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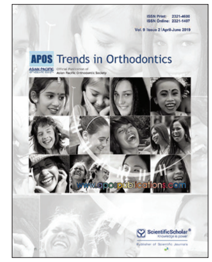

Original Article

Comparative evaluation of dental measurements using 3D virtual models and 3D printed models

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ABSTRACT

Objectives: Accurate dental measurements are essential for orthodontic diagnosis, treatment planning, and long-term patient monitoring. With the increased use of digital workflows, 3D virtual models and 3D printed models are being adopted as alternatives to traditional plaster casts. This study aimed to evaluate and compare key orthodontic dental parameters obtained from 3D virtual models and 3D printed models to determine their reliability and potential for clinical interchangeability.

Material and Methods: Seventeen pre-treatment intraoral scans (iTero, Align Technology, USA) meeting the inclusion criteria were analyzed. The scans were divided into three groups: Group A – 3D virtual models assessed using GOM Inspect software; Group B – 3D virtual models assessed using OrthoCAD software; and Group C – corresponding 3D printed models fabricated using a Phrozen Sonic Mighty 4K printer and evaluated with dental loupes and Vernier calipers. Measured parameters included maxillary and mandibular intercanine widths, intermolar widths, overjet, overbite, and Bolton's overall and anterior ratios. Normality was assessed with the Shapiro–Wilk test. One-way analysis of variance was used for intergroup comparisons, Pearson's correlation tested associations between methods, and the intraclass correlation coefficient (ICC) determined reproducibility.

Results: All measurements followed a normal distribution. No statistically significant differences were found among the three groups for any parameter ($P > 0.05$). For example, the mean maxillary intercanine width was 34.19 ± 1.36 mm (Group A), 34.41 ± 1.34 mm (Group B), and 34.17 ± 1.34 mm (Group C) ($P = 0.849$). Mean mandibular intermolar width was 44.83 ± 2.77 mm (Group A), 44.89 ± 2.88 mm (Group B), and 44.72 ± 2.69 mm (Group C) ($P = 0.982$). Overjet and overbite showed similarly close agreement, with $P = 0.999$ and 1.000, respectively. ICC analysis demonstrated excellent reproducibility across all methods (ICC = 0.98). Pearson's correlation revealed strong agreement between GOM and 3D printed models for all parameters, while OrthoCAD showed weaker correlation for sum-of-teeth measurements and Bolton's ratios.

Conclusion: 3D virtual models and 3D printed models provide equivalent and reproducible dental measurements, making them reliable alternatives to conventional plaster models for orthodontic diagnosis, treatment planning, and outcome assessment. Given their interchangeability, digital workflows can be confidently integrated into clinical practice, offering advantages in storage, accessibility, and patient communication. Future research should explore their performance in severe crowding cases, assess cost-effectiveness, and investigate optimization of software such as OrthoCAD to improve consistency.

Keywords: 3D printing, Bolton's analysis, Dental measurements, Digital models, Orthodontics

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INTRODUCTION

Dental study models are fundamental tools in orthodontics for diagnosing malocclusions and formulating treatment plans.[1] Conventional plaster casts, though widely used, are fragile, require extensive storage space, and are difficult to duplicate or share.[2,3] To address these limitations, digital models were introduced in the late 1990s.[1,4] OrthoCAD™ was among the first platforms to provide electronic models, reducing many of the problems associated with plaster casts.[5] Subsequent studies confirmed that digital models can achieve accuracy comparable to conventional casts.[6,7]

Intraoral scanners, such as the iTero® system, further advanced digital workflows by generating precise, powder-free scans. These virtual files can also be converted into tangible replicas using 3D printing technology, thereby combining the advantages of digital storage and communication with the familiarity of physical models.[8-12] Previous investigations have demonstrated the reliability of intraoral scans and their applicability in analyses such as Bolton's, supporting their clinical use.[5-7,13]

Despite these advances, limited research has directly compared the accuracy of dental measurements across different digital platforms and 3D printed models. Considering the growing adoption of digital workflows in orthodontics, it is clinically important to establish whether these approaches provide interchangeable results with plaster casts.

Accordingly, the present study evaluates intercanine and intermolar widths, overjet, overbite, and Bolton's ratios across three approaches: (i) digital models analyzed with GOM Inspect, (ii) digital models analyzed with OrthoCAD, and (iii) 3D printed models measured with calipers under magnification. The aim is to determine agreement and reproducibility among these methods, thereby providing evidence to guide the transition from plaster to digital and printed model workflows in orthodontic practice.

Aim and objectives

Aim

To evaluate and compare dental parameters measured directly on digital models versus 3D printed models.

Objectives

- To assess the overjet, overbite, intermolar and intercanine width, and Boltons analysis on digital models using GOM Software
- To assess the overjet, overbite, intermolar and intercanine width, and Boltons analysis on digital models using OrthoCAD Software
- To assess the overjet, overbite, intermolar and intercanine width, and Boltons analysis on a 3D printed model using loupes
- To compare dental parameters measured using GOM, OrthoCAD, and 3D printed models.

Null hypothesis

There is no statistically significant difference in dental parameters measured between the two intraoral scanners and 3D printed models.

MATERIAL AND METHODS

Sample size

The sample size was calculated using data from a previous study by Bootvong *et al.*[6] (correlation coefficient for overbite, $r = 0.903$), yielding a required minimum of 17 samples.

Source of data

Seventeen pre-treatment intraoral scans of patients reporting to the department of orthodontics and dentofacial orthopedics of a dental hospital were selected through random number generation from a pool of 100 eligible scans acquired over the past 2 years. Approval for the study was obtained from the Institutional Ethical Committee.

Inclusion criteria

- Full complement of permanent teeth (excluding third molars)
- Normal crown morphology
- Pre-treatment scans acquired using the iTero intraoral scanner
- Minimal to moderate crowding only (Little's Irregularity Index ≤ 4 mm) to avoid segmentation errors in software analysis.

Exclusion criteria

- Retained deciduous teeth
- Abnormal tooth morphology
- Missing teeth (excluding third molars)
- Severe crowding (>4 mm).

Study groups

- Group A: 17 digital scans evaluated through GOM Inspect software [Figure 1]
- Group B: 17 digital scans evaluated through OrthoCAD software [Figure 2]
- Group C: 17 corresponding 3D printed models evaluated using dental loupes and Vernier calipers [Figures 3 and 4].

Scanner and software settings

- iTero intraoral scanner (Align Technology, USA): Resolution: Native acquisition at 35 µm; powder-free scanning; calibrated before each use as per manufacturer protocol

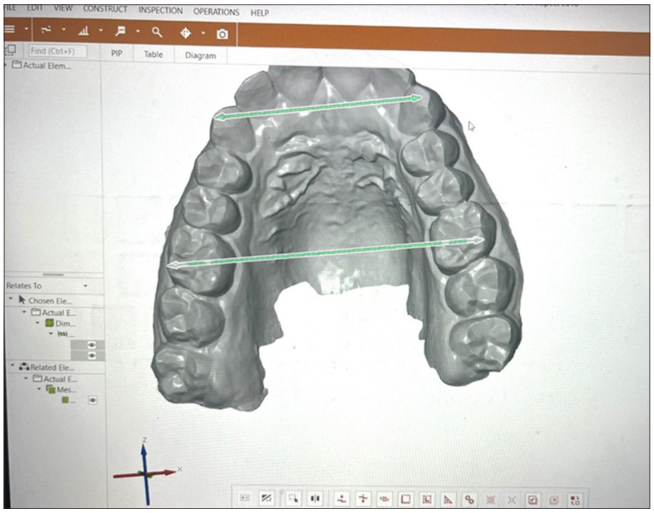

Figure 1: iTero scan.

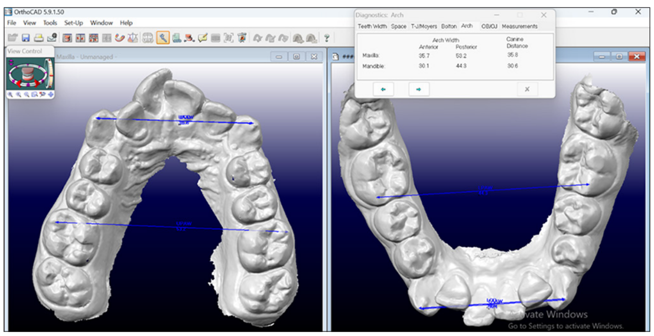

Figure 2: OrthoCAD software.

Figure 3: 3D printing process (a) ArchForm software, (b) CHITUBOX Slicer, (c) Phrozen Sonic Mighty 4k Printer and ANYCUBIC Wish and Cure Plus machine, and (d) 3D Printed models with supports attached on the platform.

- GOM inspect (GOM GmbH, Germany): Default measurement mode with two-point linear distance tool; models automatically aligned to the occlusal plane before measurement

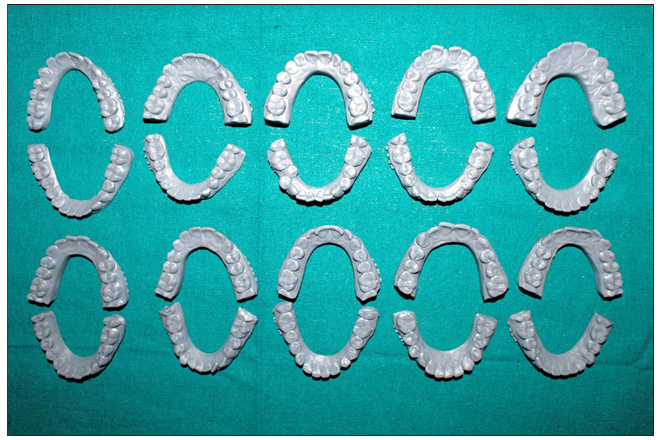

Figure 4: 3D printed models.

- OrthoCAD (Align Technology, USA): Diagnostic mode enabled; linear measurements taken in occlusal view; automatic arch alignment; and trimming applied.

All Standard Tessellation Language (STL) files were trimmed to remove excess base and soft-tissue artifacts before measurement.

3D printing protocol

Digital models (STL format) were prepared in ArchForm software for base trimming, sliced using CHITUBOX Slicer with 50 μm layer thickness, and printed on a Phrozen Sonic Mighty 4K printer using Phrozen Aqua 4K resin. Models were washed and post-cured in an ANYCUBIC Wash and Cure Plus unit. Calibration of the Phrozen Sonic Mighty 4K printer was performed before fabrication, and all printed models underwent standardized resin curing cycles to ensure dimensional accuracy and surface stability [Figure 3].

Measurement protocol

Dental parameters assessed

- Maxillary and mandibular inter-canine widths (cuspal tips of right and left canines) [Figure 5]
- Maxillary and mandibular intermolar widths (mesiobuccal cusp tips of right and left first molars) [Figure 6]
- Overjet (horizontal distance between maxillary and mandibular central incisor edges) [Figure 7]
- Overbite (vertical overlap of maxillary and mandibular central incisors perpendicular to the occlusal plane) [Figure 8]
- Bolton's anterior and overall ratios (sum of mesiodistal widths of designated teeth) [Figure 9].

Procedure

- In Groups A and B, measurements were taken directly on the virtual models using the respective software's two-point linear measurement tool [Figures 6a-8a for GOM; Figures 6b-8b for OrthoCAD].
- In Group C, measurements were taken on printed models using a stainless-steel Vernier caliper (accuracy ± 0.01 mm) under 3.5× magnification dental loupes [Figures 6c-8c].
- Each measurement was performed 3 times by the same examiner on separate days, and the mean value was recorded.

Reliability assessment

- Intra-examiner reliability: Assessed by repeating measurements on 20% of samples after a 2-week interval (ICC = 0.98)
- Inter-examiner reliability: Assessed by a second calibrated examiner on the same 20% of samples (ICC = 0.97).

Bias control and limitations

- Examiners were blinded to group allocation during measurements
- Potential sources of error, such as scanning artifacts (saliva, limited mouth opening, and tongue interference) and 3D printing inaccuracies, were acknowledged
- The degree of crowding was controlled in the inclusion criteria to reduce segmentation errors; however, other malocclusion variations were not standardized and are considered a limitation.

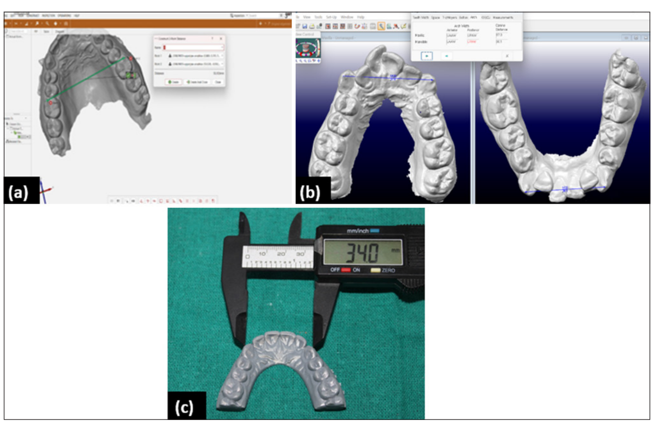

Figure 5: 2 point measurements of intercanine distance through different techniques (a) GOM software, (b) OrthoCAD software, and (c) Vernier caliper.

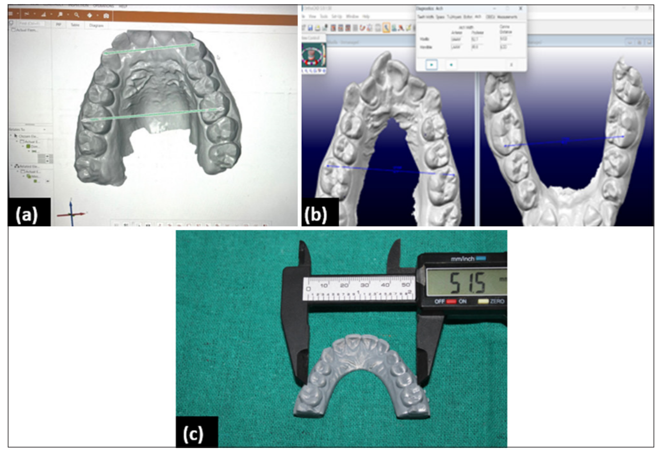

Figure 6: 2 point measurements through different techniques (a) GOM software, (b) OrthoCAD software, and (c) Vernier caliper.

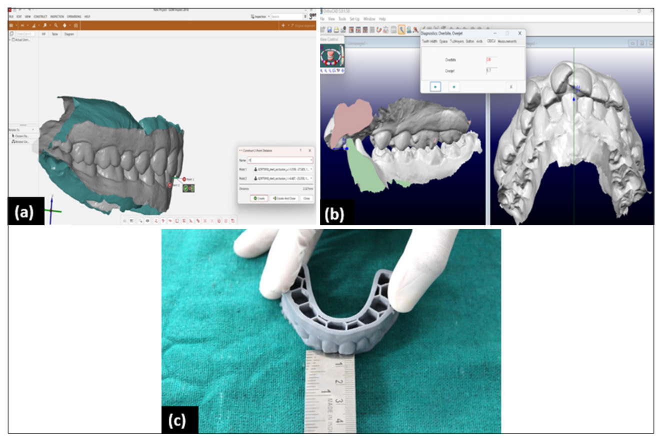

Figure 7: 2 point measurements of overjet through different techniques (a) GOM software, (b) OrthoCAD software, and (c) Vernier caliper.

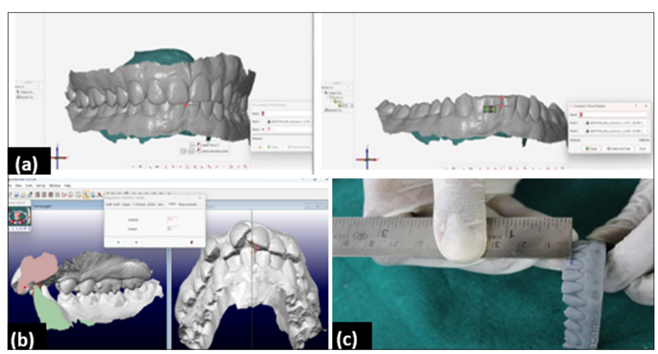

Figure 8: Two-point measurements of overbite through different techniques – (a) GOM inspect software, (b) OrthoCAD software, and (c) Manual.

Statistical analysis

All statistical analyses were performed using Statistical Package for the Social Sciences software (version 26.0, IBM Corp., Armonk, NY, USA). Data distribution was assessed using the Shapiro–Wilk test, and Levene's test confirmed homogeneity of variances. As both assumptions were satisfied, one-way analysis of variance (ANOVA) was used to compare mean values of each dental parameter among the three groups.

For each ANOVA result, 95% confidence intervals (CI) for the mean differences were calculated alongside *P*-values to provide precision estimates. Pearson's correlation coefficient (*r*) was used to determine the strength of association between each pair of methods. Intraclass correlation coefficient (ICC) analysis was performed to assess reproducibility, with ICC >0.90 interpreted as excellent agreement.

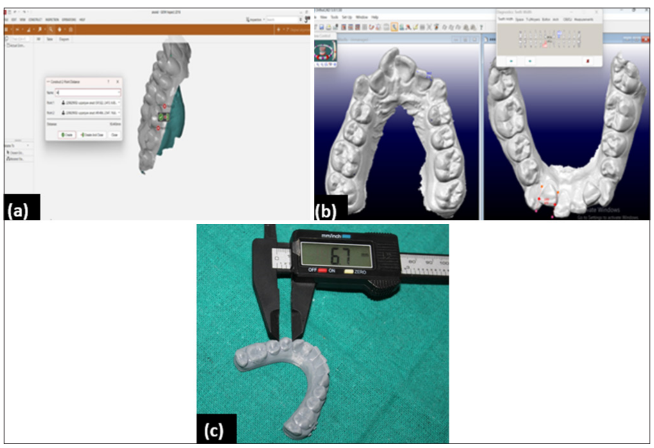

Figure 9: 2 point measurements of mesiodistal width through different techniques (a) GOM software, (b) OrthoCAD software, and (c) Vernier caliper.

Parameters where OrthoCAD demonstrated weaker correlations (notably in sum-of-teeth and Bolton's ratios) were attributed to segmentation algorithm differences, which may alter mesiodistal tooth width identification, especially in rotated teeth or with tight interproximal contacts. A significance threshold of $P \leq 0.05$ was applied for all analyses.

RESULTS

Comparison of intercanine and intermolar widths

No statistically significant differences were observed in maxillary or mandibular intercanine widths and intermolar widths among the three methods ($P > 0.05$ for all) [Table 1].

- Maxillary intercanine width: Mean (±SD) was 34.19 ± 1.36 mm (GOM), 34.41 ± 1.34 mm (OrthoCAD), and 34.17 ± 1.34 mm (3D printed). 95% CI for mean difference between GOM and 3D printed: −0.21 to 0.23 mm; $P = 0.849$; ICC = 0.98.
- Mandibular intercanine width: Means were 25.29 ± 1.91 mm, 25.53 ± 1.89 mm, and 25.24 ± 1.94 mm; 95% CI: −0.26 to 0.30 mm; $P = 0.890$; ICC = 0.99
- Maxillary intermolar width: Means were 51.46 ± 3.36 mm, 51.56 ± 3.37 mm, and 51.45 ± 3.34 mm; 95% CI: −0.20 to 0.21 mm; $P = 0.995$; ICC = 1.00
- Mandibular intermolar width: Means were 44.83 ± 2.77 mm, 44.89 ± 2.88 mm, and 44.72 ± 2.69 mm; 95% CI: −0.24 to 0.25 mm; $P = 0.982$; ICC = 0.99.

Comparison of overjet and overbite

Overjet and overbite measurements were highly consistent between methods ($P > 0.05$; ICC ≥ 0.99) [Table 2].

Table 1: Comparison of intercanine and intermolar widths among three methods with 95% CI and *P* values.

Parameter	Method	Mean	SD	95% CI	*P*-value
Maxillary intercanine width	GOM	34.194	1.355	33.55–34.84	0.849
Maxillary intercanine width	OrthoCAD	34.411	1.337	33.78–35.05	0.849
Maxillary intercanine width	3D Printed	34.171	1.342	33.53–34.81	0.849
Mandibular intercanine width	GOM	25.288	1.905	24.38–26.19	0.89
Mandibular intercanine width	OrthoCAD	25.532	1.892	24.63–26.43	0.89
Mandibular intercanine width	3D Printed	25.235	1.937	24.31–26.16	0.89
Maxillary intermolar width	GOM	51.463	3.358	49.87–53.06	0.995
Maxillary intermolar width	OrthoCAD	51.56	3.372	49.96–53.16	0.995
Maxillary intermolar width	3D Printed	51.453	3.343	49.86–53.04	0.995
Mandibular intermolar width	GOM	44.832	2.766	43.52–46.15	0.982
Mandibular intermolar width	OrthoCAD	44.894	2.875	43.53–46.26	0.982
Mandibular intermolar width	3D Printed	44.718	2.694	43.44–46.00	0.982

P-values were calculated using One-way ANOVA. Statistical significance threshold: $P \leq 0.05$ was considered significant. CI: Confidence intervals, SD: Standard deviation

- Overjet: Means were 4.14 ± 1.51 mm, 4.16 ± 1.51 mm, and 4.15 ± 1.49 mm; 95% CI: −0.19 to 0.21 mm; $P = 0.999$; ICC = 1.00.
- Overbite: Means were 2.16 ± 1.09 mm, 2.17 ± 1.09 mm, and 2.17 ± 1.01 mm; 95% CI: −0.15 to 0.17 mm; $P = 1.000$; ICC = 0.99.

Sum-of-teeth measurements

No significant differences were found in the sum of maxillary 6, mandibular 6, maxillary 12, and mandibular 12 tooth widths among the three methods ($P > 0.05$).

Strong correlations were observed between GOM and 3D printed models ($r \geq 0.99$), but OrthoCAD showed weaker, non-significant correlations with the other two methods for these parameters [Table 3].

Bolton's analysis

Both anterior and overall Bolton's ratios showed no significant intergroup differences ($P > 0.05$). ICC values between GOM and 3D printed models were ≥0.99, while OrthoCAD demonstrated weaker correlations, likely due to variations in tooth segmentation algorithms.

Table 2: Comparison of overjet and overbite among three methods with 95% CI and *P*-values.

Parameter	Method	Mean	SD	95% CI	*P*-value
Overjet	GOM	4.14	1.507	3.42–4.86	0.999
Overjet	OrthoCAD	4.157	1.509	3.44–4.87	0.999
Overjet	3D Printed	4.147	1.489	3.44–4.85	0.999
Overbite	GOM	2.164	1.086	1.65–2.68	1.0
Overbite	OrthoCAD	2.171	1.09	1.65–2.69	1.0
Overbite	3D Printed	2.165	1.013	1.68–2.65	1.0

P-values were calculated using One-way ANOVA. Statistical significance threshold: $P \leq 0.05$ was considered significant. CI: Confidence intervals, SD: Standard deviation

Overall reproducibility

The ICC for all parameters across all groups was 0.98, indicating excellent reproducibility of measurements irrespective of whether they were obtained on virtual or printed models [Table 4].

DISCUSSION

In this study, intercanine width, intermolar width, overjet, overbite, and Bolton's overall and anterior ratios did not differ significantly across measurements from GOM, OrthoCAD, and 3D-printed models (all $P > 0.05$). Reproducibility was excellent (ICC = 0.98), indicating that both digital and printed workflows yield equivalent linear measurements suitable for orthodontic diagnosis and assessment.

Our findings are consistent with previous reports showing close agreement between digital and conventional methods. Bootvong *et al.*[6] and Keating *et al.*[5,14] demonstrated good to excellent concordance between virtual and plaster models, while Camardella *et al.*[15] and Reuschl *et al.*[16] found no significant differences in transverse or overjet/overbite measurements. Kasparova *et al.*[17] and Wiranto *et al.*[18] confirmed that digital and printed models can be used interchangeably for orthodontic evaluation. In contrast, some studies have highlighted potential variability: Bootvong *et al.*[6] observed a tendency of intraoral scanning to slightly overestimate arch dimensions, and Al Jabri *et al.*[19] reported differences in Bolton's analysis depending on the model type. Leifert *et al.*[20] also noted that methodological differences between digital and manual approaches can influence results.

Table 3: Comparison of sum of maxillary and mandibular teeth among three methods with 95% CI and *P*-values.

Parameter	Method	Mean	SD	95% CI	*P*-value
Sum of Max 6	GOM	46.891	2.197	45.85–47.94	0.806
Sum of Max 6	OrthoCAD	47.058	1.923	46.14–47.97	0.806
Sum of Max 6	3D Printed	46.588	2.202	45.54–47.63	0.806
Sum of Mand 6	GOM	36.819	1.705	36.01–37.63	0.617
Sum of Mand 6	OrthoCAD	37.062	1.304	36.44–37.68	0.617
Sum of Mand 6	3D Printed	36.529	1.679	35.73–37.33	0.617
Sum of Max 12	GOM	95.66	4.34	93.60–97.72	0.828
Sum of Max 12	OrthoCAD	95.937	3.401	94.32–97.55	0.828
Sum of Max 12	3D Printed	95.1	4.298	93.06–97.14	0.828
Sum of Mand 12	GOM	86.652	3.463	85.01–88.30	0.426
Sum of Mand 12	OrthoCAD	87.517	2.865	86.16–88.88	0.426
Sum of Mand 12	3D Printed	86.049	3.44	84.41–87.68	0.426

P-values were calculated using One-way ANOVA. Statistical significance threshold: $P \leq 0.05$ was considered significant. CI: Confidence intervals, SD: Standard deviation

Table 4: Comparison of Bolton's overall and anterior ratios among three methods with 95% CI and *P* values.

Parameter	Method	Mean	SD	95% CI	*P*-value
Overall ratio	GOM	90.62	1.853	89.74–91.50	0.5
Overall ratio	OrthoCAD	91.254	2.046	90.28–92.23	0.5
Overall ratio	3D Printed	90.521	1.959	89.59–91.45	0.5
Anterior ratio	GOM	78.567	2.694	77.29–79.85	0.927
Anterior ratio	OrthoCAD	78.812	2.547	77.60–80.02	0.927
Anterior ratio	3D Printed	78.463	2.811	77.13–79.80	0.927

P-values were calculated using One-way ANOVA. Statistical significance threshold: $P \leq 0.05$ was considered significant. CI: Confidence intervals, SD: Standard deviation

These nuances align with our observation that OrthoCAD showed weaker correlations for sum-of-teeth and Bolton's indices, likely reflecting differences in segmentation algorithms that affect mesiodistal tooth width detection.[5,7,15]

From a clinical standpoint, these results support the use of digital and printed models for orthodontic diagnosis, space analysis, treatment planning, progress monitoring, and outcome assessment. Beyond measurement accuracy, digital workflows provide practical benefits. They are potentially more cost-effective, reducing the need for impression materials, plaster, and storage space, while also allowing long-term electronic archiving.[8-11] They enhance time efficiency by streamlining record acquisition, enabling rapid transmission to laboratories, and reducing turnaround for appliance fabrication.[12] Moreover, intraoral scanning improves patient comfort compared with conventional impressions, often leading to greater acceptance and cooperation. 3D-printed replicas, meanwhile, remain useful when a tangible reference or appliance fabrication model is required. Together, these advantages strengthen the case for incorporating digital workflows into everyday practice.

This investigation has certain limitations. It was conducted at a single center with a modest sample size, which may restrict generalizability. Although inclusion criteria controlled crowding to minimal–moderate levels, other malocclusion characteristics were not standardized. Inter-operator variability was assessed only in a subset of samples, and potential sources of error, such as scanning artifacts, STL trimming, printer calibration, resin shrinkage, and post-curing, were acknowledged but not quantified. Ensuring strict quality control in 3D printing and regular calibration of printers/scanners is essential to maintain accuracy and reproducibility in clinical settings. Furthermore, only linear two-point measurements were evaluated, and no patient-reported outcomes were assessed.

Nevertheless, the study has notable strengths, including examiner blinding, repeated measurements with excellent intra- and inter-examiner ICC values, and the use of a standardized 3D printing protocol with calibration and controlled post-processing. Evaluating both digital software and physical models under magnification also provides a comprehensive comparison of clinically relevant approaches.

Future research should include larger, multicenter studies encompassing severe crowding and complex malocclusions, as well as direct comparisons across scanners, printers, resins, and post-processing protocols. Algorithm-level evaluations are needed to clarify how segmentation affects Bolton's analysis and tooth width detection. Importantly, prospective studies should incorporate economic assessments, workflow efficiency metrics, and patient-reported outcomes, since these factors strongly influence clinical adoption. The development of standardized quality-control guidelines for 3D printing (including calibration and shrinkage checks) would further enhance reliability.

Overall, digital and 3D-printed models demonstrated accuracy and reproducibility comparable to plaster casts for linear dental measurements. Clinicians may confidently integrate these workflows into practice while remaining cautious of software-specific variability, such as the weaker correlations observed with OrthoCAD. Until segmentation algorithms are optimized, verification with an alternative method is advisable when clinical decisions are borderline.

CONCLUSION

This study found no statistically significant differences in intercanine width, intermolar width, overjet, overbite, or Bolton's overall and anterior ratios when comparing 3D virtual models (GOM, OrthoCAD) with 3D printed models, with all methods demonstrating excellent reproducibility (ICC = 0.98). These findings indicate that both digital and printed models can be used interchangeably in orthodontic diagnosis, space analysis, treatment planning, and progress assessment, offering a reliable alternative to conventional plaster casts. Given the comparatively weaker correlations observed for certain parameters in OrthoCAD, future work should focus on optimizing its segmentation algorithms to improve consistency with other digital workflows. Clinicians can confidently use either digital or printed models for routine orthodontic assessment, with awareness of OrthoCAD's current limitations.

Ethical approval: The research/study was approved by the Institutional Review Board at the Institute of Dental Studies and Technologies, approval number IEC/2023/06, dated 24th November 2023.

Declaration of patient consent: Patient's consent was not required as there are no patients in this study.

Financial support and sponsorship: Nil.
Conflicts of interest: There are no conflicts of interest.
Use of artificial intelligence (AI)-assisted technology for manuscript preparation: The authors confirm that they have used artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript or image creation.

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