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RESEARCH AND EDUCATION

Evaluation of strain distribution on an edentulous mandible generated by cobalt-chromium metal alloy fixed complete dentures fabricated with different techniques: An in vitro study

Simge Taşın, DDS,[a] Işıl Turp, DDS, PhD,[b] Ergün Bozdağ, PhD,[c] Emin Sünbüloğlu, PhD,[d] and Aslıhan Üşümez, DDS, PhD[e]

ABSTRACT

Statement of problem. Fixed complete dentures (FCDs) have been used in the treatment of completely edentulous patients for over 40 years. However, few reports have investigated misfit values and strain distribution in the context of FCDs fabricated with new technologies.

Purpose. The purpose of this in vitro study was to evaluate misfit values and strain distribution in FCDs and their relation to the fabrication technique of the cobalt-chromium (Co-Cr) metal framework.

Material and methods. Four implants were placed in the interforaminal region of a mandibular cast at the bone level. The Co-Cr metal alloy frameworks were fabricated using the following techniques: computer-aided design and computer-aided manufacturing (CAD-CAM), milling from hard blocks, CAD-CAM milling from soft blocks, and direct metal laser sintering (DMLS). The superstructures of equal sizes with acrylic resin bases and acrylic resin denture teeth were fabricated on the Co-Cr metal alloy framework, and a digital microscope was then used to measure the misfit between the abutments and the implants. The stress formed after the application of torque was measured with a strain-gauge stress analysis technique. Data were statistically analyzed using 1-way ANOVA and the Tukey Honestly Significant Difference test (α=.05). The correlation between the misfit and the strain values was evaluated with the Pearson Correlation test (α=.001).

Results. The lowest mean misfit values (99 ±17 µm) were observed in the hard block group (P<.05) and the highest in the DMLS group (139 ±29 µm). A statistically significant positive relationship was found between the misfit and the stress distribution after torque application (P<.05). Moreover, the lowest misfit group, hard blocks, had the lowest mean strain values (81.1 ±54 MPa) after torque application.

Conclusions. Within the limitations of this in vitro study, the fabrication technique used for Co-Cr metal alloy frameworks appears to influence the passive fit significantly (P<.05). The hard-block technique was found to be the most precise fabrication technique for Co-Cr metal alloy frameworks. A significant relationship was observed between the amount/distribution of misfit and the strain on the FCD (P<.05). (J Prosthet Dent 2019;122:47-53)

Osseointegrated implants have been used successfully to restore function and esthetics for patients with partial or total edentulism.[1] The mechanical stress that occurs around the implant surrounding the bone is an important biomechanical factor that affects the long-term clinical success of osseointegration.[2] A perfect fit between the prosthetic framework and the implant can eliminate the stresses formed on the bone-implant interface by a nonpassive prosthesis.[3-7]

Prostheses lacking passivity do not align with prosthetic abutments with sufficient precision, which results in a gap between the prosthesis framework and the abutment interface.[8-15] This gap can overload the system components because of decreased rigidity in the connection and

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[a]Assistant Professor, Department of Prosthodontics, Faculty of Dentistry, Istanbul Okan University, Istanbul, Turkey.
[b]Assistant Professor, Department of Prosthodontics, Faculty of Dentistry, Bezmialem Vakif University, Istanbul, Turkey.
[c]Lecturer, Department of Mechanical Engineering, Istanbul Technical University, Istanbul, Turkey.
[d]Associate Professor, Department of Mechanical Engineering, Istanbul Technical University, Istanbul, Turkey.
[e]Professor, Dentalplus Implant Clinics, Istanbul, Turkey.

Clinical Implications

To avoid stress at the bone-implant interface and maintain osseointegration, a restoration must have perfect fit. CAD-CAM milling from a hard block is suggested as the most precise technique for fabricating cobalt-chromium metal alloy frameworks.

an uneven distribution of loads.[16-22] Moreover, it may lead to fracture of the components, retaining screws, and cause microfractures in cancellous bone.[23]

Attempts have been made to provide criteria for the passive fit or acceptable fit of implant frameworks. Jemt[3] suggested that framework misfits of less than 150 μm are acceptable. However, a satisfactory biomechanical definition of a passive fit[4,24] and the relationship between the degree of fit and mechanical or biologic complications has yet to be determined.[25] Based on this, conventional crown and fixed partial prosthesis techniques can provide long-term success in implant treatment.[22,26]

The achievement of a passive fit framework is often limited by conventional lost wax casting (LWC) techniques.[27] Fabrication of frameworks by conventional techniques has further disadvantages such as overly complex procedures and prolonged processing times. Using computer-aided design and computer-aided manufacturing (CAD-CAM) systems for fabricating metal frameworks has overcome some of the disadvantages of the LWC technique.[28-36]

When dental fabrication is performed through computer-aided milling, rotary instruments and block-shaped materials are used.[37] This is an effective technique for fabricating the restoration and offers many choices of materials. Recently, a new technique that involves milling a soft metal block has been introduced for the manufacture of metal frameworks.[38,39] The soft block is easier to mill because its final mechanical properties, which adversely affect grinding, are reached only after sintering. The soft nature of the material also reduces the grinding time and eliminates the need for water-cooling during milling,[40] which reduces the risk of contamination.[41] Most of the current dental CAD-CAM systems use subtractive techniques, which are considered wasteful because 90% of the starting material is discarded when a prosthesis is manufactured.[42]

Alternative additive techniques involve CAM machines that use a rapid prototyping technology.[37] Direct metal laser sintering (DMLS) fabricates restorations by building up layers of solidified metal through selective laser melting of powdered material according to 3D data (model) received from CAD.[39,43-45] This additive technique has drawn attention owing to its ability to

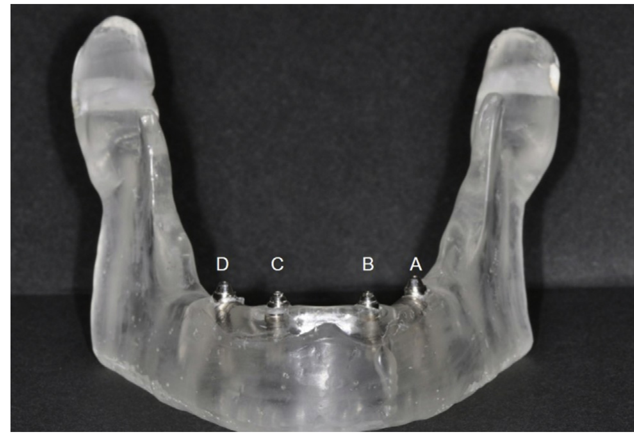

Figure 1. Edentulous mandibular cast from epoxy resin and designation of implants as A, B, C, and D.

prevent the distortion and fabrication defects associated with LWC techniques.[46]

The purpose of the present investigation was to evaluate the passivity and stress distribution in fixed complete dentures (FCDs) and around the supporting dental implants in relation to the metal substructure fabrication technique. CAD-CAM milling from hard blocks, CAD-CAM milling from soft blocks, and DMLS techniques were used. The first null hypothesis was that no difference would be found among the 3 techniques in the misfit values and strain development of fabricated FCDs and around the dental implants on the mandibular cast. The second null hypothesis was that strain development on the FCD and around the dental implants would not be influenced by the level of misfit.

MATERIAL AND METHODS

An edentulous mandibular cast was fabricated from an epoxy resin material (Epa-100; Epakem Inc). Two anterior implants (TLXP4610; BioHorizons Inc) were placed parallel to each other in axis orientation on the interforaminal region of the cast, and 2 posterior implants (TLXP4615; BioHorizons Inc) were placed at a 30-degree distal incline at the bone level. Using abutment fixation screws, straight abutments (PBMU2; BioHorizons Inc) were fixed to the anterior implants, and 30-degree angled abutments (PGMU304; BioHorizons Inc) were fixed to the posterior implants. The implants were designated as A, B, C, and D starting from the left side of the mandible (Fig. 1). The distance between implants A and B and that between implants C and D were both 15 mm, and the distance between implants B and C was 14 mm.

The mandibular cast was scanned by using a 3D laser scanner (7 Series; Dental Wings Inc), and the resulting digital image was transferred to a computer. The FCD framework was designed by an experienced user of the system software (DWOS software; Dental Wings Inc)

Figure 2. Frameworks as received: A, Hard block, B, Soft block. C, DMLS. DMLS, direct metal laser sintering.

and included bar-shaped I-beams with a cross-sectional diameter of 3.5 mm. No distal extension was designed, and the configuration of the bars was parallel to the hinge axis. The 2.2-mm-high cylindrical extensions were also designed on the bars to retain the acrylic resin components of the prosthesis (Fig. 2). The data relevant to the completed design were saved as a standard tessellation language (STL) file, which was later used in the milling or sintering CAM machines.

Two specimens were manufactured by using a milling machine (Yenadent D-43; Yenadent Inc). First, a hard metal cobalt-chromium (Co-Cr) alloy block (Magnum Lucens; Mesa Inc) was milled according to the existing design (Fig. 2A), and then the soft metal Co-Cr block (CopraBond K; Whitepeaks Dental Solutions GmbH) was similarly milled. The manufacturer had declared an estimated shrinkage of 10% during sintering, so the milling procedure was carried out with 10% magnification. The specimen was then sintered at 1280 °C for 5 hours under an argon atmosphere in a sintering oven (Calidia Sintec; Whitepeaks Dental Solutions GmbH), as suggested by the manufacturer (Fig. 2B).

The same CAD design was used with software adjustments for the DMLS technique. The design data were used for framework production with the Co-Cr alloy powder (EOS Cobalt Chrome SP2; EOS GmbH) in a laser sintering machine (EOSINT M270; EOS GmbH) with a 200 W Yb-fiber laser at a temperature of 1400 °C. The Co-Cr powder was applied to a stainless-steel plate and laser-sintered upward in subsequent layers, each of 20 μm in thickness, until the definitive product was generated (Fig. 2C). The outer surfaces of the frameworks were then airborne-particle abraded with 50-μm alumina (Korox 50; BEGO GmbH).

The framework manufactured from the hard block was screwed on the mandibular cast (PXMUPSL; BioHorizons Inc). The artificial teeth (Yamahachi; Yamahachi Dental Mfg Co) were arranged according to general principles.[47] A silicone mold of the tooth arrangement was used to standardize the FCD superstructure, which was fabricated by pouring autopolymerizing acrylic resin (Vertex Castavaria; Vertex Dental BV Asia Pte Ltd) into the mold after the insertion of the artificial teeth. The superstructure was then polished (Fig. 3).

Figure 3. Fixed complete denture.

The mandibular cast was mounted by modifying the epoxy resin in the condyle region into a modified nonarcon articulator (AVM 100M; Major Prodotti Dentari Spa) in a manner that allows the intercondylar distance to be adapted to the tested mandibular cast. To imitate the flexure of the mandibular cast under load, the bottom surface of both mandibular angles was connected to a Teflon cylinder designed to support the cast and mimic the function of masseter muscles (Fig. 4).

The vertical misfit was evaluated by using the single-screw test.[48,49] The vertical misfit between the implant shoulder and the abutment was measured on the nontightened side after the retaining screw on the posterior implant of the contralateral side was manually tightened[26] until the initial seating of the screw was felt.[48,49] The misfit between the abutments and the implants was photographed on the buccal and lingual sides of implants C and D when the abutment screw of implant A was tightened and on the buccal and lingual sides of implants A and B when the abutment screw of implant D was tightened, which totaled 8 images for each group. The misfit values were measured by using a digital microscope at ×50 magnification (USB Digital Microscope; Shenzhen Northvision Technologies Co Inc), and 1 μm of measurement accuracy and were analyzed by using analysis software (ImageJ 1.51k; National Institutes of Health). For each condition, the misfit was measured on 12 marked points around the implants: mesial, buccal,

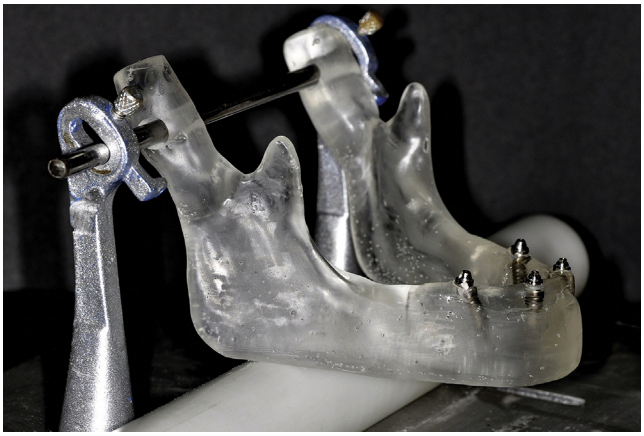

Figure 4. Teflon cylinder supporting mandibular angle to mimic masseter insertions.

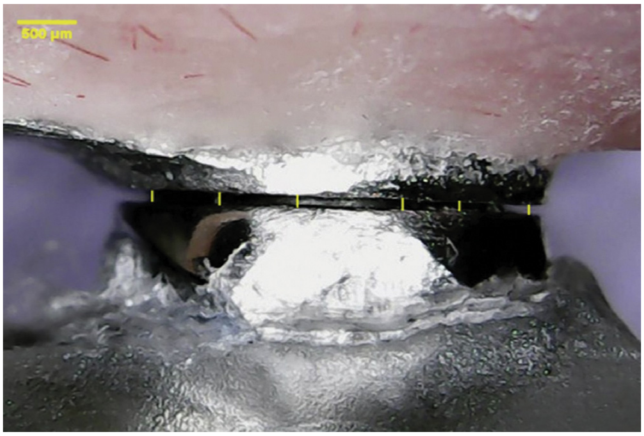

Figure 5. Digital microscope image for misfit measurement (original magnification ×50).

distal, and lingual (Fig. 5). A specific acrylic resin device was used to standardize the positioning of the mandibular cast under the digital microscope.

For the strain measurement, 3-element, 45-degree rectangular-stacked rosette strain gauges (C2A-XX-062WW-350 Vishay Micro-Measurements; Vishay Precision Group Inc) were bonded with a cyanoacrylate adhesive (M-Bond Adhesive; Vishay Precision Group Inc) 1 mm into the crestal region around each implant.[50,51] Three strain gauges were used on the mesial, buccal, and lingual aspects of each implant (Fig. 6A); they were named according to their placement and the nearest implant. Linear strain gauges (CEA-XX-062WW-350 Vishay Micro-Measurements; Vishay Precision Group Inc) were also placed on the intaglio surface of each prosthesis[52,53] (Fig. 6B), with the strain gauge foil oriented parallel to the long axis of the framework. The gauges were placed between the abutments and were labeled according to their locations. A quarter-bridge electrical circuit arrangement, provided by a multichannel and multipurpose universal data acquisition system (Model 8048; PROSIG Inc), was used to record the resistance change across the strain gauges in microvolts (µV). These values were subsequently converted into microstrains (µS).

The FCDs were seated onto the adapted articulator mandibular cast, and the screws were tightened to 15 Ncm by using a prosthetic screwdriver (IA-400; W&H Dentalwerk GmbH). The screws were secured in the following order: C, B, D, and A (B and C denote anterior implants, and A and D denote posterior implants) (Fig. 7).[54] All frameworks were placed by the same operator (S.T.). The strain gauge device was calibrated at ±10 µS before the specimens were seated onto the mandibular cast, and the screws were tightened. The readings were monitored during the tightening procedure for 1 minute, and the magnitude of strain at each strain gauge was recorded when the fourth screw was tightened. For every strain measurement, the reading was repeated 3 times, and the average value was calculated. Data on the 15 sensors were amplified and transferred by using a signal amplifier. For each framework, a new set of retaining screws was used.

All statistical analyses were performed using a statistics software program (SPSS v15.0 for Windows; SPSS Inc). The vertical misfit and strain development over the FCDs and around the implants were analyzed statistically through 1-way ANOVA (α=.05). The Tukey Honestly Significant Difference test was carried out for group comparison. The correlation between the misfit and the strain values was analyzed with the Pearson Correlation test.

RESULTS

The mean ±standard deviation values (MPa) of strain on the FCDs and around the implants, as well as the mean ±standard deviation values of the misfit (µm) for the tested groups (hard block, soft block, and DMLS), are listed in Table 1. Statistically significant differences were found in the misfit values among the groups (1-way ANOVA, df=2; F=74.156; P<.05). The highest mean misfit values (139 ±29 µm) were observed in the DMLS group, whereas the hard block group had the lowest values (99 ±17 µm). Moreover, 1-way ANOVA identified significant differences in strain values among the FCD groups (df=2; F=24.33; P<.05). The mean strain values were lowest for the hard block group (81.1 ±54 MPa), followed by those for the soft block group (235.13 ±97.4 MPa) and then the DMLS group (378.41 ±83.6 MPa). Statistically significant differences were found between the hard block and soft block groups in strain values generated around the implants (df=2; F=5.16; P<.05). The soft block group exhibited the highest strain values (636.76 ±342.51 MPa), whereas the hard block group exhibited the lowest strain values (374.8 ±222.68 MPa).

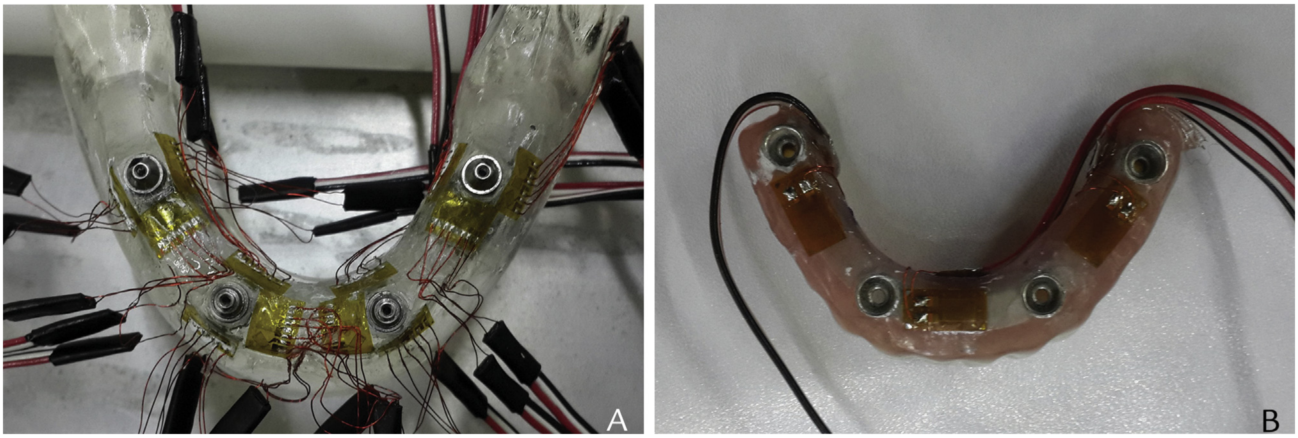

Figure 6. Location of strain gauges. A, Around each implant. B, On intaglio surface of each fixed complete denture.

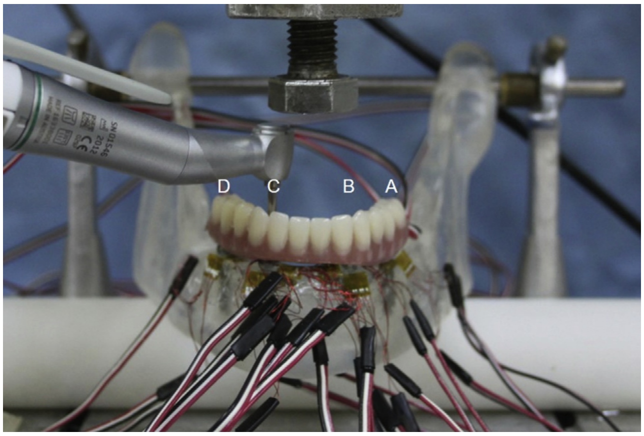

Figure 7. Experimental arrangement. Screws tightened in order C, B, D, A.

Table 1. Mean ±SD values (MPa) of strain on FCD and around implants and misfit (μm) for tested groups

Test Type	Hard Block	Soft Block	DMLS	*P*
Misfit (μm)	99 ±17^{a}	120 ±27^{b}	139 ±29^{c}	<.001
Strain on FCD (MPa)	81.1 ±54^{a}	235.13 ±97.4^{b}	378.41 ±83.6^{c}	<.001
Strain around implants (MPa)	374.8 ±222.68^{a}	636.76 ±342.51^{b}	547.9 ±424.25^{ab}	<.05

DMLS, direct metal laser sintering; FCD, fixed complete dentures; SD, standard deviation. Mean difference significant at *P*<.05. Different superscripted letters indicate statistical significance for horizontal comparisons.

Table 2. Pearson correlation test results

Test Type	*R*	*P*
Misfit-strain in FCD	0.525	<.005
Misfit-strain around implants	0.050	.606
Strain on FCD around implants	0.336	.087

FCD, fixed complete dentures; *R*, Pearson correlation coefficient. Mean difference significant at *P*<.05.

The results from the correlation tests performed between the misfit measurements were obtained through the single-screw test, and the strain measurements generated by the FCDs and supporting dental implants are presented in Table 2. A statistically significant positive relationship was found between misfit and strain on the FCDs (*R*=0.525). However, the Pearson Correlation test did not show any statistically significant correlation between misfit and strain around the implants (*R*=0.050). Moreover, no correlation was found between the strain values on the FCDs and the strain values around the implants (*R*=0.336).

DISCUSSION

This in vitro study compared the misfit and strain distribution values of FCDs made with frameworks fabricated from Co-Cr alloys through the hard block, soft block, or DMLS techniques. The first null hypothesis, which stated that the marginal misfit of a fabricated FCD would not be influenced by the manufacturing technique, was rejected; the second null hypothesis, which stated that the strain development of the FCDs and the surrounding implant would not be influenced by misfit values, was also rejected.

The misfit values were derived from the single-screw test.[26] When all the framework screws were tightened, the framework was subjected to deformation, which affected the accuracy of the marginal misfit measurement.[17] The single-screw test allowed for the measurement of the maximum misfit value.

Although the misfit of the metal frameworks produced by the cast and hard block techniques has been well documented, few studies have evaluated the misfit of Co-Cr metal frameworks produced through the DMLS[30,31] and soft block[38,39,41] techniques. In addition, little information is available on the misfit of the complete denture frameworks produced with the DMLS[32] and soft block[35] techniques. Also, the authors are unaware of a study that focused on the evaluation and comparison of misfit and stress distribution in multiple-unit implant frameworks fabricated using these 2 techniques. According to the results of the present study, the Co-Cr alloy metal framework produced by the CAD-CAM milling technique had better misfit values than the specimens produced by the DMLS technique in both metal types (hard block and soft block).

Paşali et al[35] compared the soft block technique with the LWC and hard block techniques in terms of the marginal fit of implant-supported metal-ceramic restorations and reported misfit values of 81 μm for the hard block group, 92 μm for the LWC group, and 99 μm for the soft block group. The hard block misfit values were significantly lower than those of the soft block group. These results are consistent with those of the present study in which the hard block group had the lowest mean misfit values (99 ±17 μm) with significantly different values from those of other techniques. Kim et al[41] reported the marginal misfit values of 4 fabrication techniques (LWC, hard block, selective laser melting, and soft block) and concluded that metal-ceramic restorations prepared using the soft block technique exhibit the lowest misfit values. Moreover, Park et al[36] evaluated the fit of metal-ceramic restorations fabricated using the LWC, hard block, and soft block techniques and reported that the hard block misfit values were significantly higher than those of the other groups. Kocaağaoğlu et al[38] reported that the soft block technique had the lowest misfit value for single-unit metal-ceramic restorations, followed by the hard block and DMLS techniques. A reason the results of the present study do not agree with those of this prior study is that the types of restoration and the measurement methods for the misfit differ.

The fabrication technique also affects the microgap values, probably because of the differences in surface roughness obtained by the different techniques.[8,12,13] The high surface roughness values in the specimens produced by DMLS and the necessary additional surface characterization of the specimens might explain the high misfit values generated.[34,39]

The probable reason this study found higher misfit values in the soft block specimens than in the hard block specimens is the milling procedure performed in the presintered stage. During the sintering process, the contraction of the presintered metal block is approximately 10%, producing a misfit if the amount of contraction is not calculated precisely.[35,36]

This study used the strain-gauge technique to measure the relationship between misfit and strain values. Tightening the FCDs to 15 Ncm (the value recommended by the manufacturer) produced strains in the structure. The lowest strain values were recorded in FCDs produced by the hard block technique, followed by those produced by soft block and DMLS. This relationship was linear and highly correlated; the strains increased with the increasing misfit of the FCDs. When the misfit increased, the FCDs were subjected to more deformation to close the misfit. This finding agrees with those of several other in vitro studies that assessed the implication of misfit and reported a positive relationship between the magnitude of the misfit and the induced strain.[7,16,17,19,22]

No correlation was observed between the misfit and strain around the implants. Similarly, no correlation was observed between the strain on the FCDs and around the implants. Strain gauges measure the elongation under the region in which they are glued. As this is a local surface-level measurement, they give information about these specific points only. This is a limitation that may reduce their reliability for assessing the total dimensional change on a mandibular cast.[15] In addition, this study only measured vertical misfit, whereas the strain and distortion are of a 3D nature.[5,6] This may have contributed to the lack of observable linearity between misfit and strain.

A limitation of this study is that the misfit and strain values were measured at only 1 prosthesis for each technique, which might not be representative of the technique's overall accuracy. Furthermore, a single type of metal alloy was used for each technique; different types of alloy systems might reveal different results. An increasing level of interest in digital dentistry and the search for optimal techniques and materials will improve the methods of measuring misfit.

CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn:

1. The fabrication technique of the Co-Cr metal alloy framework significantly affected the passive fit ($P<.05$).
2. The lowest mean misfit values were observed in the hard block group, followed by those of the soft block and the DMLS groups.
3. A statistically significant positive relationship was found between misfit and stress distribution on the complete dentures after torque application ($R=0.525$), with the lowest misfit group of the hard block having the lowest mean strain values.

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Corresponding author:
Dr Simge Taşın
Department of Prosthodontics
University of Istanbul Okan
Gülbahara Neighborhood, Oya Street
No:23/A, Şişli-Mecidiyeköy, Istanbul 34394
TURKEY
Email: simgetasin@gmail.com

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