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Accuracy of Removable Partial Denture Frameworks Fabricated Using Conventional and Digital Technologies

Keywords

3D Printing
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Additive Manufacturing Technologies
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ABSTRACT

This study analyzed the fit accuracy of the removable partial denture (RPD) metal frameworks produced using digital and conventional manufacturing technologies. Mandibular RPD metal frameworks (N=15, n=3 per group) were fabricated on a representative clinical case. RPDs were fabricated using one of the following manufacturing procedures: a) conventional lost-wax casting technique (C-LW), b) conventional casting of milled sacrificial patterns (C-M), c) conventional casting of printed sacrificial patterns (C-P), d) selective laser melting (SLM), e) direct metal laser sintering (DMLS) technologies. The fit accuracy of RPD frameworks was analyzed by fabricating replicas with silicone registration material and measuring with a digital microscope. A total of 11 sites and 29 areas in the RPD metal frameworks were considered for the accuracy measurements (μm). Data were statistically analyzed using Wilcoxon signed rank and Friedman test (α=0.05). Before finishing and polishing, C-M method presented overall significantly better (P<.001) fit accuracy (118 μm) than those of other methods (195-265 μm). After finishing and polishing, C-M method showed overall significantly better (P<.033) fit accuracy (205.7 μm) than C-LW and SLM methods (285.7 μm; 249 μm) and comparable fit accuracy to that of C-P and DMLS methods. Accuracy at the minor and major connector areas of RPDs were affected from the manufacturing technologies. Clinical Implications: When accuracy of RPDs are considered, digital technologies tested presented similar results to those of conventional manufacturing method except for minor and major connector areas which necessitates further improvement.

INTRODUCTION

While digital technologies have long been established in medicine and especially in dentistry, dental laboratories still give preference to conventional technologies for manufacturing removable partial denture (RPD) frameworks made out of metals.[1,2] However, with the advances and implementation of recent digital technologies, associated errors during waxing and casting could be eliminated and thereby quality control in the dental laboratories could be improved.[3-5] Currently, various digital manufacturing concepts for metal frameworks of RPDs are available where the framework can be designed either from the scanned final plaster model or from intraoral digital impressions.[3,6-17]

After the introduction of metal framework fabrication utilizing stereolithography, further rapid prototyping (RP) technologies such as Digital Light Processing (DLP), Thermojet, Drop on Demand Jetting were presented to produce the sacrificial patterns with the use of different materials.[3,6] In 2006, selective laser melting technology (SLM) was then introduced for the fabrication of the RPD metal framework directly from the digitally designed framework.[9] Furthermore, since then attempts were made to manufacture the metal frameworks made of stainless steel and Cr-Co alloy using SLM technologies where fit accuracy was of great interest.[7] Subsequent studies showed however, that not only the alloy type but also the technical parameters of the manufacturing devices affected the quality of the frameworks such as surface properties and fit accuracy.[18,19]

In RPD frameworks, it has to be noted that there is always some gap between the metal framework and soft tissues as well as dentition which could be evaluated using various methods.[17,20-25] Dunham *et al.*[25] produced replicas using vinyl polysiloxane. Other authors used various materials to evaluate the fit accuracy of the frameworks such as acrylic resin or zinc stearate disclosing powder.[20,24] Murray *et al.*[21] constructed special gauges which were used to measure the gaps between clasps and the teeth in patients. On the other hand, Ali *et al.*[23] measured the distortion between the frameworks and different maxillary models with a specially developed strain gauge apparatus and recently, the color mapping method has implemented in order to evaluate the fit accuracy of the frameworks.[16,17] Previous studies on the fit accuracy of the metal frameworks indicated that conventional cast technique revealed better overall fit accuracy when compared to 3D printed frameworks, while the RPDs using RP technologies exhibited the highest discrepancies. Furthermore, the poorest fit was recorded in the area of major connector.[16,26]

One major reason for complete implementation of digital manufacturing technologies however, requires improved fit accuracy especially in the areas of major connector which appears to be a challenge as presented in recent studies.[5,16,26] These challenges are inherent to the technologies that directly affect the quality of frameworks.

The objectives of this present study therefore were to assess and compare the fit accuracy of the mandibular RPD metal frameworks produced using digital and conventional manufacturing technologies. The null hypotheses tested were that there would be no significant difference in the accuracy of fit between the various manufacturing processes and that no significant difference within the technologies before and after polishing.

MATERIAL AND METHODS

SPECIMEN PREPARATION

Mandibular RPD Co-Cr metal frameworks (N=15, n=3 per group) were fabricated on a representative clinical case model. RPDs were fabricated using one of the following manufacturing procedures: a) conventional lost-wax casting technique (C-LW), b) conventional casting of milled sacrificial patterns (C-M), c) conventional casting of printed sacrificial patterns (C-P), d) selective laser melting (SLM), e) direct metal laser sintering (DMLS) technologies *(Figure 1, Table 1)*:

EXPERIMENTAL GROUPS

Conventional lost-wax casting technique (C-LW): In the C-LW group, the definitive mandibular cast was duplicated using a silicone-based duplication material (rema Sil; Dentaurum), and 3 refractory casts were made using phosphate-bonded investment material (Granisit; Siladent Dr. Böhme & Schöps GmbH). The prefabricated wax pattern materials were adapted on the refractory casts and invested using the same phosphate-bonded investment material. The RPD metal frameworks were then cast using centrifugal casting method in a high frequency casting machine (Degutron; Degussa) according to the manufacturer's instructions.

The RPD framework for C-M, C-P, SLM and DMLS groups was digitally designed using RPD designing software (SilaPart CAD; Siladent) *(Figure 2a-b)*.

Conventional casting of milled sacrificial patterns (C-M): In this group, STL file of the digitally designed RPD framework was transferred to the CNC Milling machine (In Lab ML X5; Sirona) for the fabrication of the sacrificial patterns (Wax BioStar CAD; Siladent). The sacrificial patterns of were then directly invested in the special investing material (Granisit RPS; Siladent) assigned for printed or milled frameworks and cast according to the same standard protocol described for C-LW group.

Conventional casting of printed sacrificial patterns (C-P): In this group, STL file of the digitally designed RPD framework was obtained as in group C-M and transferred to the 3D printer (Eden 260V; Stratasys 3D-Printer). The sacrificial patterns were then invested as described for group C-M.

In C-LW, C-M and C-P groups, Cr-Co-Mo alloy Type 5 (V-Alloy FG, DIN EN ISO 22674, Siladent) was used for casting of RPD metal frameworks.

Selective laser melting (SLM): In this group, STL file of the digitally designed RPD framework was transferred to the direct metal laser melting machine (Mlab cusing; Concept Laser) and manufactured using selective laser melting (SLM) technology. Cr-CO-W alloy powder Type 5 (Remanium star CL, DIN EN ISO 9693/DIN EN ISO 22674, Dentaurum) was used for the fabrication of RPD metal frameworks.

Direct metal laser sintering (DMLS): In this group, STL file of the digitally designed RPD framework was transferred to the direct metal laser melting machine (ProX DMP 100 Machine; 3D Systems) and manufactured using direct metal laser sintering (DMLS) technology. As a metal, Cr-Co-Mo alloy powder Type 5 (Sint-Tech, ST 2724G, NF EN ISO 22674, NF EN ISO 9693-1, SINT-TECH) was used.

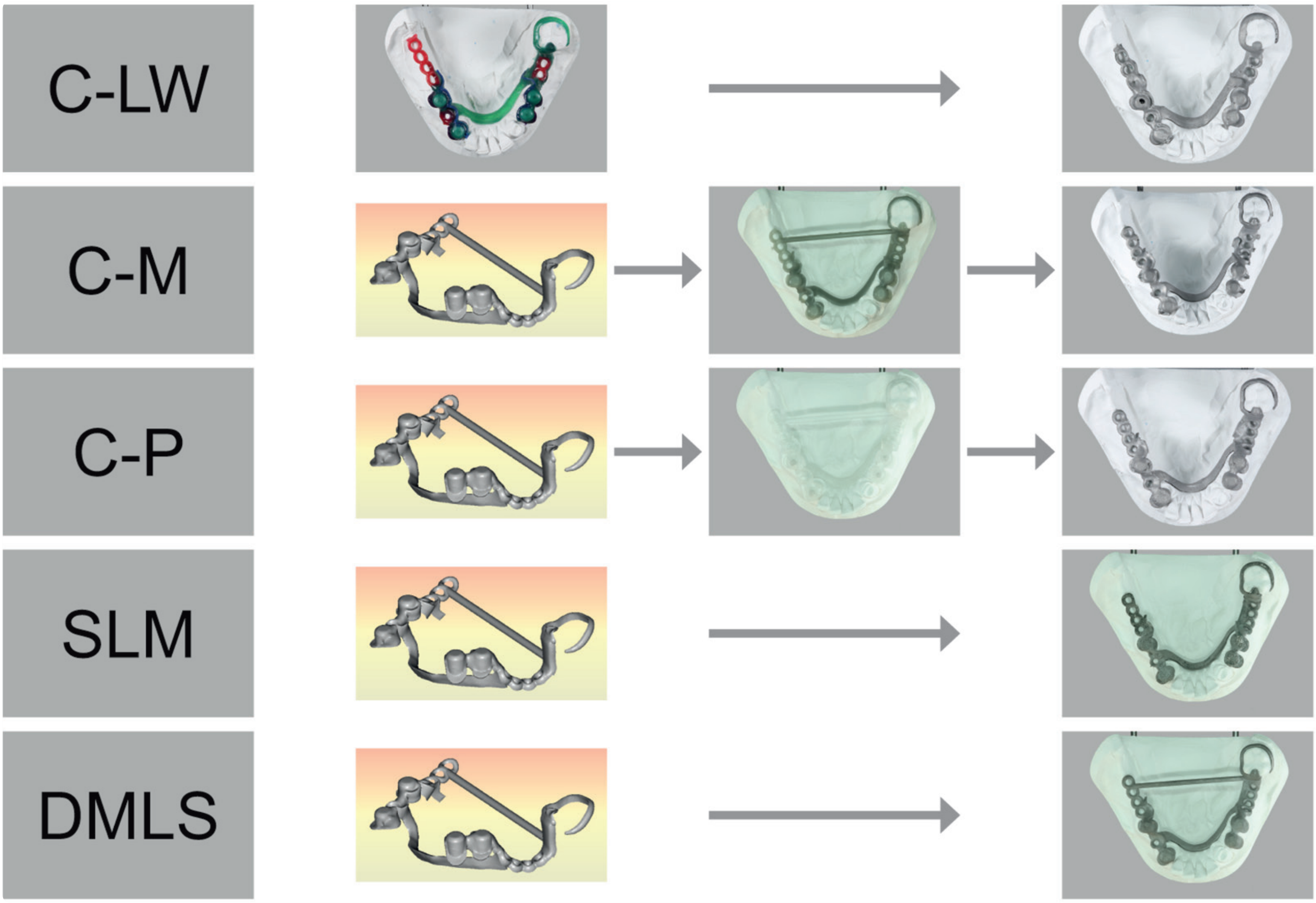

Figure 1: Workflow of five manufacturing procedures for removable partial dentures (RPD); a) conventional lost-wax and casting technique (C-LW), b) conventional casting of milled sacrificial patterns (C-M), c) conventional casting of printed sacrificial patterns (C-P), d) selective laser melting (SLM), e) direct metal laser sintering (DMLS).

Table 1. Groups, fabrication methods for frameworks techniques, sequence of manufacturing, manufacturing equipments, brands and manufacturers of materials used for fabrication of RPDs..

Groups	Fabrication Method for Frameworks	Sequence of Manufacturing	Manufacturing Equipments	Materials and Manufacturers
C-LW	Wax up	Conventional lost wax casting technique[a]	Centrifugal casting (Degutron; Degussa)	Co-Cr[b], V-Alloy FG, DIN EN ISO 22674 (Siladent)
C-M	CAD/CAM indirect/subtractive	Wax milling+ conventional lost wax casting technique[a]	In Lab ML X5 (Sirona)	Co-Cr[b], Wax BioStar CAD (Siladent)
C-P	CAD/CAM indirect/additive	Resin printing+ conventional lost wax casting technique[a]	3D-Printer, (Eden 260V; Stratasys)	Co-Cr[b], Print Resin Objet MED 610 (Stratasys)
SLM	CAD/CAM direct/additive	Selective laser melting	MLab cusing (Concept Laser)	Co-Cr, DIN EN ISO 9693/ DIN EN ISO 22674 (Remanium star CL)
DMLS	CAD/CAM direct/additive	Direct metal laser sintering	ProX DMP 100 (3D Systems)	Co-Cr, 2724G, NF EN ISO 22674, NF EN ISO 9693-1 (Sint-Tech ST)

CAD/CAM; computer aided design and computer aided manufacturing; DMLS; direct metal laser sintering; C-LW; lost-wax casting technique; C-M; milling and casting; C-P; printing and casting; SLM; selective laser melting; [a]Wax and resin frameworks were invested and casted in cobalt-chromium in groups C-LW, C-M and C-P. [b]Note that in groups C-LW, C-M and C-P, same Co-Cr alloy was used.

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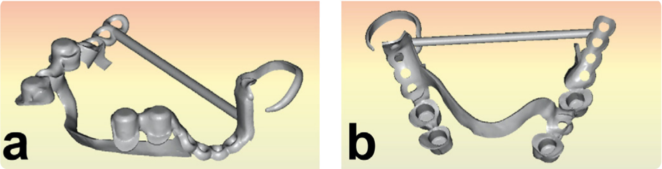


Figures 2a-b: Views of definitive RPD framework design from a) side and b) bottom.

The brands, manufacturers, chemical, and mechanical properties of the used alloys for each technology are presented in the Table 2.

FINISHING AND POLISHING PROCEDURES

The manufactured RPD metal frameworks were air-borne particles abraded with 250 μm Al_2O_3 at a pressure of 3 bar. The finishing procedure of all RPD metal frameworks was carried out with carbide burs (Horico, Hopf, Ringleb & Co. GMBH & CIE). The description and sequence of the used instruments for this purpose are presented in the Table 3. Then, all RPD metal frameworks were further air-abraded with 125 Al_2O_3 at a pressure of 3 bar covering the tip of the retentive arm with a protective varnish processed in a electrolytic polishing unit (Eltropol 300; BEGO Bremer Goldschlägerei Wilh. Herbst GmbH & Co. KG) according to the manufacturer`s instructions. Finally, the frameworks were polished (Soft Cuts PA; Shofu Inc) and bristle brushes (Robinson; Buffalo Dental MFG. CO., Inc) using a polishing paste (Ti-Cor Polish, Ti-Hi Polish; Ticonium) by one dental technician (A.K) who has experience more than 10 years in the field of removable prosthodontics. The duration of finishing and polishing of the RPD frameworks was recorded.

MEASUREMENTS PROCEDURES

The fit accuracy of RPD frameworks was analyzed through fabricating replicas with silicone registration material and measuring with a digital microscope (Keyence VHX 200). A total of 11 sites and 29 areas in the RPD metal frameworks were considered as areas of interest for the accuracy measurements (μm) *(Table 4)*. Each measurement was repeated three times before and after finishing and polishing by a calibrated operator (E.M.) who has experience more than 10 years. The master model was duplicated using a silicone-based duplication material, and 15 stone casts were used for making of replica models for each metal framework before and after finishing and polishing in order to check the accuracy of the RPD metal frameworks *(Figure 3)*.

The internal fit between duplicated master cast and RPD metal framework was determined using a silicone registration material (Fit Checker Advanced; GC Corp). An impression of the RPD, including the internal registration material, was made with an alginate impression material (Cavex Orthotrace Extra Fast Set). The silicone replicas were made using impression material (Vinylpolysiloxane Fitnis SH; Mono Kaniedenta) and silicone putty (Delta-SP 80 Softputty polyvinylsiloxan; Intertrading Dental AG). In order to analyze the accuracy of RPD metal frameworks before and after finishing and polishing, the silicone replicas were cut at locations that involved the imprint of metal framework

Table 2. Physical and mechanical properties of alloys used for production of metal frameworks of RPDs using three manufacturing technologies according to manufacturers..

Manufacturing Technology	Brand of Alloys	Elemental Composition (wt%)	E-mod (GPa)	Yield strength 0.2% (MPa)	Tensile strength (MPa)	HV	Density (g/cm^3)	Melting interval (°C)	CTE x10^{-6} K^{-1} (25 to 500°C)
Casting	Co-Cr, V-Alloy FG, DIN EN ISO 22674 (Siladent)	Co: 63 Cr: 30 Mo: 5 other constituents: Si, Mn, C	200	745 (577)	N/A	390 (327)	8.3	1300-1370	N/A
Laser Melting	Co-Cr, DIN EN ISO 9693/ DIN EN ISO 22674 (Remanium star CL)	Co: 60.5 Cr: 28 W: 9 Si: 1.5 Mn, N, Nb, Fe:<1	230	792±24 (XY) 822±14 (45° polar angle) 835±44 (Z)	1136±24 (XY) 1200±14 (45° polar angle) 1156±9 (Z)	N/A	8.6	1320 -1420	14.1
Laser Sintering	Co-Cr, 2724G, NF EN ISO 22674, NF EN ISO 9693-1 (Sint-Tech ST)	Co: Balance Cr: 29 Mo: 5.5 Mn, Si, Fe:<1	229	815	N/A	375	8.336	N/A	14.5

N/A: not available; XY: 90° in horizontal direction; Z: 0° in vertical direction

Table 3. Instruments, sequence, shape, finishing areas and speed of application (rpm: rotation per minute) for finishing RPDs.

Finishing Instruments and Sequence	Shape	Finishing area	Speed (rpm)
Horico CARBIDE Black Coated Tungsten Carbide Cutter	S274 134 060 Helical Cross Cut Fine	Rests of casting channel	15`000-20`000
Horico CARBIDE Black Coated Tungsten Carbide Cutter	S198 134 040 Helical Cross Cut Fine	Major connector, Clasp, Backings	15`000-20`000
Horico CARBIDE Black Coated Tungsten Carbide Cutter	S198 140 016 Cross Cut Fine	Hard-to-access areas, light unevenness	15`000
Horico CARBIDE Tungsten Carbide Cutter	277 134 014 FSQ Helical Cross Cut Fine	Remove of casting pearls and sharp edges	15`000-20`000
Horico CARBIDE Tungsten Carbide Cutter	277 NEF 014 Cross Cut Fine	Adjustment to master model	20`000

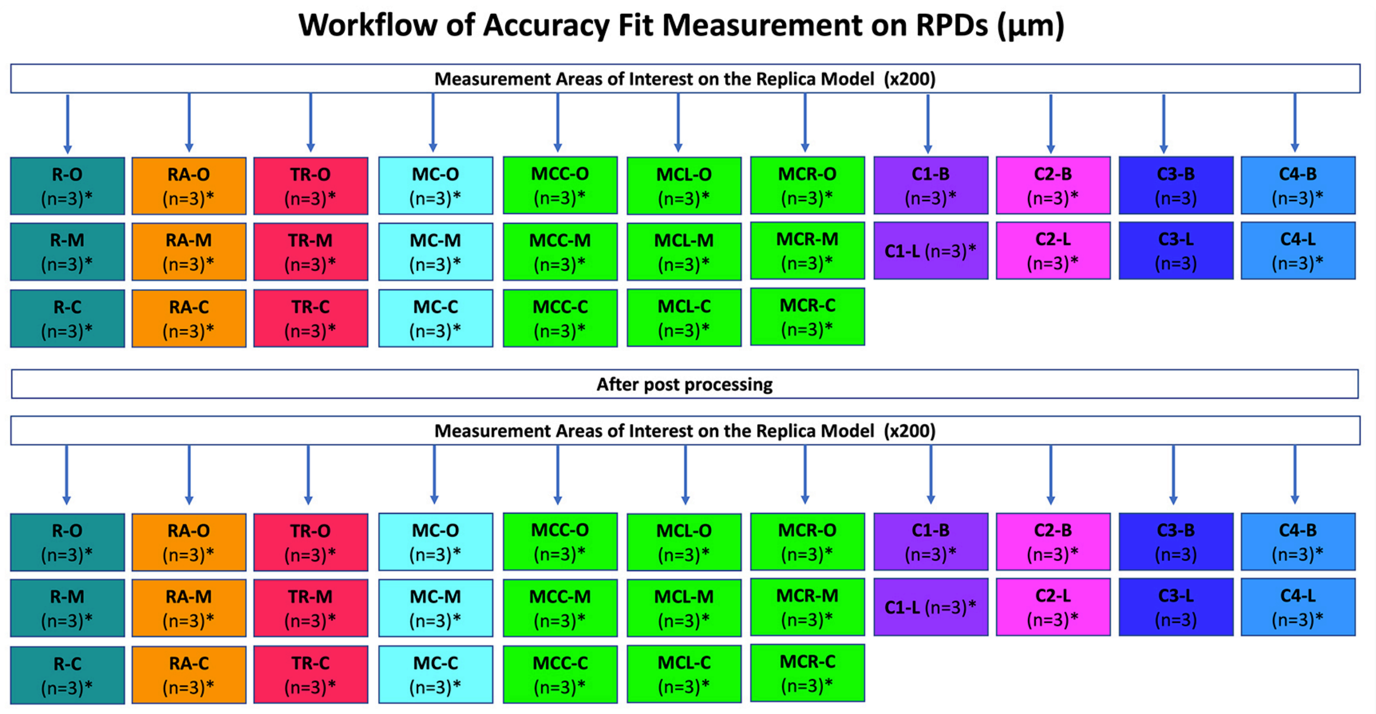


Figure 3: Sequence of accuracy fit measurement (µm) procedures at different locations of RPDs before and after finishing and polishing. R-O, R-M, R-C – rest occlusal, rest middle, rest cervical; RA-O, RA-M, RA-C – reciprocal arm occlusal, reciprocal arm middle, reciprocal arm cervical; TR-O, TR-M, TR-C – transition from reciprocal arm to retentive arm occlusal, transition from reciprocal arm to retentive arm middle, transition from reciprocal arm to retentive arm cervical; MC-O, MC-M, MC-C – minor connector occlusal, minor connector middle, minor connector cervical; MCC-O, MCC-M, MCC-C – major connector occlusal central, major connector middle central, major connector cervical central; MCL-O, MCL-M, MCL-C – major connector occlusal left, major connector middle left, major connector cervical left; MCR-O, MCR-M, MCR-C – major connector occlusal right, major connector middle right, major connector cervical right; C1-B, C1-L – Cap 1 buccal, Cap 1 lingual; C2-B, C2-L - Cap 2 buccal, Cap 2 lingual; C3-B, C3-L – Cap 3 buccal, Cap 3 lingual; C4-B, C4-L – Cap 4 buccal, Cap 4 lingual; *number of measurements per area (N=87 measurements per replica model).

components where the thickness of the silicone registration material in those areas was measured (*Figure 4*).

The measurements were made in the following sites of the RPD: rest, reciprocal arm, transition from reciprocal to retentive arm, proximal plates of minor connector, major connector (right, left sides and in the middle) and four caps. Each site was measured at three regions (buccal, middle, lingual) except for caps where measurements were made only at two areas (buccal and lingual). The thickness of the registration material in each area was measured with a digital microscope (Keyence VHX-200) at x200 magnification. Each measurement was repeated three times yielding to a total of 87 measurements from 11 sites and 29 areas of interest on each unfinished and finished RPD metal framework.

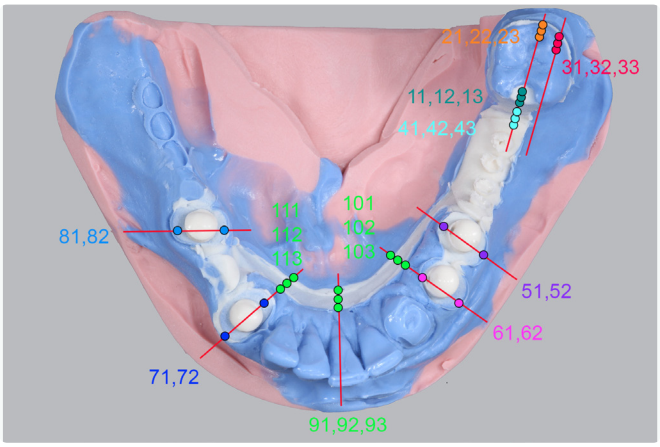


Figure 4: Replica model with section lines and measuring areas. 11, 12, 13 – R-O, R-M, R-C; 21, 22, 23 – RA-O, RA-M, RA-C; 31, 32, 33 – TR-O, TR-M, TR-C; 41, 42, 43 – MC-O, MC-M, MC-C; 51, 52 – C1-B, C1-L; 61, 62 – C2-B, C2-L; 71, 72 – C3-B, C3-L; 81, 82 – C4-B, C4-L; 91, 92, 93 – MCC-O, MCC-M, MCC-C; 101, 102, 103 – MCL-O, MCL-M, MCL-C; 111, 112, 113 – MCR-O, MCR-M, MCR-C. See Figure 3 for the abbreviations.

STATISTICAL ANALYSIS

Statistical analyses of the data were performed using Friedman test and Conover binary comparison to evaluate the differences between the manufacturing technologies. The Wilcoxon signed ranks test was used to compare the fit accuracy for each area of interest in the metal frameworks before and after finishing within the same manufacturing method. *P* values less than .05 were considered to be statistically significant in all tests.

RESULTS

Both the manufacturing technologies (*P*<.05) and the measurement location (*P*<.05) significantly affected the fit accuracy results *(Tables 4a-b*).

Before finishing and polishing, regardless of the measurement location, C-M method presented significantly better (*P*<.001) fit accuracy (118 µm) than those of other methods (195-265 µm) *(Table 4a*).

After finishing and polishing, C-M (205.7), demonstrated significantly better fit accuracy compared to C-LW (285.7 µm) group (*P*=.033) *(Table 4b*).

Before finishing and polishing, while in the cervical region of minor connector, SLM method showed significantly the worse accuracy (255 µm) (*P*=.022), in the mid-center major connector region, C-LW (367 µm) and SLM (484 µm) groups showed significantly less accuracy compared to those of other methods (*P*=.043) *(Table 4a*).

After finishing and polishing, while in the mid-center major connector region, C-LW (368 µm) and SLM (567 µm) methods showed the least accuracy (*P*=.031), on the left part of major connector C-M (114µm; 124 µm) and C-P (103 µm; 181 µm) showed significantly better accuracy (*P*=.038; .043) *(Table 4b*).

Among the RPD frameworks that were manufactured using direct additive technologies, the DMLS frameworks had a much smoother surface than the SLM frameworks *(Figure 5A-D*).

The longest finishing and polishing time, in average 2 hours, was recorded for the C-LW RPD frameworks, followed by the SLM frameworks with an average of 100 minutes. The shortest finishing and polishing time was recorded for the C-M RPD frameworks with 1 hour followed by the DMLS and C-P RPD frameworks (1.5 hours).

DISCUSSION

This study was undertaken in order to evaluate the fit accuracy of the RPD metal frameworks produced using conventional lost-wax casting technique and 4 different available digital technologies before and after the finishing and polishing. Based on the results obtained, significant effect of the manufacturing technologies was observed on the fit accuracy of the metal framework of RPDs but this was limited to some measurement sites only. Likewise, except for some areas of minor and major connectors, fit accuracy was not significantly affected before and after finishing and polishing. Therefore, the null hypotheses were not accepted.

From clinical perspective, the fit accuracy of RPD frameworks is an essential parameter in order to decrease plaque accumulation, food impaction, patient comfort, covering the alveolar ridge which had been an interest of research in removable prosthodontics.

Fit accuracy has been measured using different methods based on manual and digital approaches where the latter may contain software inherent elements.[17,20-25] Recently, digital technologies such as color mapping has been used to assess the fit accuracy of RPD frameworks.[16,17] While silicone replicas presents limited access to the very small areas of RPD such as reciprocal arm or transition from the reciprocal arm to the retentive arm this technique was used in this study. In an attempt to increase the validity of the measurements, from each selected site, repeated 3 measurements were made by a calibrated operator.

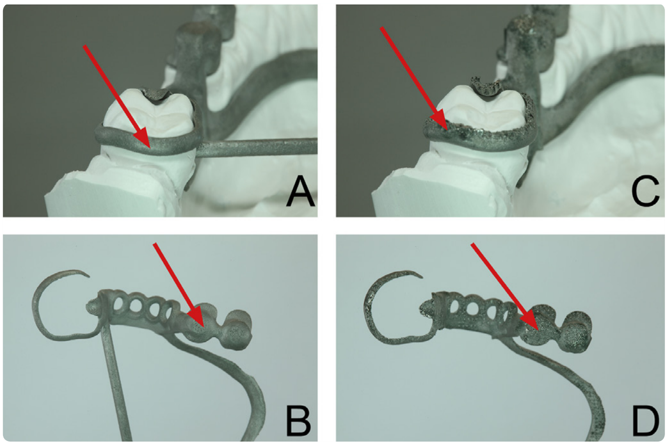
Conventional lost-wax casting technique is being substituted by digital casting technologies based on subtractive or additive methods. Several studies reported on the clinically acceptable fit accuracy of the CAD/CAM metal frameworks without quantifying them.[3,6-9,12] On the other hand, quantifications reported in a limited number of studies where CAD/CAM metal frameworks were compared to those of conventional manufacturing process, frameworks produced through the lost-wax casting technique presented better fit.[16,26] In the present study, the groups in which the conventional casting technique was used, namely, C-LW, C-M, C-P demonstrated similar accuracy fit in all measurement sites except for minor and central part of the major connector before finishing and polishing.

Table 4a. Median (min-max) values (µm) for fit accuracy of RPD frameworks before finishing and polishing. Different superscript letters in each column indicate significant differences between manufacturing methods.

Measurement sites	Group I (C-LW)	Group II (C-M)	Group III (C-P)	Group IV (SLM)	Group V (DMLS)	*P*
R-O	302(259-576)	204(185-281)	788(365-1185)	696(309-929)	360(260-485)	0,113
R-M	264(198-690)	181(122-327)	822(374-1371)	802(431-982)	511(448-563)	0,255
R-C	196(187-647)	153(67-276)	639(305-1316)	802(395-971)	440(425-560)	0,255
RA-O	147(108-475)	135(70-149)	474(364-835)	406(375-500)	234(195-259)	0,189
RA-M	53(37-343)	58(55-82)	182(81-285)	122(75-195)	122(113-132)	0,338
RA-C	257(176-394)	68(55-272)	82(68-163)	73(65-81)	87(73-88)	0,082
TR-O	102(97-458)	114(69-188)	518(215-857)	394(270-640)	299(233-330)	0,255
TR-M	76(72-222)	80(78-82)	176(155-358)	208(115-381)	137(131-142)	0,406
TR-C	70(55-79)	88(72-215)	136(46-419)	178(40-192)	132(93-167)	0,569
MC-O	136(108-182)	78(74-126)	154(123-175)	244(78-344)	76(57-90)	0,113
MC-M	121(116-147)^{a,b}	63(53-107)^{c}	86(68-101)^{c,d}	228(187-338)^{a}	143(82-148)^{b,d}	*0,043
MC-C	97(85-102)^{a}	51(51-57)^{d}	86(50-88)^{d}	255(229-389)^{b}	179(119-193)^{c}	*0,022
MCC-O	287(237-302)	170(143-278)	198(189-270)	723(613-769)	205(160-249)	0,171
MCC-M	367(334-407)^{a}	170(155-319)^{b}	238(231-268)^{b}	484(398-560)^{a}	252(234-261)^{b}	*0,043
MCC-C	318(81-336)	170(155-319)^{b}	276(264-309)	291(182-348)	231(221-247)	0,525
MCL-O	129(115-163)	252(196-307)	143(112-304)	428(94-525)	187(157-247)	0,878
MCL-M	254(207-262)	276(197-490)	297(208-320)	329(232-443)	205(200-251)	0,483
MCL-C	305(230-403)	211(198-423)	278(100-413	325(281-450)	214(210-234)	0,525
MCR-O	299(173-521)	145(69-189)	119(69-149)	618(190-643)	294(207-314)	0,092
MCR-M	267(217-417)	94(91-149)	128(87-279)	192(178-265)	342(340-375)	0,092
MCR-C	242(218-421)	112(109-167)	131(50-403)	216(181-241)	243(143-373)	0,339
C1-B	78(23-221)	51(22-52)	208(58-488)	157(47-211)	188(108-219)	0,281
C1-L	110(22-568)	38(36-45)	205(64-751)	240(155-347)	449(342-451)	0,209
C2-B	159(61-308)	62(47-158)	192(166-326)	99(98-100)	69(64-144)	0,267
C2-L	152(65-278)	61(28-82)	334(178-602)	188(174-340)	198(158-239)	0,107
C3-B	210(195-224)	118(104-340)	195(168-356)	141(102-166)	102(88-109)	0,092
C3-L	104(97-111)	44(38-141)	69(57-91)	134(61-323)	147(136-167)	0,107
C4-B	242(195-298)	267(152-298)	304(259-774)	764(181-897)	83(65-100)	0,155
C4-L	39(35-160)	180(111-181)	135(63-570)	668(108-764)	152(134-195)	0,483
Total	195 (22,3-690,3)^{a}	118 (22,3-490,3)^{c}	231,3 (46-1371)^{a}	265 (40-982,3)^{b}	204,7 (57,3-562,7)a	**<0,001**

Table 4b. Median (min-max) values (µm) for fit accuracy of RPD frameworks after finishing and polishing. Different superscript letters in each column indicate significant differences between manufacturing methods.

Measurement sites	Group I (C-LW)	Group II (C-M)	Group III (C-P)	Group IV (SLM)	Group V (DMLS)	*P*
R-O	510(272-676)	331(303-452)	505(139-899)	327(137-735)	384(270-571)	0,856
R-M	306(233-531)	421(413-442)	762(387-873)	463(298-832)	358(327-460)	0,406
R-C	406(259-637)	418(349-453)	628(526-689)	442(263-850)	406(390-526)	0,339
RA-O	317(121-429)	172(132-212)	164(76-251)	178(80-522)	78(63-223)	0,736
RA-M	136(129-232)	85(83-87)	62(39-84)	79(57-107)	96(51-112)	0,199
RA-C	293(86-323)	46(24-67)	106(55-156)	67(47-130)	53(40-118)	0,267
TR-O	207(169-245)	NA	212(196-228)	235(91-384)	214(182-290)	0,392
TR-M	126(79-233)	NA	106(100-112)	NA	94(61-138)	1,000
TR-C	129(103-249)	NA	95(59-131)	NA	83(64-117)	0,607
MC-O	290(167-305)	154(85-238)	183(44-215)	132(56-141)	178(132-336)	0,443
MC-M	233(157-270)	127(49-180)	92(53-107)	163(39-165)	265(178-333)	0,189
MC-C	141(109-225)	73(28-101)	45(38-65)	194(39-239)	251(240-283)	0,066
MCC-O	368(310-384)^{a}	296(136-352)^{c}	236(54-310)^{b,c}	567(415-940)^{a}	274(127-295)^{b}	***0,031**
MCC-M	424(404-427)	316(206-395)	208(133-256)	249(241-736)	240(170-303)	0,102
MCC-C	408(295-424)	377(265-383)	277(265-307)	235(135-596)	304(194-391)	0,663
MCL-O	223(205-256)^{a}	114(59-131)^{b}	103(48-107)^{b}	642(340-649)^{a}	337(214-380)^{a}	***0,038**
MCL-M	328(312-351)^{a}	124(98-153)^{b}	181(120-227)^{b}	300(294-483)^{a}	440(389-465)^{a}	***0,043**
MCL-C	400(306-421)	198(154-264)	242(159-258)	180(114-387)	417(377-483)	0,059
MCR-O	436(254-539)	363(227-619)	355(163-542)	273(157-811)	264(161-305)	0,569
MCR-M	451(386-498)	348(274-557)	254(211-519)	159(89-731)	283(208-424)	0,569
MCR-C	445(338-489)	342(264-509)	341(263-422)	100(65-669)	213(213-274)	0,281
C1-B	152(121-295)	141(101-206)	167(63-334)	266(259-451)	95(40-113)	0,082
C1-L	124(65-268)^{a}	90(68-188)^{a}	164(151-438)^{b}	261(190-483)^{b}	279(160-382)^{b}	***0,043**
C2-B	188(137-317)	214(186-224)	308(140-339)	308(294-322)	175(86-225)	0,355
C2-L	213(75-295)	90(86-194)	193(169-434)	298(297-432)	257(210-304)	0,171
C3-B	188(135-276)	236(138-329)	180(167-265)	294(78-298)	61(56-211)	0,281
C3-L	89(87-202)	66(46-213)	51(43-68)	200(106-248)	124(112-181)	0,339
C4-B	286(182-286)	305(223-325)	442(254-658)	147(73-266)	78(47-87)	0,074
C4-L	55(50-70)	155(119-204)	292(113-376)	137(123-172)	128(98-214)	0,126
Totally	285,7(49,7-676)^{a}	205,7(23,7-619)^{c}	210,7(38-898,7)^{a,b,c}	249(39-940)^{a,b}	240(40-571,3)^{b,c}	**0,033**



Figures 5A-D: Surfaces of RPD frameworks fabricated by A-B) DMLS and C-D) SLM technique before finishing and polishing. Note rough surfaces especially more on RPD manufactured by SLM technique (indicated by arrow).

After processing and polishing, the overall gap for the cast frameworks of the C-M group only remained significantly lower compared to the frameworks of the C-LW group with cast frameworks. Arnold *et al.*[26] showed also that the RPD frameworks fabricated using indirect milling techniques have comparable fit in areas of the clasps as the conventional cast frameworks. In contrast to the C-M, C-P and SLM groups, the frameworks of the C-LW group showed no visible tension or rocking movements on the master models. This observation is in accordance with previous studies by Arnold *et al.*[26] , who reported that the RPD frameworks fabricated using indirect rapid prototyping or SLM techniques were unstable on the master model and unsuitable for clinical use. In the indirect CAD-CAM manufacturing processes, the wax or resin patterns were conventionally cast without using a refractory cast. With these techniques, there was accordingly greater distortion in the metal framework during the manufacturing process. Thus, the errors could arise either when embedding or removing the resin pattern from the support medium and led to tension and rocking movements after processing the frameworks on the master model as well as to the greater distortion compared to the frameworks from the C-LW group.

When comparing the RPD frameworks produced with the direct additive technologies, the frameworks produced using DMLS technology presented a significantly lower gap in the areas of the major and minor connectors than those from the SLM group before polishing and in the area of the minor connector after polishing. Furthermore, in contrast to the SLM frameworks, two out of three DMLS frameworks were stable on the master model and did not show any rocking motion. In the visual assessment of the RPD frameworks of the two groups, the SLM frameworks had a much rougher surface than the DMLS frameworks which required more effort and time to finish such surfaces eventually affecting the fit accuracy. This observation is in accordance with the study by Takaichi *et al.*,[19] who showed that microstructure and porosity of Co-Cr-Mo alloys are dependent not only on the alloy but also on the operational parameters of the SLM device. It is known that technical parameters such as energy density, scanning speed, scanning strategy, layer thickness and laser spot diameter of the manufacturing inherent parameter can affect the accuracy of metal RPD frameworks.[18] In order to improve the accuracy of fit of the digitally produced metal frameworks, further studies are required to optimize the technical parameters of the additive technologies.

When comparing the RPD frameworks of SLM and DMLS groups with the conventional cast frameworks before polishing, the significant differences were in the areas of major and minor connectors. These findings are in accordance with Soltansadeh *et al.*[16] study, who found that the conventional cast frameworks revealed significantly better fit particularly in the major connector and guide plates in comparison to the frameworks manufactured using CAD-printing technology.

It has to be emphasized that while in this study, as an RPD design Kennedy Class II 2 was chosen, for mandible, in the other studies, as a classification Kennedy Class III in the maxilla was chosen where the latter has no rotation axis yielding to fewer rocking motions. Furthermore, while in the study of Arnold *et al.*[26], optical microscope was used as a measurement method accuracy of fit without using replicas, Soltanzadeh *et al.*[16] utilized color mapping and studied the overall adaptation and only major connectors without clasps and adaptation clasps without major connectors. Moreover, the intaglio surfaces of the RPDs were not finished and polished.

In this study, after finishing and polishing, in the area of the rests, C-LW metal frameworks showed the gap from 233 to 676 µm. Dunham *et al.*[25] reported similar values with the range of 0 to 828 µm. They also found that the most contacts were on the unprepared suprabulge surface and that the majority of the rests had no contact with the intended surface. This observation correlates with the results of the present study, in which the gap between the reciprocal arm and transition from reciprocal arm to the retentive arm and the intended surface was smaller than in the area of rests with the accuracy fit ranging between 79 and 429 µm. Likewise, in the present study, a similar observation was made concerning the areas of minor connector resulting in accuracy fit values between 109 and 305 µm, providing that Dunham *et al.* measured only the rest areas of the frameworks. Based on these results, it can be stated that effectively measured distance between the metal framework and the master model is also dictated by the degree of rocking.

The distortion during the manufacturing process have a considerable influence on the accuracy of fit of the metal framework which could also take place during finishing and polishing as a function of the alloy composition.[23] The results of the present study have shown that not only the effectively measured distance between the metal framework and the master model below represents its actual fit.

After finishing and polishing, there was only one uniform increase in accuracy fit between all the components of the RPD framework and the master models in C-LW group. In all other groups, there were uneven changes in the fit accuracy. The average values of metal loss from the surface of the RPD framework after finishing and polishing were significantly below the 127 µm reported by Brudvik and Reimers.[22] This observation confirms the importance and influence of the human factor in the manual treatment of the metal frameworks. On the other hand, after finishing and polishing, the gaps for major and minor connectors in the DMLS group were comparable to the C-LW group and were significantly lower than in the SLM group. These observations and the fact that all frameworks of the SLM group rocked on the master models after finishing and polishing suggest a distortion, especially in the area of the major and minor connectors during the manufacturing process. In the DMLS group, two out of three frameworks showed good adaptation without rocking movements after processing. A distortion caused by the manual finishing could be an issue in this case.

The silicone replicas were not ideally formed in areas where the frameworks were very close to the duplicated master casts. Some measurement points in the areas of the rigid arm and the transition from rigid to elastic arm on the silicone replicas could not be assessed because the silicone registration material tore off either from the silicone impression material or from the framework. These events happened at least in one area and in one of the three silicone replicas of the respective framework groups which could be considered as a limitation of this study. Furthermore, the findings of this study are based on Kennedy II 2 classification which needs to be verified for other Kennedy classifications. In addition, the design of the RPD frameworks accessed in the present study does not correspond to the classic RPD framework design and contains elements of hybrid prosthesis. For this reason, our results cannot be compared with the results of other studies.

In future studies, the results of this pilot study should be verified on larger sample size with different Kennedy classes in classical RPD designs and compared with the non-contact measurement methods such as color mapping.

CONCLUSIONS

Within the limitation of this pilot study, the following conclusions were drawn:

1. Accuracy at the minor and major connector areas of RPDs appears to be affected the most from the manufacturing technologies compared to other components of RPDs when conventional method is associated with digital technologies.
2. When accuracy of RPDs are considered, digital technologies tested presented similar results to those of conventional manufacturing method expect for minor and major connector areas which necessitates further improvement.
3. Among additive technologies, DMLS presented superior accuracy compared to that of SLM.

DISCLOSURE STATEMENT

The authors did not have any commercial interest in any of the materials and manufacturing techniques used in this study.

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