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Evaluation of trueness and precision of removable partial denture metal frameworks manufactured with digital technology and different materials

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PURPOSE. The aim of this study is to evaluate the accuracy of removable partial denture (RPD) frameworks produced using different digital protocols. **MATERIALS AND METHODS.** 80 frameworks for RPDs were produced using CAD-CAM technology and divided into four groups of twenty (n = 20): Group 1, Titanium frameworks manufactured by digital metal laser sintering (DMLS); Group 2, Co-Cr frameworks manufactured by DMLS; Group 3, Polyamide PA12 castable resin manufactured by multi-jet fusion (MJF); and Group 4, Metal (Co-Cr) casting by using lost-wax technique. After the digital acquisition, eight specific areas were selected in order to measure the Δ-error value at the intaglio surface of RPD. The minimum value required for point sampling density (0.4 mm) was derived from the sensitivity analysis. The obtained Δ-error mean value was used for comparisons: 1. between different manufacturing processes; 2. between different manufacturing techniques in the same area of interest (AOI); and 3. between different AOI of the same group. **RESULTS.** The Δ-error mean value of each group ranged between -0.002 (Ti) and 0.041 (Co-Cr) mm. The Pearson's Chi-squared test revealed significant differences considering all groups paired two by two, except for group 3 and 4. The multiple comparison test documented a significant difference for each AOI among group 1, 3, and 4. The multiple comparison test showed significant differences among almost all different AOIs of each group. **CONCLUSION.** All Δ-mean error values of all digital protocols for manufacturing RPD frameworks optimally fit within the clinical tolerance limit of trueness and precision. [J Adv Prosthodont 2023;15:55-62]

KEYWORDS
Removable partial denture; CAD-CAM; Accuracy; Metrological measurements; Digital framework

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INTRODUCTION

In the last two decades, CAD-CAM technology became the gold standard in the manufacturing of metal frameworks for removable partial dentures (RPD), and a consistent number of studies confirmed the role of digital technology as a viable alternative to metal casting of RPD framework.[1-7] Nowadays, commercially available 3D dental modeling software comes with improved tools and different options to design RPD.[8] The use of an intraoral scanner (Trios; 3Shape, Erlangen, Germany) allows an accurate digital intraoral impression that reproduces both hard and soft tissues. The accuracy of the scanner has to be within a clinically acceptable range defined by literature; in particular, for the edentulous areas, the trueness varies between 54 to 180 mm and the precision ranges between 109 to 205 mm, as reported by Hayama *et al*..[9] However, analog impressions followed by the digitalization of the stone model remain a viable alternative to functionalize the RPD prosthetic borders.[10-13] Once the digital models are obtained, the path of insertion is determined and the design of RPD framework is laid out with the major connector, retention grids, clasps and rests. After completing the design of the RPD framework, the Standard Tessellation Language (STL) file is used for manufacturing process. Two main methods are possible: subtractive technologies (milling) or additive manufacturing (AM) protocols. The latter allows the following two different strategies: producing an intermediate product of castable resin which will be subsequently invested and casted; or, on the other hand, manufacturing the RPD framework directly from the digital design. In order to obtain the final product, several manufacturing technologies can be used: the direct metal laser sintering (DMLS), the selective laser melting (SLM), the fused deposition model (FDM), and the multi-jet fusion model (MJF).[14-17]

To evaluate the accuracy of produced RPD, the gold standard is the superimposition (best-fit) between the reference file (digital design) and the digitalized actual product (measuring points). The reported deviations are expressed in terms of trueness and precision (accuracy). In this study, due to the complex and small morphology of some components of the RPD (clasps, rests, retention grids), the superimposition approach was further improved by implementing a "local best-fit", meaning that the superimposition is applied to a limited portion of the RPD recognized as the most stable and, therefore, less prone to manufacturing deformations.

The aim of this study is to compare the accuracy, in terms of trueness and precision, of RPD frameworks produced using different digital protocols. The examined protocols are digital (DMLS with titanium and Co-Cr metal powder) and combined analog-digital (lost-wax casting technique, using calcinable PA12 polyamide resin manufactured by multi-jet fusion [MJF] instead of the RPD waxing). For the DMLS technology, the 3D EOSINT M280 DLMS-printer (EOS, Krailling, Germany) is used with Ti-6Al-4V grade 23 powder (group 1) and the Mediloy S-Co type 5 powder (group 2). For the MJF technology, the HP Multi Jet Fusion 4200 (HP Inc., Palo Alto, CA, USA) is used with the Polyamide HP 3D High Reusability PA12 powder (group 3). The polyamide frameworks are traditionally casted using the alloy Heraenium NF (Kulzer GmbH, Hanau, Germany). The null hypothesis is that no difference is found between the manufacturing techniques and that no difference is found between different areas of the RPD.

MATERIALS AND METHODS

80 frameworks for RPDs were produced and divided into four groups (n = 20): Group 1, Titanium frameworks manufactured by DMLS; Group 2, Co-Cr frameworks manufactured by DMLS; Group 3, Polyamide PA12 castable resin manufactured by MJF; and Group 4, Metal (Co-Cr) casting by using lost-wax technique. Frameworks of group 4 were casted using the polyamide framework of group 3, with the specific aim to investigate the accuracy of the intermediate resin frameworks, digitally manufactured, as a different term from the accuracy of the final casted product.

A model was randomly selected from the stone models' archive and then scanned with an intraoral scanner (Trio; 3-Shape, Erlngen, Germany) in order to first obtain a digital surface. Then, the framework components were designed using the manufacturing module for metal frameworks of a CAD-CAM software

(Exocad; Exocad GmbH, Darmstadt, Germany). All of the components were specifically designed to the extent of covering the widest possible variability of morphology: a lingual bar as the major connector, a Bonwill double clasp, an I-bar, a circumferential clasp, occlusal rests, and retention grids. The material used for Group 1 was the Ti-6Al-4V grade 23 powder for 3D EOSINT M280 DLMS-printer (EOS, Krailling, Germany); for Group 2, the Mediloy S-Co type 5 powder was used with the 3D EOSINT M270 DLMS-printer (EOS); for Group 3, the Polyamide HP 3D High Reusability PA12 powder was used with the HP Multi Jet Fusion 4200 (HP Inc., Palo Alto, CA, USA); for Group 4, the alloy Heraenium NF (Kulzer GmbH, Hanau, Germany) was used according to the conventional (analog) lost-wax technique.

All of the samples (n = 80) were scanned without any surface polishing, using a lab scan (Aurum 3D; Open Technologies, Bergamo, Italy) and the software OpticalRevEng (Open Technologies, Bergamo, Italy). The high density measuring points were exported in STL format for further analysis. Eight specific areas were selected for measuring the Δ-error value at the intaglio surface of RPD (Fig. 1): major connector (lingual bar) area; anterior rest of the circumferential clasp; retentive part of Bonwill double clasp; reciprocal part of Bonwill double clasp; I-bar; posterior rest of circumferential clasp; circumferential clasp (except rests); and interproximal rests of Bonwill double clasp. The reference file was then segmented so that only the areas of interest (AOI) were retained in the model. The comparison was made by superimposing the segmented file of the digital design (reference) to the STL-file of the digitalization of manufactured frameworks. Data were processed using GOM Inspect software (Handonmetrology, Zeiss group, Oberkochen, Germany). Since the lingual bar is the widest part of the RPD, the superimposition was applied, locally, solely to this area. A uniform point sampling is defined in each area. For each sampled point, the normal distance between the reference model and the actual intaglio surface was calculated.

The minimum necessary number of sample points was scientifically determined by the sensitivity analysis. This aimed to measure the mean deviation for each area and obtain a stable result that is not affected by the sample's density (i.e., over that minimum number of points, the result of Δ-error would be the same despite the density of points should be higher). Different sample point densities were considered from 3 to 0.3 mm considering a cut-off value of 15 µm.

RESULTS

The minimum necessary point sampling density, derived from the sensitivity analysis (Table 1), was 0.4 mm (i.e., the interdistance between two consecutive points) in all areas except lingual bar. Since the lingual bar is the widest among all the considered areas, in this case, the point sampling has been set to 0.9 mm.

Although all samples were manufactured starting from the same STL-file, from a statistical point of view, they were considered as independent and equally distributed. Three levels of analysis were calculated: a comparison between different manufac-

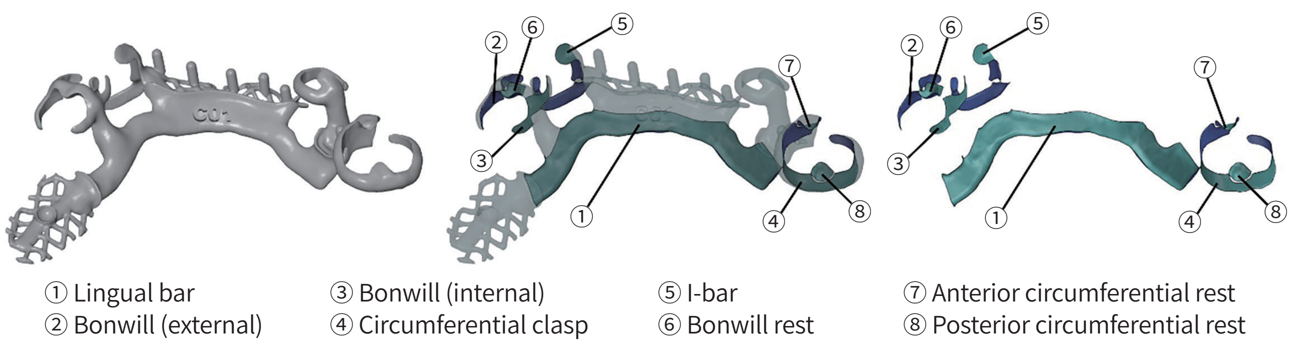

Fig. 1. Eight specific areas selected for measuring the Δ-error value at the intaglio surface of removable partial denture (RPD).

Table 1. Sensitivity analysis of Group 1 (Titanium DLMS): yellow highlighted the Δ-error values under the cut-off arbitrary value (< 15 μm)

Area/interdistance	3	2	1.5	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3
Rest_circ_ant	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.016	0.013	0.002	0.000
Bonwill ext.	0.025	0.011	0.011	0.011	0.011	0.007	0.005	0.004	0.004	0.003	0.000
I-bar	0.026	0.024	0.015	0.015	0.012	0.009	0.003	0.003	0.002	0.001	0.000
Post.rest-circumferential clasp		0.027	0.013	0.012	0.012	0.012	0.004	0.001	0.001	0.001	0.000
Circumferential clasp	0.027	0.026	0.020	0.020	0.016	0.012	0.006	0.002	0.001	0.000	
Lingual bar	0.009	0.009	0.004	0.004	0.000						
Bonwill ext	0.080	0.037	0.037	0.032	0.032	0.032	0.032	0.008	0.005	0.005	0.000
Bonwill int	0.014	0.008	0.008	0.008	0.007	0.006	0.006	0.005	0.005	0.005	0.000

Rest_circ_ant: Rest of anterior circumferential clasp, Bonwill ext.: retentive part of Bonwill double clasp, I-bar: I-bar clasp, Post. rest-circumferential: Posterior rest of circumferential clasp, Bonwill ext: occlusal rest of Bonwill double clasp, Bonwill int: mesial and eciprocal part of Bonwill double rclasp.

turing processes (Titanium DLMS, Co-Cr DLMS, MJF, casting) (Level 1); a Δ-error mean value comparison between different manufacturing techniques in the same area of interest (AOI) (Level 2); and a comparison between the Δ-error mean value of different AOI in the same group (Level 3).

Level 1 analysis: comparison between groups

Considering all measurements (absolute values) (Table 2), Kruskal-Wallis test was significant ($P < .001$), meaning that at least one group presents a significantly different shift in the distribution of the absolute Δ-error. To evaluate the significant difference between paired groups, the post-hoc test using the asymptotic Dwass, Steel, Critchlow-Fligner non-parametric test showed a statistically significant difference between Group 1 and 2; both of the groups exhibited a significant difference from Group 3 and Group 4, while no significant difference was displayed between Group 3 and 4. The homoscedasticity was analyzed using the Hartley non-parametric test and it evidenced a significant difference of variability among the groups.

The Pearson's Chi-squared test was used to show whether any significant difference existed among groups in terms of positive or negative Δ-error values. Significant differences were shown among all groups, paired two by two.

Level 2 analysis: comparison between groups in each AOI

This level of analysis investigated the trueness and precision of a manufacturing technique related to a specific AOI (n = 8). The Figure 2 shows the distribution of the Δ-error mean of absolute values for each AOI and material (group). In the comparison of the different manufacturing processes, the non-parametric test of Friedman showed that at least one process was significantly different to the other ($P < .001$). Consequently, the Wilcoxon- Nemenyi-McDonald-Thompson test for multiple comparisons documented a significant difference for each AOI among the Group 1, 3, and 4. No significant difference resulted between Group 1 and 2 in all AOI.

Table 2. Absolute (abs) and relative mean values of the inter-group comparison (mm)

Material	Mean abs (Δ)	SD abs (Δ)	Mean Δ	SD Δ
Titanium	0.0423	0.0492	-0.0024	0.0648
Co-Cr	0.0801	0.0719	0.0409	0.0995
Resin	0.1432	0.1657	0.0344	0.2163
Metal casting	0.1366	0.1582	0.0205	0.2080

SD: standard deviation.

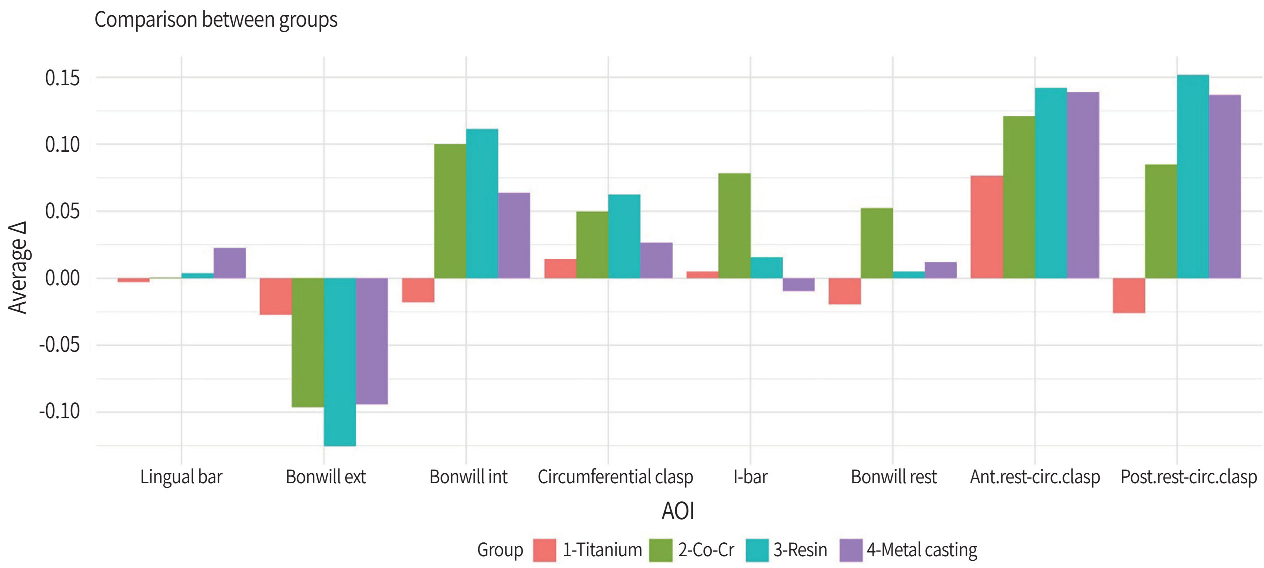

Fig. 2. Comparison between groups in each Area of interest (AOI) (Relative values).

Level 3 analysis: comparison between AOIs of each group

This level of analysis evaluated the accuracy of different AOIs in each group in order to determine whether a treatment effect of the manufacturing method exists in a specific framework component. Each group was singularly analyzed.

Group 1: Titanium (DMLS). The Kruskal-Wallis test was used to investigate if a treatment effect existed between different AOIs. As $P < .001$ resulted, the multiple comparison test of Dwass-Steel-Critchlow-Fligner showed significant differences among almost all different AOIs. Table 3 showed the Δ-error mean value of each AOI: the mesial rest of the circumferential clasp showed the lowest trueness value (0.0823 mm) and the highest was the lingual bar area (0.0279). In terms of precision, the lowest value was the I-bar connector that showed the highest SD range (-0.076/1.267 mm).

Group 2: Co-Cr (DLMS). The same statistical tests were performed for the AOIs of group 2, and the obtained result was the same for the Kruskal-Wallis test ($P < .001$) and the multiple comparison test of Dwass-Steel-Critchlow-Fligner (Table 3). The Δ-error mean values of this group are higher than those of group 1. The AOI that showed the main value coincided with group 1 (mesial rest of the circumferential clasp) but presented a lower trueness value (0.1354 mm). The best trueness value was found in the lingual bar (0.0188 mm) (Table 3).

Table 3. Mean Δ-error between AOIs (Level 3-analysis)

	Group 1 - Titanium	Group 2 - Co-Cr	Group 3 - Resin	Group 4 - Casting
Lingual bar	0.0279	0.0188	0.0406	0.0628
Bonwill ext	0.0375	0.0664	0.1107	0.1380
Bonwill int	0.0378	0.0902	0.1532	0.1392
Circumferential clasp	0.0380	0.0987	0.1970	0.1633
I-bar	0.0409	0.1003	0.1990	0.1759
Bonwill rest	0.0418	0.1136	0.2163	0.1795
Ant.rest -circumferential clasp	0.0622	0.1295	0.2203	0.1926
Post.rest-circumferential clasp	0.0823	0.1354	0.2835	0.2111

Group 3: PA12 Resin (MJF). The Kruskal-Wallis rank sum test showed significant result ($P < .001$) and the Dwass-Steel-Critchlow-Fligner showed significant differences among the AOIs. The highest Δ-error mean value was found in the distal rest of the circumferential clasp (0.2835 mm), and the lowest in the lingual bar (0.0406 mm) (Table 3).

Group 4: Metal casting. Significant value ($P < .001$) resulted with the Kruskal-Wallis test and the Dwass-Steel-Critchlow-Fligner showed significant differences among the AOIs. The distal rest of the circumferential clasp showed the highest Δ-error mean value (0.2111 mm), and the lingual bar showed the lowest Δ-error mean value (0.0628 mm)(Table 3).

DISCUSSION

Both the null hypothesis and the secondary null-hypothesis were rejected. As a matter of fact, differences were found among different manufacturing techniques and among different components of the RPD for all the techniques used in this study. The Δ-error mean value was evaluated for each component of the RPD, through a comparison and an analysis of the post-manufacturing digitalized result reference model in order to document positive (overcontouring) or negative (undercontouring) values of inaccuracies.

Differentely from other studies,[18,19] random positions of a limited number of points were chosen to calculate the accuracy. In this study, the mean Δ-error values of the AOIs were measured in 768 points of each framework, resulting in more than sixty thousand measure points in total.

The sensitivity analysis was used in order to determine the minimum number of sampling points and to obtain a stable value of the Δ-mean error value. Stable value refers to the fact that the sampling density of points has no effect over that number of points, and the Δ-mean error value does not show any significant variation despite of an eventual further increase.

Moreover, in this study, local best-fit was used rather than total best-fit. This specific choice is because total best-fit, generally employed as the gold standard for measuring the differences between two digital surfaces, minimizes the Δ-mean error value, flattening all negative and positive measures around the zero value. This result may lead to an under-estimation of the Δ-mean error values.[20] Furthermore, due to the framework's specific geometry, it is expected to have localized deformation in the retention mesh area of the prosthesis. If these areas are used for the alignment, they can heavily influence the alignment reproducibility. The digital surface of the framework was subdivided into 8 different areas, and the wider one (lingual bar) was used for the local best-fit. Due to its width and its massive size, this area is less prone to manufacturing deformations and thereby allows a more reproducible alignment, reducing the possible misfit error usually generated by heavily deformed surfaces. Although being viable, the hypothesis that the reduced surface of these AOIs could cause a consequent inaccuracy and underestimation, needs further investigations in order to be confirmed.

Xie *et al*.[21] showed that plane orientation of the AOI is correlated to the accuracy of the manufacturing process, meaning that the reciprocal and retentive clasps showed more accurate results when they were oriented parallel to the printing platform. In this study, we considered this evidence as a guide for orienting the model in the manufacturing machine.

Once the manufacturing process was over, in order to avoid any eventual bias caused by the manual refining process, no sample was smoothed and polished before measuring. All the scans were acquired by the same operator.

Results showed a notable difference between the Δ-mean error value of titanium (2 μm) and Co-Cr (40 μm) (Table 2), and the same difference for each AOI (Fig. 2). The different values obtained for titanium and Co-Cr may be attributed to the different manufacturing machines. Specifically, Co-Cr manufacturing machine is characterized by a lower layer sintering thickness (0.04 mm), a lower laser speed (1144 mm/s), and a lower power (195 W) than titanium one. The titanium manufacturing machine presents these parameters respectively: 0.06 mm, 1200 mm/s, and 340 W. Furthermore, the post-contouring was different for each metal. The post-contouring of Co-Cr was carried out using a speed of 300 mm/s and a power of 120 W, while that of titanium was used a speed of 1200 mm/s and a power of 190 W. However, further studies are necessary in order to confirm a correlation between these parameters and the different accuracy of the manufacturing process.

In terms of absolute values of measurements, the polyamide frameworks showed a Δ-mean error value (143 µm) and a SD (165 µm) higher than titanium, Co-Cr, and lost wax casting technique. However, no significant difference between resin and casted frameworks was found. The findings presented in Table 2 showed a reduction of the absolute and relative Δ-mean error values after casting of the correspondent resin samples of group 3. This result may be explained by the post processing metal shrinkage (range: 2 - 2.3%),[22] especially when considering the Co-Cr that exhibits higher percentage due to its higher casting point. Further studies are necessary to correlate these variables.

A study by Stern *et al*.[23] documented a microgap at the intaglio surface of the rest seat of frameworks in the range of 69 - 387 µm; Gowri *et al*.[24] reported the inaccuracy at the intaglio surface of the maxillary major connector in the range of 167 ± 101.8 µm at the anterior strap and 426.3 ± 242.6 µm at the posterior strap; Dunham *et al*.[25] showed an inaccuracy at the intaglio surface of occlusal rest to tooth tissue rest of 130 ± 160 µm without any significant difference to the tooth-supported rest (230 ± 222 µm). Chen *et al*.[26] investigated different SLS techniques for fabricating metal frameworks and reported the inaccuracy at the intaglio surface ranging from 150 to 330 µm and, for some framework SLS types, no statistically significant difference to the cast frameworks. A clinical study by Lee *et al*.[27] showed a gap at the intaglio surface in the rest seat area of 249.27 ± 134.84 µm and of 380.00 ± 111.75 µm in the major connector area. The study by Oh *et al*.[28] summarized these data, concluding that an inaccuracy of the intaglio surface of the frameworks ranging between 69 - 425.3 µm may be considered clinically acceptable. Data obtained in this study optimally fit within this range. From a clinical point of view, Titanium proved to be the ideal material for digital manufacturing, providing the best trueness and precision in all AOIs; Co-Cr showed lower levels of accuracy in specific AOIs as the occlusal rest and the guide plane of the I-bar. Further studies are needed in order to investigate the mechanical properties of the different metals and manufacturing processes presented in this study.

CONCLUSION

Based on the data presented in this study, the following conclusions may be drawn:

Titanium frameworks for removable partial denture, digitally manufactured by DMLS, showed the best result in terms of trueness and precision.

The local best fit was useful to test the actual values of inaccuracy and allowed to avoid underestimating the negative or positive Δ-mean error values.

All Δ-mean error values of the RPD frameworks, digitally manufactured with the different materials used in this study, optimally fit within the clinical tolerance limit of trueness and precision.

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