In Vitro Fit and Distortion of CAD/CAM-Fabricated Implant-Fixed Titanium and Zirconia Complete Dental Prostheses Frameworks

THESIS

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By

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Abstract

Purpose: The aim of this study was to compare the marginal fit and 3-dimensional distortion of implant-fixed screw-retained computer-aided designed and computer-aided manufactured (CAD/CAM) zirconia and titanium complete dental prostheses (CDP) fabricated on 4 implants.

Materials and Methods: A master edentulous model with 4 implants (#3, 6, 11, 14) was used in this study. Multi-unit abutments (Nobel Biocare) were digitally scanned using scan bodies and a laboratory scanner (S600 ARTI, Zirkonzahn). A CAD software (Zirkonzahn) was used to design complete-arch screw-retained implant prostheses and the file was sent to a milling machine for CAM. Titanium (n=5) and zirconia (n=5) frameworks were milled on 4 implants. All frameworks were scanned at one-screw test position (screw tightened only into implant #14) using an industrial computed tomography (CT) scanner (Nikon / X-Tek XT H 225kV MCT Micro-Focus). The direct CT scans were reconstructed to generate polygonal mesh models (STL) from the voxel data set and transported to a volume graphics analysis software (PolyWorks, Innovmetric) from which measurements were extracted. The 3D gap measurement between the circular mating surfaces of the frameworks and implant abutments were measured for implant #11 (Gap 2), implant #6 (Gap 3) and implant #3 (Gap 4). In addition, color maps were generated to show the gap size between the mating surfaces using +/- .500 mm color scale ranges. To calculate the 3D distortion of the titanium
and zirconia frameworks, STL files of the direct CT scans were aligned to the CAD model using a sum of the least squares best fit algorithm. Surface comparison points were placed on the CAD model on the mid-facial aspect of all teeth. The 3D distortion of each direct scan to the CAD Model was calculated using inspection software (PolyWorks, Innovmetric). In addition, color maps of the scan to CAD comparison were constructed using +/- .500 mm color scale range.

**Results:** Results showed that the material type (zirconia or titanium) was not significant for 3D gap measurements (p=.9038). However, 3D gap measurement values were significantly different between Gap 3 and 4 within each group (P=.0003). The mean 3D gap measurement for Gap 2 for titanium was 48.2 μm (SD 2.6). The mean 3D gap measurement for Gap 3 for titanium was 74.0 μm (SD 15.0) and 84.4 μm (SD 12) for zirconia. The mean 3D gap measurement for Gap 4 for titanium was 102 μm (SD 26.7) and 93.8 μm (SD 30) for zirconia. All 3D gap measurements showed values <135 μm. Results for the 3D distortion from the CAD model showed that both materials exhibited distortion. However, there was no significant difference in the amount of distortion from the CAD model between the materials (p =.7475).

**Conclusions:** Within the limitations of this in vitro study, implant-fixed CAD/CAM-fabricated titanium and zirconia frameworks showed comparable marginal fit. 3D micro gap measurements of frameworks showed clinically acceptable misfit values. In addition, zirconia and titanium frameworks showed similar 3D distortion when compared to the CAD model. Absolute passive fit was not achieved.
Dedication

I would like first to thank God for his countless blessings in my life, who also handed me the most precious gift, my wonderful wife Hanadi, the love of my life and the mother of my handsome newborn son Rayan.
Acknowledgments

I would like to express my very great appreciation to my committee members, Dr. Burak Yilmaz, Dr. Edwin McGlumphy and Dr. William Brantley for sharing their knowledge and for their useful and constructive recommendations. I wish to acknowledge the help and assistance of Dr. William Johnston in the development and the interpretation of the statistics of this study.
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Minor Fields: Prosthodontics

Dental Materials
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Chapter 1: Introduction

Since the early days of osseointegration, Brånemark demonstrated the successful rehabilitation of edentulous patients by splinting dental implants routinely together.\textsuperscript{1-4} Numerous authors have reported on the rationale for splinting.\textsuperscript{5-12} Splinting distributes occlusal forces\textsuperscript{5,6,7}, reduces stress levels around individual implants\textsuperscript{8,9,10}, decreases mechanical complications\textsuperscript{11} and reduces the overall treatment cost, because fewer implants are needed.\textsuperscript{12} Although splinting of implants has obvious advantages, it may be extremely challenging to achieve an absolute passive fit.

The rationale for passive fit in implant prostheses:

Several authors have reported the importance of a passive fit of implant frameworks. It is accepted that the need for passivity of fit is greater in implant-supported restorations than in conventional tooth-supported restorations because of the stiff ankylosic fixation of implants compared to the elastic anchorage of teeth through the periodontal ligament. However, to date, there is no consensus on the exact level of misfit in implant frameworks that is considered acceptable.\textsuperscript{13,14,15} In 1983, Brånemark was the first to quantify the passive fit of implant frameworks and proposed that the misfit should be not more than 10 microns. Meanwhile, Jemt\textsuperscript{16} stated that a misfit around 150 microns is acceptable, and he introduced the screw resistance test. More recently, Sahin et al\textsuperscript{17} and Watanabe et al\textsuperscript{18} defined the passive fit of implant-supported frameworks as one that does not exert any strains to the implants in the preloaded condition.
Methods to evaluate fit of implant prosthesis:

Implant framework fit can be evaluated by two methods\textsuperscript{13}: in vivo and in vitro. In vivo or clinical methods are used to evaluate the passivity of implant frameworks and to determine their clinical acceptability. Kan et al.\textsuperscript{14} proposed several clinical assessment methods to evaluate implant framework misfit:

(1) The alternate finger pressure:
The clinician evaluates the prosthesis for any rocking and watches for any saliva bubbling around the misfit gap.

(2) Direct vision and tactile sensation:
The dental explorer can be used to verify the marginal fit. This technique is restricted by the size of the explorer tip. A new explorer tip is around 60 microns in diameter.

(3) Radiographs:
The periapical radiograph is a useful tool in the identification of gap formation.\textsuperscript{19} However, radiographs should be taken perpendicular to the implant/ framework interface to avoid overlapping of implant structures that may appear on the radiograph as if passive fit has been accomplished.\textsuperscript{19}

(4) The Sheffield test or the “one-screw test”:
This test is one of the most popular tests for clinical evaluation of framework fit.\textsuperscript{13,16,20} When one screw on the most distal abutment is completely tightened without creating a gap between the rest of abutments and cylinders, the framework is considered to be clinically acceptable.\textsuperscript{21,22} This method is particularly applicable for full arch frameworks, in which the gap size tends to increase at the rest of the unscrewed abutments.
The problem with the one screw test is that misfit are not detected in 3 dimensions and can be difficult to detect if the distortion has occurred in the horizontal plane.\textsuperscript{21,22}

(5) The screw resistance test:

Jemt\textsuperscript{16} presented the screw resistance test and deemed that 150 \(\mu\)m is an acceptable vertical discrepancy. His protocol involved tightening each screw individually until initial finger resistance was achieved. A misfit was diagnosed if more than half a turn was needed to torque the screw in order to close the theoretical 150-micron gap. This technique is applicable only in implant systems where the thread pitch of the abutment screw is 300 microns such as the Nobel Biocare prosthetic screw. This test might not be applicable with other implant systems as not all prosthetic screws are designed similarly.\textsuperscript{14,16}

**Mechanical and biological complications:**

There are mechanical and biological complications for inadequately fitting implant frameworks. The most common described mechanical complication was the loosening or fracture of the implant prosthetic screw.\textsuperscript{17,23,24,25} Also, the micro gaps between the implant and framework may be inhabited by bacteria, which may be detrimental to the remodeling process of the crestal bone and the overall health of the peri-implant tissues.\textsuperscript{26} Animal studies failed to demonstrate that misfits of 500 or even 1000 microns have any negative effects on osseointegration and bone remodeling.\textsuperscript{27,28,29,30,31} However, all reported animal studies in the literature assessed the stresses only in the unloaded condition. The stresses are believed to rise significantly during function and may cause a different possible outcome. Until clear guidelines regarding the acceptable misfit are present, clinicians should strive for the best framework fit possible to decrease any potential complications.
It can be assumed that the higher the precision of fit of an implant-supported prosthesis is, the less likely any biological or technical complications are encountered in the long term.\textsuperscript{32}

**Methods to improve fit of implant frameworks:**

Historically “the lost wax technique” was the most popular approach for FPD framework fabrication. This technique involves many unavoidable steps and materials that can cause distortions. Many methods have been described in the literature to improve implant framework fit. In general, these methods can be divided into two main categories\textsuperscript{33}:

1. **The addition of fit refinement steps:**
   In 2003, Stupmel\textsuperscript{34} described a technique to improve fit by intra-orally luting pre-machined cylinders to the metal implant framework. This technique has the advantage that the intentional space between the cylinder and framework that will be filled with adhesive will compensate for any distortions that might have occurred. Laboratory studies have presented that intraoral luting of frameworks have a positive effect on the strains formed around implants. Clelland and van Putten\textsuperscript{35} used a bone simulant to measure strains generated by conventional frameworks compared to resin-luted frameworks. Their results showed a statistically significant reduction of strains produced in the bone around implants when the frameworks were luted. Other techniques include sectioning and soldering the framework, vertical welding with use of the CrescoTi Precision TM (Astra Tech AB, Mölndal, Sweden) technique, where distortion of the prostheses is improved through horizontal sectioning and laser welding.\textsuperscript{36}

2. **The elimination of certain fabrication steps:**
   The ability of (CAD/CAM) to improve the accuracy of implant-supported frameworks is
achieved through skipping some of the conventional manufacturing steps, such as impression, waxing, investing, and casting.\textsuperscript{37,38,39} However, with CAD/CAM technologies, some steps like scanning, software design, milling, and material processing may introduce imprecisions.\textsuperscript{38} A limitation of the available scanning systems is their level of resolution; in addition, point clouds that are acquired through the scanning process are converted through the CAD software algorithm to produce a continuous surface, which in turn may cause some loss in accuracy.\textsuperscript{40-42} In a comprehensive review by Abduo\textsuperscript{33} in 2014 on the fit of CAD/CAM implant frameworks, results indicated that the accuracy of CAD/CAM frameworks surpassed that of the one piece cast frameworks and laser-welded frameworks.

\textbf{3D distortion of dental frameworks:}

Irrespective of which method is used in the fabrication process of an implant supported prosthesis, distortion can occur on three planes x, y, and z, in addition, rotation in each of those axis may be evident.\textsuperscript{22,43} The distortion is noticeable in the horizontal plane (x and y), and it is directly proportional to the increase in width or curvature of the arch.\textsuperscript{44} Vertical discrepancies may cause higher strains than those resulting from distortions in the horizontal plane.\textsuperscript{16,44,45} In 1999 Wee at al\textsuperscript{43} proposed the concept of the “Distortion Equation”. This concept implies that implant framework misfit is a result of accumulative distortions that occurred during clinical and laboratory steps of the final prosthesis fabrication. The distortion equation includes all the following clinical and laboratory procedures\textsuperscript{43}: impression procedures, implant component positioning, master cast fabrication, wax pattern fabrication, investment and casting procedures, porcelain firing, prosthesis try-in, and prosthesis delivery. According to the “Distortion Equation” the
passive fit can be achieved if the summation of all these distortions equals zero. Although the distortion of each individual factor may be clinically insignificant, the summation of error may result in a final distortion that causes significant internal stress within the implant prosthesis complex. The most popular material for CAD/CAM implant prosthesis frameworks is titanium. Recently zirconia has been more often used in the fabrication of implant-supported prosthesis due to its superior esthetic and biomechanical properties.\textsuperscript{33} CAD/CAM-fabricated titanium implant frameworks have been reported to have a high degree of accuracy for complete arch and partial arch prostheses. However, zirconia frameworks were confirmed to exhibit an accurate fit for partial arch prostheses only.\textsuperscript{34} On natural teeth, Beuer et al\textsuperscript{46} and Sachs et al\textsuperscript{47} evaluated the marginal and internal fit of single crowns, compared to fourteen-unit fixed dental prosthesis made out of zirconia. The fourteen-unit fixed dental prosthesis showed significantly higher marginal openings than single crowns when fabricated under the same conditions. The literature on the fit of CAD/CAM implant-supported complete prosthesis made from pre-sintered zirconia is very limited. In the recent review by Abduo\textsuperscript{33} on the fit of CAD/CAM implant frameworks, it was found that milled titanium and zirconia frameworks revealed a comparable fit.\textsuperscript{48,49,50} One study even found a slightly better fit for the zirconia frameworks.\textsuperscript{51} However, those mentioned studies used short-spanned three-unit fixed implant prostheses. More recently, in 2014 Katsoulis\textsuperscript{52} compared the precision of fit of long span vs. short span implant-supported screw-retained fixed dental prostheses made from CAD/CAM titanium. In this study, all frameworks showed clinically acceptable values. However, short span FDPs were statistically more precise than the long span prostheses. In another study\textsuperscript{53} by the same
authors, the precision of fit of CAD/CAM implant-supported complete arch prostheses made from pre-sintered zirconia was studied, and it was found that the titanium frameworks had the most consistent precision. In addition to the framework length, the framework configuration may have a role in the overall fit. In 1995, Jemt\textsuperscript{44} studied the distortions on implant-supported prostheses using a photogrammetric technique and showed a close correlation between 3D center point distortion and the width, as well as the curvature of the implant arch. The distortion was more pronounced the wider and more curved the arch was. In addition, the distortion of the frameworks seemed to increase when multiple units were fabricated. The anterior dental arch is usually curved while the posterior regions are linearly configured. One study\textsuperscript{54} examined the fit of anterior frameworks made from pre-sintered zirconia and concluded that straight configurations produced a superior fit when compared to curved configurations. The authors described that the initial partially-sintered zirconia undergoes shrinkage during the subsequent sintering process, which might have affected the final fit of the fixed dental prostheses. A main concern with the CAD/CAM system is encountered when milling a full arch zirconia framework, other than titanium; zirconia has to be milled in an enlarged state to compensate for the post-sintering shrinkage.

**Specific aims and hypotheses:**

The aim of this study was to compare the marginal fit and distortion of complete arch implant-fixed screw-retained CAD/CAM zirconia and titanium complete dental prostheses (CDP).

The first null-hypothesis was that there would be no difference in 3D micro gap values between zirconia and titanium CAD/CAM CDP frameworks.
The second null-hypothesis was that a potential distortion of zirconia and titanium frameworks would be similar during fabrication through a CAD reference model. In other words, the produced titanium and zirconia frameworks would have the same accuracy of the datasets when compared to a highly accurate reference dataset with the use of an inspection software.
Chapter 2: Materials and Methods

The master model and the resin framework prototype:

A master cast simulating an edentulous maxilla with four implants (NobelActive RP 4.3 x 13 mm) resembling the all-on-4 concept (Nobel Biocare Model) was used. The two anterior implants were in a parallel and vertical alignment, whereas the two posterior implants were angulated by 30° in the sagittal plane. Straight multi-unit abutments RP 2.5 mm were placed on positions #6 and 11, and 30° multi-unit abutments RP 3.5 mm on positions #3 and 14 (Figures 1 and 2).

Figure 1: Master model sagittal view
Figure 2: Master model occlusal view

Based on denture teeth set-up, a complete arch resin prototype (Pattern Resin LS) was fabricated with four copings (Multiunit Titanium Abutment Level) for screw retention (Prosthetic Screw Multi-Unit) (Figures 3 and 4).

Figure 3: The resin prototype
A facial matrix was used to control a 1.5 mm even cut-back on the facial aspect of all teeth except for the molars on both sides (Figure 5 and 6).

Figure 5: Facial cut-back with matrix
The scanning and milling procedure:

The master model and resin prototype were both digitized with a laser scanner (S600 ARTI, Zirkonzahn). In order to scan the master model, implant scan bodies (Scanmarker NP RP, Zirkonzahn) were screwed on abutments #3, 6, 11 and 14. Then, the resin prototype was scanned after application of a scanning spray (Zirko Scanspray, Zirkonzahn) that facilitated the digitizing process (Figures 7, 8, 9, 10, 11, and 12).
Figure 8: Scanmarker NP RP, Zirkonzahn

Figure 9: Scanning the master model
Figure 10: Laser scanner (S600 ARTI, Zirkonzahn)

Figure 11: Completed scan of prototype surface
Figure 12: Completed scan of implant position

After completing the scanning process, a CAD model was constructed using special software (Zirkonzahn). This CAD model was the basis for milling of both titanium and zirconia frameworks (Figure 13 and 14).
Figure 13: 3D CAD model
The zirconia and titanium framework fabrication process:

All frameworks were fabricated with the same equipment and materials by one experienced dental technician. A new set of milling burs was used after each framework milling procedure. A total of five-zirconia frameworks were milled from a solid pre-sintered zirconia block with aid of a five-axis +1 milling machine (Milling Unit M5 Heavy, Zirkonzahn). The software calculated the desired framework dimensions, as well the expected 20% linear shrinkage that is encountered after the sintering process. All frameworks were then sintered for 9.5 hours to full density in a special furnace (Zirkonofen700, Zirkonzahn) (Figures 15, 16, 17, 18, 19, 20 and 21).
Figure 15: Zirconia block

Figure 16: Manufacturer value of 20% linear shrinkage for the zirconia block
Figure 17: Milling Unit M5 Heavy (Zirkonzahn)

Figure 18: Milling burs
Figure 19: Sintering furnace (Zirkonofen700, Zirkonzahn)

Figure 20: Completed zirconia framework
Then, a total of five titanium frameworks were milled from a solid block with the same milling unit mentioned above (Figures 22, 23, and 24). All frameworks, whether made from titanium or zirconia, were not finished in any form. Only the sprues that attached the framework to the block were cut and smoothed manually with a bur.
Figure 22: Titanium block

Figure 23: Completed titanium framework
Direct CT scanning of titanium and zirconia frameworks:

All measurements were obtained from the same master model and by one trained investigator. The one-screw test, described by Jemt in 1991, was implemented for the quantitative assessment of the gap measurement. Before CT scanning, each framework was secured on the master model with screws #6 and 14 tightened, first by hand, to avoid any horizontal displacement. Only screw #14 was then tightened to a torque of 15 N cm using a calibrated manual torque wrench (Nobel Biocare), and the other screw was then removed (Figures 25, 26, and 27).
Figure 25: Completed titanium and zirconia implant frameworks

Figure 26: (Gap 2) Implant #11, (Gap 3) Implant #6 and (Gap 4) Implant #3
All 5 titanium and 5 zirconia frameworks were scanned with same one-screw test procedure mentioned above using an industrial CT scanner (Nikon / X-Tek XT H 225kV MCT Micro-Focus Industrial CT Scanner). All inspections were performed with an instrument calibrated with standards traceable to the international system of units (SI) through a national metrological institute (NMI) or an ISO17025 accredited laboratory. The expanded measurement uncertainty was 11+30L micrometers, where L = measured length in meters. Uncertainty was expressed at approximately a 95% level of confidence using k = 2.00. The direct CT scans were reconstructed to generate polygonal mesh models (surface tessellation language, STL) from voxel data sets and transported to a volume graphics analysis software (PolyWorks, Innovmetric) from which measurements were extracted (Figures 28 and 29).
Figure 28: Industrial CT Scanner (Nikon / X-Tek XT H 225kV MCT Micro-focus)

Figure 29: Industrial CT Scanner showing test specimen
Data collection process for the gap measurement:

The 3D gap measurement between the circular mating surfaces of the frameworks and implant abutment were measured only for Implant #11 (Gap 2), Implant #6 (Gap 3), and Implant #3 (Gap 4). The mating surfaces at Gap 1 were not reported since they were completely in contact. In addition, color maps were generated to show the gap size between the mating surfaces at Gaps 2, 3, and 4 using a +/- .500 mm color scale range. Gaps were measured using planes created from scan data of the mating surfaces at 2, 3, and 4. Planes were fit to the data using a maximum-fit algorithm, rather than a best-fit algorithm. The maximum-fit algorithm fits a plane at only the highest eligible data points. This type of fit was used because it best mimics how the surface would mate with another surface. The standard method for measuring the distance between two planes involves using one plane as a reference. The measurements were made by creating a line normal to the reference plane surface. This line was constructed to begin at the reference plane and end at the centroid of the other plane being considered. The 3D distance reported was the length of this line. The gap measurements made in this study used the flat abutment surfaces as the reference plane (Figures 30, 31, 32, and 33).
Figure 30: CT Image (Gap 2) implant #11

Figure 31: CT Image (Gap 3) implant #6 and (Gap 4) implant #3
Figure 32: 3D gap measurement

Figure 33: Color map of gap location (values within boxes are in millimeters)
Data collection process for the scan to CAD comparison:

The direct CT scans of the titanium and zirconia frameworks were converted to STL files and aligned to the CAD model using a sum of the least-squares best-fit algorithm (Figure 34).

Figure 34: Area in red was used to align the data

Surface comparison points were placed on the CAD model on the mid-facial aspect of all 12 teeth. Surface comparison points were maintained at the same x, y and z location in the CAD model coordinate system. For example, the “Surface comparison point 1” always had the same x, y, z coordinates and normal direction in every part sample. Once scan data were aligned to the CAD model, the data were compared to the CAD model at each surface comparison point location. The reported deviation was the distance of the measured data point from the surface of the CAD model, constrained to the normal vector of the reference
model surface at that point location. The software calculated the deviations in x, y and z-axis between each direct scan to the CAD Model (Figures 35, 36, 37, 38, and 39).

Figure 35: Surface comparison points 4 to 12

Figure 36: Surface comparison points 1 to 10

In addition, color maps of the scan to CAD comparison were constructed using +/- 0.500 mm color scale range. The positive deviations mean that the scan data were above the CAD model surface and negative deviations mean the scan data was below the CAD model surface. Areas shown in grey represent areas of the scan that were either outside of the scale area shown or areas in which no data was collected and are not compared.
Figure 37: Color map of scan to CAD deviations (numerical values in boxes are in millimeters)

Figure 38: Color map of scan to CAD deviations (numerical values in boxes are in millimeters)
Figure 39: Color map of scan to CAD deviations (numerical values in boxes are in millimeters)

Statistical analysis:

Part 1: 3D Gap measurement

The 3D gap distances were analyzed by a repeated measures analysis of variance (MIXED procedure, SAS (r) Proprietary Software 9.3, SAS Institute, Inc., Cary, NC, USA) using the maximum likelihood estimation method to eliminate the need for normality and equality of variances. The factors were the material and gap distance, with all interactions included in the statistical model. For this analysis, the repeated measure was gap distance, with the subject being the specimen of each material.

Part 2: Distortion from CAD model

The total deviation in three directions were analyzed by a repeated measures analysis of variance (MIXED procedure, SAS (r) Proprietary Software 9.3, SAS Institute, Inc., Cary,
NC, USA) using the maximum likelihood estimation method to eliminate the need for normality and equality of variances. The factors were the material, the point, and the direction, with all interactions included in the statistical model. For this analysis, the repeated measures were both the point and the direction, with the subject being the specimen of each material.
Chapter 3: Results

Part1: 3D gap measurements

Results showed that the material type (zirconia or titanium) was not significant for 3D gap measurements ($p=.9038$). The difference in 3D micro gap values between implant-fixed CAD/CAM-fabricated zirconia and titanium CDP frameworks was not shown to be significant. However, 3D gap measurement values were significantly different between Gap 3 and Gap 4 within each group ($P=.0003$). The mean 3D gap measurement for Gap 2 for titanium was 48.2 µm (SD 2.6). The mean 3D gap measurement for Gap 3 for titanium was 74.0 µm (SD 15.0) and 84.4 µm (SD 12) for zirconia. The mean 3D gap measurement for Gap 4 for titanium was 102 µm (SD 26.7) and 93.8 (SD 30) for zirconia. All 3D gap measurements showed values <135 µm.
Figure 40: Mean 3D gap measurements with standard deviations
Table 1: Mean 3D Gap Measurement (numerical values in microns)

According to the two-way ANOVA, the effect of material type (zirconia and titanium) was not significant on 3D marginal gap (p=.9038), and the 3D gap measurements were significant only within groups (P=.0003). There was a significant difference of the 3D micro gap values between Gap 3 and 4 with in each group.

Table 2: ANOVA summary for the 3D gap measurements
Table 3: Post hoc analysis for the 3D gap measurement

**Part 2: Distortion from CAD model**

According to the three-way ANOVA, both materials exhibited distortion from the CAD model; however, there was no significant difference in the amount of distortion between the materials from the CAD model ($p = .7475$).
Figure 41: Deviations from the CAD model in the x direction, with standard deviations
Figure 42: Deviations from the CAD model in the y direction, with standard deviations
Figure 43: Deviations from the CAD model in the z direction, with standard deviations
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<tr>
<th>Effect</th>
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Table 4: ANOVA summary for distortions from CAD model
Chapter 4: Discussion

The first null hypothesis that there would be no difference in 3D micro gap values between zirconia and titanium CAD/CAM CDP frameworks was accepted. The second null hypothesis that a potential distortion of zirconia and titanium frameworks would be similar during fabrication through a CAD reference model was also accepted.

The results of this study are in agreement with previous investigations that absolute passive fit of fixed dental prosthesis does not yet exist.\textsuperscript{17,33,55} The dental literature presents extensive information regarding fit of implant frameworks; however, there has been no agreement on a specified number to be considered acceptable. Generally, misfits ranging from 10 to 150 microns may be considered to be within the clinically acceptable range.\textsuperscript{5,16}

There are substantial differences in the fabrication methods for both titanium and zirconia frameworks. Zirconia frameworks are usually milled in the pre-sintered form, in which the CAD software has to calculate for the anticipated shrinkage by milling an oversized restoration that will then shrink precisely to the desired dimensions. During the sintering process, volume changes result from the relocation of the material via bulk diffusion, surface diffusion or gas phase transport.\textsuperscript{56,57,58,59} The success of this numerical compensation depends on the composition and homogeneity of the pre-sintered zirconia blanks.\textsuperscript{47} In addition, different design of the sintering foot and the supporting pins have been reported to influence the sintering shrinkage and the overall accuracy.
Machinability is defined as the relative ease to cut or grind a material. Titanium is considered to be a difficult material to machine due to its inherent physical properties such as high strength, low modulus of elasticity and low thermal conductivity. Controlling the distortion of the titanium frameworks involves the engineering principle of “machining-induced distortion”. Titanium is usually milled under high speed and high cutting force, which can cause deformation of the milling unit, the titanium block and milling burs. In addition, frictional heat generated during the milling procedure and the low heat dissipation of titanium can cause expansion of the titanium block and the milling burs which in turn can cause distortion. Moreover, the milling burs are subjected to corrosion during this milling procedure, which can affect the surface of the specimen. All those factors are not encountered when machining pre-sintered zirconia blanks.

The direct comparison of results from this study to previous publications in regards to gap measurement is difficult since there is a lack of standardization on the definition of passive fit and the measurement methods used. Some authors used the “final fit”, with all screws tightened, for their measurements. The majority of those studies found that when all the retaining screws were fully tightened the vertical gaps were eliminated even for gaps ranging from 30 to 500 µm. Some authors suggested that the machining tolerance could help minimize the final distortion. Passive fit could occur if the machining tolerance was more than or equal to the final distortion.

The in vitro methods for the quantitative assessment of the marginal gap reported differed in various studies. A microscope was used in several studies for the direct measurement of the interface; however, this method is efficient in detecting distortion in
two dimensions and is only able to measure the vertical gap. Since distortion can occur in three dimensions this method may be not sufficient. Other studies measured the gap distances indirectly by the use of sectioned impression materials that were injected between the implant and framework interface. This technique is prone to inconsistencies due to manual discrepancies and errors.

Advances and improvements in CT scanning have led to their extensive use in the industry. Some of the major uses for CT scanning have been in the non-destructive testing of components such as flaw detection, failure analysis, metrology and reverse engineering. In this study, a highly accurate industrial CT scanner was used to scan the completed restoration and measure the 3D distortion of the framework when compared to the CAD model; at the same time 3D micro gap values were obtained with the aid of the one-screw test. This method allows for measurement of distortion that occurs similarly to the clinical and laboratory conditions. The provided software mathematically calculated values in all planes and dimensions. Using an industrial CT scanner has the advantage over optical scanners (laser and photogrammetric scanners) that no spray coating is necessary to facilitate digitization of the frameworks. The spray coating thickness can range from 5 to 15 micron that, in turn, may cause inaccuracy of the framework dimension. In addition, optical scanners are not able to penetrate the framework to digitize the internal surface of the framework (for example, abutment / implant interface).

Several studies have used a coordinate-measuring machine (CMM) to determine the distortion of implant-supported frameworks. The CMM consists of a probe, which can be positioned to measure the framework dimensions in three dimensions. However, these
CMM acquire limited points from the surface of the sample to be tested. In addition, the tip of the tactile probe has a certain diameter that will make areas smaller than the tip not accessible for measurement.\textsuperscript{13}

A limitation of this study was that the accuracy of the industrial CT scanner that depends on the size and density of the material to be scanned. The final accuracy of the data set is called measurement uncertainty and can be determined for this particular industrial CT scanner using the formula $(11 + 30L)$ microns, where L equals length, measured in meters. The length is determined from the size of the part being measured. In this case, the frameworks were about 53 mm across at their largest length (about 0.053 meters). From the above formula, $11 + 30 (0.053)$ equals 12.59 microns; hence, 12.59 microns is the measurement uncertainty across the surface the framework. The measurements in this study were in much smaller dimensions (less than 1 mm) so we would estimate $11+30 (0.001)$ or 11.3 microns for the final measurement uncertainty. Measurement uncertainty also considers factors beyond the accuracy of the equipment being used, such as repeatability, environmental factors and accuracy of the equipment, which was used to calibrate the CT scanner.

Another possible limitation of this study was that dental scanners use point clouds while industrial CT scanners use voxels to acquire the surface data from a specimen. In order to transfer the acquired data from the dental and industrial CT scanners into the inspection software for comparison, a 3D CAD model has to be generated in the form of a standard tessellation language (STL) file. During the generation of STL datasets from both methods (point clouds, voxel), the accuracy of measurements might have been affected. The focus
of this study was on the fit and distortion of frameworks that started with the CAD procedure and ended with the CAM in milling. All frameworks were fabricated on the same master model to minimize manual errors. The application of the clinical situation to the master model could have affected the overall misfit values.
Chapter 5: Conclusion

Within the limitations of this in vitro study, implant-fixed CAD/CAM-fabricated titanium and zirconia complete dental prosthesis frameworks showed comparable marginal fit. 3D micro gap measurements of frameworks showed clinically acceptable misfit values. In addition, zirconia and titanium frameworks showed similar 3D distortion when compared to the CAD model. Absolute passive fit was not achieved.
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