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Influence of straight versus angulated screw channel titanium bases on failure loads of two-piece ceramic and titanium implants restored with screw-retained monolithic crowns

Dissertation

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## Zusammenfassung

Diese Dissertation untersucht den Einfluss von geraden gegenüber abgewinkelten Titanbasen auf die Versagenslasten und Biegemomente bei zweiteiligen Keramik- und Titanimplantaten, die mit monolithischen Zirkonoxidkronen versorgt wurden. Ziel dieser Studie war es, die Auswirkungen des Abutmentdesigns auf die Stabilität dieser Implantatsysteme nach thermomechanischer Belastung zu bewerten. In der Studie wurden 32 monolithisch verschraubte Zirkonoxidkronen in vier Gruppen unterteilt: Zwei Gruppen wurden auf Titan-Zirkon-Implantaten (Ti-Zr) und zwei Gruppen auf Keramikimplantaten (CI) befestigt. Die Implantate hatten identische Abmessungen (4,1 x 12 mm), wiesen jedoch unterschiedliche Abutments auf die entweder gerade (Ti-Zr-0/CI-0) oder abgewinkelt konfiguriert waren (Ti-Zr-25/CI-25). Alle Proben wurde einer dynamischen Belastung von 1,2 Millionen Zyklen bei 49 N und 1,6 Hz sowie einer thermischen Belastung im Temperaturbereich von 5°C bis 55°C ausgesetzt. Anschließend wurden die Prüfkörper bis zum Versagen in einer Universalprüfmaschine belastet, um die Biegemomente zu berechnen. Die Analyse der Bruchflächen erfolgte mittels Lichtmikroskopie und SEM (Rasterelektronenmikroskop), die um Frakturcharakteristik zu bestimmen. Die statistische Auswertung wurde mit ANOVA und Mann-Whitney-U-Tests durchgeführt, wobei eine Signifikanzgrenze von p < 0.05festgelegt wurde. Die Ergebnisse zeigten, dass alle Proben die thermomechanische Belastung ohne Komplikationen überstanden. Die höchsten mittleren Biegemomente wurden bei abgewinkelten Abutments und Keramikimplantaten gemessen, wobei die Ti-Zr-25-Gruppe 303  $\pm$  86 Ncm, die Cl-25-Gruppe 434  $\pm$  71 Ncm, die Ti-Zr-0-Gruppe 241  $\pm$  45 Ncm und die CI-0-Gruppe 326  $\pm$  58 Ncm erreichte. Abgewinkelte Abutments (p = 0,001) sowie Keramikimplantate (p < 0,001) zeigten eine signifikant höhere Stabilität im Vergleich zu geraden Abutments und Titanimplantaten. In der Studie traten bei Titanimplantaten nur plastische Verformungen auf, während zwölf von sechzehn Keramikimplantaten Frakturen zeigten. Die Ergebnisse sind klinisch relevant für die Implantologie, insbesondere bei der Auswahl von Abutmentdesign und Implantatmaterial zur Optimierung der Stabilität und des langfristigen Erfolgs. Abgewinkelte Titanbasen und Keramikimplantate zeigten eine höhere Widerstandsfähigkeit gegenüber mechanischen Belastungen. Daher könnte das abgewinkelte Titanabutment in Kombination mit Keramikimplantaten eine vielversprechende Alternative zum Goldstandard der geraden Titanabutments auf Titanimplantaten darstellen.

## Abstract

This dissertation investigates the influence of straight versus angled titanium bases on the failure loads and bending moments of two-piece ceramic and titanium implants restored with monolithic zirconia crowns. The objective of this study was to evaluate the effect of abutment design on the stability of these implant systems following thermomechanical loading. In the study, 32 monolithic screw-retained zirconia crowns were categorized into four groups: two groups were mounted on titanium-zirconium implants (Ti-Zr), and two groups were mounted on ceramic implants (CI). The implants had identical dimensions (4.1 x 12 mm) but featured different abutments, which were configured either as straight (Ti-Zr-0/Cl-0) or angled (Ti-Zr-25/Cl-25). All samples were subjected to dynamic loading comprising 1.2 million cycles at 49 N and 1.6 Hz, as well as thermal cycling across a temperature range of 5°C to 55°C. Following these stress tests, the specimens were loaded to failure using a universal testing machine to calculate bending moments. Fracture surface analysis was performed using light microscopy and scanning electron microscopy (SEM) to determine the fracture characteristics. Statistical evaluation was conducted using ANOVA and Mann-Whitney U-tests, with a significance level set at p < 0.05. The results indicated that all samples endured the thermomechanical loading without complications. The highest mean bending moments were measured in angled abutments and ceramic implants, with the Ti-Zr-25 group achieving 303 ± 86 Ncm, the CI-25 group 434 ± 71 Ncm, the Ti-Zr-0 group 241 ± 45 Ncm, and the CI-0 group  $326 \pm 58$  Ncm. Angled abutments (p = 0.001) and ceramic implants (p < 0.001) exhibited significantly greater stability compared to straight abutments and titanium implants. While titanium implants showed only plastic deformation under stress, twelve of the sixteen ceramic implants exhibited fracture. The present findings suggest that angled titanium bases and ceramic implants exhibit higher resistance to mechanical stresses under the tested parameters. This study provides valuable insights for implantology, particularly regarding the selection of abutment design and implant material. In this context, angled titanium abutments in combination with ceramic implants could be recommended as a promising alternative to the gold standard of titanium implants with straight abutments.

# List of abbreviations

ASC	angulated-screw-channel
CI	ceramic-implant
С	temperature in degrees Celsius
FEG-SEM	field-emission-gun-scanning-electronic-microscopy
Ν	newton
Ncm	Newton centimeter
р	p-value
SCC	straight-screw-channel
SEM	scanning-electronic-microscopy
SLF	surviving specimens were loaded-until-failure
Ti-Zr	titanium-zirconium-implant

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# **1** Introduction

Achieving successful and predictable outcomes in the esthetic zone presents a significant challenge in dental implantology, particularly in the maxillary anterior zone (Buser et al., 2004; Chen et al., 2023). This region requires both precise functional integration and optimal aesthetic outcomes. The complex anatomical structures of the maxillary anterior zone, combined with variable bone and soft tissue conditions, necessitate meticulous planning and execution to ensure predictable long-term success. Dental implantology has traditionally relied on titanium implants, which are extensively researched and continue to dominate the market (Brunello et al., 2022). However, a disadvantage of titanium is the documented evidence of oxide layer shearing into biological tissues under intraoral stress (Schliephake et al., 1991). Additionally, the increasing prevalence of patients with hypersensitivity to titanium, coupled with growing awareness of the potential adverse effects of metal implants, is driving a shift in both patient preferences and clinical practices (Müller-Heupt et al., 2022). Despite their functional success, titanium implants also present certain aesthetic limitations due to their metallic appearance. These limitations become particularly pronounced in cases of soft tissue recession or thin gingival biotypes, where the implant structure may become exposed, posing a significant challenge in the esthetic zone. Ceramic implants were introduced in the 1980s for use in implantology but failed to gain widespread acceptance due to their insufficient fracture resistance (Kohal et al., 2003). With the introduction of oxide ceramics and their improved mechanical properties, ceramics re-entered the field of dental implantology. The biological safety of yttrium oxide-stabilized zirconia was demonstrated in several studies, showing no carcinogenic or toxic effects on bone or soft tissues (Akagawa et al., 1998; Covacci et al., 1999). Initial clinical studies on endosseous screw implants made of zirconia yielded promising short-term results comparable to those of titanium implants (Mellinghoff, 2006). In recent years, zirconia implants have gained considerable attention as a promising alternative to titanium (Mohseni et al., 2023). Zirconia implants present significant advantages in the aesthetic zone, particularly due to their tooth-like color, which is especially beneficial in areas with thin gingival biotypes (Kajiwara et al., 2015). Additionally, zirconia is renowned for its high fracture toughness and biocompatibility, making it a durable and biologically favorable material for dental applications (Spies et al., 2018). Moreover, studies have demonstrated that zirconia exhibits a lower affinity for bacterial adhesion compared to titanium, potentially reducing the risk of peri-implant infections and enhancing long-term clinical outcomes (Roehling et al., 2019). Furthermore, zirconia implants have been found to support comparable levels of osseointegration to titanium, suggesting that they can provide the necessary structural integration to meet functional demands (Sivaraman et al., 2018). Immediate implant placement, traditionally explored with titanium, can also be considered for zirconia implants and should not be excluded on principle (Kiechle et al., 2023). This expands the potential of zirconia implants, particularly in cases where immediate placement may help preserve soft- and hard-tissue contours while also reducing overall treatment time. Preclinical and clinical research on two-piece zirconia implants is warranted. Although one-piece ceramic implants offer advantages in terms of stability, they lack the prosthetic flexibility required for adjusting abutment angulation, which is essential for achieving optimal alignment and function of the restoration (Balmer et al., 2022). The two-piece implant design provide greater prosthetic flexibility, allowing for adjustments in abutment angulation and improving overall clinical outcomes (Janner et al., 2018; Spies et al., 2016). A recent prospective study indicated that two-piece zirconia dental implants exhibit favorable clinical performance, with a high survival rate and a low occurrence of biological and prosthetic complications over an observation period of up to 12 years (Karapataki et al., 2023). Anatomical conditions and alveolar ridge defects often complicate the positioning of dental implants, presenting challenges for practitioners. As a result, variability in supraconstruction is required to accommodate these factors. Guidelines recommend screw-retained restorations over cementretained ones to minimize the risk of peri-implant infections caused by residual cement, which can be difficult to be completely removed (Sailer et al., 2022; Staubli et al., 2017; Wilson, 2009). However, in cases of anatomical variations and implant positioning, the proper alignment of the screw access hole on the palatal side can be compromised, potentially hindering the axial loading of the implant (Chappuis et al., 2013; Pitman et al., 2022). To address these challenges, the concept of angulated screw channels (ASCs) for titanium implants was introduced in 2015. This innovation provides a solution for improving esthetic outcomes by relocating the screw access hole to a more favorable palatal position, thereby enhancing both the functionality and appearance of the restoration (Garcia-Gazaui et al., 2015; Pitman et al., 2022; Rella et al., 2021). Despite the advantages of angulated abutments and clinical trials reporting high survival rates for angulated screw channel reconstructions on titanium implants (Di Fiore et al., 2023; Lv et al., 2021; Rella et al., 2021), technical complications may still pose a concern. These issues highlight the need for further research to optimize the use of angulated screw channels, particularly in esthetic cases. To date, limited research has focused on the mechanical performance of angulated screw channel (ASC) implant crowns for two-piece ceramic implants, particularly in the esthetic zone, when compared to titanium implants. As a result, further investigation is needed to better understand the mechanical behavior and failure modes of these systems. To examine the properties and performance of the ASC in this specific context, an in vitro study was conducted to assess the mechanical behavior of ceramic implants with an angled titanium base for the prosthetic restoration of the central maxillary incisor. This was achieved through fatigue testing with thermodynamic loading at a 30° angle, simulating the clinical conditions that these implants would encounter in the oral environment.

# 2 Aims

The objective of this laboratory study was to determine whether the type of titanium base (SSC vs. ASC) and implant material (ceramic vs. titanium) have an impact on the failure load and bending moments of two-piece zirconia implants with screw-retained anterior monolithic zirconia crowns after fatigue testing. The null hypotheses tested were that the type of (i) titanium base and implant material (ii) do not affect the failure load and bending moments of these restorations.

**3** Publication: Influence of straight versus angulated screw channel titanium bases on failure loads of two-piece ceramic and titanium implants restored with screw-retained monolithic crowns, Helal, E., Gierthmuelen, P. C., Bonfante, E. A., Campos, T. M. B., Pott, L. S., Lange, R., Spitznagel, F. A., Clinical Oral Implants Research, 34, 1217-1229 (2023),

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Influence of straig bases on failure lo implants restored in-vitro study E. Helal <sup>1</sup>   P. C. Gierthmu	ht versus angulated screw channel tit ads of two-piece ceramic and titaniur with screw-retained monolithic crown ehlen <sup>1</sup>	anium n ns: An
L. S. Prott <sup>1</sup>   R. Langner	<sup>3,4</sup> <sup>©</sup>   F. A. Spitznagel <sup>1</sup> <sup>©</sup>	
<sup>1</sup> Department of Prosthodontics, Medical Faculty and University Hospital Düsseldorf, Heinrich-Heine-University Düsseldorf, Düsseldorf, Germany <sup>2</sup> Department of Prosthodontics and Periodontology, Bauru School of Dentistry, University of Sao Paulo, Bauru, Brazil <sup>3</sup> Institute of Systems Neuroscience, Medical Faculty, Heinrich-Heine- University Düsseldorf, Düsseldorf, Germany <sup>4</sup> Institute of Neuroscience and Medicine, Brain and Behavior (INM-7), Research Center Jülich, Jülich, Germany <b>Correspondence</b> F. A. Spitznagel, Department of Prosthodontics, Medical Faculty and University Hospital Düsseldorf, Heinrich- Heine-University, Moorenstraße 5, 40225 Düsseldorf, Germany. Email: frank.spitznagel@med.uni- duesseldorf.de	Abstract Objective: To analyze the influence of titanium-base (straight [SSC]/angle channel [ASC]) on failure-loads and bending-moments of two-piece titanium-zirconium implants restored with monolithic-zirconia crowns Materials and Methods: Thirty-two anterior monolithic-screw-retec crowns were divided into four groups ( $n=8$ /group) according to the fa- of implant material: two-piece titanium-zirconium implant (Ti-Zr; cont sus two-piece ceramic implant (CI; test-group) and (2) type of titanium angle) versus ASC (25°). An intact implant was used for field emission electronic microscopy (FEG-SEM) characterization and Raman spe phase analyses and residual stress quantification. All samples were of tigue with thermodynamic loading (1.2-million-cycles, 49 N, 1.6Hz, 5- angle. Surviving specimens were loaded until failure (SLF) and bending the recorded. Failed samples were examined using light microscope and S analyses included ANOVA and Mann–Whitney U-test. <b>Results:</b> Raman-spectroscopy revealed the presence of residual comprece FEG-SEM revealed a roughened surface between threads and polished cervical-collar of the ceramic implant. All samples survived fatigue and complications. Mean bending-moments ( $\pm$ SD) were: Ti-Zr-0: 241 $\pm$ 451 303 $\pm$ 86Ncm, Cl-0: 326 $\pm$ 58Ncm, Cl-25: 434 $\pm$ 71Ncm. Titanium-bases material had significant effects in favor of ASC titanium bases ( $p=.001$ implants ( $p<.001$ ). Failure analysis after SLF revealed severe fractu implants, whereas titanium implants were restricted to plastic deformat <b>Conclusions:</b> Ceramic and titanium implants exhibited high reliability with no failures. From a mechanical perspective, titanium bases with A ommended for both ceramic and titanium implants and are safe for clinic	ulated-screw- a ceramic and after fatigue. ained zirconia ctors: (1) type rol-group) ver- -base: SSC (0° gun-scanning ctroscopy for exposed to fa- 55°C) at a 30° moments were EM. Statistical ssive stresses. surface at the d were free of Ncm, Ti-Zr-25: e and implant- ) and ceramic- res in ceramic tion. after fatigue, SC can be rec- cal application.
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KEYWORDS

aging, ceramics, dental implant, fatigue, material testing, zirconia

#### 1 | INTRODUCTION

In the quest for a suitable tooth-colored and non-metallic alternative to the gold-standard of titanium dental implants, ceramic implants made of alumina-toughened zirconia (ATZ) or 3mol% yttria-doped tetragonal zirconia (Y-TZP) have evolved (Balmer et al., 2022; Cionca et al., 2017). Ceramic implants might serve especially in the esthetic zone as a valuable treatment addendum for dental implantology owing to their appealing esthetic outcome and tooth-like color (Kniha et al., 2019). Experimental studies have confirmed equivalent osseointegration processes, bone-to-implant contact, and soft tissue healing for ceramic and titanium implants in both, preclinical and clinical investigations (Bienz et al., 2021; Roehling et al., 2019; Thoma et al., 2015). Clinical trials and systematic reviews have reported high mid-term survival rates of 94.3%–97.7% after 5 years of observation for ceramic implants (Gahlert et al., 2022; Kohal et al., 2020; Spitznagel et al., 2022).

To date, most studies have primarily investigated one-piece ceramic implants with good mechanical stability and high fracture resistance (Balmer et al., 2022; Bethke et al., 2020). However, a significant disadvantage of one-piece ceramic implants is limited prosthetic versatility and lack of compensation for abutment angulation (Balmer et al., 2022). Consequently, two-piece ceramic implants have been developed, first with an adhesive joint and then with a screw-retained connection (Janner et al., 2018; Spies et al., 2016). One of the first clinical trials reported a 100% survival rate after 15 months of functional loading for screw-retained restorations supported by a novel two-piece ceramic implant (Lorenz et al., 2022).

The esthetic zone of the maxilla presents a great clinical challenge for predictable functional and esthetic long-term success in implant dentistry (Buser et al., 2004; Chen et al., 2023). Therefore, the correct three-dimensional implant position according to the prosthetic plan is paramount to prevent complications and adverse esthetic outcomes (Chen et al., 2023).

Considering recent recommendations regarding the retention of implant-supported single crowns, screw-retained reconstructions are favored over cement-retained restorations to prevent the risk of peri-implant infections with possible residual cement surpluses (Sailer et al., 2022; Staubli et al., 2017; Wilson Jr., 2009). However, anatomical variations with undercuts, post-extraction ridge alterations, insufficient bone volume, and natural angulation of the maxillary teeth hamper palatal positioning of the screw-access hole and axial loading of the implant (Chappuis et al., 2013; Pitman et al., 2022).

To overcome poor esthetic results due to an access hole on the vestibular surface, the concept of angulated screw channels (ASCs) for titanium implants was introduced in 2015 (Garcia-Gazaui et al., 2015; Pitman et al., 2022; Rella et al., 2021). Depending on the system, ASCs allow an axis correction of up to 25° and shift of the screw-access hole to the more favorable palatal position (Edmondson et al., 2022; Rella et al., 2021). A recent cone-beam computed tomography study compared the prevalence of screw-retained reconstructions with straight versus angulated abutments in the anterior maxilla (Edmondson et al., 2022). Angulated abutments with an average axis compensation of 15° were enabled in 76% coses of screwretained reconstruction, whereas only 24% could be enabled with a straight abutment (Edmondson et al., 2022).

Despite meeting esthetic demands, technical complications such as chipping of the veneering ceramic, abutment fracture, and screw loosening and fracture remain with angulated abutment solutions.

Recent evidence suggests that angulated abutments might be associated with higher mechanical complications due to off-axis loading and inferior preload on the abutment screw; this may result in premature screw loosening, followed by fracture and restoration failure (Hein et al., 2021; Hotinski & Dudley, 2019; Opter et al., 2020). However, clinical trials have reported high survival rates of 92%-96% for ASC reconstructions on titanium implants up to 3years, with only a few technical complications (Di Fiore et al., 2023; Lv et al., 2021; Rella et al., 2021).

To the best of our knowledge, there is currently no study which investigates ASC implant crowns for two-piece ceramic implants, compared to that of titanium implants from a mechanical perspective in the esthetic zone. Therefore, this topic needs to be elucidated.

Fatigue testing under cyclic loads is an accepted method for estimating the lifetime and failure mode of implant-supported reconstructions (Bonfante & Coelho, 2016).

Therefore, the aim of the present laboratory study was to test whether screw-retained titanium bases (straight screw channel [SSC] vs. ASC) affect failure load and bending moments of two-piece zirconia implants, compared to those of two-piece titanium implants. The tested null hypotheses suggested that the type of (i) titanium base (SSC vs. ASC) and (ii) implant material (ceramic vs. titanium) do not influence the failure load and bending moments of screw-retained anterior monolithic zirconia crowns after fatigue.

#### 2 | MATERIALS AND METHODS

#### 2.1 | Study design

A total of 32 occlusal screw-retained monolithic translucent multilayer zirconia crowns (Katana UTML, Kuraray Noritake) were either supported by a two-piece ceramic implant system (PURE Ceramic Implant [CI]  $4.1 \times 12$ mm, ZLA; Straumann) as test groups or a two-piece titanium-zirconium alloy implant system (Standard Plus  $4.1 \times 12$ mm, Roxolid, SLA; Straumann) serving as control. The two groups were further divided into two subgroups (n=8 each) according to their respective titanium bases (SSC vs. ASC) (Figures 1 and 2).



FIGURE 1 Experimental test setup.



FIGURE 2 Overview of different test groups with respective titanium bases and anterior monolithic zirconia crowns (b: buccal, p: palatal): (a) Group Ti-Zr-0, (b) Group Ti-Zr-25, (c) Group CI-0, (d) Group CI-25.

Group Ti-Zr-O (control): A two-piece titanium-zirconium implant with a SSC titanium base (RN Variobase, AH 4mm, Straumann). Group Ti-Zr-25 (test): A two-piece titanium-zirconium implant with an ASC titanium base (RN Variobase AS, AH 4mm, Straumann).

Group CI-0 (test): A two-piece zirconia implant with a SSC titanium base (CI RD PURE Base, AH 3.5 mm, Straumann).

Group CI-25 (test): A two-piece zirconia implant with an ASC titanium base (CI RD PURE Base, AL  $3.5\,mm$ , Straumann).

#### 2.2 | Ceramic implant characterization

The microstructure of a pristine ceramic implant was analyzed using a field-emission gun scanning electron microscope (FEG-SEM; MIRA3-TESCAN). SEM micrographs were obtained using secondary (SE) and backscattered (BSE) electron detectors, at high vacuum, 5kV accelerating voltage, and magnifications from 10,000 to 100,000x. Two regions of interest were evaluated: the cervical collar and the region between threaded areas. Wiley Online Library for

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Residual stress was measured using Raman spectroscopy. The specimens were fixed to a specially designed compressive loading device and placed on a confocal Raman spectrometer (LabRAM HR Evolution). The spectra were recorded between 520 and 700 cm<sup>-1</sup>, slit size of 100 $\mu$ m, with an acquisition time of 30s and 2 cycles. Residual compressive stress was determined according to the following equation (Tanaka et al., 2009).

 $v = v_0 + \Pi \Delta \sigma$ 

where  $\nu$  is the Raman peak position shift of the aged specimen,  $\nu_0$  is the Raman peak position of the immediate sample, and  $\Pi$  is the coefficient for uniaxial stress (constant=5.43 cm^{-1} GPa^{-1}).

#### 2.3 | Fabrication of specimens

All implants were embedded perpendicularly in a dual-curing composite (LuxaCore Z Dual, DMG), with a modulus of elasticity of 9.3 GPa in polyether ether ketone (PEEK) tubes. To mimic reported clinical conditions with marginal bone losses of 0.7 mm after 1 year and 0.99 mm after 5 years for zirconia implants, a bony recession of 0.5-1 mm between the implant neck and the resin surface was set (Gahlert et al., 2022; Pieralli et al., 2017; Roehling et al., 2018).

#### 2.4 | Fabrication of implant restorations

The study design simulated the replacement of a central incisor in the esthetic zone. For standardization, one implant in each subgroup was embedded in the prosthetically correct position (Group Ti-Zr-0 and CI-0) at the location of the maxillary central incisor (FDI 21) or at a 25° deviation from this position (Group Ti-Zr-25 and CI-25) for screw-retained restoration in a master model (Frasaco-Model). Subsequently, a scan body (Ti-Zr: Cares RN Mono-Scan body and CI: Cares CI RD Mono-Scan body, Straumann) was screwed into the respective implant, and a digital impression (Trios3, 3Shape) was obtained. A standardized central incisor was designed in a CAD-software (Ceramill Mind V3.0-7783, Amann Girrbach). A master design was used for all monolithic crowns to produce identical and comparable test samples for each subgroup. Implant crowns were milled in a five-axis milling machine (Ceramill Motion 2, Amann Girrbach) out of a 5Y-TZP multilayer zirconia disc (Katana UTML, Kuraray Noritake) with a flexural strength of 557 MPa (according to the manufacturer), followed by sintering and glazing (Cerabien ZR Clear Glaze, Kuraray Noritake). All implant restorations were produced by one experienced dental technician, according to the manufacturer's recommendations. Prior to adhesive bonding, the inner surfaces of the zirconia crowns were air abraded with 50µm aluminum oxide at a pressure of 2 bar. Subsequently, the implant crowns and their corresponding titanium bases were conditioned with a 10-methacryloyloxydecyl dihydrogen phosphate (MDP) primer (Clearfil Ceramic Primer Plus, Kuraray Noritake) and resin-bonded with a self-curing composite cement (Panavia V5 opaque, Kuraray Noritake).

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Both straight and angulated monolithic zirconia crowns were tightened to their corresponding implants at 35 N cm using a torque control (Ratchet and Torque Control Device, Straumann), and retightened after 10min to prevent screw loosening (Farina et al., 2014; Spazzin et al., 2010). The screw access holes were filled with Teflon tape (Kirchhoff GmbH) and closed using a resin composite (Tetric Evo Ceram A2, Ivoclar).

#### 2.5 | Fatigue analysis

All specimens were subjected to cyclic mechanical loading (1.2 million cycles, 49 N, 1.6 Hz) with simultaneous thermocycling (5-55°C, dwell time 120 s) in a chewing simulator (CS-4.8 professional line, SD Mechatronik). The specimens were loaded 2mm below the incisal edge on the palatal surface at a 30° angle using a steatite ball antagonist (r=3mm; Hoechst Ceram Tec) adapted from ISO 14801 (Cantarella et al., 2021; ISO14801, 2016). The vertical movement during each chewing cycle was 2mm. During loading, the specimens were regularly examined for cracks, fractures (socsening/debonding). The survival rate after fatigue was calculated based on complications, which were divided into non-serious events (e.g., cracks and screw loosening) and serious failures (e.g., fractures).

#### 2.6 | Single load to failure

All samples were loaded until failure (crosshead speed of 1.5 mmmin<sup>-1</sup>) in a universal testing machine (Zwick Z010/TN2S. Zwick Roell). Load was applied to the palatal surface of the implant restoration at an angle of 30°, as during fatigue (ISO14801, 2016). To avoid force peaks and guarantee an even force distribution during static loading, a tin foil of 0.5 mm thickness (Dentaurum) was placed between the specimens and the load indenter (stainless steel ball with 6 mm diameter) (Cantarella et al., 2021). Failure was defined as either a visible crack or fracture of the implant-restoration complex, or a 20% decrease in the maximum load (Fmax) without an obvious fracture. Apart from load to failure (N), bending moments (M) were individually calculated for each sample in Ncm according to the formula  $M=0.5 \times F \times I$ , wherein variable "F" and the lever arm "I" correspond to the maximum load (N) and the vertical distance from the simulated bone level to the center of load (cm), respectively (Cantarella et al., 2021).

#### 2.7 | Failure and Fractographic analysis

Failure analyses were performed after fatigue and single load-tofailure testing using a polarized light microscope (Zeiss Axiocam 208 color, Carl Zeiss Microscopy). To improve the depth of focus, Z-stack mode (ZEN Core 3.3, Carl Zeiss Microscopy) was used to

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capture several images with varying depths and stitch planes within the same image. Hereafter, the most representative samples were analyzed by SEM (Vega 3, Tescan) to further assess the mode and origin of failure.

#### 2.8 | Statistical analysis

Power calculation (G\*Power 3.1.9.2) provided an estimated power of >80% using eight samples per group, assuming any effect of at least large size (Cohen's effect size of f>0.4) with respect to statistical testing using analysis of variance (ANOVA) and a two-sided type-lerror threshold of p <.05 for the two factors: (i) type of titanium base (SSC vs. ASC) and (ii) choice of implant material (titanium vs. ceramic) and their interactions.

Data were analyzed using the statistical software SPSS 26 (IBM Corp.). Levene's test was applied to test for homogeneity of error variance before using ANOVA for main effects and interactions of the two factors of interest (type of titanium base and implant material), followed by Mann-Whitney U-test for pairwise comparison of titanium base and implant material. The level of significance was defined as p < .05 (95% confidence interval [CI]) for all tests; data were visualized as boxplots.

#### 3 | RESULTS

#### 3.1 | Ceramic implant characterization

Figure 3 presents the FEG-SEM micrographs of the zirconia implant at both the cervical collar (Figure 3a-c) as well as in between the threads (d-f), with magnifications ranging from 10,000 to 100,000x. The magnified images (Figure 3b,c) show apparent polishing marks. Micrographs d, e, and f depict a roughened surface with shallow valleys. Under higher magnification (f), some particles encrusted over the zirconia surface can be observed. Figure 4 depicts the Raman spectra of the zirconia implant in the cervical collar and regions between the threads. Bands corresponding to tetragonal or cubic zirconia were observed at both spots. The presence of monoclinic zirconia with defined peaks, that were not very intense, could be detected in both regions. A relevant finding is the dislodgement of band  $634 \, \mathrm{cm^{-1}}$  (Figure 4) suggesting the presence of residual compressive stresses, which can be calculated by the amount of dislodgement by the following formula:  $\Delta \nu = \prod \Delta \sigma$  (Prado et al., 2020; Tanaka et al., 2009), wherein  $\Delta \nu =$  band dislodgement,  $\prod = (\text{constant} = 5.43 \, \text{cm^{-1}} \text{GPa}^{-1})$  and  $\Delta \sigma =$  variation in tensile stress. Based on these calculations, a value of -450 MPa was obtained.

#### 3.2 | Dynamic loading

All samples survived the dynamic loading test, suggesting a simulated 5-year survival rate of 100% for all tested groups. Fracture of the implant or restoration, screw loosening, or debonding of the implant crown from the titanium base was not observed in any sample. All samples were free of serious or non-serious complications.

#### 3.3 | Single load to failure

Failure loads varied from 226–681 N for titanium implants to 340– 889 N for ceramic implants (Table 1). Bending moments for titanium implants were in the range of 138–444 N cm and for ceramic implants in the range of 235–598 N cm, respectively (Table 1; Figures 5 and 6).

The type of titanium base (SSC vs. ASC) and implant material (titanium vs. ceramic) had significant effects on failure load [titanium base: F(1,28)=14.45, p=.001; implant material: F(1,28)=15.94, p<.001] and bending moment [titanium base: F(1,28)=12.99, p=.001; implant material: F(1,28)=20.81, p<0.001]. A significant interaction between the two factors (type of titanium base and implant material) for either failure load [F(1,28)=0.36, p=.552] or bending moments [F(1,28)=1.00, p=0.327] was missing.

FIGURE 3 FEG-SEM micrographs showing an overview of the zirconia implant (left side) and increasing magnifications of the cervical collar (a, b, and c) and the area between the threads (d, e, and f). A polished surface is depicted at the cervical collar. A roughened surface is evident in the regions between the threads.



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FIGURE 4 Raman spectra of the zirconia implant cervical collar (a) and the region between the threads (b); m, monoclinic zirconia; t/c, tetragonal or cubic zirconia.

TABLE 1 Descriptive statistics of failure load (mean±standard deviation) and bending moment (mean±standard deviation) of titanium-zirconium and ceramic implants with straight and angulated screw channel titanium bases.

Group	Load (N)	Bending moment (N cm)
Ti-Zr-0	$360 \pm 64$	$241 \pm 45$
Ti-Zr-25	473±131	303±86
CI-0	480±83	$326 \pm 58$
CI-25	$635 \pm 108$	434±71

The highest mean failure loads and bending moments were reported for Group Cl-25 ( $635\pm108N$ ,  $434\pm71Ncm$ ), followed by groups Cl-0 ( $480\pm83N$ ,  $326\pm58Ncm$ ), Ti-Zr-25 ( $473\pm131N$ ,  $303\pm86Ncm$ ), and Ti-Zr-0 ( $360\pm64N$ ,  $241\pm45Ncm$ ) (Table 1; Figures 5 and 6).

Post-hoc Mann-Whitney *U* tests revealed significant differences in failure load and bending moment in favor of ASC (vs. SSC) titanium bases for both titanium (failure load: U = 10.0, p = .021; bending moment: U = 11.0, p = .028) and ceramic implants (failure load and bending moment: U = 6.0, p = .005). Comparison of the implant materials separately for each type of titanium base revealed significant differences in the failure load and bending moment in favor of ceramic (vs. titanium) implants for both, straight (failure load: U = 8.0, p = .01; bending moment: U = 9.0, p = .015) and ASC titanium bases (failure load and bending moment: U = 7, p = .007).

#### 3.4 | Failure modes and Fractographic analysis

Failure modes were subdivided into crown, abutment, and implant failures based on the level and origin of complications (Table 2).

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Group CI specimens showed severe fracture failures at the implant level, with a higher incidence in ASC titanium bases (100%) than the straight ones (50%). The two main modes of failure at the implant level were as follows: a horizontal fracture just below the level of the embedding material and below the apical tip of the abutment screw or a combination of the former and an additional longitudinal fracture of the implant neck up to the horizontal fracture line (Figure 7). Half of the specimens (50%) in group CI-0 showed plastic deformation at the abutment level with a clear bend at the loading site, leading to failure (Figure 8). Failures at the crown level were not observed in either of the CI groups.

Samples from both Ti-Zr groups did not fracture catastrophically at the crown, abutment, or implant levels; however, they showed a slight plastic and ductile deformation at the abutment and implant levels, leading to failure (Table 2). Representative SEM micrographs of the fractured samples in both, SSC and ASC zirconia implant groups, showed several hackle lines, suggesting a centrifugal direction of crack propagation and fracture originating at the implantabutment interface. Twist hackles were observed at the margin of the implant, and compression curls indicated fracture origin on the opposite side (Figures 9 and 10).

#### 4 | DISCUSSION

The present in-vitro study analyzed the influence of SSC and ASC titanium bases on the failure load and bending moments of twopiece ceramic and titanium-zirconium implants after fatigue. The tested null hypotheses were rejected because the titanium base and implant material had significant effects on failure load and bending moment.

The microstructural appearance of the ceramic implant revealed by FEG-SEM images of regions between the threads resembles a sandblasted and acid-etched surface with the aim to increase roughness (Ramos et al., 2019) to eventually improve osseointegration parameters (Nishihara et al., 2019). Airborne particle abrasion methods can lead to occurrence of compressive residual stresses, as quantified by the Raman spectra. Similar findings have been reported previously by studies wherein sandblasting was performed on alumina alloys leading to the occurrence of compressive residual stresses (Righetti et al., 2020). Grain contours and typical zirconia microstructures were not observed in the micrographs of the zirconia implant cervical collar, where a machined surface appeared, as previously shown (Alves et al., 2022).

All specimens survived cyclic mechanical loading with simultaneous thermocycling and were free of serious and non-serious complications. The applied fatigue testing protocol with 1.2 million chewing cycles simulates mid-term aging equivalent to 5 years of clinical observation (Delong et al., 1985; Kern et al., 1999; Rosentritt et al., 2009). Although this test protocol does not simulate long-term behavior (for 10-40 years), it can predict potential early mechanical failures and is a well-accepted method that has been used in

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test setup with dynamic loading and simultaneous thermocycling imitated a hostile oral environment to the best possible extent. The load during chewing simulation was applied at an angle of 30° to the vertical axis, as recommended by ISO 14801 (2016). To mimic a more clinically relevant scenario, the embedding procedure, restoration with anatomical crowns instead of loading hemispheres, differed from that of ISO 14801 (2016). The simulated bony recession of 0.5–1mm does not correspond to the worst case scenario of 3mm as described by ISO 14801; however, it is closer to clinical reality with reported marginal bone losses of 0.7–0.99 mm after up to 5 years of follow-up for ceramic implants (Gahlert et al., 2022; Pieralli et al., 2017; Roehling et al., 2018). To add to the stress on the implant-restoration complex, horizontal shear forces and an aqueous environment were applied, although this is not demanded by the ISO standard (Zhang et al., 2020). Studies are difficult or impossible to compare unless bending moments or individual lever arms to calculate bending moments are reported in addition to failure loads on deviation from the ISO standard (Bethke et al., 2020).

The investigated two-piece ceramic implant is a cylindrical screw-type Y-TZP soft tissue level zirconia implant with an endosteal diameter of 4.1mm, a 1.8mm machined collar with a 4.8 diameter, and an internal connection with a rotational lock (Janner et al., 2018). The corresponding titanium base is narrow, with a diameter smaller than that of the implant platform, which enables contact of the implant crown with the surrounding soft tissue (Lorenz et al., 2022). The titanium base has two heights—short (3.5mm for Cl and 4mm for Ti-Zr) and long (5.5mm for Cl and 6mm for Ti-Zr). use; O/

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Group	Crown fracture	Abutment fracture	Abutment deformation	Implant fracture	Implant deformation
Ti-Zr-0	0% (0/8)	0% (0/8)	100% (8/8)	0% (0/8)	100% (8/8)
Ti-Zr-25	0% (0/8)	0% (0/8)	100% (8/8)	0% (0/8)	100% (8/8)
CI-0	0% (0/8)	0% (0/8)	50% (4/8)	50% (4/8)	0% (0/8)
CI-25	0% (0/8)	0% (0/8)	0% (0/8)	100% (8/8)	0% (0/8)



FIGURE 7 Characteristic failed sample of group CI-25 with implant fracture. (a) longitudinal implant fracture and (b) detailed view. (c) Horizontal implant fracture and (d) detailed view. (e) Schematic illustration of main fracture modes.



FIGURE 8 Characteristic failed sample of group CI-0 with titanium base deformation. (a) Overview. (b) and (c) detailed view with pronounced bend up on the loading site (flexion) leading to failure.

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TABLE 2 Overview of failure modes after single load-to-failure testing.

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As a shorter titanium base was used in this study for both the SSC and ASC samples, it can be concluded that a longer abutment height can lead to higher failure loads and bending moments. The rationale for using a short rather than a long abutment height was to further simulate a possible worst-case scenario with an unfavorable loading condition (Zhang, Yu, & Yu, 2022). Finite element analysis studies on titanium implants have shown that angulation and deviation from an ideal central implant position to the buccal side could affect stress distribution, leading to increased mechanical strain on the implant and restorative components, especially the prosthetic screw, titanium base neck, and upper cortical bone (Korkmaz & Kul, 2022; Zhang, Yu, & Yu, 2022).

In the present investigation, mean failure load values and respective bending moments ranged for Ti-Zr groups from 360–473N and 241–303Ncm, and for CI groups from 480–635N and 326– 434Ncm. A comparable study reported failure loads of 942N for

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titanium-zirconium implants and 650N for two-piece zirconia implants (Hanes et al., 2022). The implants in that investigation were from the same manufacturer as in the present study, restored with anatomical incisor crowns, loaded in a 30° angle, embedded with a 3mm recession according to ISO 14801, and aged at 37°C for 90 days in an incubator. However, thermomechanical fatigue protocol was not applied, and a longer titanium base (5.5 mm) was used (Hanes et al., 2022). Unfortunately, bending moments or individual lever arms for calculating the bending moments have not been reported to allow for direct comparison.

A similar study investigated both incisor- and molar-shaped screw-retained monolithic zirconia crowns supported by either Ti–Zr or two-piece zirconia implants artificially aged in a chewing simulator (1.2 million cycles, 50N, 1Hz) (Joos et al., 2020). The recorded complications and failures are highly dependent on the simulated jaw position. Ti–Zr implants showed higher reliability in the anterior region, whereas zirconia implants showed fewer events in the molar region. None of the anterior two-piece zirconia implants survived aging (0% survival rate), and the complications during



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FIGURE 10 Representative SEM micrographs of a fractured zirconia implant with angulated-screw-channel titanium base (Group CI-25-same specime as in Figure 4). (a) Overview of fractured implant where hackle lines (dotted arrows) suggest the direction of crack propagation, also seen in (b) in backscattered mode. Compression curl indicates that tensile stresses were present at the opposite side, probably at the location of fracture origin. The dotted rectangle magnified in (c) shows its location near the implant-abutment interface where magnification in (d) and (e) depicts a defect (pointer). (f) The matching fractured piece with titanium abutment screw (TS) and hackle lines (dotted arrows) reflecting the direction of crack propagation towards the margins of the ceramic implant.

thermomechanical loading included implant and screw fractures, and crown loosening or fracture (Joos et al., 2020).

Another in-vitro study reported lower bending moments of  $173.7 \pm 20.1$  N cm for Ti-Zr implants and  $171.1 \pm 46.1$  N cm for twopiece zirconia implants from the same manufacturer (Cantarella et al., 2021). Implants were embedded according to ISO 14801 (30° angle, 3 mm bony recession), restored with anatomical incisor crowns (straight titanium base, short height 3.5 mm), and fatigued using a chewing simulator (1.2 million cycles, 49N, 1.67Hz). The

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recorded survival rates for Ti-Zr implants were 100% and 83.3% (10/12) for two-piece ceramic implants with two serious abutment failures after thermomechanical loading (Cantarella et al., 2021). Non-serious events included screw loosening in 58.3% (7/12) of the Ti-Zr implants and 10% (1/10) of the ceramic implants, which could be retightened before fracture testing. The authors attributed the higher mechanical stability at the screw level of the zirconia implant compared to that of the titanium implant to the reduced horizontal joint component with an internal connection. The fractures observed after static loading occurred solely at the crown level. Therefore, in that investigation, the weakest link was the all-ceramic lithium disilicate crown leading to lower bending moments and fractures at the level of the crown, compared to the present study, where implants were restored with monolithic zirconia crowns, leading to failures at the implant level and higher bending moment values. The specimens in the present study were free of complications after thermodynamic loading and screw loosening did not occur. Retightening after 10 min may have positively influenced and decreased the complication rate of screw loosening for both SSC and ASC titanium bases on Ti-Zr and zirconia implants in this study (Farina et al., 2014; Spazzin et al., 2010). The fact that ASC titanium bases on ceramic implants might exert a lower preload on the abutment screw due to angulation, leading to lower retaining forces, was not reflected in our results. A laboratory study compared torque differences between SSC and ASC implant crowns on titanium implants before and after simulated functional loading (Swamidass et al., 2021), Differences were not observed between the groups. However, on application of torque values lower than those recommended by the manufacturer, the ASC implant crowns showed a higher percentage of torque differences between the initial and final screw torque values after cyclic loading (Swamidass et al., 2021). Accordingly, the manufacturer's specifications should be observed carefully

Based on a systematic review, the mechanical threshold for bending moments of ceramic implants should be no less than 200N cm to ensure clinical safety (Bethke et al., 2020). This threshold value results from the fact that the highest measured bending moment of implants in humans is 95Ncm, and if a 100% safety buffer is added, zirconia implants should have a fatigue strength of at least 200Ncm for clinical applications (Bethke et al., 2020; Morneburg & Pröschel, 2003). The investigated two-piece zirconia implant exceeded this threshold with mean bending moments of 326Ncm for SSC and 434Ncm for ASC titanium bases by far.

Failure analysis revealed different results for the Ti-Zr and Cl groups. All specimens of the Ti-Zr groups showed plastic deformation at the abutment and implant levels, while 75% (12/16) of the zirconia implants fractured seriously during single load-to-failure testing at the level of the implant. This might be attributed to the difference in material properties, as titanium shows improved bending and flexural resistance, leading to plastic deformation, whereas zirconia resists greater compressive stress, leading to fracture (Piconi & Maccauro, 1999). Moreover, the observed failure modes suggest that, especially in the presence of excessive and eccentric masticatory

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forces (e.g., as seen in bruxers), ceramic implants are more likely to cause catastrophic failures compared to titanium implants and may consequently need surgical intervention. In-depth fractographic SEM analysis of ceramic implants revealed important markings, including compressive curls and hackle lines, which indicated that the origin of the failure started from the loading site (Zhang et al., 2020). Fractures occurred either just below the prosthetic screw tip and embedding material, or in combination with a longitudinal fracture of the implant neck on the compression side of the implant, exposing the abutment screw. This fracture pattern indicates that the implant abutment connection might be the weakest link in this system, owing to the reduced wall thickness around the screw (Kohal et al. 2023) Similar fracture schemes have been observed in other two-piece ceramic implant systems (Kohal et al., 2023; Zhang et al., 2020; Zhang, Monzavi, et al., 2022). The observed fracture patterns may have clinical relevance, particularly in peri-implant-infected implants with reduced bony support in the crestal region. In this scenario, the implant abutment connection is exposed to increased stress, particularly under eccentric forces, which may lead to mechanical failure Remarkably, high load-to-failure values beyond the physiological maximum bite force and implant survival during fatigue could also be correlated with the presence of compressive residual stresses observed in the Raman spectra. In addition, discrete monoclinic peaks were observed in the cervical collar and thread regions.

One limitation of this in-vitro study is the deviation from the ISO standard. However, the present test setup might be closer to observed clinical conditions; the reported bending moments allow comparison with other studies. In addition, an extended chewing simulation with up to 10 million cycles can lead to failure during fatigue.

To the best of our knowledge, this is the first study to investigate the mechanical performance of ASC on two-piece ceramic implants using in-depth fractographic analysis. From a mechanical perspective, the key discoveries of the present study indicate that titanium bases with ASC and ceramic implants are at least equal or even superior in performance to SSC titanium bases and titanium-zirconium implants.

Therefore, ASC allows two-piece ceramic implants to be less invasive in the esthetic zone and permits screw-retained reconstruction in a greater number of clinical cases.

Future and current research avenues in the field of ceramic implantology should explore bone-level two-piece zirconia implants as well as those with a reduced diameter, taper, and short height (<8mm) (Burkhardt et al., 2021). The next generation of ceramic implants has the potential to allow for a wider range of clinical indications and is expected to gain greater popularity among patients and clinicians.

#### 5 | CONCLUSION

Within the limitations of this in-vitro study, ASC titanium bases and ceramic implants showed significantly higher mean failure load values and bending moments than SSC titanium bases

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and titanium-zirconium implants. Both ceramic and titaniumzirconium implants showed high reliability after aging and were free of complications, with a 100% survival rate. However, most ceramic implants exhibit severe fractures after single load-tofailure testing, whereas titanium implant failures are restricted to plastic deformation.

Therefore, from a mechanical perspective, titanium bases with ASCs appear to be as reliable as SSC titanium bases for ceramic and titanium implants. The tested two-piece zirconia implant, with its prefabricated SSC and ASC titanium base, seem suitable for clinical applications and can withstand high failure loads. Prospective clinical studies are required to corroborate the results of the present study.

#### AUTHOR CONTRIBUTIONS

E. Helal: Data curation; Visualization; Investigation; Writingoriginal draft; Formal analysis. P. C. Gierthmuehlen: Resources; Project administration; Funding acquisition; Writing-review and editing; Conceptualization; Validation; Supervision. E. A. Bonfante: Writing-review and editing; Validation; Formal analysis; Data curation. T. M. B. Campos: Visualization; Writing-review and editing; Data curation. L. S. Prott: Writing-review and editing; Data curation; Formal analysis. R. Langner: Writing-review and editing; Visualization; Formal analysis; Software. F. A. Spitznagel: Supervision; Conceptualization; Writing-original draft; Data curation; Investigation; Project administration; Funding acquisition; Formal analysis; Methodology.

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#### CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

#### DATA AVAILABILITY STATEMENT

The datasets from this study are available from the corresponding author upon reasonable request.

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## 4 Discussion and conclusion

Preclinical and clinical evidence from previous studies supports the comparable performance of ceramic implants to titanium implants in key biological processes, including osseointegration, bone-to-implant contact, and soft tissue healing (Balmer et al., 2022; Cionca et al., 2017; Bienz et al., 2021; Roehling et al., 2019; Thoma et al., 2015). The present in-vitro study is one of the first investigations to evaluate the influence of straight screw channels (SSC) and angulated screw channels (ASC) in titanium bases on the failure load and bending moments of two-piece ceramic and titanium-zirconium implants after fatigue testing. The results indicate that both the implant material and the abutment design had a significant impact on the failure load and bending moment. Consequently, the null hypotheses tested in this study were rejected. The testing assembly, comprising the implant and restoration, was subjected to a standardized testing protocol to evaluate simulated clinical functionality (Kelly, 1999). The experimental setup followed the ISO 14801:2016 testing guidelines, with specific modifications to better simulate clinical conditions. Implants were embedded with 0.5-1 mm of simulated bone loss, deviating from the 3 mm stipulated by the ISO standard. Dynamic loading was applied at a 30° angle, in alignment with ISO specifications. The findings demonstrated that angulated implant placement and buccal deviations lead to increased stress distribution in critical regions, including the prosthetic screw, the neck of the titanium base, and the cortical bone. These stress concentrations highlight the mechanical challenges associated with non-ideal implant positioning (Korkmaz & Kul, 2022; Zhang et al., 2022). Comparable studies have utilized anatomical incisor crowns as implant restorations, typically incorporating 3 mm of bone loss and a 5.5 mm titanium base to replicate a worst-case scenario (Hanes et al., 2022). In contrast, the present study introduced a more demanding test condition by employing shorter titanium bases measuring 3.5 mm for all samples, thereby intensifying the stress conditions in accordance with prior findings (Zhang, Yu, & Yu, 2022). The experimental setup was specifically designed to simulate a mid-term loading duration, representing a clinical scenario equivalent to five years of functional fatigue, rather than focusing on long-term behavior (DeLong & Douglas, 1983; DeLong et al., 1985; Kern, Strub, & Lü, 1999). A total of 1.2 million chewing cycles in a thermocycling oral environment was applied, a methodology known to predict potential early failures effectively. This approach is consistent with protocols utilized in comparable studies (Cantarella et al., 2021; Joos et al., 2020). The thermodynamic loading results revealed a 100% survival rate, with no failures observed during testing. Notably, complications

such as screw loosening, which have been reported in other studies (Cantarella et al., 2021), were absent in this investigation. Furthermore, in line with recommendations from prior research, retightening abutment screws after 10 minutes proved to have a positive effect on the stability of the abutment-implant connection within this experimental setup (Farina et al., 2014; Spazzin et al., 2010). Based on evidence from previous studies highlighting the biological advantages of screw-retained implant crowns over cemented implant crowns, a screw-retained anatomical implant crown was chosen for this investigation (Kraus et al., 2022). Static compressive strength tests, as performed in the present study, provide a valuable complement to dynamic fatigue testing by facilitating the assessment of material failure occurring in the early stages of loading (Rosentritt et al., 2008; Rosentritt et al., 2009). The mean fracture load values and corresponding bending moments for the two-piece ceramic implants were measured at 480 N and 326 Ncm (CI-0), and 635 N and 434 Ncm (CI-25), respectively. For the comparison group of two-piece titanium implants, the values were 360 N and 241 Ncm (Ti-Zr-0), and 473 N and 303 Ncm (Ti-Zr-25), respectively. Although there were slight deviations from ISO standards, the experimental setup closely simulated clinical conditions, allowing for meaningful comparisons. A recent comparable study reported fracture load values of  $712 \pm 76$  N for ceramic implants and  $1207 \pm 202$  N for titanium implants (Sadid-Zadeh et al., 2024). The comparative study evaluated 48 screw-retained implant crowns placed on ceramic and titanium implants from Straumann, closely reflecting the implant systems utilized in the present study. The titanium bases in both studies were comparable, featuring a standardized height of 3.5 mm. A key distinction between the studies lies in the choice of implant crown and implant placement. The comparative study investigated implants in the maxillary first premolar position, whereas the present study focused on the maxillary central incisor. Additionally, the implant platforms in the comparative study were positioned either above or at the level of the PMMA cylinders, with no simulation of bone loss. These differences, particularly the choice of implant position and the associated crown wall thickness, appear to have a significant impact on the fracture load (Sadid-Zadeh et al., 2024). A comparable study employing a crown design similar to that used in the present investigation reported fracture strengths of zirconia crowns on Ti-Zr and CI implants of 942 N and 650 N, respectively (Hanes et al., 2022). Both the study by Hanes et al. and the current study report fracture strength values that exceed the established occlusal forces of 220 N for the anterior region (Zonfrillo et al., 2008). However, the absence of data on lever arms and bending moments limits the ability to make direct comparisons. To enable meaningful comparisons, especially in cases where ISO standards are not strictly adhered to in in

vitro studies, it is strongly recommended to include measurements of bending moments and lever arms (Bethke et al.2020). Failure analysis revealed distinct differences between Ti-Zr and ceramic implants in the present study. Ti-Zr specimens exhibited plastic deformation, indicating their capacity to absorb mechanical loads. In contrast, 75% of zirconia implants experienced catastrophic fractures, highlighting their brittleness. These findings are consistent with the material properties: titanium demonstrates superior resistance to bending and flexural stresses, whereas zirconia, while possessing higher compressive strength, has a lower tolerance to eccentric loading (Piconi & Maccauro, 1999). Fractures in zirconia implants have been associated with reduced wall thickness around the screw channel, a mechanical vulnerability that is exacerbated under high stress conditions (Kohal et al., 2023). Recent studies suggest that the material of the screw does not significantly impact performance, but the design of the screw channel may have clinical implications, particularly in compromised bone situations (Kohal et al., 2024). In addition to the fracture analysis, microstructural evaluation of the intact ceramic implant using FEG-SEM revealed a sandblasted and etched surface in the endosseous portion, designed to promote osseointegration (Nishihara, Haro Adanez, Art, 2019; Ramos et al., 2019). The surface enlargement achieved through alumina sandblasting can induce residual compressive stresses, which can be quantified using Raman spectroscopy. Raman spectroscopy further revealed the presence of these residual stresses as well as the three distinct zirconia phases. This study has several limitations, including deviations from ISO standards and the use of implants from a single manufacturer. However, as one of the first studies to investigate angulated titanium bases on two-piece ceramic implants, it highlights the mechanical effectiveness of ASC titanium bases for both ceramic and Ti-Zr implants, thereby supporting their increasing clinical applicability. The reliability of these systems under simulated conditions provides a basis for further research aimed at optimizing ceramic implant systems for more complex clinical scenarios. The combination of mechanical strength, aesthetic advantages, and functional resilience of ASC configurations positions them as a promising alternative in modern dental implantology. Future research should focus on evaluating the performance of implants in molar and premolar regions to deepen the understanding of their mechanical and clinical behavior. Additionally, investigating implants with varying diameters and lengths would help to expand the treatment scope of ceramic implants.

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