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Effect of fatigue loading on the fracture strength and failure mode of lithium disilicate and zirconia implant abutments

Adham Elsayed | **Sebastian Wille** | **Majed Al-Akhali** | **Matthias Kern**

Department of Prosthodontics, Propaedeutics and Dental Materials, School of Dentistry, Christian-Albrechts University, Kiel, Germany

Correspondence
Adham Elsayed, Department of Prosthodontics, Propaedeutics and Dental Materials, School of Dentistry, Christian-Albrechts University, Kiel, Germany.
Email: aelsayed@proth.uni-kiel.de

Abstract

Objective: The aim of this study was to test five types of implant restorations using titanium, zirconia and lithium disilicate abutments after being subjected to long-term fatigue loading.

Materials and methods: Forty single-tooth implant restorations were assembled on titanium implants (FairTwo; FairImplant). The restorations differed only in the type of abutment used and were divided into five groups [Ti: titanium; Zr: zirconia with no metal base; ZrT: zirconia with titanium base; LaT: lithium disilicate abutment with titanium base; and LcT: lithium disilicate hybrid-abutment–crown with titanium base]. Specimens were subjected to dynamic load of 49 N up to 1,200,000 cycles using a dual-axis chewing simulator (Kausimulator; Willytech). The surviving specimens were subjected to quasi-static loading using a universal testing machine (Z010; Zwick) until the implant–abutment connection failed. The values of force (N) at which fracture or plastic deformation of the restoration occurred were calculated and the rate of deformation was analyzed. The data was then analyzed using Mann–Whitney tests.

Results: Groups Ti, ZrT, LaT and LcT withstood 1,200,000 fatigue load cycles and higher forces than physiological occlusal forces without fracture or debonding of the ceramic suprastructure. In group Zr, some specimen did not survive the chewing simulation and this group showed the lowest resistance to failure with a median of 198 N.

Conclusions: Within the limitations of this study, it could be concluded that lithium disilicate abutments and hybrid-abutment–crowns show promising durability and strength after long-term dynamic loading. The use of titanium base enhances the strength of the zirconia abutments.

KEYWORDS
ceramic abutments, fatigue loading, implant abutments, lithium disilicate, zirconia

1 | INTRODUCTION

The goal to be achieved in implant dentistry is not just to place an implant, but to restore functions and esthetics of a missing tooth. Thus, the success of the implant restorations does not depend only on osseointegration and function, but also on achieving natural and harmonious appearance of the replaced missing teeth, which depends on the materials used for both the implant abutment and the crown.

Titanium abutments restored with porcelain fused to metal crowns have been known to be the standard treatment option in implant dentistry with high survival rates (Leonhardt, Grondahl, Bergstrom & Lekholm, 2002; Linkevicius & Vaitelis, 2015; Pjetursson, Sailer, Zwahlen & Hämmerle, 2007; Sailer, Pjetursson, et al., 2007; Zembic, Kim, Zwahlen & Kelly, 2014). Nonetheless, when using titanium, the esthetic results of the final restoration can be compromised through a gray color that may be transmitted through the peri-implant tissues giving an unnatural bluish appearance (Heydecke, Sierraalta &

Razzoog, 2002; Leblebicioglu, Rawal & Mariotti, 2007; Park, Da Silva, Weber & Ishikawa-Nagai, 2007).

Due to the well-documented high fracture resistance, good esthetics and superior biocompatibility, zirconia ceramic has attracted significant interest that led to its use as implant abutment (Apholt, Bindl, Luthy & Mormann, 2001; Glauser et al., 2004; Kerstein & Radke, 2008; Scarano, Piattelli, Caputi, Favero & Piattelli, 2004). Zirconia abutments manufactured using computer-aided design/computer-aided manufacturing (CAD/CAM) technology is one of the most popular treatment options in implant dentistry especially in the esthetic zone (Att, Kurun, Gerds & Strub, 2006b; Protopapadaki, Monaco, Kim & Davis, 2013).

Zirconia abutments have been used with and without a metal base. Studies showed that implementing a titanium base provides more support to brittle ceramics, more precise fit with the implant and improves the fracture resistance of the abutment (Chun et al., 2015; Ebert, Hedderich & Kern, 2007; Elsayed, Wille, Al-Akhali & Kern, 2017; Truninger et al., 2012; Yilmaz, Salaita, Seidt, McGlumphy & Clelland, 2015). This avoids the weakest point of the zirconia abutment at the implant–abutment contact area, and the undesirable color of the metal can then be masked with the zirconia suprastructure. Such an assembly makes use of both advantages of metal and zirconia abutments.

The whitish color of the zirconia abutment offers favorable esthetics compared to the grayish color of titanium in clinical situation of thin peri-implant mucosa or all-ceramic crowns (Jung, Sailer, Hämmerle, Attin & Schmidlin, 2007; Mitsias, Koutayas, Wolfart & Kern, 2014; Sailer, Zembic, et al., 2007; Watkin & Kerstein, 2008). However, increasing the grain size and the porosity of zirconia to achieve a greater strength results in greater opacity (Dias et al., 2008). Lithium disilicate glass ceramics have proven to be successful esthetic options compared to zirconia which has poorer translucency and that often is too white for an optimal esthetic appearance (Aboushelib, Kleverlaan & Feilzer, 2008; Baldissara, Llukacej, Ciocca, Valandro & Scotti, 2010; Heffernan et al., 2002).

A recent study evaluated the effect of zirconia and lithium disilicate abutments bonded to titanium base on the bone and soft tissue of minipigs regarding the effect of the material as well as the adhesive joint between the suprastructure and the base (Mehl, Gaβling, et al., 2016). It was found that abutment material and the use of two-piece abutment did not influence the bone loss or soft tissue around the implant, except for a longer junctional epithelium around the zirconia and one-piece titanium abutments. Another study showed that using dental abutments with machined surfaces are preferred concerning cell adhesion than rough or polished surfaces, and when cell adhesion to titanium, zirconia and lithium disilicate disks with machined surfaces was compared, it showed no significant difference in the results (Mehl, Kern, Schütte, Kadem & Selhuber-Unkel, 2016). Both studies support the use of ceramic abutments made of zirconia or lithium disilicate bonded to titanium base in regard to biocompatibility.

There are two possibilities of using lithium disilicate abutments: as a hybrid-abutment bonded on titanium base and on top of it an all-ceramic crown, or as hybrid-abutment–crown where the abutment and crown are manufactured as one piece that is bonded to titanium base and screwed to the implant (Elsayed et al., 2017; Kurbad & Kurbad, 2013; Lin, Harris, Zandinejad, Martin & Morton, 2014; Selz, Vuck & Guess, 2016).

To be considered a reliable treatment alternative, the performance of the lithium disilicate abutments must be comparable to the widely used titanium and zirconia abutments. Few articles and case reports are available regarding the use of lithium disilicate ceramic as a material for implant abutments (Elsayed et al., 2017; Kurbad & Kurbad, 2013; Lin et al., 2014; Mehl, Gaβling, et al., 2016; Selz et al., 2016).

Only in one laboratory study, the static fracture resistance of lithium disilicate abutments and hybrid-abutment–crowns was tested and compared to zirconia abutments with and without titanium base as well as to titanium abutments (Elsayed et al., 2017). However, to more closely simulate the clinical situation, the influence of fatigue loading which was missing in the aforementioned study should be evaluated. Therefore, this study aimed at testing the fracture strength and behavior of zirconia and lithium disilicate implant restorations after subjecting them to fatigue loading through 1.2 million chewing simulation cycles that is supposed to correspond to 5-year clinical fatigue (Kern, Strub & Lu, 1999).

2 | MATERIALS AND METHODS

The current study was designed to follow the materials and methods described in a previous laboratory study for means of comparisons (Elsayed et al., 2017). Manufacturing the abutments and crowns were carried out using CAD/CAM technology. The manufacturing process and the dimensions of the restorations followed those reported in the abovementioned study.

Forty single implant-supported restorations were assembled using 40 titanium implants with a diameter of 4.2 mm and length of 11.5 mm, having internal conical connection and platform switch (FairTwo; FairImplant, Bönningstedt, Germany). Forty ceramic crowns made of lithium disilicate glass ceramic (IPS emax CAD; Ivoclar Vivadent, Schaan, Liechtenstein) were produced to replace a maxillary right central incisor of 11 mm length and 8.5 mm width. For the purpose of this study, the specimens were standardized except for the abutment material, which differed between the test groups. The implants were randomly divided, according to the abutment material and type, into five groups of eight implants each (Ti: titanium abutment; Zr: zirconia abutment with no metal base; ZrT: zirconia abutment with titanium base; LaT: lithium disilicate abutment with titanium base; and LcT: lithium disilicate hybrid-abutment–crown with titanium base). Figure 1 shows an overview of the five different restorations used in this study.

All abutments were attached to the implants with titanium screws of 9 mm length and 1 mm diameter. A new screw was used for each assembly to avoid any stress of the screw made during forehand tightening and loosening. Before the new screw was placed, antiseptic gel (Chlorhexamed; GSK, Bühl, Germany) was placed at the implant connection to simulate clinical procedures (Kern & Harder, 2010). At first, torque wrenches were checked with a calibrated Torque Tester

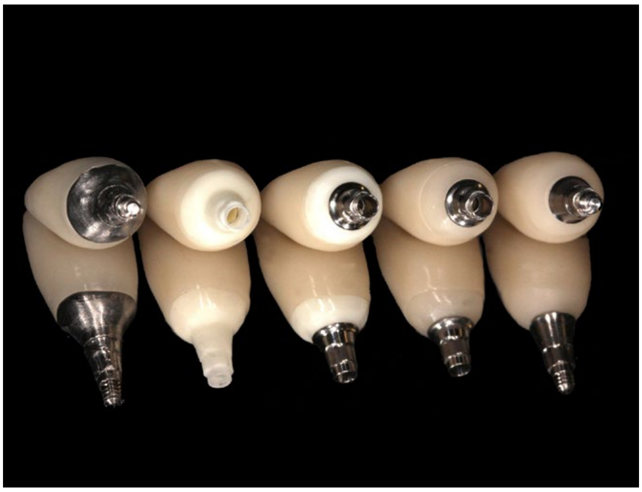

FIGURE 1 Overview of the five different restorations used in the study. From left to right: Ti, Zr, ZrT, LaT and LcT

(Crane Electronics, Hinckley, UK) to ensure that the desired torque was delivered during tightening. Then, the screws were tightened with 25 Ncm. After 10 min, the screws were retightened to avoid any screw loosening (Farina, Spazzin, Consani & Mesquita, 2014; Siamos, Winkler & Boberick, 2002; Spazzin et al., 2010). The implants were embedded in an autopolymerizing polyester resin (Technovit 4000; Heraeus Kulzer, Wehrheim, Germany) covering the implant to the first thread.

Titanium base (FairImplant) was adhesively cemented to the ceramic suprastructures (zirconia in group ZrT and lithium disilicate in groups LaT and LcT). Surface treatment of titanium base was performed using air abrasion with 50 μm alumina particles at 0.25 MPa. The zirconia suprastructures were air-abraded using 50 μm alumina particles at 0.1 MPa (Kern, 2009; Kern, Barloi & Yang, 2009). For the lithium disilicate abutments and hybrid-abutment–crowns, the inner surfaces were etched according to the manufacturers' instructions for 20 s with 4.5% hydrofluoric acid (IPS Ceramic Etching Gel, Ivoclar Vivadent). Bonding of the zirconia and lithium disilicate suprastructures was made using a self-curing luting composite resin developed for laboratory bonding procedures (Multilink Hybrid Abutment, Ivoclar Vivadent) under a constant load of 750 g, after the surfaces were primed with a universal primer for ceramics and metals (Monobond Plus, Ivoclar Vivadent) (Azimian, Klosa & Kern, 2012).

Crowns were also adhesively cemented to the abutments. The bonding surfaces of titanium and zirconia abutments were air-abraded with 50 μm alumina particles at 0.25 MPa pressure for titanium and 0.1 MPa pressure for zirconia. After air abrasion, the abutments were ultrasonically cleaned in 99% isopropanol for 3 min and dried. The lithium disilicate abutments (group LaT) as well as all the crowns were etched using 4.5% hydrofluoric acid for 20 s. Bonding areas of all abutments and crowns were primed (Monobond Plus) for 60 s and were again air-dried. In all groups, the crowns were then bonded to the abutments using a dual-curing luting composite resin (Multilink Automix, Ivoclar Vivadent) under a constant load of 49 N. After removal of excess luting resin, a glycerin gel (Liquid strip, Ivoclar Vivadent) was applied to the abutment–crown interface. Light curing (Elipar 2500; 3M ESPE, Neuss, Germany) was then applied for 20 s from labial and palatal sides. Before subjecting the specimens to fatigue loading tests, they were stored in distilled water at 37°C for 3 days to ensure that autopolymerization of the resin cement was complete.

According to the study outline, all specimens were subjected to dynamic loading in a computer-controlled dual-axis chewing simulator (Chewing Simulator CS-4; SD-Mechatronik, Westerham, Germany) for 1,200,000 loading cycles. A loading force of 49 N was applied at an angle of 30° degrees to the implant axis, 3 mm below the incisal edge on the oral aspect of the crown at a frequency of 1.6 Hz using a ceramic ball with a 6 mm diameter (Steatite Hoechst Ceram Tec, Wunsiedel, Germany). In order to simulate wet conditions of the oral cavity and to subject the ceramic to a wet environment, all specimens were soaked in distilled water at room temperature for the whole period of testing. Video recording cameras were placed for each specimen throughout the test to detect the number of cycles the specimen survived in case of failure during dynamic loading.

After the loading cycles were complete, all specimens were checked for screw loosening and for incipient fracture visually and under low power (50×) stereo-magnification with the use of an optical microscope (Carl Zeiss, Jena, Germany). Any fracture or crack of the ceramic as well as screw loosening was defined as failure. Then, all survived specimens were subjected to quasi-static loading using a universal testing machine (Zwick Z010; Zwick, Ulm, Germany). A semi-spherical loading stamp was positioned 3 mm below the incisal edge on the oral aspect of the crown. However, a 0.5-mm-thick tin foil (Zinnfolie; Dentaurum, Ispringen, Germany) was placed between loading stamp and crown to achieve homogenous stress distribution. Then, a compressive force was applied at the same angle of 30° degrees to the implant axis under stroke control with a cross-head speed of 2 mm/min until failure which was perceived as a fracture, a sudden reduction in force or deflection of 3 mm. Deflection was measured until 3 mm in order to test whether there will be another form of failure such as crack or fracture in the assembly and to detect any differences in the fracture strength or the bonding of the ceramic suprastructure between the different groups. Video recordings of all the tests were made with an integrated video camera that allows replay of the test simultaneously while checking the graph; this helps to exactly detect the force at which failure happened as well as the mode of failure. The failure loads were recorded using a commercial software program (testXpert II V3.3; Zwick). This software also allows the detection of any minor failures which are difficult to determine visually, such as cracks in the ceramic or the adhesive layer; this is shown as sudden sharp drop of the force curve in the graph generated by the software.

After the quasi-static loading, all specimens were again examined visually and under optical microscope (Carl Zeiss) and representative photographs of failed specimens were taken. The microscopic evaluation was performed to assess the mode of failure. Therefore, all tested specimens were examined for incipient fractures and the mode of failure was reported according to the locations of possible fractures.

TABLE 1 Traverse distance (in μm) indicating deformation of titanium base at given forces and statistically significant differences between groups. Medians (IQR)

	dL (100–200 N)	dL (200–300 N)	dL (300–400 N)
Ti	349 (346)^A	356 (436)^A	560 (651)^A
ZrT	150 (26)^B	168 (27)^B	197 (23)^B
LaT	207 (141)^B	151 (34)^B	205 (30)^B
LcT	179 (106)^B	163 (20)^B	189 (18)^B

In a column, different letters indicate statistically significant differences between groups (Mann–Whitney tests with $\alpha = .05$). Overall Kruskal–Wallis test $\alpha = .001$.

Randomly selected specimens were cut into two vertical halves after being placed in stycast for support for further investigations of the failure mode.

The bending conduct of the metal in groups Ti, ZrT, LaT and LcT was investigated. The graphs produced by testXpert software of Zwick were analyzed and the forces of 100, 200, 300 and 400 N were detected and marked on the graph; then, the deformation (in μm) of the metal performed at each given force was also determined. The distance traveled by the metal (in μm) for each 100 N increase in force was measured and a table was made to show deformation from 100 to 200 N, from 200 to 300 N and from 300 to 400 N for each group (Table 1). Normality distribution was tested using Shapiro–Wilk test, which revealed that the data were not normally distributed. The data were then analyzed using Kruskal–Wallis ($p = .001$) test followed by multiple pairwise comparisons of the groups using Mann–Whitney tests at $p \le .05$. Significance levels were adjusted with the Bonferroni–Holm correction for multiple testing to reveal statistically significant differences between groups.

3 | RESULTS

All test specimens of groups Ti, ZrT, LaT and LcT survived 1,200,000 cycles of dynamic loading in the chewing simulator. No screw loosening or incipient fracture in the ceramic abutments or crowns was recorded. In group Zr, three specimens failed at approximately 185,000, 230,000 and 310,000 loading cycles, respectively. The failure mode was similar for these three specimens and was exhibited as fracture of the zirconia abutment at the abutment–implant connection area slightly above the implant shoulder.

All specimens ($n = 8$) of groups Ti, ZrT, LaT and LcT and five specimens of group Zr (after failure of three specimens during dynamic loading) were subjected to quasi-static loading until failure using a universal testing instrument (Zwick Z010; Zwick).

The median fracture load for group Zr was 198 N. All specimens of groups Ti, ZrT, LaT and LcT showed plastic deformation of the titanium abutments and titanium bases, respectively. In group Zr, the mode of failure for all specimens was represented as ceramic fracture at or slightly above the level of the implant shoulder. The fractured components always remained inside the internal connection part of the implants.

Whereas all specimens of the other groups (groups Ti, ZrT, LaT and LcT) failed due to a permanent plastic deformation at the screw and internal connection of the titanium abutment or base and slight distortion of the labial implant platform without ceramic displacement or fracture. All restorations with a titanium base showed high fracture strengths, exceeding 900 N for most of the specimens. When used with titanium base, zirconia abutments (group ZrT) withstood mean loading forces up to 944 N without fracture. Lithium disilicate abutments successfully resisted fracture and tolerated forces of mean up to 970 N for group LaT and 980 N for group LcT.

Analyzing the bending behavior, the titanium bases in groups ZrT, LaT and LcT did not show any significantly different behavior of plastic deformation.

Failure mode of samples of groups Zr, ZrT, LaT and LcT is represented in Figure 2. To analyze the failure mode, randomly selected implant–abutment assemblies were cut into two vertical halves (Figure 3).

4 | DISCUSSION

Laboratory studies support the use of zirconia abutments in the anterior regions after exploring the feasibility to withstand functional loading in simulated oral environment (Att et al., 2006a,b; Butz, Heydecke, Okutan & Strub, 2005). In these studies, single implant all-ceramic crowns of a maxillary incisor placed on zirconia abutments were tested up to 1,250,000 cycles in a chewing simulator under a loading force of 30–49 N. The restorations in all these studies noted high survival rates of 100% after an equivalent of 5-year chewing simulation without any screw loosening, in agreement with the present study. This could also be verified by a recent systematic review that showed a low clinical failure rate of ceramic abutments of 2.5% after 5 years (Zembic et al., 2014).

The ISO 14801 specifications for dynamic fatigue testing of dental implants require embedding the implant in the holding device 3 mm below the nominal bone level to imitate worst-case conditions. However, several studies testing the ceramic implant abutment did not follow this specification and used a simulation of normal conditions (Att et al., 2006a,b; Butz et al., 2005; Elsayed et al., 2017; Mitsias et al., 2014; Protopapadaki et al., 2013; Steinebrunner, Wolfart, Ludwig & Kern, 2008). For the purpose of comparing the findings of the current study to those of the aforementioned studies, a normal condition rather than a worst-case condition was simulated.

In the present study, all the specimens of groups Ti, ZrT, LaT and LcT survived 1,200,000 cycles of exposure to the simulated oral environmental testing. In group Zr, five specimens survived the dynamic fatigue loading test, while three specimens showed fracture of the zirconia ceramic during the dynamic loading. Before the survived specimens of all groups were tested with quasi-static loading, they were checked visually and under microscope to detect any incipient fracture

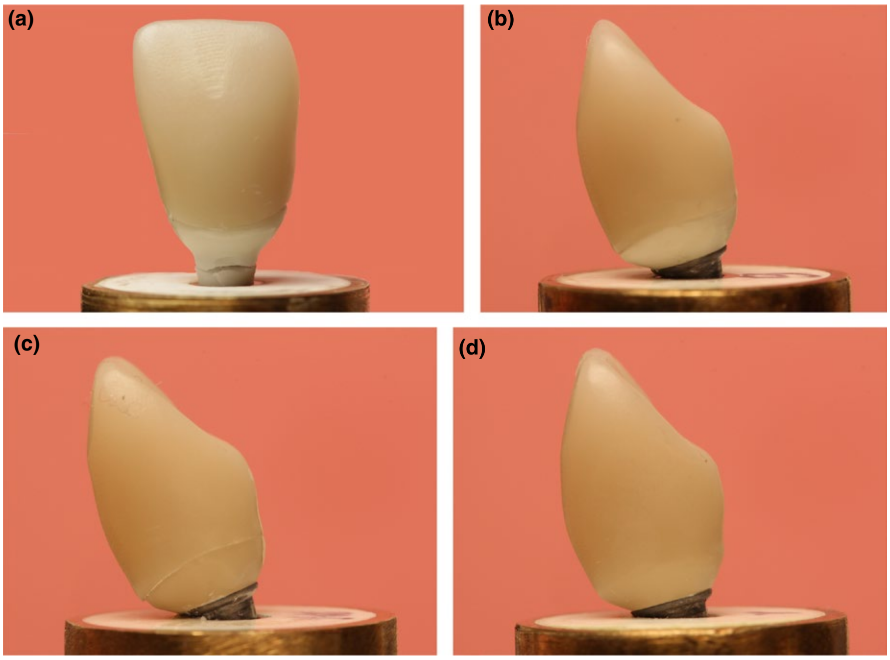

FIGURE 2 Failure modes. (a) Fracture of the zirconia ceramic in a sample of group Zr. (b) Plastic deformation of the titanium base in a sample of group ZrT. (c) Plastic deformation of the titanium base in a sample of group LaT. (d) Plastic deformation of the titanium base in a sample of group LcT

FIGURE 3 A sectioned specimen of group Ti, showing plastic deformation of the screw and the abutment without any fracture

or screw loosening. However, all components of the specimen, including the implant, abutment, screw and the all-ceramic crown, were found in perfect condition without any fractures, revealing that the ceramic abutments supported by a titanium base successfully withstood 5-year aging simulation.

Maximal occlusal forces reported in the anterior region were in the range of 150–235 N with a mean of 206 N (Haraldson, Carlsson & Ingervall, 1979). Bruxism and other functional disorders can induce higher bite forces (Nishigawa, Bando & Nakano, 2001). Loads of these extents were tolerated and exceeded by specimens of groups Ti, ZrT, LaT and LcT, but not by specimens of group Zr.

All zirconia abutments without metal base (group Zr) showed fractures that were located at the cervical aspect of the abutments at or slightly above the level of the implant–abutment internal connection. Fractures occurred through the most tapered part, toward the platform level, and this typical failure pattern was observed in all specimens regardless of the loading mode. No damage or plastic deformation of the implant or abutment screw occurred. This is consistent with the results of other studies (Att et al., 2006b; Elsayed et al., 2017; Foong, Judge, Palamara & Swain, 2013; Mitsias, Silva, Pines, Stappert & Thompson, 2010; Nothdurft, Doppler, Erdelt, Knauber & Pospiech, 2011; Yildirim, Fischer, Marx & Edelhoff, 2003).

All restorations with a titanium base showed high resistance to forces generated in the universal testing machine. Nonetheless, the values of the loading resistance of these groups could not be reported as fracture strength as the test was stopped before any restorations fractured when a deflection of more than 3 mm was noticed. This failure criterion was included in the study design to imitate closely what would clinically be considered as a failure and to follow that of the previous study (Elsayed et al., 2017). The statistical analysis of the bending behavior (plastic deformation) between the three groups with titanium bases (ZrT, LaT and LcT) did not show any significant differences. The results correspond to those from a previous study which used the same materials and implants as the current study (Elsayed et al., 2017).

In a lever of second class, the input effort is located at the end of the bar and the fulcrum is located at the other end of the bar opposite to the input, while the point of output load is between the input and the fulcrum. When abutments with internal conical connection are used and subjected to forces applied at an angle of 30° to the implant axis, second class levering effects are induced. Therefore, the output load is applied in area of the internal cone of the abutment. Thus, internal cone of the abutment seems to be a high loaded component that receives torque and stress concentrations. This might explain why all abutments failed at the area of connection, which was seen in either fracture of zirconia ceramic in group Zr or plastic metal deformation at this particular area in the other four groups. However, it was illustrated both in laboratory and in clinical studies that internal connections of abutments tend to be beneficial regarding fracture strength and screw stability (Sailer et al., 2009; Truninger et al., 2012).

In this study, two methods were used to manufacture implant-supported restorations made of lithium disilicate and both showed no difference in the fracture resistance or the failure mode. As cement-retained or screw-retained restorations have specific advantages and disadvantages, the choice of the type of the restoration depends on many factors including the clinician's preference (Chaar, Att & Strub, 2011; Taylor, Agar & Vogiatzi, 2000). The use of hybrid-abutment–crowns can combine some advantages of both the cement-retained and the screw-retained restoration by eliminating some of the problems of both. It allows ease of access to the screw through the composite resin coverage. Moreover, it eliminates crown margins and the need for cementation. Nonetheless, the need for an optimal surgical implant positioning is required, as an incorrect implant axis could lead to a hole in the labial surface of the incisors created by the screw cavity, which would be unacceptable due to the high esthetic requirements in this area. According to the results of the current study, both hybrid-abutments and hybrid-abutment–crowns made of lithium disilicate could withstand high loading forces with no difference in fracture resistance or mode of failure, providing two convenient treatment options depending on the indications and case selection.

Promising fracture strengths were reported for the lithium disilicate and zirconia abutments with titanium base (Elsayed et al., 2017). However, the former study was conducted without fatigue loading. Therefore, the current study was designed to exactly follow the aforementioned study regarding the manufacturing of the restorations, but to apply dynamic fatigue loading. When comparing the results, after fatigue loading, the zirconia abutments without metal base fractured at lower loads than those reported in the previous study. In contrast, after fatigue loading, abutments supported by a titanium base still exhibited high fracture loads and showed similar modes of failure.

5 | CONCLUSIONS

Hybrid-abutments and hybrid-abutment–crowns made of lithium disilicate show promising durability and strength after long-term dynamic loading. The use of a titanium base enhances the strength of the zirconia ceramic abutments.

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CONFLICT OF INTEREST

The authors report no conflicts of interest related to this study.

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