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Dimensional accuracy of mock-ups fabricated using conventional, additive, and subtractive manufacturing techniques: an in vitro study

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Abstract

Background

Mock-ups are used to preview esthetic and functional outcomes and may also guide minimally invasive tooth preparation. This in vitro study compared the dimensional accuracy of six-unit anterior mock-ups fabricated using conventional molding, additive manufacturing, and subtractive manufacturing relative to a reference digital design.

Methods

Digital smile design data from 10 patients were used to fabricate one canine-to-canine mock-up per patient with each manufacturing technique (n = 10 per technique; 30 specimens). Conventional mock-ups were produced using a silicone index and bis-acryl resin, additive mock-ups were fabricated with a liquid crystal display-based three-dimensional printer, and subtractive mock-ups were milled from prepolymerized polymethyl methacrylate discs. Specimens were digitized with an industrial optical scanner and superimposed on the reference digital waxing. Surface-to-surface matching percentages, absolute digital and analog linear deviations, and signed depth deviations at nine standardized points per tooth were assessed. Data were analyzed using one-way analysis of variance and Kruskal-Wallis tests with appropriate post-hoc comparisons ($\alpha = 0.05$).

Results

Surface-to-surface matching differed significantly among the techniques ($p = 0.001$). The subtractive group showed the highest matching percentage (74.54 ± 12.26%), followed by the additive (58.72 ± 18.84%) and conventional (42.80 ± 12.46%) groups; the subtractive group differed significantly from the conventional group ($p = 0.001$), whereas the other pairwise comparisons were not significant. No significant differences were observed in digital or analog absolute linear deviations ($p > 0.05$). The conventional group showed significantly lower signed depth deviation values than the subtractive ($p = 0.001$) and additive ($p = 0.021$) groups. Depth deviations differed by tooth type, with the highest values in canines and the lowest in central incisors ($p = 0.001$), but not by mesio-distal region ($p = 0.453$).

Conclusions

Manufacturing technique influenced the three-dimensional accuracy of anterior mock-ups, although selected linear dimensions were reproduced similarly. Subtractive manufacturing showed the highest surface matching, while additive manufacturing showed intermediate matching and mean depth deviations close to zero. Region-specific deviations observed with conventional molding should be considered when mock-ups are used as preparation guides.

BACKGROUND

Esthetic dentistry has evolved into a multidisciplinary discipline that aims not only to restore function but also to improve facial esthetics and patient psychosocial well-being [1]. In recent years, patient expectations regarding dental appearance have increased considerably, with growing importance attributed to esthetic outcomes [2]. Among the available esthetic solutions, porcelain laminate veneers have become a clinically reliable and minimally invasive treatment option, providing excellent long-term esthetic success while preserving sound tooth structure [3, 4]. Because the bonding of veneers relies on an adhesive cementation technique, preserving as much enamel as possible is essential to ensure durable clinical outcomes [5]. Within this context, digital smile design (DSD) has become a fundamental tool, enabling clinicians to analyze facial and dental proportions and to predict treatment outcomes before initiating irreversible procedures [6, 7].

Mock-ups are provisional simulations used to preview the form and dimensions of the final restoration intraorally. They allow clinicians to evaluate esthetic, phonetic, and functional parameters at a stage where modifications can still be easily made according to the patient's requests, while facilitating communication among the clinician, dental technician, and patient [8, 9]. Beyond their esthetic role, mock-ups serve as guides for tooth preparation, particularly in minimally invasive laminate veneer treatments. Mock-up–guided preparation driven by the final restorative volume, rather than freehand reduction, limits tooth reduction to the necessary areas, thereby avoiding over-preparation and preserving the maximum amount of enamel for more predictable bonding and esthetics [10, 11].Consequently, the dimensional accuracy of mock-ups, particularly their thickness, is closely related to preparation depth control, marginal adaptation, and the clinical predictability of the definitive restoration [12].

Traditionally, mock-ups have been fabricated using a conventional molding technique, in which a silicone index obtained from diagnostic waxing is filled with bis-acryl resin and transferred to the model or intraorally. Although this method is inexpensive and easy to apply, it is a complex and highly operator-dependent procedure. The most common problems associated with this technique include uneven positioning of the silicone matrix, inhomogeneous pressure during resin polymerization, difficulties in removing excess resin, and polymerization shrinkage of the material [13, 14]. With the widespread adoption of digital workflows, mock-ups can also be produced using subtractive manufacturing, based on milling from prepolymerized blocks, or additive manufacturing, based on layer-by-layer 3D printing. These digital approaches may improve reproducibility and reduce operator dependency [15, 16]. In this regard, both subtractive and additive manufacturing techniques may offer advantages over conventional molding by enabling a more standardized digital workflow, reducing operator-dependent manual steps, and improving the reproducibility of mock-up fabrication [13, 15–17].

Each manufacturing approach has distinct characteristics that may influence dimensional accuracy. Subtractive manufacturing uses industrially polymerized, homogeneous blocks, thereby reducing the effect of polymerization shrinkage during fabrication [18], but it may generate material waste and

present geometric limitations related to bur diameter [19]. Additive manufacturing, by contrast, builds restorations layer by layer and enables the fabrication of complex geometries with minimal material waste. However, its accuracy may be affected by printing parameters, layer thickness, post-curing procedures, and layer-related deviations, particularly on complex curved surfaces [17, 20].

Previous studies have mainly evaluated mock-up accuracy using overall three-dimensional trueness, linear measurements, or thickness measurements [20–22]. When mock-ups are used as preparation guides, localized deviations in the facial contour or thickness may result in under- or overestimation of the restorative volume and may affect the planned amount of tooth reduction [21, 22]. Therefore, a region-specific evaluation of depth deviations according to tooth type and anatomical levels may provide more clinically meaningful information than global measurements alone [21, 23].

Although several studies have investigated the dimensional accuracy of mock-ups [13, 16, 21], comparative evidence remains limited. A recent study compared mock-ups fabricated using conventional, additive, and subtractive workflows; however, the assessment was mainly limited to overall surface trueness and linear measurements [17]. Evidence is still lacking regarding depth deviations of anterior mock-ups according to tooth type and anatomical regions, particularly in the inciso-cervical dimension, which is clinically relevant for preparation guidance and enamel preservation in minimally invasive procedures.

Therefore, the present in vitro study aimed to evaluate and compare the dimensional accuracy of six-unit anterior mock-ups fabricated using conventional molding, additive manufacturing, and subtractive manufacturing techniques relative to a reference digital design. Accuracy was assessed through surface-to-surface matching analysis, digital and analog linear measurements, and depth deviations analyzed according to tooth type, inciso-cervical level, and mesio-distal region. The null hypothesis was that there would be no significant difference in dimensional accuracy among the three manufacturing techniques.

METHODS

This study was approved by the Trakya University Faculty of Medicine Non-Interventional Scientific Research Ethics Committee (Protocol No: TÜTF-GOBAEK 2024/314; Decision No: 12/24; Date: 24 June 2024). All patients were fully informed about the nature of this study and signed an informed consent form prior to their participation.

Study design and specimen preparation

This in vitro study followed a three-group parallel design. Mock-ups were fabricated using three different manufacturing techniques: conventional molding (CM), subtractive manufacturing (SM), and additive manufacturing (AM). Based on the digital smile design (DSD) data of 10 patients who had been previously planned for maxillary anterior laminate veneer treatment, one six-unit (canine-to-canine)

mock-up per patient was fabricated with each manufacturing technique, resulting in a total of 30 specimens (n = 10 per group).

Sample size calculation

The required sample size was calculated using G*Power software (version 3.1.9.6), based on a one-way analysis of variance, assuming a conservative effect size of f = 0.80, a statistical power of 95%, and a type I error probability of α = 0.05. Under these conditions, 10 specimens per group were considered sufficient, yielding a total sample size of 30 and an actual power of 0.968.

Patient selection

Patients were selected according to the following inclusion criteria: (1) planned for maxillary anterior laminate veneer treatment; (2) all maxillary anterior teeth present with no missing teeth; (3) no advanced caries, large restorations, or existing prosthetic restorations in the anterior region; (4) no severe malocclusion or crossbite.

Digital data acquisition and smile design

Intraoral scans of all patients were obtained using an intraoral scanner (TRIOS 3, 3Shape A/S, Copenhagen, Denmark) and exported in Standard Tessellation Language (STL) format. Standardized extraoral photographs were taken with a digital camera (Canon EOS 6D; Canon, Tokyo, Japan) equipped with a 100 mm macro lens (EF 100 mm f/2.8L Macro IS USM) and a wireless flash trigger (Godox X1T-C) under standardized lighting conditions.

The intraoral scan data and frontal photographs were imported into a digital smile design software (Exocad DentalCAD 3.2 Galway, Exocad GmbH, Darmstadt, Germany). Using the Smile Creator module, the facial midline, pupillary line, and lip curvature were identified and used as references for anterior tooth positioning. The dimensions and contours of the six anterior teeth were designed in accordance with the patient's facial proportions, smile esthetics, and lip curvature. After completing the digital waxing design, the files were exported in STL format and used as the reference model for all subsequent fabrication and analysis procedures. Stages of the digital smile design and the completed three-dimensional digital waxing are shown in Fig. 1.

Fabrication of mock-ups

Conventional molding group (CM)

The STL file of the digital waxing was converted into a virtual model using the model creator module of the CAD software program (exocad DentalCAD 3.2 Galway; exocad GmbH, Darmstadt, Germany). The file

was then exported in STL format and additively manufactured using a 3D printer (Phrozen Sonic Mini 8K; Phrozen Technology Co., Taipei, Taiwan) to obtain a physical reference model containing the digital waxing. Silicone indices were fabricated on these printed reference models using a polyvinylsiloxane (PVS) impression material (Express XT Quick, 3M ESPE, Seefeld, Germany). Excess silicone material at the margins was carefully trimmed with a scalpel, and the seating accuracy of each silicone index was verified on the corresponding preoperative model. The silicone index was then filled with a bis-acryl composite resin (Protemp 4, 3M ESPE, Seefeld, Germany) and seated on the corresponding preoperative model. Excess resin material at the buccal and palatal margins was removed during the gel phase. After complete polymerization, the silicone index was removed, and the conventionally molded mock-up was finished to its final form.

Subtractive manufacturing group (SM)

The digital waxing STL files were imported into CAD/CAM milling software. Milling parameters and block positioning were determined, and the restorations were milled from pre-polymerized polymethylmethacrylate (PMMA) discs (Fusion Ceram, shade B1, 98 × 16 mm; Fusion Ceram, Istanbul, Turkey) using a 5-axis dry milling unit (vhf K5, VHF Camfacture AG, Ammerbuch, Germany). After milling, the restorations were carefully separated from the disc.

Additive manufacturing group (AM)

The digital waxing STL files were transferred to an LCD-based 3D printer (Phrozen Sonic Mini 8K; Phrozen Technology Co., Taipei, Taiwan) for additive manufacturing. The mock-ups were fabricated using a dental temporary resin material (ArmaResin Temp, shade B1; ArmaResin, Istanbul, Turkey). After printing, the specimens were immersed in 96% isopropyl alcohol for 4 minutes to remove residual uncured resin. The specimens were then air-dried and post-cured in a UV light-curing unit according to the resin manufacturer's recommendations. Support structures were carefully removed, and the seating of all printed mock-ups was verified on the corresponding preoperative models.

Following fabrication, the seating of all mock-ups was verified on their corresponding preoperative models. The preoperative model and a six-unit anterior mock-up seated on the corresponding model are shown in Fig. 2.

Digitization of specimens

All fabricated mock-ups were seated on their respective reference models and scanned using an industrial optical scanner (ATOS Triple Scan, GOM GmbH, Braunschweig, Germany) to obtain high-resolution STL files of each specimen. The reference digital waxing STL served as the reference dataset for all comparative analyses.

Dimensional accuracy assessment

Alignment procedure

All comparative analyses were performed using metrology software (GOM Inspect Professional 2017, GOM GmbH, Braunschweig, Germany). Prior to analysis, each specimen STL was aligned to the reference digital waxing using a local best-fit alignment method. The labial surfaces of the six anterior teeth (canine-to-canine) were selected as the reference region for alignment, as this region represents the primary esthetic evaluation zone.

Surface-to-surface matching analysis

Surface deviation maps were generated by superimposing each specimen STL file onto the reference digital waxing. The areas within the predefined tolerance range were displayed in green on the color-coded deviation maps. The percentage of the labial surface area shown in green was calculated for each specimen. Higher percentages indicated greater conformity to the reference digital design.

Linear measurements

Five linear parameters were evaluated for each specimen using both digital and analog methods. Digital measurements were performed using the metrology software (GOM Inspect Professional 2017, GOM GmbH, Braunschweig, Germany) directly on the STL files of each specimen. Analog measurements were made on the mock-ups seated on their respective reference models using a digital caliper (Hogetex Digital Caliper, 0.01 mm resolution). All measurements were performed by the same operator. The parameters assessed were: (1) maxillary right central incisor width, (2) maxillary left central incisor width, (3) maxillary right central incisor height, (4) maxillary left central incisor height, and (5) intercanine distance (measured as the projected distance between the most distal points of the canines). For both methods, the absolute difference between each specimen measurement and the corresponding reference digital waxing measurement was recorded.

Depth deviation analysis

Depth deviations were evaluated at nine standardized points per tooth across three inciso-cervical levels (incisal, middle, cervical) and three mesio-distal positions (mesial, middle, distal), for each of the six anterior teeth. Positive values indicated outward deviation (specimen surface located labial to the reference), while negative values indicated inward deviation (specimen surface located lingual to the reference). Deviations were analyzed according to manufacturing group, tooth type (central incisor, lateral incisor, canine), inciso-cervical level, and mesio-distal region. Examples of the dimensional accuracy assessment procedures are shown in Fig. 3.

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics software (version 27.0, IBM Corp., Armonk, NY, USA). The normality of the data distribution was assessed using the Kolmogorov-Smirnov and Shapiro-Wilk tests. For normally distributed parameters, group comparisons were performed using

one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) post-hoc test. For non-normally distributed parameters, the Kruskal-Wallis test was used, with Dunn's test applied for pairwise comparisons. The level of statistical significance was set at $p < 0.05$.

RESULTS

Surface-to-surface matching analysis

Surface-to-surface matching percentages showed a significant overall difference among the manufacturing groups (p = 0.001). The SM group showed the highest matching percentage (74.54 ± 12.26%), followed by the AM group (58.72 ± 18.84%) and the CM group (42.80 ± 12.46%). Posthoc comparisons revealed that the SM group had a significantly higher matching percentage than the CM group (p = 0.001), whereas the AM group did not differ significantly from either the SM or CM group (p > 0.05) (Table 1).

Table 1
Surface-to-surface matching percentages among manufacturing groups (%)

Manufacturing group	Surface-to-surface matching, mean ± SD (%)
AM	58.72 ± 18.84^{ab}
SM	74.54 ± 12.26^{a}
CM	42.80 ± 12.46^{b}
p	0.001*

One-way ANOVA followed by Tukey HSD test. *$p < 0.05$. Different superscript lowercase letters indicate statistically significant differences between groups. AM, additive manufacturing; SM, subtractive manufacturing; CM, conventional molding.

Linear measurements

No statistically significant differences were found among the three manufacturing groups for any of the digital linear measurement parameters, including right central incisor width, left central incisor width, right central incisor height, left central incisor height, and intercanine distance (p > 0.05) (Table 2). Similarly, no statistically significant differences were observed among the groups for any of the analog linear measurement parameters (p > 0.05) (Table 3).

Table 2
Comparison of digital absolute linear deviations among manufacturing groups (mm)

Group	Right central incisor width	Left central incisor width	Right central incisor height	Left central incisor height	Intercanine distance
	Mean ± SD (median) (min-max)	Mean ± SD (median) (min-max)	Mean ± SD (median) (min-max)	Mean ± SD (median) (min-max)	Mean ± SD (median) (min-max)
AM	0.09 ± 0.07 (0.07) (0.01–0.23)	0.09 ± 0.07 (0.05) (0.01–0.22)	0.27 ± 0.33 (0.19) (0.01–1.11)	0.32 ± 0.34 (0.2) (0.03–1.08)	0.41 ± 0.47 (0.24) (0.03–1.32)
SM	0.1 ± 0.12 (0.04) (0-0.3)	0.08 ± 0.07 (0.06) (0.01–0.25)	0.36 ± 0.28 (0.2) (0.05–0.78)	0.35 ± 0.3 (0.19) (0.05–0.79)	0.5 ± 0.52 (0.35) (0.02–1.39)
CM	0.15 ± 0.16 (0.1) (0.01–0.51)	0.13 ± 0.1 (0.11) (0-0.29)	0.12 ± 0.13 (0.08) (0.01–0.37)	0.22 ± 0.2 (0.12) (0.05–0.64)	0.48 ± 0.31 (0.51) (0.04–0.97)
p	0.634	0.304	0.113	0.466	0.692

Kruskal-Wallis test.

AM, additive manufacturing; SM, subtractive manufacturing; CM, conventional molding.

Table 3
Comparison of analog absolute linear deviations among manufacturing groups (mm)

Group	Right central incisor width	Left central incisor width	Right central incisor height	Left central incisor height	Intercanine distance
	Mean ± SD (median) (min-max)	Mean ± SD (median) (min-max)	Mean ± SD (median) (min-max)	Mean ± SD (median) (min-max)	Mean ± SD (median) (min-max)
AM	0.16 ± 0.12 (0.12) (0.03–0.4)	0.07 ± 0.04 (0.07) (0.01–0.15)	0.46 ± 0.24 (0.41) (0.22–1.05)	0.33 ± 0.18 (0.3) (0.11–0.75)	0.55 ± 0.46 (0.45) (0-1.41)
SM	0.13 ± 0.12 (0.1) (0.01–0.34)	0.12 ± 0.09 (0.1) (0.02–0.3)	0.37 ± 0.28 (0.33) (0.04–0.97)	0.28 ± 0.15 (0.26) (0.05–0.57)	0.68 ± 0.47 (0.71) (0.1–1.66)
CM	0.23 ± 0.17 (0.21) (0.02–0.53)	0.11 ± 0.11 (0.07) (0-0.32)	0.41 ± 0.4 (0.3) (0.04–1.28)	0.46 ± 0.34 (0.46) (0.02–0.89)	0.72 ± 0.4 (0.74) (0.15–1.47)
p	0.279	0.399	0.599	0.557	0.500

Kruskal-Wallis test.

AM, additive manufacturing; SM, subtractive manufacturing; CM, conventional molding.

Depth deviation analysis

Overall depth deviations differed significantly among the manufacturing groups (p = 0.001). Although the mean depth deviation values were numerically close to zero in all groups, the CM group showed a significantly lower mean depth deviation value than both the SM (p = 0.001) and AM (p = 0.021) groups. No significant difference was found between the SM and AM groups (p > 0.05) (Table 4).

Table 4
Comparison of overall depth deviations among manufacturing groups (mm)

Manufacturing group	Mean ± SD	Median (min, max)
AM	0.01 ± 0.12[a]	0.01 (-0.96, 0.49)
SM	0.02 ± 0.06[a]	0.02 (-0.16, 0.22)
CM	-0.002 ± 0.13[b]	-0.01 (-0.30, 0.46)
p = 0.001*		

Kruskal-Wallis test followed by Dunn test. *$p < 0.05$. Different superscript lowercase letters indicate statistically significant differences between groups.

AM, additive manufacturing; SM, subtractive manufacturing; CM, conventional molding.

When inciso-cervical levels were analyzed within each manufacturing group and tooth type, neither the AM nor the SM group showed significant differences among levels for any tooth type ($p > 0.05$). In the CM group, however, significant differences were observed among inciso-cervical levels for central incisors ($p = 0.001$) and lateral incisors ($p = 0.015$), but not for canines ($p = 0.484$). In the central incisors of the CM group, depth deviation values decreased from the cervical to the incisal level. In the lateral incisors of the CM group, the cervical level showed significantly higher values than the incisal level ($p = 0.004$) (Table 5).

Depth deviations differed significantly according to tooth type ($p = 0.001$). Canines showed the highest mean depth deviation values (0.08 ± 0.11), followed by lateral incisors (0.001 ± 0.07), while central incisors showed the lowest values (-0.05 ± 0.10). Pairwise comparisons revealed significant differences among all tooth types ($p = 0.001$) (Table 6).

No significant differences were found among mesio-distal regions ($p = 0.453$) (Table 7).

Table 5
Inciso-cervical depth deviations by manufacturing group and tooth type (mm)

Group	Tooth type	Cervical	Middle	Incisal	p
		Mean ± SD (median) (min, max)	Mean ± SD (median) (min, max)	Mean ± SD (median) (min, max)	
AM	Central incisor	-0.05 ± 0.06 (-0.05) (-0.20, 0.07)	-0.05 ± 0.09 (-0.05) (-0.35, 0.14)	-0.07 ± 0.20 (-0.03) (-0.96, 0.14)	0.675
	Lateral incisor	-0.01 ± 0.05 (-0.01) (-0.14, 0.09)	0.002 ± 0.05 (-0.01) (-0.12, 0.09)	0.02 ± 0.07 (0.03) (-0.14, 0.20)	0.177
	Canine	0.08 ± 0.09 (0.07) (-0.10, 0.30)	0.09 ± 0.09 (0.08) (-0.10, 0.30)	0.12 ± 0.12 (0.11) (-0.08, 0.49)	0.330
SM	Central incisor	-0.01 ± 0.06 (0) (-0.16, 0.09)	0.002 ± 0.04 (0) (-0.11, 0.08)	-0.02 ± 0.04 (-0.02) (-0.10, 0.05)	0.263
	Lateral incisor	0.03 ± 0.06 (0.05) (-0.15, 0.11)	0.03 ± 0.05 (0.03) (-0.10, 0.17)	0.02 ± 0.04 (0.02) (-0.04, 0.13)	0.183
	Canine	0.05 ± 0.08 (0.06) (-0.15, 0.22)	0.05 ± 0.07 (0.06) (-0.07, 0.19)	0.03 ± 0.07 (0.03) (-0.09, 0.20)	0.161
CM	Central incisor	-0.01 ± 0.06[a] (-0.02) (-0.12, 0.18)	-0.07 ± 0.07[b] (-0.07) (-0.25, 0.07)	-0.13 ± 0.09[c] (-0.14) (-0.30, 0.07)	0.001*
	Lateral incisor	0.0003 ± 0.07[a] (0.01) (-0.14, 0.14)	-0.02 ± 0.07[ab] (-0.03) (-0.18, 0.16)	-0.07 ± 0.10[b] (-0.08) (-0.22, 0.15)	0.015*
	Canine	0.08 ± 0.14 (0.06) (-0.23, 0.46)	0.09 ± 0.14 (0.09) (-0.27, 0.36)	0.11 ± 0.15 (0.13) (-0.20, 0.44)	0.484

Kruskal-Wallis test followed by Dunn test. *$p < 0.05$. Different superscript lowercase letters indicate statistically significant differences among inciso-cervical levels within the same tooth type and manufacturing group.

AM, additive manufacturing; SM, subtractive manufacturing; CM, conventional molding.

Table 6
Comparison of depth deviations among tooth types (mm)

Tooth type	Mean ± SD	Median (min, max)
Central incisor	-0.05 ± 0.10[a]	-0.03 (-0.96, 0.18)
Lateral incisor	0.001 ± 0.07[b]	0.01 (-0.22, 0.20)
Canine	0.08 ± 0.11[c]	0.07 (-0.27, 0.49)
p = 0.001*		

Kruskal-Wallis test followed by Dunn test. *p < 0.05. Different superscript lowercase letters indicate statistically significant differences between tooth types.

Table 7
Comparison of depth deviations among mesio-distal regions (mm)

Mesio-distal region	Mean ± SD	Median (min, max)
Mesial	0.001 ± 0.11	0.01 (-0.96, 0.49)
Middle	0.02 ± 0.10	0.01 (-0.30, 0.43)
Distal	0.02 ± 0.11	0.01 (-0.39, 0.46)
p = 0.453		

Kruskal-Wallis test.

DISCUSSİON

Mock-ups are important diagnostic and clinical tools in esthetic rehabilitation. They allow the planned restorative outcome to be evaluated before irreversible tooth preparation and facilitate communication among the clinician, dental technician, and patient [8, 10, 13, 16]. In minimally invasive laminate veneer treatments, their importance is not limited to esthetic previewing; they may also serve as preparation guides by defining the planned restorative volume and helping preserve enamel [10, 11, 14, 22]. Therefore, the dimensional accuracy of mock-ups is directly related to the reliability of esthetic simulation, preparation depth control, and the predictability of the definitive restoration.

In the present study, the dimensional accuracy of six-unit anterior mock-ups fabricated using conventional molding, additive manufacturing, and subtractive manufacturing techniques was evaluated using surface-to-surface matching analysis, digital and analog linear measurements, and depth deviation analysis. The null hypothesis was partially rejected. Significant differences were found among the manufacturing techniques in terms of surface matching and depth deviation, whereas no significant

differences were observed for linear measurements. These findings indicate that the manufacturing technique affects the three-dimensional and volumetric accuracy of mock-ups, although the evaluated techniques may reproduce selected macroscopic linear dimensions with comparable accuracy.

Surface-to-surface matching analysis showed that the subtractive manufacturing group had the highest agreement with the reference digital design, followed by the additive manufacturing and conventional molding groups. This finding is consistent with Cattoni et al. [13], who reported significantly lower deviations for milled mock-ups than for conventionally molded mock-ups, indicating higher accuracy with a fully digital milling workflow. Similarly, Taha et al. [17] reported that CAD mock-ups fabricated by subtractive manufacturing showed the lowest root mean square (RMS) deviation values among the evaluated workflows. In contrast, Falahchai et al. [21] reported higher trueness for conventionally fabricated mock-ups than for digitally fabricated mock-ups. This discrepancy may be attributed to differences in study design, reference datasets, clinical and in vitro conditions, scanning protocols, materials, manufacturing systems, and evaluation methods. In particular, intraoral placement and scanning procedures may introduce variables that differ from model-based in vitro workflows. These contrasting findings indicate that mock-up accuracy is determined not only by whether the workflow is digital or conventional, but also by the specific protocol, material, device, operator, and evaluation method used. In the present study, the higher surface accuracy of the subtractive group may be attributed to the use of prepolymerized PMMA discs, which provide homogeneous material properties and are not affected by polymerization shrinkage during fabrication [23]. The additive manufacturing group showed intermediate surface matching values in this study. Although additive manufacturing offers advantages such as reduced material waste, simplified digital workflow, and the ability to fabricate complex geometries, its accuracy may be affected by the layer-by-layer manufacturing mechanism and production parameters [15, 16]. Print orientation, layer thickness, photopolymerization shrinkage, printer technology, resin composition, and post-curing procedures may influence the final dimensional accuracy of printed restorations [17, 20, 24]. Moon et al. [20] reported that the dimensional accuracy of three-dimensionally printed temporary restorations fabricated using DLP and LCD systems varied according to printer type and restoration size, with larger restorations showing higher RMS values. In the present study, the use of an LCD-based three-dimensional printer may have contributed to localized deviations, particularly on curved labial surfaces where staircase effects related to layer-by-layer manufacturing and polymerization shrinkage may occur [20, 24]. Nevertheless, the additive group showed numerically higher surface matching than the conventional group and depth deviation values close to zero. This suggests that additive manufacturing may be a clinically relevant alternative when printing and post-processing parameters are properly controlled.

The lower surface matching values observed in the conventional molding group may be explained by the operator-dependent nature of the silicone index technique. Cattoni et al. [13] reported that molded mock-ups showed higher deviations than milled mock-ups and emphasized that the conventional workflow is more operator dependent. Taha et al. [17] also stated that the incorporation of an index fabrication step, whether conventional or digital, may introduce discrepancies and reduce accuracy compared with fully digital workflows. In the present study, the conventional group showed a significant inward volumetric

deviation. This finding supports the assumption that manual procedures, silicone index seating, pressure application, and finishing steps may affect the final morphology of the mock-up.

No statistically significant differences were found among the three manufacturing groups for any of the digital or analog linear measurements. This result indicates that all techniques were able to reproduce global tooth dimensions, such as central incisor width, central incisor height, and intercanine distance, with comparable fidelity to the reference design. However, the absence of significant differences in linear measurements should not be interpreted as equivalent overall three-dimensional accuracy. Linear measurements evaluate only selected distances between defined anatomical points and may fail to detect localized surface contour deviations or regional volumetric changes. This explains why significant differences were detected in surface matching and depth deviation analyses, whereas linear measurements remained statistically similar. Lo Giudice et al. [25] also emphasized that caution is needed when interpreting digital measurements of scanned objects, since dimensional changes occurring during digitization may influence the relationship between virtual analysis and clinical behavior.

Depth deviation analysis represents one of the clinically most relevant aspects of the present study. The subtractive and additive manufacturing groups showed mean depth deviations close to zero, with no significant difference between them, whereas the conventional molding group exhibited a significant negative deviation tendency. This finding suggests that conventionally fabricated mock-ups may deviate from the reference digital design in the facial dimension and may affect the accurate transfer of the planned restorative volume when the mock-up is used as a preparation guide. Therefore, deviations in mock-up thickness may lead to errors in preparation depth control and reduce the predictability of the space required for ceramic restoration [14, 22].

The clinical importance of mock-up thickness has been emphasized by Li et al. [14] and Luo et al. [22]. Li et al. [14] reported that mock-ups fabricated using silicone matrices were generally thicker than their corresponding diagnostic waxings and that silicone matrix design significantly affected thickness accuracy. Luo et al. [22] also found that mock-ups were significantly thicker than digital waxings, with the greatest discrepancy observed at the cervical region. Although these studies reported positive deviations, whereas the present study found a negative deviation tendency in the conventional group, the available evidence collectively indicates that conventionally fabricated mock-ups are highly sensitive to procedural variables. The direction and magnitude of deviation may vary depending on silicone matrix design, seating pressure, resin flow, polymerization behavior, and the timing and extent of excess material removal.

Depth deviations also differed significantly according to tooth type. In the present study, the highest values were observed in canines, whereas the lowest values were observed in central incisors. This finding may be related not only to the anatomical morphology of the anterior teeth but also to the distribution of pressure applied during conventional molding. Li et al. [14] applied constant pressure from the bilateral premolar region during silicone matrix seating and reported that thickness deviations

tended to increase with increasing distance from the premolar areas. In the present study, pressure was applied from the central region; therefore, increasing distance from the pressure application area may have affected index stability and resin distribution, particularly in the canine region. In addition, Lo Giudice et al. [25] suggested that curvature differences in the canine region may influence measurement deviation ranges. Therefore, the higher depth deviations observed in canines may be explained by the combined effects of pressure application direction, silicone index support, resin flow, and the anatomical curvature of the canine region [14, 25].

The inciso-cervical analysis showed that the subtractive and additive manufacturing groups had a more homogeneous volumetric distribution. In contrast, the conventional molding group demonstrated a progressive inward deviation from the cervical to the incisal level in central and lateral incisors. This finding suggests that digitally fabricated mock-ups may reproduce the planned restorative volume more consistently along the inciso-cervical dimension. Conversely, the conventional technique may be more susceptible to localized dimensional changes related to index seating, pressure application, resin flow, and finishing procedures. Luo et al. [22] reported that the greatest discrepancy was observed in the cervical region. In the present study, however, a more pronounced inward deviation was observed toward the incisal region in the conventional group. This difference suggests that the inciso-cervical deviation pattern of molded mock-ups is not uniform and may vary depending on the fabrication protocol used.

No significant differences were observed among mesio-distal regions. This result indicates that volumetric deviations were relatively homogeneously distributed in the mesio-distal direction for all three manufacturing techniques. Therefore, the dimensional errors observed in the present study appear to be influenced more by tooth morphology and inciso-cervical anatomy than by mesio-distal position. This finding supports the importance of evaluating the facial surface not only with whole-surface averages but also according to clinically relevant anatomical regions.

From a clinical perspective, the results of this study support the use of fully digital workflows when high dimensional accuracy is required, particularly in mock-up-guided minimally invasive veneer preparations. Subtractive manufacturing showed the highest surface matching and stable volumetric behavior. Additive manufacturing showed depth deviations close to zero and may be considered a practical alternative when optimized printing parameters are used. Conventional molding remains a simple, inexpensive, and widely used technique. However, when the mock-up is intended not only for esthetic previewing but also for guiding preparation depth, its susceptibility to operator-dependent and region-specific dimensional deviations should be considered [13, 14, 22].

Limitations

This study has several limitations. First, all fabrication and measurement procedures were performed under in vitro conditions; therefore, intraoral factors such as saliva, soft tissue interference, temperature changes and moisture were not simulated. Second, only one LCD-based three-dimensional printer, one five-axis milling unit, and specific resin materials were evaluated, which limits the generalizability of the

findings to other devices, printing technologies, and material formulations [20]. Third, all procedures were performed by a single experienced operator. Although this improved standardization, it did not allow assessment of inter-operator variability, which is particularly relevant for conventional molding [13, 21]. Future studies should include different additive and subtractive manufacturing systems, different silicone index designs, multiple operators, and in vivo validation to further evaluate the clinical relevance of these findings.

CONCLUSIONS

Within the limitations of this in vitro study, the manufacturing technique affected the dimensional accuracy of anterior mock-ups. Subtractive manufacturing showed the highest surface-to-surface matching with the reference digital design; however, this difference was significant only when compared with the conventional molding group. Additive manufacturing showed intermediate surface matching values and may be considered a clinically applicable alternative when printing and post-processing parameters are properly controlled. Although mean depth deviation values were numerically close to zero in all groups, the conventional molding group showed significantly lower values than both digitally fabricated groups, indicating a tendency toward more inward deviations. No significant differences were found among the groups in digital or analog linear measurements, suggesting that all three techniques reproduced selected macroscopic dimensions with comparable accuracy. Depth deviations differed according to tooth type and inciso-cervical level, whereas no significant differences were observed among mesio-distal regions. Therefore, when mock-ups are used as preparation guides, tooth-specific, inciso-cervical, and operator-dependent dimensional deviations should be considered, particularly for conventionally fabricated mock-ups.

Abbreviations

AM
Additive manufacturing
ANOVA
Analysis of variance
CAD/CAM
Computer-aided design/computer-aided manufacturing
CM
Conventional molding
DLP
Digital light processing
DSD
Digital smile design
LCD
Liquid crystal display
PMMA

Polymethyl methacrylate
PVS
Polyvinylsiloxane
RMS
Root mean square
SM
Subtractive manufacturing
STL
Standard Tessellation Language

Declarations

Ethics approval and consent to participate

This study was approved by the Trakya University Faculty of Medicine Non-Interventional Scientific Research Ethics Committee (Protocol No. TÜTF-GOBAEK 2024/314; Decision No. 12/24; 24 June 2024). Written informed consent was obtained from all participants before their data were used in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

ÖA conducted the study, performed the experimental procedures and data collection, and prepared the initial draft of the manuscript. AK supervised the study and contributed to the study design and

interpretation of the findings. ODD critically reviewed and revised the manuscript. All authors read and approved the final manuscript.

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Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Figures

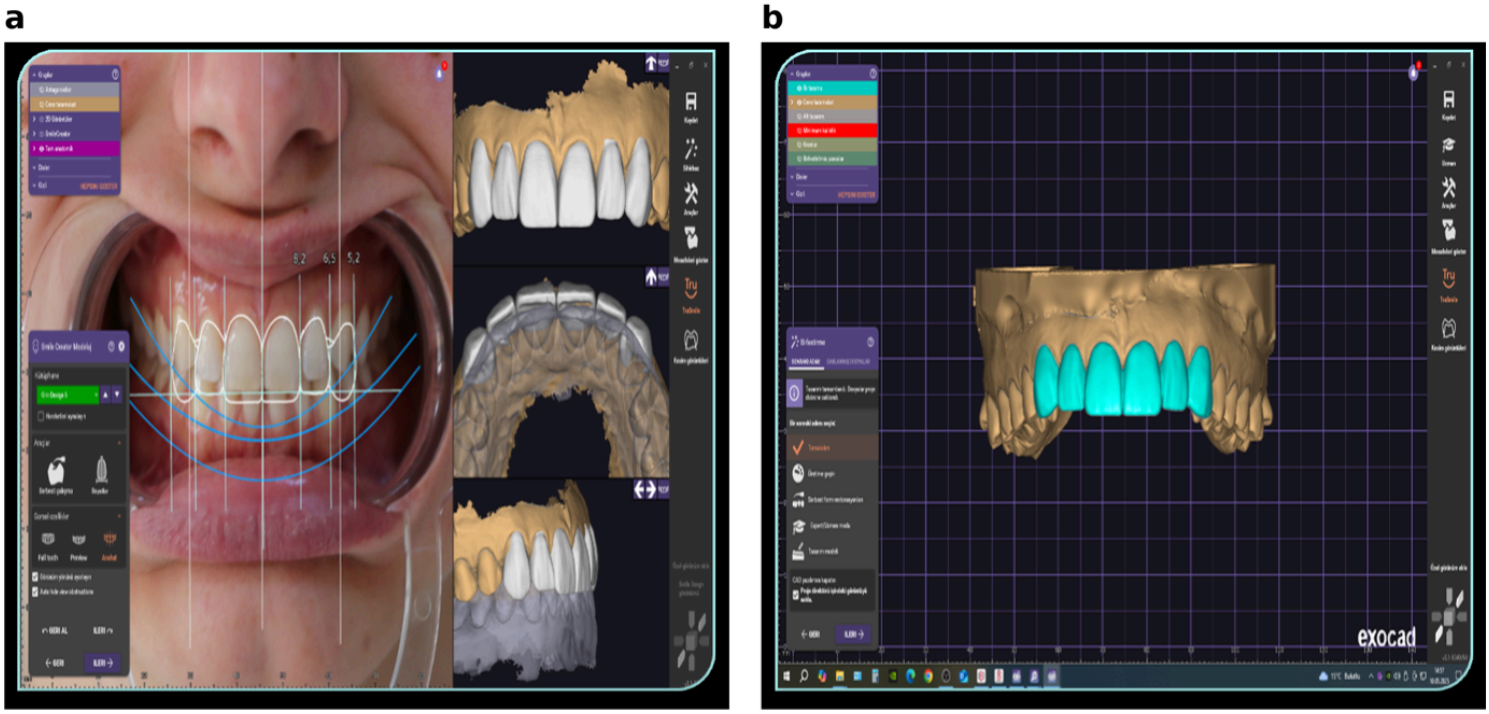


Figure 1

Digital smile design and three-dimensional digital waxing. a Smile design based on facial and dental reference lines with simultaneous three-dimensional visualization. b Completed six-unit maxillary anterior digital waxing.

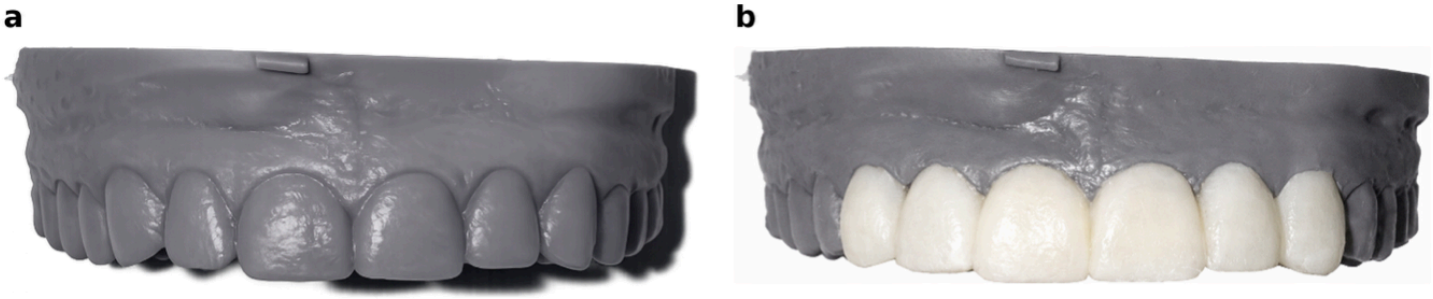


Figure 2

Preoperative model before and after mock-up seating. a Preoperative maxillary model. b Six-unit anterior mock-up seated on the corresponding preoperative model.

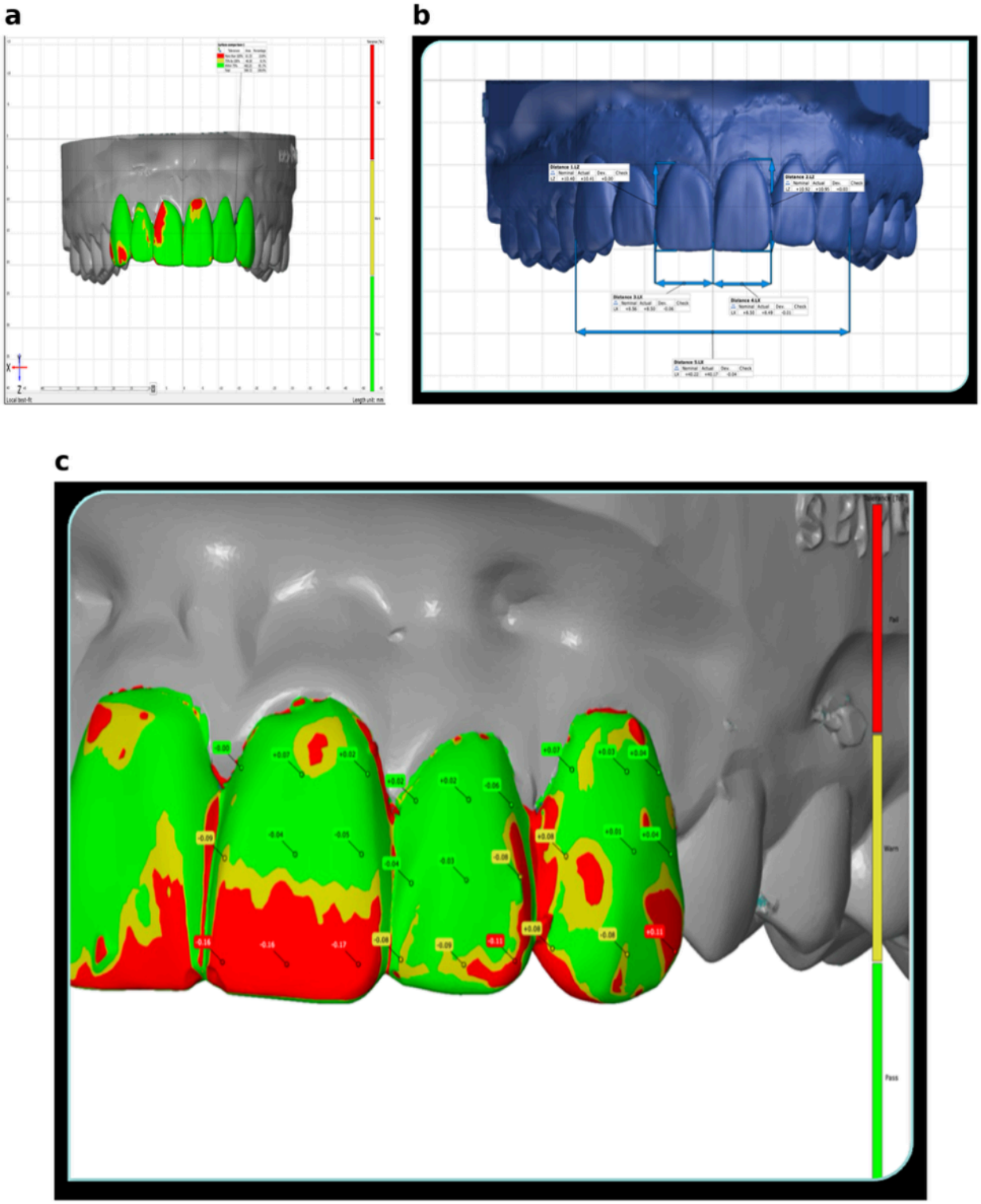


Figure 3

Dimensional accuracy assessment procedures. a Surface-to-surface matching analysis using a color-coded deviation map. b Digital linear measurements of the right and left central incisor widths and heights and the intercanine distance. c Depth deviation analysis at nine standardized points on the labial surfaces of the anterior teeth.