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Load bearing capacity of 3-unit screw-retained implant-supported fixed dental prostheses with a mesial and distal cantilever on a single implant: A comparative in vitro study

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ABSTRACT

Objectives: To assess the mechanical durability of monolithic zirconia implant-supported fixed dental prostheses (iFDP) design on one implant, with a distal and a mesial extension cantilever bonded to a titanium base compared to established designs on two implants.

Materials and methods: Roxolid Tissue level (TL), and tissue level x (TLX) implants were used to manufacture screw-retained 3-unit iFDPs (n = 60, n = 10 per group), with following configurations (X: Cantilever; I: Implant, T: Test group, C: Control group): T1: X-I-X (TL); T2: X-I-X (TLX); T3: I–I-X (TL); T4: I–I-X (TLX); C1: I-X-I (TL); C2: I-X-I (TLX). The iFDPs were thermomechanically aged and subsequently loaded until fracture using a universal testing machine. The failure load at first crack ($F_{initial}$) and at catastrophic fracture (F_{max}) were measured and statistical evaluation was performed using two-way ANOVA and Tukey's post-hoc tests.

Results: The mean values ranged between 190 ± 73 and 510 ± 459 N for $F_{initial}$ groups, and between 468 ± 76 and 1579 ± 249 N for F_{max}, respectively. Regarding $F_{initial}$, neither the implant type, nor the iFDP configuration significantly influenced measured failure loads (all $p > 0.05$). The choice of implant type did not show any significant effect ($p > 0.05$), while reconstruction design significantly affected F_{max} data (I–I-X[a] < X-I-X[b] < I-X-I[c]) ($p < 0.05$). The mesial and distal extension groups (X-I-X) showed fractures only at the cantilever extension site, while the distal extension group (I–I-X) showed one abutment and one connector fracture at the implant/reconstruction interface.

Conclusion: Results suggest that iFDPs with I-X-I design can be recommended regardless of tested implant type followed by the mesial and distal extension design on one implant abutment (X-I-X).

1. Introduction

Implant-supported fixed prostheses (iFDPs) are a predictable treatment option for replacing missing teeth in partially edentulous patients (Pjetursson et al., 2007; Albrektsson and Donos, 2012).

Replacing 2 or 3 adjacent missing teeth can be a clinical challenge as, in many situations, mesio-distal space may be compromised. In these situations, there are varying treatment options, one being the possibility to place a single implant to support a single crown (SC) or an implant fixed dental prostheses (iFDP) with one cantilever extension (Brägger et al., 2005; Aglietta et al., 2012; Storelli et al., 2018). Besides the 2-unit iFDP option presents good 5–10 years survival rates of 98.4% for implants and 99.2% for restorations. This option enables avoiding the need for additional implant placement which can increase the cost, and morbidity. For the replacement of three teeth by means of an implant supported reconstruction, standard treatment comprises an iFDP with

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two end-abutments i.e., i36-x-i34. Alternatively, a cantilever extension FDP i.e., x-i35-i34 or i36-i35-x can be applied (Roccuzzo et al., 2023). There is clinical evidence that the best performance is achieved by conventional iFDPs with end abutments (Pjetursson et al., 2004). However, cantilevered extension iFDPs show similar survival rates, however, with a higher chance for technical complications (Pjetursson et al., 2004). To the knowledge of the authors, a double extension FDP (one mesially and one distally) supported by one implant in the center has not been considered as a treatment option yet.

As for the prosthetic material choice for fixed implant prostheses, metal-ceramics or metal-acrylic resins are still commonly used and majority of long-term scientific reports are on the performance of these two material combinations (Abou-Ayash et al., 2017; Bagegni et al., 2019). However, in the last decade, fixed all-ceramic implant restorations are more commonly used than before due to their favorable technical, esthetic, and biological results, and increased cost of dental alloys (Aglietta et al., 2012; Albrektsson and Donos, 2012; Lops et al., 2015; Lemos et al., 2019). All-ceramic fixed single and multiple-unit implant-supported restorations have been demonstrated to be a viable treatment option, with high survival rates at least over short- and medium-term follow-up periods (Abou-Ayash et al., 2017; Bagegni et al., 2019; Lemos et al., 2019). The most current used material for multiple-unit fixed implant restorations is zirconium dioxide, also known as zirconia (ZI). In the early times of implant-supported ZI restorations (3Y-TZP), the use of this material resulted in technical complications, as well as poor esthetics due to its high opacity. However, recently, ZI has evolved with increased amount of yttria (4Y-TZP) in its composition allowing monolithic use, providing improved optical properties particularly with the use of multilayered blanks. The absence of layered feldspathic ceramic reduces the chipping risk (Pjetursson et al., 2021; Auzani et al., 2020; Lümkemann et al., 2021). However, lower resistance to bending and fracture toughness compared to traditional first generation 3Y-TZP is a critical factor to consider for all-ceramic restorations (Bidra and Rungruanganunt, 2013; Linkevicius and Vaitelis, 2015; Joda et al., 2018; Pieralli et al., 2018; Schnider et al., 2018). Monolithic zirconia enables the fabrication of single and partial implant-supported restorations, which consist of a ZI customized crown or mesoabutment bonded to a standardized titanium base abutment to be screw-retained to the implant as one piece (Bidra and Rungruanganunt, 2013; Linkevicius &Vaitelis, 2015; Pieralli et al., 2018; Rocuzzo A et al. 2023). Even though these material combinations have demonstrated adequate clinical performance for single restorations, the evidence for their use for posterior iFDPs is limited, mostly, to in vitro research studies (Joda, Huber & Bürki, 2015; Joda, Ferrari & Brägger, 2017; Joda et al., 2018; Schnider et al., 2018; Yilmaz et al., 2018; Yilmaz, Batak and Seghi, 2019). Considering the reported data and the literature in relation to tissue level implant connections (Camps-Font et al., 2023), internal connections such as the octagonal 8° conical connection provide greater stability, and better distribution of occlusal forces, besides internal connections has been reported as a reliable option for cantilever iFDP, nevertheless the due to the recent introduction of hexagonal 7° conical Torx connection needs to be investigated. Due to the increase in the use of monolithic zirconia in implant dentistry, the promising results that have been reported in single restorations on implants and given its limited evidence for cantilever restorations, the evaluation of new restorative design is necessary. The present study aimed to assess the fatigue performance and thereafter load bearing capacity of monolithic zirconia implant-supported fixed dental prostheses (iFDP) bonded on titanium base abutments (Variobase abutments) with both, a distal and a mesial extension cantilever design using failure load at first crack (Finial) and at catastrophic fracture (Fmax) measurements. Both parameters should be considered in the evaluation of the mechanical strength parameter load bearing capacity, as an initial crack does not necessarily result in a fracture or complete failure of the restoration and the necessity to replace the restoration. The null hypothesis tested was that the mechanical performance (fatigue and load bearing capacity) of monolithic zirconia iFDP design on one implant, and with two a distal and a mesial extension cantilever, bonded to a titanium base abutment would not be different than that established designs on two implants.

2. Materials and methods

A total of sixty 3-unit implant-supported FDPs were designed as screw-retained, implant-supported 3-unit FDPs and divided into three different prosthetic configurations (X-I-X; I–I-X; I-X-I (I: Implant; X: cantilever/pontic)) using varying number and designs of implants and abutments. The study setup consisted of screw-retained reconstructions on one or two implants (Tissue Level Implant SLA RN 4.1 mm × 12 mm, Institute Straumann AG, Basel, Switzerland or TLX RB 4.5 mm × 12 mm, Institute Straumann AG, Basel, Switzerland) based on 60 dental implants. Tissue level (TL), and tissue level x (TLX) implants were used to manufacture screw-retained 3-unit iFDPs ($n = 60$, $n = 10$ per group), with following configurations (X: Cantilever; I: Implant, T: Test group, C: Control group): T1: X-I-X (TL); T2: X-I-X (TLX); T3: I–I-X (TL); T4: I–I-X (TLX); C1: I-X-I (TL); C2: I-X-I (TLX).

2.1. Experimental groups

The sample size was determined on a global level testing for group median inequalities using both Kruskal-Wallis (KW) and Fisher-Pitman (FP) tests. As there is no closed formula for the power for both abovementioned tests, the power function was simulated based on 2000 replications. The optimal sample size was reached if the less powerful of both abovementioned tests had showed a power of at least 80%. The overall significance level alpha was set to 5%. The minimum total number of specimens included (n) was 32 ($n = 8$ per group). Means and SD of groups were based on previous similar reports (Rahman Alkharrat et al., 2018; Rues et al., 2020). In consideration of the calculated power, in the present study, the sample size was set at 10 specimens per group.

Individualized holders were manufactured for each prosthetic configuration ($n = 60$) using acrylic resin (CandiQuick, ScanDia, Hagen, Germany). The implants were placed using a specialized application tool embedded in a clamping device to place the implant at 3.0 mm, 0.5 mm below the top of the implant platform to mimic physiologic bone loss according to *DIN ISO 14801*.

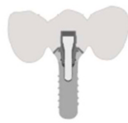
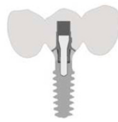
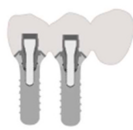
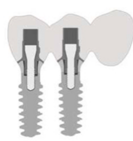
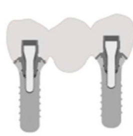
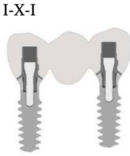
2.2. Prosthetic configuration

Ten 3-unit implant-supported variobase screw-retained abutment restorations with 3 premolars were fabricated per group with following configurations (Table 1). The six groups were divided into 4 test and 2 control groups. The four experimental groups (Test 1–4) included the two different prosthetic configurations (X-I-X for Test 1 and 2) and (I–I-X for Test 3 and 4) and 2 different implant systems (Standard RN implant for Test 1 and 3) and (TLX implant for Test 2 and 4). The two control groups (Control 1 and 2) had the prosthetic configuration (I-X-I) and the two different implant systems (Standard RN implant for Control 1) and (TLX implant for Control 2).

2.3. Specimen fabrication

Restorations for each group ($n = 10$) were manufactured following the design of a first, second, and “third” mandibular premolar as the customized master abutment. The framework shape of the master abutment was digitally designed by using the CAD software (Straumann Cares Visual, Straumann AG, Basel, Switzerland) for a regular platform implant (Standard Plus RN, Straumann AG, Basel, Switzerland or TLX concept, Straumann AG, Basel, Switzerland) using a 12 mm^2 connector cross-section. All restorations were designed as monolithic zirconia hybrid reconstructions bonded on a titanium base abutment. Then, the restorations were milled (Prettau 4 Anterior, Zirkonzahn, Gais BZ, Italy),

Table 1
Prosthetic configurations of the six 3-unit groups using 1 (Test 1 and 2) or 2 supporting implants (Test 3, 4 and Control 1 and 2) using various cantilever extension and abutment configurations.

Group	Implant-prosthetic configuration		Implant reconstruction set-up and material
T1	 X-I-X	TL Straumann implant, Variobase abutment	 Prettau 4 Anterior, Zirkonzahn
T2	 X-I-X	TLX Straumann implant, Variobase abutment	
T3	 I-I-X	TL Straumann implant, Variobase abutment	
T4	 I-I-X	TLX Straumann implant, Variobase abutment	
C1	 I-X-I	TL Straumann implant, Variobase abutment	
C2	 I-X-I	TLX Straumann implant, Variobase abutment	

sintered, and cemented on one or two titanium base abutments (Straumann Cares Visual, Straumann AG, Basel, Switzerland; Esthetic Ease Concept, Straumann AG, Basel, Switzerland) using a resin cement (Panavia 21, Kuraray Noritake, Aichi, Japan) according to manufacturer's instructions. The cementation process for the superstructure and the abutment were performed conditioning the ZI with a ceramic (Clearfil Ceramic Primer, Noritake Aichi, Japan) and the titanium base abutment with a metal (Metal Alloy Primer, Kuraray, Noritake, Aichi, Japan) primer before the application of the resin cement (Panavia 21, Kuraray, Noritake, Aichi, Japan). Once the reconstructions were cemented, they were tightened to implants with a 35 Ncm torque by using a calibrated manual torque control ratchet.

2.4. Chewing simulation and artificial aging

After the screws were tightened, the abutment-screw access holes were plugged with a Teflon tape and a composite resin material (Tetric, Ivoclar Vivadent). Then, the specimens were mounted onto a custom-made chewing simulator (1′200′000 cycles, 49N force and 1.67 Hz loading frequency, and 5–55 °C) (Krejci et al., 1990). In case of screw loosening, the screws were retorqued to 35 Ncm and the tests were performed. In case of framework fractures, the specimens were excluded and recorded as failures.

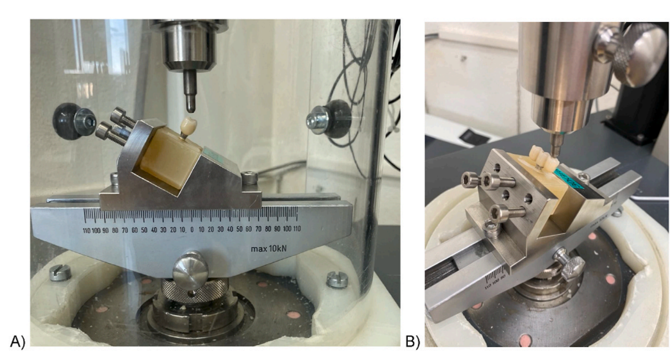


Fig. 1. Experimental set-up showing A) lateral and B) occlusal intender positioning on the cantilever in the X-I-X groups. (X: cantilever; I: Implant).

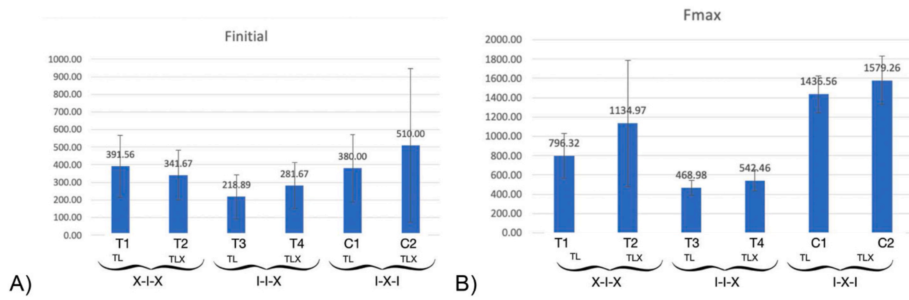


Fig. 2. A) The failure load at first crack ($F_{initial}$) and B) catastrophic fracture (F_{max}) for all groups studied in this study. Mean and standard deviation (SD) in Newton (N).

2.5. Load-to-failure tests

The maximum load (N) until fracture of the reconstructions was measured using a universal testing machine (Zwick/Roell Z010, Zwick, Ulm Germany, 1 mm/min). Therefore, the samples of test groups 1,2,3 and 4 were fixed at a 30° ± 2° angle to the loading direction and the control groups 1 and 2 at a 90° angle of the testing machine and the Quasi-static load was applied with 1 mm/min, following the ISO Norm 14801:2016. The force was applied on the end portion of the cantilever extension in groups 1,2,3,4 and on the pontic in control 1 and 2 (Fig. 1). The antagonist was corrosion-free steel indenter with a diameter of 8 mm. The center was chosen as the meeting point of the mesiopalatinal and distobuccal enamel cusps. The expected failure load (F in N) was measured at the first crack ($F_{initial}$) and catastrophic fracture (F_{max}) (see Fig. 2).

2.6. Failure analysis

After the evaluation of mechanical resistance, all samples were analyzed using a digital optical microscope (VHX, 2000D, Keyence, Osaka, Japan) to determine the origin and location of the failure between the implants. The cantilever extension failures were classified as, 1) Catastrophic failure of the abutment and/or crown due to fracture (partial, complete) with or without plastic deformation, 2) Line of visible crack in the abutment and/or crown with or without plastic deformation, 3) Plastic deformation of the components (implant, abutment, screw) without fracture.

To analyze the characteristics of the abutment/crown failure after mechanical resistance phase, the samples from each group were evaluated using a SEM device (Hitachi TM4000 II Benchtop SEM: Hitachi) at 10 kV, 40x and 200x magnification.

2.7. Statistical analysis

The fatigue and load bearing capacity data were evaluated using nonparametric 2-way analysis of variance (ANOVA) and Tukey's post-hoc tests (alpha = 0.05). Comparisons between the groups were done using unpaired t-tests. All analyses were performed with SPSS software 22.0 (IBM SPSS, 2021) program for Windows.

3. Results

During thermomechanical test, no screw loosening or debonding occurred. Therefore, all specimens were included in load-to-failure tests. Considering the general evaluation among the groups, the mean $F_{initial}$ results ranged between 190 and 510N in the following ascending order, T3 < T4 ($p = 0.997$) < T2($p = 0.940$) < C1 ($p = 0.998$) < T1 ($p = 1.000$) < C2 ($p = 0.903$) with no significant differences between groups (Fig. 1A). The Fmax ranged between 468 ± 76 and 1579 ± 249 N in the ascending order, group $T3^{a} < T4^{a} < T1^{a,b} < T2^{a,b,c} < C1^{c} < C2^{c}$ (Fig. 1B). [The groups with the same superscript were not significantly different from each other ($p > 0.05$)]. Regarding $F_{initial}$ between the implant types (TLX, TL) and among reconstruction designs (X-I-X; I–I-X; I-X-I), no significant difference was found in measured data ($p > 0.05$). The implant type (TLX, TL) did not show any significant effect, while the reconstruction design ($I–I-X^{a} < X-I-X^{b} < I-X-I^{c}$) showed significant difference in Fmax data across all designs. The iFDPs with the mesial and distal extension (X-I-X) showed solely fractures of the extension, while the distal extension group (I–I-X) also presented one abutment and one connector fracture at the implant/reconstruction interface. Fig. 3 shows a SEM image of the most common fracture pattern in the 3-unit bridges presenting the typical areas: 1) origin, starting point of crack propagation, 2) mirror, smooth and featureless region surrounding origin and 3) mist, micro splitting and bifurcation as energy is converted to additional fracture surface area. Fig. 4 shows examples of the most common occurred failure types in this study.

4. Discussion

In this in-vitro study, the fatigue performance and load bearing capacity of three different prosthetic configurations for iFDPs manufactured by multilayer monolithic zirconia bonded on titanium base abutment on two internal connection type implants were tested. Considering the findings, the mechanical properties of the one central implant group showed better results than the group with one mesial and one central implant, and one cantilever extension. However, the control groups resulted in higher F_{max} compared to the test groups using the same implant systems. The null hypothesis was rejected since significant differences in load-to failure data were found among groups.

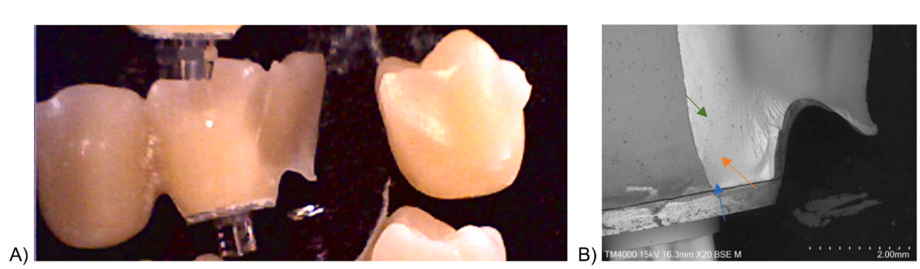
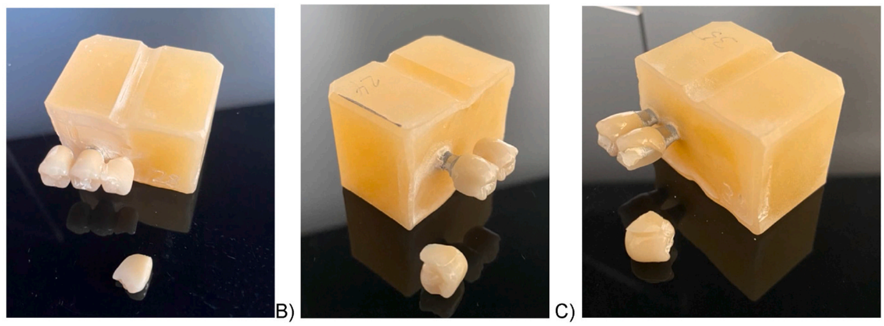


Fig. 3. A) Macroscopic and B) microscopic failure pattern showing origin (blue arrow), mirror (orange arrow) and mist (green arrow) area of fracture.



A) B) C)

Fig. 4. Example of A) Catastrophic failure of the cantilever due to partial and B) complete fracture or C) line of visible crack in the abutment.

The use of iFDP cantilever extension treatment option has been extensively described in the literature (Schmid et al., 2020, 2021; Roccuzzo et al., 2023a,b). However, most of the studies were describing the distal or mesial cantilever extension (Storelli et al., 2018). The present study reported the use of conventional 3-unit iFDPs with or without cantilever extension in different distribution, comparing to an iFDP design with an implant at the center and a cantilever extension on each side.

When the reconstructions design is evaluated, the X-I-X design performed better resulting in higher fracture forces needed compared to the I–I-X design. This fact could be due to a higher tension caused by screwing the bridge on two implants. When the clinical application of the proposed designs is evaluated, mesial and distal cantilever extension X-I-X design may be considered as a favorable treatment alternative to the use of conventional cantilever extension iFDPs to due to its favorable mechanical properties. The proposed test set-up can provide an alternative treatment option, particularly in patients with anatomical limitations for implant placement such as mental nerve proximity, or bone limitations due to alveolar ridge resorption or post peri-implantitis alveolar defects (Romanos et al., 2012; Storelli et al., 2018) and therefore further surgical interventions can be avoided.

When the implant type is considered, the use of an alloy combination of zirconium and titanium can play an important role since this material has reported excellent outcomes in the last decade. Although in the present study standard platform implants were used, in terms of implant stability and survival, zirconia titanium combination has been reported to be a reliable and safe option for single and multiple unit reconstructions on short, standard length or narrow dental implants (Altuna et al., 2016). Further studies may focus on different implant materials such as other titanium alloys or zirconia.

Considering the implant Synocta connection type versus Torqfit, analyzed in the present study, no statistical differences were found. It should be mentioned that both systems were internal connections with the difference of the engagement design, having the Synocta an 8° Morse taper angle and the Torqfit a 7° angle. When the findings of the implant-abutment connections performance are assessed, a possible explanation can be that both implant-abutment connections present a tight connection sealing on the implant platform and therefore a better stress distribution (Camps-Font et al., 2023; Çakmak et al., 2023). In agreement with this statement, the use of internal conical connection implants and abutments are related with favorable clinical outcomes in terms of implant-abutment stability, occlusal forces distribution and biological parameters compared to external connections (Lemos et al., 2019; Vinhas et al., 2020).

Previous studies have evaluated the influence of the titanium base abutment design on the mechanical performance of monolithic zirconia by means of static loading (Karasan et al., 2021, 2022; Calderon et al., 2022). In the proposed methodology a single abutment shape was used based on an engaging connection type. Although conical and/or non-engaged connection have been proposed to achieve a favorable passive fit, this design is not extent from complications (Calderon et al., 2022) and considering the experimental distal and mesial extension study set up, the use of an engaging abutment provide a favorable design for these reconstructions. Although metal-ceramic based iFDPs with and without distal or mesial extensions have been widely investigated both in clinical and preclinical studies, there is limited evidence for monolithic zirconia reconstructions based on titanium abutments for iFPDs cantilever extension protheses (Karasan et al., 2021; Karasan et al., 2022; Rohr et al., 2022; Roccuzzo et al., 2022).

With the improvement in the design and manufacturing techniques of monolithic zirconia, there has been a rise in the use of zirconia bonding reconstructions on prefabricated titanium abutments. Several studies have been published, however, mainly focusing on single implant reconstructions, demonstrating favorable outcomes. Accordingly, these favorable clinical outcomes in terms of technical and biological behavior demanded to investigate the possible application of that concept for iFDPs and more specifically for cantilever extensions. The advantages of the computer-aided design/computer-aided manufacturing (CAD/CAM) technologies allow to fabricate high strength ceramics reconstructions in a predictable and safe way (Mühlemann et al., 2021).

Some studies reported a lower resistance to bending and fracture toughness compared to traditional first generation 3Y-TZP (Jerman et al., 2020; Lümkemann et al., 2021). Although titanium base abutment and zirconia reconstruction combination concept have reported favorable clinical data for single restorations, there is lack of evidence for posterior iFDP with cantilever extensions, limited to some in vitro and in vivo research studies (Pjetursson et al., 2021; Rues et al., 2020; Karasan et al., 2021; Karasan et al., 2022; Calderon et al., 2022; Roccuzzo et al., 2023a,b). It should be noted that there is limited knowledge regarding mechanical properties (Rues et al., 2020; Karasan et al., 2021, 2022; Calderon et al., 2022), therefore further studies should assess and compare the aforementioned material with other monolithic zirconia to evaluate the bending and torsion capacity and of the used material.

Considering the fracture pattern, the obtained results showed that the mesial and distal extension (X-I-X) had solely fractures of the extension side. While in the distal extension group (I–I-X) presented one abutment and one connector fracture at the implant/reconstruction interface. These results are in agree with was previously investigated in similar studies. (Chong et al., 2014; Karasan et al., 2021, 2022; Rohr et al., 2022). When the clinical relevancy of the obtained results is considered, clinicians should be carefully interpreted the data since, the applied maximum forces are higher that the reported in humans (Varga et al., 2011; Ferrario et al., 2004; Nouh et al., 2019), and although the fractures were produced in critical areas, these results can be the starting point of future clinical investigations to confirm its potential applicability in an in-vivo setting.

The methodology of the present study was based on the use of fatigue and load bearing capacity tests following ISO specifications to evaluate the clinical limit of the proposed prosthetic set up. In this respect, this method has been widely used in similar studies and is considered as reliable and reproducible (Nouh et al., 2019; Pitta et al., 2019, 2021;

Calderon et al., 2022).

Considering that posterior bite forces with implant-supported reconstruction have been reported to range between 200 and 900N (Ferrario et al., 2004; Nouh et al., 2019) the set-up in the present study applied a Fmax ranged between 468 ± 76 and 1579 ± 249; therefore, obtained results showed a favorable scenario for the proposed reconstruction. In addition, an aging process was performed, and the use of the reported protocol provides additional and valuable information since providing and artificial aging, more similar oral conditions are given. It was previously reported that loading cycles of 240′000 to 250′000 using a chewing simulator machine corresponds to one-year of clinical occlusal function (Steiner et al., 2009). Regarding this data, applied 1′200′000 cycles result in almost five years of clinical function and therefore, the data may be considered as clinically relevant. The loading position and the providing occlusal contacts were based following greater similarity to in vivo settings, the previous studies and ISO standards considering the limitations of an in vitro providing the study with reliability and reproducibility.

When the limitations of the study are considered, the in vitro methodology cannot provide a direct and real scenario; nevertheless, obtained promising results justify a clinical pilot study to test the concept in vivo. Therefore, future clinical studies focused on proposed prosthetic set up comparing with conventional control groups as tested in the present study can provide valuable information.

When the methodology is assessed, the conventional pontic configuration was loaded at 90°, however, experimental group pontic were loaded at 30°. In addition, the aging process was based on a nonaggressive oral environment (saliva) and with no grinding motion and two engaging abutments were used also for the FDPs with the two implants, which is not recommended by the manufacturer.

5. Conclusions

From this study, the following can be concluded.

1 The conventional iFDP design with no cantilever extension (I-X-I) performed favorably, followed by the mesial and distal extension X-I-X design on one implant abutment regardless of the implant type.
2 The use of multilayer monolithic zirconia bonded on hybrid titanium base abutment with an implant at the center and one cantilever extension both at mesial and distal may be considered as an option for 3-unit iFDPs.
3 Mesial and distal cantilever extension X-I-X design may be considered as a favorable treatment alternative to the use of conventional cantilever extension reconstructions to due to its acceptable mechanical properties to its favorable mechanical properties.

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CRediT authorship contribution statement

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Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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