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Effect of Internal Design Modification on the Mechanical Properties of Laser Sintered Cobalt-Chromium Multi-Unit Metal-Ceramic Frameworks

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Keywords
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Abstract

Purpose: The purpose of the study was to assess the effect of internal design modifications on the mechanical properties of multi-unit Cobalt-Chromium (Co-Cr) metal-ceramic frameworks manufactured by direct metal laser sintering.
Material and methods: Four-unit fixed partial denture metal-ceramic frameworks were digitally designed on a metal die model using 3D software. A total of 30 specimens were prepared using Co-Cr alloy powder with direct metal laser sintering ($n = 10$). The control group specimens were solid where the inside of the specimens was completely full. For the test groups, the internal design of the framework was modified. Leaving the outer shell thickness of the framework at 0.5 mm, two different internal designs with hollow geometries were created (1.5 mm and 2 mm inner bar distances) and a cross section area of the connector was calculated. The weights of the specimens were measured and subjected to a 3-point-bending test at 1 mm/min crosshead speed. Data were statistically analyzed using One-way ANOVA followed by Tukey ($\alpha = 0.05$).
Results: There was a statistically significant difference among the groups in terms of weight of the specimens ($p \leq 0.05$). However, no significant difference was observed among groups in term of both flexural strength and flexural modulus ($p \leq 0.05$).
Conclusions: Within the limitations of the study, it was concluded that changing the internal design of the metal frameworks decreases the weight of the framework, but does not affect the flexural strength and flexural modulus. Therefore, clinical applications of internally modified frameworks seem promising for metal-ceramic restorations.

Metal-ceramic restorations combine the esthetics of ceramics with the strength and durability of metals. Cobalt-Chromium (Co-Cr) alloys are commonly used for manufacturing the metal framework of fixed partial dentures due to their superior mechanical properties, high bond strength with ceramics, high price of noble alloys and improved manufacturing and handling capabilities.[1–3] Although, the conventional casting technique has been used to produce Co-Cr frameworks for decades, it has been widely replaced by rapid production techniques.[4]

Direct metal laser sintering (DMLS) is a rapid production technology for producing metal-ceramic frameworks. This technology enables the sintering of alloy powder with laser energy layer by layer to create final metal parts.[5,6] Production through DMLS yields results superior to conventional casting methods in terms of mechanical properties, clinical marginal fit, and axial wall adaptation.[7] Moreover, this new technology has been found successful for bond strength between metal and ceramic materials, biocompatibility, and corrosion resistance.[8–14]

Another advantage of the technology is that it allows production of final objects with almost unlimited designs. DMLS devices can manufacture all details in the computer-aided design (CAD) data, such as undercuts, voids, and complex internal geometries.[5–7] Lattice structures can be fabricated within the closed-hollow geometries. With this hollow design, not only can lighter objects be fabricated, but also the production time and the amount of powder used can be considerably reduced, and productivity can be increased dramatically.[15] However, there is very limited data in the literature on how internal design changes affect mechanical properties such as tensile strength, flexural strength, and elastic modulus, etc. Ekren et al[15] evaluated mechanical properties of internally modified Cobalt-Chromium specimens produced by DMLS. The group reported that by changing the

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Table 1 Device specifications that were used for manufacturing the current specimens

Device	Energy used (W)	Scan speed (m/sec)	Production speed (m^3/sec)	Spot laser diameter (μm)	Layer thickness (μm)
EOSint M270	195	7	20	100-500	20

internal design, a considerable amount of alloy powder could be saved, manufacturing time can be significantly reduced, and most importantly, the altered internal design still satisfies the mechanical properties criteria for ISO Type 5 materials (tensile strength: >500 MPa; percent elongation: >2%; elastic modulus: >150 GPa).[16] However, the group used a tensile test with dumb-bell shape test specimens. For simulating clinical practice, a flexural strength test with a metal-ceramic framework design is needed because bending properties have been more clinically relevant to test than pure tension.[6,17–20]

Therefore, this study aimed to evaluate the effect of internal design changes on the weight, flexural strength, and flexural modulus of laser-sintered Cobalt-Chromium metal-ceramic frameworks fabricated with DMLS. The null hypothesis is that the internal design modification does not affect the weight, flexural strength, and flexural modulus of the specimens.

Materials and methods

For determination of the sample per group, a power analysis was performed (effect size 0.6, $\alpha = 0.05$, power = 0.8, number of groups 3, minimum total sample size 30). The Control group (CG) and two test groups, TG-1.5 (1.5 mm inner bar distance) and TG-2.0 (2 mm inner bar distance), were designed in the study (n = 10).

An acrylic jaw (Ivoclar Vivadent, Schaan, Lichtenstein) representing a partially dentate right posterior side of the mandible with 2 abutments, first premolar and second molar teeth, was duplicated with dental stone (Fujirock EP, GC Europe, Leuven, Belgium) by using polyvinyl siloxane type-A impression material (Elite HD, Zhermack S.p.A, Plinesine, Italy). The metal master model was fabricated by traditional casting. The master model was scanned using a scanner (7series; Dentalwings Inc, Montreal, Canada). The scan data were transferred to a design software program (CAD Solidworks Premium; Dassault Systèmes Solidworks Corp, Waltham, MA) and a metal-ceramic framework (the programmed cement space: 100 μm; retainer coping thickness: 0.5 mm; connector area: 12 mm^2[22]) was designed.

The connector area and pontic of the framework in control group specimens were completely solid. For the test groups, the internal design of the connector area and pontic of the specimens were modified. Leaving the outer shell 0.5 mm thick, a lattice pattern was created inside the connector and the pontic of the framework (Fig 1). Two different distances (1.5 mm and 2 mm) were created between the bars creating the lattice. The diameter of the bars was 0.5 mm and the angle between the bars was 45°. The mid-cross-section area of the connectors of the framework where the fracture is to be expected was calculated with software for test groups (TG1.5 = 7 mm^2, TG2 = 6.8mm^2) (Geomagic, Geomagic Inc, Waltham, MA) (Fig 2).

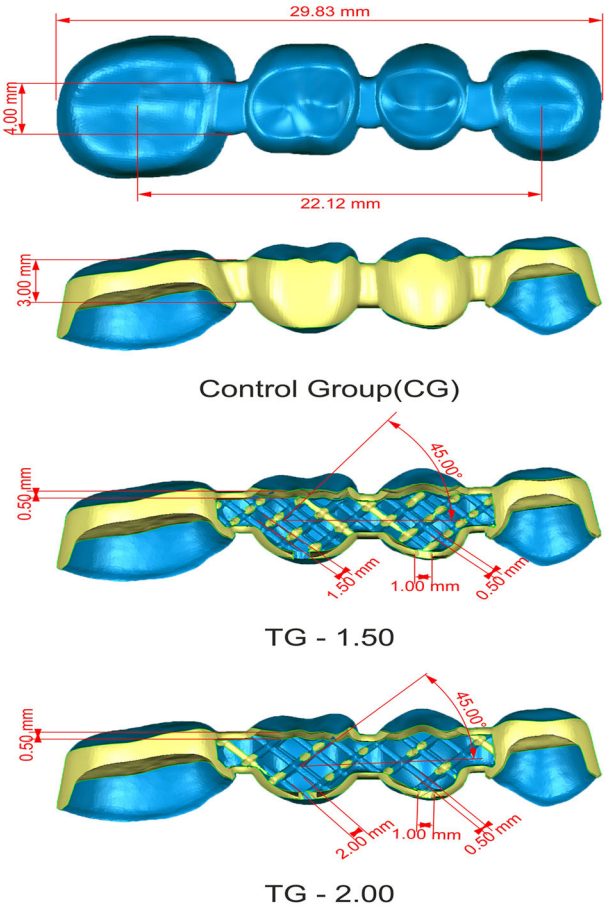


Figure 1 Metal-ceramic framework design.

Table 2 The study design

Group	Angles between internal bars (degrees)	Distance between internal bars (mm)
CG	-	-
TG-1.5	45	1.5
TG-2.0	45	2.0

CG = Control group; TG = Test group.

Finally, a total of 30 specimens were fabricated by DMLS device (EOSINT M270; EOS GmbH, Krailling, Germany), using Co-Cr alloy powder with a percent composition of Co 63.9, Cr 24.7, W 5.4, Mo 5.0, Si1.0 (Bego Mediloy S-Co, Bego GmbH, Bremen, Germany). The specifications of the DMLS device are presented in Table 1 and the study design is presented in Table 2.

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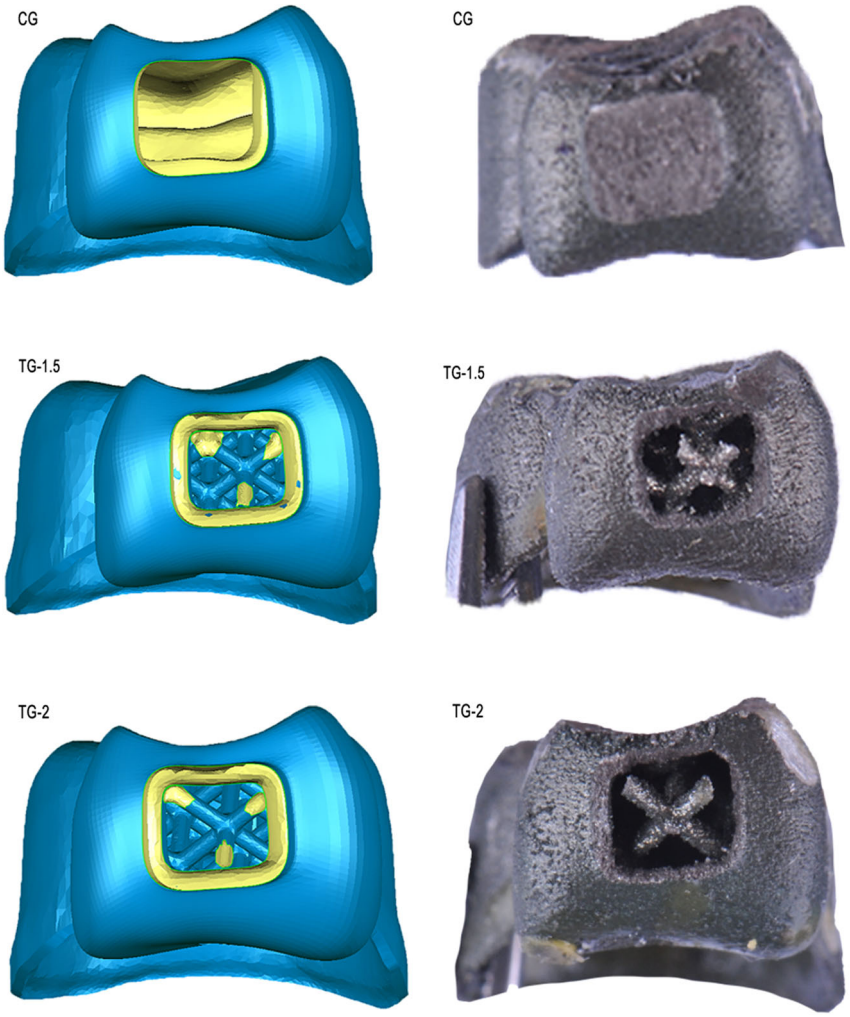


Figure 2 Cross-section view of CG, TG-1.5, and TG-2.

Before initiating the flexural strength test, all specimens were weighed individually with an electronic weighing device (Electronic Balance Type AX120, Shimadzu Corp, Kyoto, Japan) and weights were noted. A randomization chart was prepared using a free internet program (Research Randomizer, Version 4.0) to determine the test sequence.[21]

The specimens were subjected to a 3-point bending (3PB) test using a universal testing device (AT-M500 25kN; Testometric Co Ltd, Rochdale, Lancashire, UK) with a load cell of 2500 kg force (Testometric, type 2500 kg, Ser no 19023, Rochdale, England). All specimens were loaded with a stainless-steel rod-like indenter along the connector area between the 2nd premolar and 1st molar with a 1 mm/min crosshead speed (Fig 3). The flexural strength and elastic modulus were calculated according to following formulas.[20,22] $s = 3PL/2wh^2$ for flexural strength and $E_{flex} = L^3 P/ 4wh^3d$ for flexural modulus where

where σ is the flexural strength (MPa), L is the distance between the supports (mm), w is the width of the connector (mm), h is the thickness of the connector (mm), d is the deflection due to the load applied at the middle of the beam (mm), and P is the peak load at the point of fracture (N).

One-way ANOVA followed by Tukey test was used for statistical analysis ($\alpha = 0.05$) using a statistical software (IBM SPSS Statistics v21.0; IBM Corp, Armonk, NY).

Results

The mean (±SD) bar weight, flexural strength, and flexural modulus of the groups are presented in Table 3. There was a statistically significant difference between the control group and the test groups in terms of weight ($p < 0.001$). No significant difference was observed between test and control groups in terms of flexural strength ($P_{CG-TG1.5} = 0.998$, $P_{CG-TG2} = 0.548$, $P_{TG1.5-TG2} = 0.589$) and flexural modulus ($P_{CG-TG1.5} = 0.542$, $P_{CG-TG2} = 0.750$, $P_{TG1.5-TG2} = 0.938$).

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Table 3 Respective means (±SD)

Group	Weight (mg)	Flexural strength (MPa)	Flexural modulus (GPa)
CG	6327 ±18.5^{A}	4311 ±324.2^{A}	218 ±23^{A}
TG-1.5	4858 ±82.5^{B}	4298 ±618.6^{A}	235 ±48^{A}
TG-2.0	4668 ±86.7^{C}	4096 ±366.2^{A}	230 ±29^{A}

Different uppercase letters indicate statistically significant differences ($p \leq 0.05$).
CG = Control group; TG = Test group.

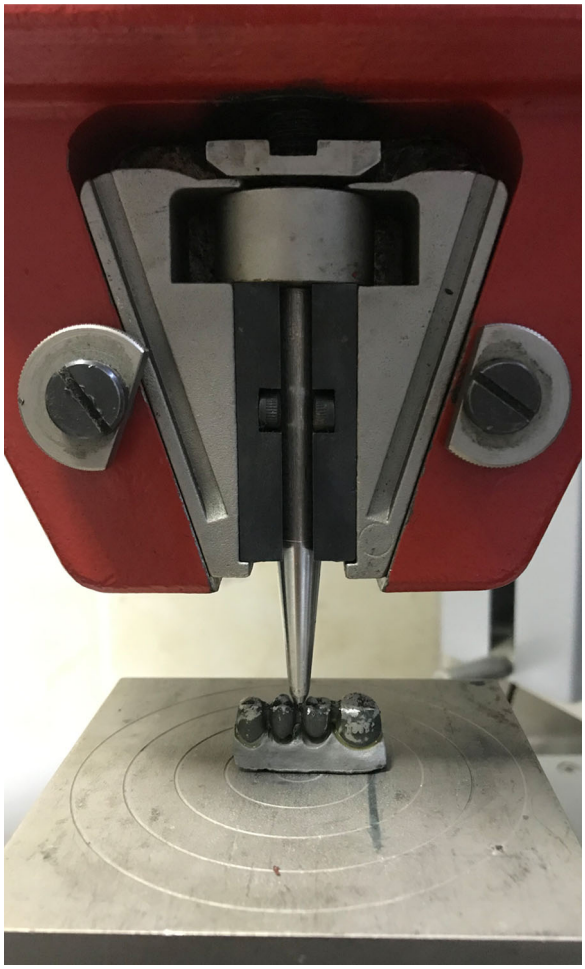


Figure 3 Three point bending test assembly.

Discussion

The results of the study showed that, although a significant decrease was observed with internal design modifications between the weight of control and test groups, no significant differences were observed in the flexural modulus or flexural strength. Thus, the null hypothesis was rejected for weight parameter, but not rejected for flexural modulus and flexural strength.

To investigate the mechanical properties of metal-ceramic frameworks, dumbbell-shape tensile test specimens have been used in the literature.[4,12,13] However, some researchers preferred using a flexural strength test rather than a pure tensile test due to the clinical relevancy.[6,18,19] Bae et al[14] investigated the bond and the fracture strength of metal-ceramic restorations formed by selective laser sintering and reported 1087 MPa of flexural strength. Kaleli et al[6] evaluated the effect of layer thickness on the flexural strength of multiple unit laser-sintered metal frameworks. The group claimed that layer thickness did not affect the flexural strength and reported 1188 MPa for 20 μ, 1050 MPa for 30 μ, and 1019 MPa for 40 μ layer thickness. The flexural strength of the control group in the current study (4311 MPa) was higher than in previous studies. This can be attributed to the differences in the study designs. Bae et al used bar shaped specimens to calculate fracture strength. Kaleli et al, on the contrary, used metal-ceramic frameworks to calculate flexural strength but with different connector dimensions (9 mm^2) than the current study (12 mm^2). Low flexural resistance may cause fractures or chipping in the porcelain layer of the metal-supported porcelain restorations. In general, high flexural strength is preferred in metal-ceramic restorations.[12] In the current study, no statistically significant results were obtained between the flexural strength of the control and the test groups. The results of the current study contradict the results of a previous study.[15] Ekren et al published an article on how the internal design changes affect the mechanical properties of Cobalt-Chromium specimens.[15] The authors reported that changing the internal design of the laser-sintered specimens negatively affected the flexural strength of the specimens. One limitation of the Ekren et al study is that the authors failed to calculate the actual cross section area of the internally modified specimens and inevitably reported lower flexural strength values compared to control group. In the current study, by using a dedicated software, the actual cross-section area of the internally modified test specimens was determined and used for calculating flexural strength and flexural modulus of the specimens.

The flexural modulus should be high in metal-ceramic alloys. The resistance of the metal alloy to bending eliminates alloy-related fractures in the porcelain layer.[15] The results of the current study are highly important to show that the flexural modulus of the frameworks can be maintained even if the internal design is modified (CG: 218 GPa, TG1.5: 235 GPa and TG2: 230 GPa).

The specimens were designed by adhering to their dental morphology. In studies where mechanical properties are evaluated with metal frameworks, connector sizes are different from each other.[6,18,19] Although there is no consensus about minimum connector size for fixed partial dentures, it is well known that connector size must be increased as the length or

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the pontic number increases.[20] In the current study, a four-unit metal-ceramic framework with 2 pontics was designed with a connector size of cross-sectional area 12 mm^2. The authors are aware of the fact that differences in connector size result in different mechanical test results.

A statistically significant difference was observed between the control and test groups regarding the mean weight. The decrease in weight also indicates a decrease in the amount of powder used. The study results regarding weight are in accordance with the study of Ekren et al.[15] Saving the amount of powder used in the production process will also contribute to the productivity of DMLS. The time needed for fabricating an internally modified framework with DMLS will be much shorter than a non-modified framework because the sum of the cross-sectional area of layers that need to be scanned will be lesser.[15] So, the production time and the amount of the alloy powder to be used can be decreased considerably.

Limitations of the study include that the actual production time per specimen could not be calculated individually due to dental laboratory regulations. Therefore, statistical data cannot be presented regarding the production time. Future clinical studies are needed to evaluate the clinical performance of the metal-ceramic restorations with internally modified frameworks.

Conclusions

Within the limitations of the current study, it was concluded that modification in the internal design of the metal-ceramic framework decreases the weight but has no effect on the flexural strength and the flexural modulus. Clinical studies are needed for long-term prognosis of internally modified metal-ceramic frameworks.

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Conflict of interest

The authors of the study declare no conflict of interest.

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