal connection (38%). Among the external connection implants, 2 implant body fractures were recorded (0.3%), while among the internal connection implants, 5 implant body fractures were recorded (1%). The authors concluded that there was no significant difference between these two types of implants: when subjected to forces, external and internal connection implants exhibit different force distributions. In an external connection implant, when an external force is applied, the stress is transmitted to the abutment screw, which is the most fragile part, often leading to screw failure before the implant body. Conversely, in an internal connection implant, an external force is directly transmitted to the implant body.

Following the *in vitro* study done by Gehrke (Gehrke, 2013), the static fatigue resistance of implants with various connection types and crown heights was tested. As the prosthetic height increases, an imbalanced crown-to-implant ratio can lead to a higher risk of fractures due to increased cantilever forces. In this research, 60 conical implants and 60 abutments were tested, each with a diameter of 3.5 mm and a length of 13 mm. The compression tests followed ISO 14801 guidelines. Results showed that all three implant types had similar resistance at the same height. However, as crown heights increased, the behavior of the abutments varied. The Morse Taper abutments bent but did not completely fracture. With external connection screws fractured, and the edge of the implant platform deformed. With internal hexagon connection, the fractures occurred at the implant neck, specifically at the internal hexagon and the screw.

The study (Gehrke, 2013) concluded that both the crown-to-implant ratio and the type of connection significantly impact resistance to non-axial forces. The findings suggest no major difference between internal and external connection implants in terms of fracture patterns, though Morse taper implants were more fracture-resistant, making them a preferable option for high crown-to-implant ratios.

4.5. Fixture fracture classification proposal

According to the analyzed studies, the design, in particular the type of connection, the diameter and the composition of the dental implant play a key role in the risk of fracture and have a direct influence on the type, position and direction of the fixture fracture.

To facilitate the classification and identification of various fixture fractures, a detailed proposal definition is provided below. This classification covers all types of fixture fractures found in the analyzed studies, categorized by their type, orientation, location, and direction and adopts a following structured approach:

"Type.Orientation. Zone.Origin-Direction."

Each fracture is therefore identified by four fields:

1. The first field in uppercase corresponds to the **Type** of fracture that can be identified by "F" for fracture or "C" for crack. Fracture can be either partial, not completely dividing the implant into separate parts, or total, resulting in the

implant being separated into two or more distinct parts (e.g., at the angle of the fixture platform or as a band strip).

2. The second field identifies the **Orientation** of the fracture. Studies show that fixture fractures in implants correspond to the progression of cracks, which can be either:
 - horizontal (h)
 - vertical (v)
 - oblique (o)
 - complex (c), involving a combination of multiple crack progressions.
3. The third field specifies the **zone** of the fracture. We defined six distinct zones to cover a wide range of possible cases:
 - "**p**" (platform): fracture occurs on the upper part of the implant fixture (includes the bottom edge of the hexagonal structure in case of external connection)
 - "**j**" (joint): fracture occurs at the junction zone between the implant fixture and the abutment.
 - "**mt**" (micro-thread): fractures that occur on the fixture micro-thread.
 - "**sc**" (screw): fractures that occur on fixture thread in the zone corresponding to the end of the screw.
 - "**ts**" (thread): fractures that occur on fixture thread in the region extending to the tip of the screw. For more precision we can precise which thread is concerned, example ts2
 - "**t**": (thread): fractures that occur on the fixture thread on a one-piece implant or beyond to the tip of the screw in the case of internal connection. For more precision we can precise which thread is concerned, example t4.
4. The fourth field is optional, composed one or two segments and concerns the direction and/or the origin of the crack or fracture.

The first segment corresponds to the origin of the fracture and the following segment correspond to the direction.

We have defined six distinct zones to cover a wide range of possible **origin** cases:

- **"a"** (abutment)
- **"p"** (platform): fracture occurs on the upper part of the implant fixture (includes the bottom edge of the hexagonal structure in case of external connection)
- **"j"** (joint): fracture occurs at the junction zone between the implant fixture and the abutment.
- **"ts"** (thread): fractures that occur on fixture thread in the region extending to the tip of the screw. For more precision we can precise which thread is concerned, example ts2
- **"mt"** (micro-thread): fractures that occur on the fixture micro-thread.
- **"sc"** (screw): fractures that occur on fixture thread in the zone corresponding to the end of the screw.
- **"t"**: (thread): fractures that occur on the fixture thread on a one-piece implant or beyond to the tip of the screw in the case of internal connection. For more precision we can precise which thread is concerned, example t4.

We have also defined four possible directions:

- **"u"** (upward direction)
- **"d"** (downward direction)
- **"ie"** (internal to external direction)
- **"ei"** (external to internal direction)
- **"o"** (opposite)

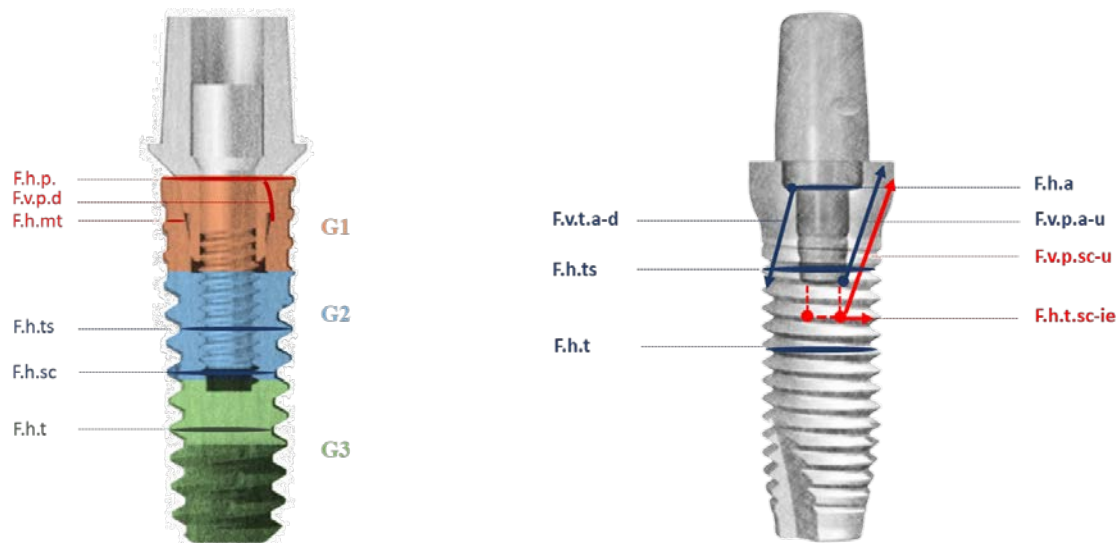
Below, you will find a proposed classification diagrams, designed to illustrate the various positions and types of fractures analyzed based of the definition classification proposal. This will aid in the identification and discussion process.

These diagrams will be based on their composition and types:

- Zirconia (one-piece and two-piece)
- Titanium or Zirconium alloys (TiZr)

Figure 2

Classification of fixture fractures in selected studies



Note: On the left, the diagram represents the fractures position and classification encountered in selected studies for commercially pure titanium or titanium alloy implants. On the right, the fractures encountered in selected studies for zirconia dental implants. G1 related to the platform of the implant, G2 corresponding to the region extending from the end of platform to the tip of the screw and G3 related to the region extending from the end of the screw to the final section of the implant.

Yamaguchi et al., (2018), that investigates the fatigue behavior of **grade IV titanium screwed** dental implants with different fixture-abutment joint types through *in vitro* fatigue tests and *in silico* finite element analysis. The focus is on the protocol used for the tests, as well as the position and direction of the fractures observed. Specimens were subjected to cyclic loading until failure, and fatigue cracks were analyzed using a micro-CT which are consistent with previous research findings. The analysis of fracture shows for:

- Internal connection implant with fixture fractures mainly located **at the platform**. Specifically, vertical cracks were observed near the buccal side of the screw hole in the fixture body, indicating that this area acts (edge and the screw hole) as a stress concentrator leading to fatigue crack initiation. This fracture is therefore classified as “**F.v.p.d**”. Fractures were also found in the threads between the first and the second thread classified as “**F.h.ts**” associated with bent abutment screws.

- External connection dental implants, where cracks/fractures typically occurred at:
 - at the bottom edge of the hexagonal structure with vertical direction classified as “**F.v.p.d**”. This region is mechanically weaker due to the tensile forces at the edge, making it more prone to fractures.
 - Joints classified as “**F.h.j**”, with horizontal direction where the different components of the implant system connect. Indeed, the juncture between the hexagonal structure and the platform exhibits mechanical weakness, leading to edge tensile stresses. (In contrast, for internal connection, this weak point is situated between the inner cylindrical section of the fixture and the base of the abutment)

The findings indicate that fatigue crack initiation was observed at the fractured platform of the implant fixture, and angles of crack lines of external connection type is $137.6^\circ \pm 4.5^\circ$ were significantly greater than that of internal connection type ($114.8^\circ \pm 4.3^\circ$). Furthermore, the observed crack lines in implants *in vitro* corresponded to the displacement vectors of the implant fixture as shown by *in silico* 3D FEA. These results imply that displacement vectors can forecast crack initiation directions. The study clarified that the design of the fixture-abutment joint type affects the direction of vertical fractures. The direction of displacement vectors occurring on the fixture platform might explain the vertical fractures of internal fixtures (Yamaguchi et al., 2018).

Following the study done by On *et al* (On et al., 2022), that aims to compare the mechanical behaviors of three dental implant fixtures with different abutment connection designs. The goal was to evaluate the maximum fracture load and fatigue limits, with a focus on understanding how these designs influence the positions and patterns of fractures. The fatigue test was started with a load of approximately 90% of the average maximum compressive load obtained through the static load test, and the final fatigue limit, which was obtained by incrementally lowering the load. Based on the microscopic examination using the SEM technique, the fracture areas under cyclic loading for the fatigue test differed for each implant type have been identified (On et al., 2022):

- **TiZr alloy** dental implant featuring an internal conical connection with a **Torx design** (BLX):
 - at the level uppermost edge of the fixture with a load of 80% of the nominal peak value classified as “**F.v.p**”

- between the first and second threads (**F.h.ts**) or the beginning of the microthread (**F.h.mt**) with a load of 90% of the nominal peak value. As the load increased, the fractured areas gradually progress from the uppermost edge to the apex of the fixture fracture.
- **Titanium (grade 4)** dental implant featuring an internal conical connection with a **Torx plus design** (Torx++) implants was located at the level of the thinnest part of the fixture between the first and second thread (**F.h.ts**).
- **Titanium (grade 4)** dental implant featuring an internal conical connection with a **Hex** (IU) located at the uppermost edge (**F.v.p**). The fractured area exhibited a tendency to progress from the uppermost edge to the apex of the fixture fracture.

Furthermore, all three implants endured up to 50% of the nominal peak value in the fatigue test; the BLX implant, in particular, was able to withstand up to 70% of the nominal peak. This simulation represents the worst-case scenario in the harshest environment (On et al., 2022). Finally, considering the assumption of a resorption of the marginal alveolar bone in ISO 14801, the fracture risk of the TORX++ implant rises when the bone level drops to the thinnest point (between the first and second thread) of the fixture as the alveolar bone resorbs. The BLX and IU implants are prone to fracture at the uppermost edge of the fixture; however, as the overload increases, the fractured areas in BLX and IU fixtures tend to move downwards. Assuming that the alveolar bone is not resorbed in this study, the TORX++ implant can avoid fixture fracture by preventing the overload and peri-implantitis that lead to marginal bone loss (On et al., 2022).

Following (Choi et al., 2019) that aimed to investigate the fracture behavior of dental implants by Changing the Internal Connection Design with Osseospeed® EV (EV) and Osseospeed® TX (TX). With TX sample showed a tendency of fixture-level fracture around the first and second threads apical to the micro-thread area (**F.h.ts**). For the EV samples, the group loaded at 50% exhibited a distinct propensity for clean-cut fractures occurring at the initial thread level (**F.h.ts**). Conversely, the remaining groups displayed a tendency to exhibit torn-out patterns both apically and coronally to the first thread, with the fractured area nearly aligning with the thinnest section of the fixture, classified as complex fracture at thread level (**F.c.ts**).

The findings indicate that the first thread area was at the same level as the thinnest part in the EV fixture, while they were not at the same level in the TX. This suggests that the

weakest part, not necessarily the thinnest part, of the TX and EV fixtures was located around the first thread area. Indeed, the thinnest part of the TX implant, excluding the coronal portion of the fixture, was located at the micro-thread area, approximately 0.5–1 mm coronal to the first thread of the implant fixture (Choi et al., 2019).

Following Yu & Qiu (Yu & Qiu, 2022), that aimed to analyze the incidence of implant body fractures and identify possible risk factors through a long-term retrospective evaluation of patients who received implants from five different systems:

- 37.8% of implants failed at the end of the screw. That presents a change in geometry along the implant, in which the thread notches into the implant cross-section, becoming a weak point (**F.h.sc**).
- 24.3% of the fractures happened precisely at the thread area (**F.h.ts**) and all of these fractures were associated with the Ankylos system. The Ankylos implants feature a tapered internal connection utilizing a Morse taper system, which generates a clamping force to reduce micromovements.
- 37.8% of the fractures were located in the narrowest part of the implant neck and extended downward towards the implant threads, leading to a fracture of the implant body (**F.v.p**).

Following Chrcanovic et al., (2017), 3 implants had fractures located at the most coronal part of the implant (**F.v.p**) and the other implants presented transversal fracture along the implant body (thread area) (**F.h.ts**).

In the study conducted by Kim et al. (2020), a comparison of the fatigue characteristics and fracture patterns between single-directional loading conditions, as specified by the ISO 14801 standard, and multi-directional loading conditions was performed on dental implant fixtures made with Ti-6Al-4V alloy material. A single direction with only axial force was applied to the AO group (axial/occlusal), while multi-directional force with a 2° angulation was applied to the AOFL (AO with facial/lingual) and AOMD (AO with Mesial-Distal) groups.

The two groups subjected to multi-directional loading conditions were found to have fatigue cycle values that were five times lower, showing a statistically significant difference. Based on the FE-SEM micrographs, there were no differences in surface morphology characteristics among the three groups under single and multi-directional loading. However, comparing the AO and AOMD groups, only the AOMD group

displayed a vertical slip band in the direction of crack propagation (**F.c.ts**). At 1000x magnification, secondary fractures were present at the final fracture site for all three groups, but at the crack initiation site, secondary fractures were observed only in specimens subjected to multi-directional loading (Kim et al., 2020).

Following the study conducted by Zhang *et al* (Zhang et al., 2022), which analyzed factors that may have led to the fracture of zirconia implants through macro/micro-fractography. The implants consisted of monotype (one-piece) and two-piece ceramic implants from two manufacturers (Z-Systems and CeraRoot). All implants were fully ceramic, made from 3 mol% yttria-stabilized zirconia (3Y-TZP) powder:

- all one-piece implants (parallel-walled or tapered) have experienced fracturing in the endosseous segment within the constricted area situated between two threads (**F.h.t**) at similar locations, where the implants cross-section is at its narrowest. A wide v-notch shaped cut was present at the implant surface connected to the fracture origin. The fracture origins for all one-piece implants were directly linked to surface flaws in the constriction region between two threads.
- two-piece implants have experienced different fracture-initiation locations:
 - at the endosseous part, in the constriction region between two external threads (**F.h.ts**), its narrowest section. The failure origin was located below the abutment-implant connection, while the abutment was not exposed. A significant precipitate that corresponds to Al_2O_3 , with a darker contrast, was observed at the fracture origin of this two-piece implant break.
 - at the inner surfaces of the abutment-implant connections for cemented abutment and self-tapping tissue-level implants, the fracture initiate at the internal abutment-implant angles. The fracture went downwards with the origin on the upper part (angle) (**F.v.ts.a-d**) between the fixture and the abutment contact or upwards with the origin on the lower part (angle) contact between the fixture and the abutment contact (**F.v.p.a-u**). Or the fracture initiate at the implant-abutment angle connection and propagated horizontally along the implant walls (**F.h.ts.a-ie**)
 - For screw retained implants, the fracture initiate at the implant-screw connections and propagated horizontally along the implant walls (**F.h.ts.sc-ie**) or upward to the implant shoulder (**F.v.p.sc-u**).

- Like the Z-Systems one-piece implants, both CeraRoot one-piece implants experienced fractures in the constricted area between two threads (**F.h.t.o**). The fractures originated on the external surface, with hackle marks radiating from the surface in the direction of the crack propagation.
- All compressive curls are evident on the fracture surface of all retrieved implants, with the fracture origin identified on the side opposite to the compressive curl.

According to the study done by Gahlert et al. (2012), that analyzes the mechanical failures one-piece zirconia dental implants, out of 170 implants inserted in 79 patients, 13 experienced fractures after prosthetic loading. The fractures were examined using both macroscopic and microscopic methods, including scanning electron microscopy (SEM). Most fractures (12 out of 13) occurred in implants with a 3.25 mm diameter and one was found in an implant with a 4 mm diameter. Fractures were caused by bending forces and the direction of crack propagation was consistently from the palatal (or lingual) side to the buccal side, indicative of stress similar to biting actions. Initial crack site was localized at:

- the first thread (**F.h.t**), suggesting good bone integration for (10 out of the 13 fractured implants).
- the third thread for one fractured dental implant and at the fifth and eighth threads for a bridge on two implants, implying bone loss in those areas (**F.h.t**).

The translational study by Scherrer et al. (2019), involved the examination of 15 fractured zirconia implant parts, recovered with their cemented all-ceramic crowns. These implants were first-generation products from manufacturers like AXIS Biodental, Z-Systems, Straumann, and Swiss Dental Solutions. The study employed fractographic analysis to identify the origin and features of the cracks. A mathematical model incorporating 2D and 3D images of the crown-implant parts was used to calculate bending moments, stresses, and crack onset locations. Fractures were observed originating from the periphery of the most anterior diameter of the implant and adjacent to the bone level. The implants had significantly small diameters at their constriction points in the fracture zones. The cracks that initiated the fractures started at the constriction areas between two threads where the implant diameters were smallest, and these horizontally predisposed cracks were classified as “**f.h.t.o**”. All fractured implants also exhibited a hackle, twist hackle (th), several arrest lines (ar) (horizontal lines above the origin, for AXIS broken

implants) and a compression wave, confirming the bending component during the fracture process. The opposite side to the compression curl is where the fracture origin is located.

The PURE Ceramic implant (Straumann) was the only one that fractured approximately 5 mm within the bone. This fracture was classified as “**F.h.t**” as shown in the diagram 8. The cracks in the AXIS and SDS implants were 40 µm in size, with stress values around 600 MPa. For SDS implants, the fracture did not originate from external surface damage, as the implant surface appeared smooth with very fine hackles extending from distal to mesial. The early implant failure was attributed to the high occlusal contact load, which generated bending moments in the small-diameter implant (3.7 mm) for the large-sized crown (Scherrer et al., 2019).

In both ceramic-processed implants and transgranular and intergranular fracture implants, the microstructure present on the fracture surfaces was similar. The fracture propagated more transgranularly near the fracture origin. These types of horizontal and bone-adjacent fractures at the thinnest point of AXIS Biodental, SDS, and Z-Systems implants are classified as **F.h.t**.

5 CONCLUSION

In this thesis, we have developed a comprehensive classification system for various fractures of fixture dental implants, focusing on those made from titanium, Titanium-Zirconium and zirconia. Through an extensive review of the literature and the analysis of clinical and *in vitro* studies, we have studied the influence of risk factors on implant fractures. These risk factors, which can originate from prosthetic, implant, or patient-related sources, must be anticipated and assessed to ensure the longevity of implant treatments. The classification system proposed in this thesis categorizes fractures based on their location, type (e.g., bending, complete fracture), and influencing factors (e.g., crown diameter, connection type). This classification not only aids in understanding the fracture mechanisms but also provides a framework for predicting potential failure points.

One of the most other significant contributions of this classification system is the establishment of a standardized language for describing implant fractures. This common terminology will facilitate clearer communication among researchers, clinicians, and manufacturers, ensuring that everyone is on the same page when discussing implant fractures. This uniformity is crucial for advancing research and improving clinical practices.

6 BIBLIOGRAPHY

- Adell, R., Eriksson, B., Lekholm, U., Brånemark, P. I., & Jemt, T. (1990). Long-term follow-up study of osseointegrated implants in the treatment of totally edentulous jaws. *The International journal of oral & maxillofacial implants*, 5(4), 347–359
- Al-Johany, S. S., Al Amri, M. D., Alsaeed, S., & Alalola, B. (2017). Dental Implant Length and Diameter: A Proposed Classification Scheme. *Journal of prosthodontics : official journal of the American College of Prosthodontists*, 26(3), 252–260. <https://doi.org/10.1111/jopr.12517>
- Anchieta, R. B., Machado, L. S., Hirata, R., Bonfante, E. A., & Coelho, P. G. (2016). Platform-Switching for Cemented Versus Screwed Fixed Dental Prostheses: Reliability and Failure Modes: An In Vitro Study. *Clinical implant dentistry and related research*, 18(4), 830–839. <https://doi.org/10.1111/cid.12363>
- Anusavice, K. J., Phillips, R., Shen, C., & Rawls, H. (2013). *Phillips' Science of Dental Materials* (12 ed.). Saunders Co Ltd. <http://ci.nii.ac.jp/ncid/BA28261773>
- Assunção, W. G., Tabata, L. F., Barão, V. A., & Rocha, E. P. (2008). Comparison of stress distribution between complete denture and implant-retained overdenture-2D FEA. *Journal of oral rehabilitation*, 35(10), 766–774. <https://doi.org/10.1111/j.1365-2842.2008.01851.x>
- Baggi, L., Cappelloni, I., Di Girolamo, M., Maceri, F., & Vairo, G. (2008). The influence of implant diameter and length on stress distribution of osseointegrated implants related to crestal bone geometry: a three-dimensional finite element analysis. *The Journal of prosthetic dentistry*, 100(6), 422–431. [https://doi.org/10.1016/S0022-3913\(08\)60259-0](https://doi.org/10.1016/S0022-3913(08)60259-0)
- Baleani, M., Viceconti, M., & Toni, A. (2000). The effect of sandblasting treatment on endurance properties of titanium alloy hip prostheses. *Artificial organs*, 24(4), 296–299. <https://doi.org/10.1046/j.1525-1594.2000.06486.x>
- Balshi T. J. (1996). An analysis and management of fractured implants: a clinical report. *The International journal of oral & maxillofacial implants*, 11(5), 660–666.
- Bayraktar, M., Gultekin, B. A., Yalcin, S., & Mijiritsky, E. (2013). Effect of Crown to Implant Ratio and Implant Dimensions on Periimplant Stress of Splinted Implant-Supported Crowns. *Implant Dentistry*, 22(4), 406–413. <https://doi.org/10.1097/id.0b013e31829c224d>
- Berglundh, T., Persson, L., & Klinge, B. (2002). A systematic review of the incidence of biological and technical complications in implant dentistry reported in prospective longitudinal studies of at least 5 years. *Journal Of Clinical Periodontology*, 29(s3), 197–212. <https://doi.org/10.1034/j.1600-051x.29.s3.12.x>
- Bozkaya, D., Muftu, S., & Muftu, A. (2004). Evaluation of load transfer characteristics of five different implants in compact bone at different load levels by finite elements analysis. *The Journal of prosthetic dentistry*, 92(6), 523–530. <https://doi.org/10.1016/j.prosdent.2004.07.024>
- Brunski J. B. (1988). Biomaterials and biomechanics in dental implant design. *The International journal of oral & maxillofacial implants*, 3(2), 85–97

- Carlsson, L., Röstlund, T., Albrektsson, B., Albrektsson, T., & Brånemark, P. I. (1986). Osseointegration of titanium implants. *Acta orthopaedica Scandinavica*, 57(4), 285–289. <https://doi.org/10.3109/17453678608994393>
- Chang, M., Chronopoulos, V., & Mattheos, N. (2013). Impact of excessive occlusal load on successfully-osseointegrated dental implants : a literature review. *Journal Of Investigative And Clinical Dentistry*, 4(3), 142-150. <https://doi.org/10.1111/jicd.12036>
- Chézeau, L., Tchinda, A., Pierson, G., Bravetti, P., Ferrari, L., Joubert, O., Zaiou, M., & Rihn, B. H. (2022). In Vitro Molecular Study of Titanium-Niobium Alloy Biocompatibility. *Biomedicines*, 10(8),1898. <https://doi.org/10.3390/biomedicines10081898>
- Chiapasco, M., Casentini, P., Zaniboni, M., Corsi, E., & Anello, T. (2012). Titanium-zirconium alloy narrow-diameter implants (Straumann Roxolid®) for the rehabilitation of horizontally deficient edentulous ridges: prospective study on 18 consecutive patients. *Clinical oral implants research*, 23(10), 1136–1141. <https://doi.org/10.1111/j.1600-0501.2011.02296.x>
- Choi, N. H., Yoon, H. I., Kim, T. H., & Park, E. J. (2019). Improvement in Fatigue Behavior of Dental Implant Fixtures by Changing Internal Connection Design : An In Vitro Pilot Study. *Materials*, 12(19), 3264. <https://doi.org/10.3390/ma12193264>
- Chrcanovic, B. R., Kisch, J., Albrektsson, T., & Wennerberg, A. (2018). Factors influencing the fracture of dental implants. *Clinical implant dentistry and related research*, 20(1), 58–67. <https://doi.org/10.1111/cid.12572>
- Cumpston, M. S., McKenzie, J. E., Welch, V. A., & Brennan, S. E. (2022). Strengthening systematic reviews in public health : guidance in the Cochrane Handbook for Systematic Reviews of Interventions, 2nd edition. *Journal Of Public Health*, 44(4), e588-e592. <https://doi.org/10.1093/pubmed/fdac036>
- Davarpanah, M., Martinez, H., Tecucianu, J. F., Celletti, R., & Lazzara, R. (2000). Small-diameter implants: indications and contraindications. *Journal of esthetic dentistry*, 12(4), 186–194. <https://doi.org/10.1111/j.1708-8240.2000.tb00221.x>
- De Carvalho, N. A., de Almeida, E. O., Rocha, E. P., Freitas, A. C., Jr, Anchieta, R. B., & Kina, S. (2012). Short implant to support maxillary restorations: bone stress analysis using regular and switching platform. *The Journal of craniofacial surgery*, 23(3), 678–681. <https://doi.org/10.1097/SCS.0b013e31824dbab7>
- Dhima, M., Paulusova, V., Lohse, C., Salinas, T. J., & Carr, A. B. (2014). Practice-based evidence from 29-year outcome analysis of management of the edentulous jaw using osseointegrated dental implants. *Journal of prosthodontics : official journal of the American College of Prosthodontists*, 23(3), 173–181. <https://doi.org/10.1111/jopr.12084>
- Eckert, S. E., Salinas, T. J., & Akça, K. (2015). Implant fractures : etiology, Prevention, and treatment. *Dental Implant Complications, S.J. Froum (Ed.)*, 132-144. <https://doi.org/10.1002/9781119140474.ch6>
- Esposito, M., Hirsch, J. M., Lekholm, U., & Thomsen, P. (1998). Biological factors contributing to failures of osseointegrated oral implants. (II). Etiopathogenesis. *European journal of oral sciences*, 106(3), 721–764. <https://doi.org/10.1046/j.0909-8836..t01-6-.x>

- Esposito, M., Hirsch, J. M., Lekholm, U., & Thomsen, P. (1998). Biological factors contributing to failures of osseointegrated oral implants. (I). Success criteria and epidemiology. *European journal of oral sciences*, 106(1), 527–551. <https://doi.org/10.1046/j.0909-8836..t01-2-.x>
- Fernandes, D. J., Elias, C. N., & Valiev, R. Z. (2015). Properties and Performance of Ultrafine Grained Titanium for Biomedical Applications. *Materials Research*, 18(6), 1163–1175. <https://doi.org/10.1590/1516-1439.005615>
- Freitas, A. C., Jr, Bonfante, E. A., Rocha, E. P., Silva, N. R., Marotta, L., & Coelho, P. G. (2011). Effect of implant connection and restoration design (screwed vs. cemented) in reliability and failure modes of anterior crowns. *European journal of oral sciences*, 119(4), 323–330. <https://doi.org/10.1111/j.1600-0722.2011.00837.x>
- Gahlert, M., Burtscher, D., Grunert, I., Kniha, H., & Steinhauser, E. (2012). Failure analysis of fractured dental zirconia implants. *Clinical oral implants research*, 23(3), 287–293. <https://doi.org/10.1111/j.1600-0501.2011.02206.x>
- Gahlert, M., Burtscher, D., Pfundstein, G., Grunert, I., Kniha, H., & Roehling, S. (2013). Dental zirconia implants up to three years in function: a retrospective clinical study and evaluation of prosthetic restorations and failures. *The International journal of oral & maxillofacial implants*, 28(3), 896–904. <https://doi.org/10.11607/jomi.2211>
- Gargallo Albiol, J., Satorres-Nieto, M., Puyuelo Capablo, J. L., Sánchez Garcés, M. A., Pi Urgell, J., & Gay Escoda, C. (2008). Endosseous dental implant fractures: an analysis of 21 cases. *Medicina oral, patologia oral y cirugia bucal*, 13(2), E124–E128
- Gealh, W. C., Mazzo, V., Barbi, F., & Camarini, E. T. (2011). Osseointegrated implant fracture: causes and treatment. *The Journal of oral implantology*, 37(4), 499–503. <https://doi.org/10.1563/AAID-JOI-D-09-00135.1>
- Gehrke, S. A. (2013). Importance of Crown Height Ratios in Dental Implants on the Fracture Strength of Different Connection Designs : An In Vitro Study. *Clinical Implant Dentistry And Related Research*, 17(4), 790–797. <https://doi.org/10.1111/cid.12165>
- Geng, J. P., Xu, D. W., Tan, K. B., & Liu, G. R. (2004). Finite element analysis of an osseointegrated stepped screw dental implant. *The Journal of oral implantology*, 30(4), 223–233. <https://doi.org/10.1563/0654.1>
- Gil, F. J., Espinar, E., Llamas, J. M., & Sevilla, P. (2014). Fatigue life of bioactive titanium dental implants treated by means of grit-blasting and thermo-chemical treatment. *Clinical implant dentistry and related research*, 16(2), 273–281. <https://doi.org/10.1111/j.1708-8208.2012.00468.x>
- Goiato, M. C., Pellizzer, E. P., Da Silva, E. V. F., Da Rocha Bonatto, L., & Santos, D. M. D. (2015). Is the internal connection more efficient than external connection in mechanical, biological, and esthetical point of views ? A systematic review. *Oral And Maxillofacial Surgery*, 19(3), 229–242. <https://doi.org/10.1007/s10006-015-0494-5>
- Goodacre, C. J., Bernal, G., Rungcharassaeng, K., & Kan, J. Y. (2003). Clinical complications with implants and implant prostheses. *The Journal of prosthetic dentistry*, 90(2), 121–132. [https://doi.org/10.1016/S0022-3913\(03\)00212-9](https://doi.org/10.1016/S0022-3913(03)00212-9)

- Huang, H., Hsu, J., Fuh, L., Tu, M., Ko, C., & Shen, Y. (2008). Bone stress and interfacial sliding analysis of implant designs on an immediately loaded maxillary implant : A non-linear finite element study. *Journal Of Dentistry*, 36(6), 409-417. <https://doi.org/10.1016/j.jdent.2008.02.015>
- İplikçioğlu, H., & Akça, K. (2002). Comparative evaluation of the effect of diameter, length and number of implants supporting three-unit fixed partial prostheses on stress distribution in the bone. *Journal of dentistry*, 30(1), 41–46. [https://doi.org/10.1016/s0300-5712\(01\)00057-4](https://doi.org/10.1016/s0300-5712(01)00057-4)
- Jansen, V. K., Conrads, G., & Richter, E. J. (1997). Microbial leakage and marginal fit of the implant-abutment interface. *The International journal of oral & maxillofacial implants*, 12(4), 527–540
- Kim, J., Yoon, Y., Pae, A., & Kwon, Y. (2023). Clinical outcome of narrow diameter dental implants : a 3-year retrospective study. *Maxillofacial Plastic And Reconstructive Surgery*, 45(1). <https://doi.org/10.1186/s40902-023-00394-6>
- Kim, W. H., Song, E. S., Ju, K. W., Lim, D., Han, D., Jung, T., Jeong, Y., Lee, J., & Kim, B. (2020). Mechanical Assessment of Fatigue Characteristics between Single- and Multi-Directional Cyclic Loading Modes on a Dental Implant System. *Materials*, 13(7), 1545. <https://doi.org/10.3390/ma13071545>
- Kochar, S. P., Reche, A., & Paul, P. (2022). The Etiology and Management of Dental Implant Failure: A Review. *Cureus*, 14(10), e30455.<https://doi.org/10.7759/cureus.30455>
- Kong, L., Gu, Z., Li, T., Wu, J., Hu, K., Liu, Y., Zhou, H., & Liu, B. (2009). Biomechanical optimization of implant diameter and length for immediate loading: a nonlinear finite element analysis. *The International journal of prosthodontics*, 22(6), 607–615
- Koyano, K., & Esaki, D. (2015). Occlusion on oral implants: current clinical guidelines. *Journal of oral rehabilitation*, 42(2), 153–161. <https://doi.org/10.1111/joor.12239>
- Lekholm, U., Zarb, G. A., & Albrektsson, T. (1985). In: Patient selection and preparation. Tissue integrated prostheses: osseointegration in clinical dentistry. Chicago: Quintessence Publishing Company. p. 199–209
- Lee, C. K., Karl, M., & Kelly, J. R. (2009). Evaluation of test protocol variables for dental implant fatigue research. *Dental Materials*, 25(11), 1419-1425. <https://doi.org/10.1016/j.dental.2009.07.003>
- Lee, D., Kim, N., Lee, Y., Oh, Y., Lee, J., & You, H. (2019). Implant fracture failure rate and potential associated risk indicators : An up to 12-year retrospective study of implants in 5,124 patients. *Clinical Oral Implants Research*, 30(3), 206-217. <https://doi.org/10.1111/clr.13407>
- Liu, X., Chen, S., Tsoi, J. K. H., & Matinlinna, J. P. (2017). Binary titanium alloys as dental implant materials-a review. *Regenerative biomaterials*, 4(5), 315–323. <https://doi.org/10.1093/rb/rbx027>
- Manda, M. G., Psyllaki, P. P., Tsipas, D. N., & Koidis, P. T. (2009). Observations on an in-vivo failure of a titanium dental implant/abutment screw system: a case report. *Journal of biomedical materials research. Part B, Applied biomaterials*, 89(1), 264–273. <https://doi.org/10.1002/jbm.b.31211>

- McCracken M. (1999). Dental implant materials: commercially pure titanium and titanium alloys. *Journal of prosthodontics: official journal of the American College of Prosthodontists*, 8(1), 40–43. <https://doi.org/10.1111/j.1532-849x.1999.tb00006.x>
- Misch, C. E., Strong, J. T., & Bidez, M. W. (2015). Scientific Rationale for Dental Implant Design. Dans *Elsevier eBooks* (p. 340-371). <https://doi.org/10.1016/b978-0-323-07845-0.00015-4>
- Moraschini, V., Poubel, L. A., Ferreira, V. F., & Barboza, E.dosS. (2015). Evaluation of survival and success rates of dental implants reported in longitudinal studies with a follow-up period of at least 10 years: a systematic review. *International journal of oral and maxillofacial surgery*, 44(3), 377–388. <https://doi.org/10.1016/j.ijom.2014.10.023>
- Morgan, M. J., James, D. F., & Pilliar, R. M. (1993). Fractures of the fixture component of an osseointegrated implant. *The International journal of oral & maxillofacial implants*, 8(4), 409–414
- Nam, D. H., Kim, P. J., Koo, K. T., Seol, Y. J., Lee, Y. M., Ku, Y., Rhyu, I. C., Kim, S., & Cho, Y. D. (2024). The cumulative survival rate of dental implants with microthreads: a long-term retrospective study. *Journal of periodontal & implant science*, 54(1), 53–62. <https://doi.org/10.5051/jpis.2203240162>
- Nicholson, J. W. (2020). Titanium Alloys for Dental Implants : A Review. *Prosthesis*, 2(2), 100-116. <https://doi.org/10.3390/prosthesis2020011>
- Oh, J., Pyo, S., Chang, J., & Kim, S. (2023). Up to a 15-Year Survival Rate and Marginal Bone Resorption of 1780 Implants with or without Microthreads : A Multi Center Retrospective Study. *Journal Of Clinical Medicine*, 12(6), 2425. <https://doi.org/10.3390/jcm12062425>
- Oh, S. L., & Barnes, D. (2016). Managing a fractured implant: A clinical report. *The Journal of prosthetic dentistry*, 115(4), 397–401. <https://doi.org/10.1016/j.prosdent.2015.08.027>
- Okumura, N., Stegaroiu, R., Kitamura, E., Kurokawa, K., & Nomura, S. (2010). Influence of maxillary cortical bone thickness, implant design and implant diameter on stress around implants: a three-dimensional finite element analysis. *Journal of prosthodontic research*, 54(3), 133–142. <https://doi.org/10.1016/j.jpor.2009.12.004>
- On, S. W., Yi, S. M., Park, I. Y., Byun, S. H., & Yang, B. E. (2022). Fracture and Fatigue of Dental Implants Fixtures and Abutments with a Novel Internal Connection Design: An In Vitro Pilot Study Comparing Three Different Dental Implant Systems. *Journal of functional biomaterials*, 13(4), 239. <https://doi.org/10.3390/jfb13040239>
- Osman, R. B., & Swain, M. V. (2015). A Critical Review of Dental Implant Materials with an Emphasis on Titanium versus Zirconia. *Materials*, 8(3), 932-958. <https://doi.org/10.3390/ma8030932>
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., McGuinness, L. A., ... Moher, D. (2021). The PRISMA

- 2020 statement: an updated guideline for reporting systematic reviews. *BMJ (Clinical research ed.)*, 372, n71. <https://doi.org/10.1136/bmj.n71>
- Pessoa, R. S., Muraru, L., Júnior, E. M., Vaz, L. G., Sloten, J. V., Duyck, J., & Jaecques, S. V. (2010). Influence of Implant Connection Type on the Biomechanical Environment of Immediately Placed Implants – CT-Based Nonlinear, Three-Dimensional Finite Element Analysis. *Clinical Implant Dentistry And Related Research*, 12(3), 219-234. <https://doi.org/10.1111/j.1708-8208.2009.00155.x>
- Petrie, C. S., & Williams, J. L. (2005). Comparative evaluation of implant designs: influence of diameter, length, and taper on strains in the alveolar crest. A three-dimensional finite-element analysis. *Clinical oral implants research*, 16(4), 486–494. <https://doi.org/10.1111/j.1600-0501.2005.01132.x>
- Pierrisnard, L., Renouard, F., Renault, P., & Barquins, M. (2003). Influence of Implant Length and Bicortical Anchorage on Implant Stress Distribution. *Clinical Implant Dentistry And Related Research*, 5(4), 254-262. <https://doi.org/10.1111/j.1708-8208.2003.tb00208.x>
- Pita, M. S., Anchieta, R. B., Barão, V. A., Garcia, I. R., Jr, Pedrazzi, V., & Assunção, W. G. (2011). Prosthetic platforms in implant dentistry. *The Journal of craniofacial surgery*, 22(6), 2327–2331. <https://doi.org/10.1097/SCS.0b013e318232a706>
- Pommer, B., Bucur, L., Zauza, K., Tepper, G., Hof, M., & Watzek, G. (2014). Meta-Analysis of Oral Implant Fracture Incidence and Related Determinants. *Journal Of Oral Implants*, 2014, 1-7. <https://doi.org/10.1155/2014/263925>
- Rahmitasari, F., Ishida, Y., Kurahashi, K., Matsuda, T., Watanabe, M., & Ichikawa, T. (2017). PEEK with Reinforced Materials and Modifications for Dental Implant Applications. *Dentistry journal*, 5(4), 35. <https://doi.org/10.3390/dj5040035>
- Renouard, F., & Nisand, D. (2006). Impact of implant length and diameter on survival rates. *Clinical oral implants research*, 17 Suppl 2, 35–51. <https://doi.org/10.1111/j.1600-0501.2006.01349.x>
- Saini, M., Singh, Y., Arora, P., Arora, V., & Jain, K. (2015). Implant biomaterials: A comprehensive review. *World journal of clinical cases*, 3(1), 52–57. <https://doi.org/10.12998/wjcc.v3.i1.52>
- Sánchez-Pérez, A., Moya-Villaescusa, M. J., Jornet-Garcia, A., & Gomez, S. (2010). Etiology, risk factors and management of implant fractures. *Medicina oral, patología oral y cirugía bucal*, 15(3), e504–e508. <https://doi.org/10.4317/medoral.15.e504>
- Sanivarapu, S., Moogla, S., Kuntcham, R. S., & Kolaparthi, L. K. (2016). *Journal Of Indian Society Of Periodontology*, 20(1), 6-11. <https://doi.org/10.4103/0972-124x.154190>
- Scherrer, S. S., Mekki, M., Crottaz, C., Gahlert, M., Romelli, E., Marger, L., Durual, S., & Vittecoq, E. (2019). Translational research on clinically failed zirconia implants. *Dental materials : official publication of the Academy of Dental Materials*, 35(2), 368–388. <https://doi.org/10.1016/j.dental.2018.11.033>
- Shemtov-Yona, K., & Rittel, D. (2015a). An Overview of the Mechanical Integrity of Dental Implants. *BioMed Research International*, 2015, 1-11. <https://doi.org/10.1155/2015/547384>

- Shemtov-Yona, K., & Rittel, D. (2015b). On the mechanical integrity of retrieved dental implants. *Journal of the mechanical behavior of biomedical materials*, 49, 290–299. <https://doi.org/10.1016/j.jmbbm.2015.05.014>
- Shemtov-Yona, K., & Rittel, D. (2016a). Fatigue failure of dental implants in simulated intraoral media. *Journal Of The Mechanical Behavior Of Biomedical Materials/Journal Of Mechanical Behavior Of Biomedical Materials*, 62, 636-644. <https://doi.org/10.1016/j.jmbbm.2016.05.028>
- Shemtov-Yona, K., & Rittel, D. (2016b). Fatigue of Dental Implants: Facts and Fallacies. *Dentistry journal*, 4(2), 16. <https://doi.org/10.3390/dj4020016>
- Shemtov-Yona, K., Rittel, D., & Dorogoy, A. (2014a). Mechanical assessment of grit blasting surface treatments of dental implants. *Journal of the mechanical behavior of biomedical materials*, 39, 375–390. <https://doi.org/10.1016/j.jmbbm.2014.07.027>
- Shemtov-Yona, K., Rittel, D., Levin, L., & Machtei, E. E. (2012). Effect of Dental Implant Diameter on Fatigue Performance. Part I : Mechanical Behavior. *Clinical Implant Dentistry And Related Research*, 16(2), 172-177. <https://doi.org/10.1111/j.1708-8208.2012.00477.x>
- Shemtov-Yona, K., Rittel, D., Machtei, E. E., & Levin, L. (2014b). Effect of dental implant diameter on fatigue performance. Part II: failure analysis. *Clinical implant dentistry and related research*, 16(2), 178–184. <https://doi.org/10.1111/j.1708-8208.2012.00476.x>
- Strong, J., Misch, C., Bidez, M., & Nalluri, P. (1998). Functional surface area: Thread-form parameter optimization for implant body design. *Compend Contin Educ Dent*, 19(3), 4-9
- Sykaras, N., Iacopino, A. M., Marker, V. A., Triplett, R. G., & Woody, R. D. (2000). Implant materials, designs, and surface topographies: their effect on osseointegration. A literature review. *The International journal of oral & maxillofacial implants*, 15(5), 675–690
- Tabrizi, R., Behnia, H., Taherian, S., & Hesami, N. (2017). What Are the Incidence and Factors Associated With Implant Fracture?. *Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons*, 75(9), 1866–1872. <https://doi.org/10.1016/j.joms.2017.05.014>
- Tada, S., Stegaroiu, R., Kitamura, E., Miyakawa, O., & Kusakari, H. (2003). Influence of implant design and bone quality on stress/strain distribution in bone around implants: a 3-dimensional finite element analysis. *The International journal of oral & maxillofacial implants*, 18(3), 357–368
- Tallarico, M., Luzi, C., Galasso, G., Lione, R., & Cozza, P. (2017). Comprehensive rehabilitation and natural esthetics with implant and orthodontics (cranio): An interdisciplinary approach to missing maxillary lateral incisors. *J Oral Sci Rehabil*, 3:8-16
- Tang, C., Liu, S., Zhou, G., Yu, J., Zhang, G., Bao, Y., & Wang, Q. (2012). Nonlinear finite element analysis of three implant–abutment interface designs. *International Journal Of Oral Science/International Journal Of Oral Science*, 4(2), 101-108. <https://doi.org/10.1038/ijos.2012.35>

- Tey, V. H. S., Phillips, R., & Tan, K. (2016b). Five-year retrospective study on success, survival and incidence of complications of single crowns supported by dental implants. *Clinical Oral Implants Research*, 28(5), 620-625. <https://doi.org/10.1111/clr.12843>
- Tribst, J. P. M., Werner, A., & Blom, E. J. (2023). Failed dental implant : When titanium fractures. *Diagnostics*, 13(12), 2123. <https://doi.org/10.3390/diagnostics13122123>
- Tsuge, T., & Hagiwara, Y. (2009). Influence of lateral-oblique cyclic loading on abutment screw loosening of internal and external hexagon implants. *Dental Materials Journal*, 28(4), 373-381. <https://doi.org/10.4012/dmj.28.373>
- Van de Velde, T., Collaert, B., Sennerby, L., & De Bruyn, H. (2010). Effect of implant design on preservation of marginal bone in the mandible. *Clinical implant dentistry and related research*, 12(2), 134–141. <https://doi.org/10.1111/j.1708-8208.2008.00145.x>
- Velasco-Ortega, E., Flichy-Fernández, A., Punset, M., Jiménez-Guerra, A., Manero, J. M., & Gil, J. (2019). Fracture and Fatigue of Titanium Narrow Dental Implants: New Trends in Order to Improve the Mechanical Response. *Materials (Basel, Switzerland)*, 12(22), 3728. <https://doi.org/10.3390/ma12223728>
- Welch, V., Petticrew, M., Tugwell, P., Moher, D., O'Neill, J., Waters, E., White, H., & PRISMA-Equity Bellagio group (2012). PRISMA-Equity 2012 extension: reporting guidelines for systematic reviews with a focus on health equity. *PLoS medicine*, 9(10), e1001333. <https://doi.org/10.1371/journal.pmed.1001333>
- Yamaguchi, S., Yamanishi, Y., Machado, L. S., Matsumoto, S., Tovar, N., Coelho, P. G., Thompson, V. P., & Imazato, S. (2018). In vitro fatigue tests and in silico finite element analysis of dental implants with different fixture/abutment joint types using computer-aided design models. *Journal of prosthodontic research*, 62(1), 24–30. <https://doi.org/10.1016/j.jprior.2017.03.006>
- Yi, Y., Koak, J. Y., Kim, S. K., Lee, S. J., & Heo, S. J. (2018). Comparison of implant component fractures in external and internal type: A 12-year retrospective study. *The journal of advanced prosthodontics*, 10(2), 155–162. <https://doi.org/10.4047/jap.2018.10.2.155>
- Yokoyama, K., Ichikawa, T., Murakami, H., Miyamoto, Y., & Asaoka, K. (2002). Fracture mechanisms of retrieved titanium screw thread in dental implant. *Biomaterials*, 23(12), 2459-2465. [https://doi.org/10.1016/s0142-9612\(01\)00380-5](https://doi.org/10.1016/s0142-9612(01)00380-5)
- Yu, H., & Kim, Y. (2020). Fractures of implant fixtures : a retrospective clinical study. *Maxillofacial Plastic And Reconstructive Surgery*, 42(1). <https://doi.org/10.1186/s40902-020-00258-3>
- Yu, H., & Qiu, L. (2022). Analysis of fractured dental implant body from five different implant systems: a long-term retrospective study. *International journal of oral and maxillofacial surgery*, 51(10), 1355–1361. <https://doi.org/10.1016/j.ijom.2022.04.010>
- Zhang, F., Monzavi, M., Li, M., Čokić, S., Manesh, A., Nowzari, H., Vleugels, J., & Van Meerbeek, B. (2022). Fracture analysis of one/two-piece clinically failed zirconia dental implants. *Dental materials : official publication of the Academy of Dental Materials*, 38(10), 1633–1647. <https://doi.org/10.1016/j.dental.2022.08.004>

Zhang, L., & Chen, L. (2019). A Review on Biomedical Titanium Alloys : Recent Progress and Prospect. *Advanced Engineering Materials*, 21(4).
<https://doi.org/10.1002/adem.201801215>