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A Comparative Study of Plaster Casts and Digital Models for Orthodontic Measurements in Different Crowding Severities

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Abstract

Objectives: This study aimed to evaluate the accuracy of linear measurements between the traditional gold-standard plaster model and digital models (cast scans and intraoral scans) across different severities of dental crowding.

Methods: Fifteen subjects requiring orthodontic treatment were divided into two groups based on crowding severity: mild (≤3.0 mm) and moderate to severe (>3.0 mm). For each subject, three types of models were generated: plaster cast (PC), digital cast scan (CS), and intraoral scan (IOS). Linear measurements were taken using digital calipers for PC and Ortho Analyzer™ software for CS and IOS. The accuracy of measurements was determined using the deviation between the plaster casts and digital models. The accuracy was analyzed using Welch's ANOVA and the Games–Howell multiple comparison test ($p<0.05$).

Results: All three model types demonstrated high intra- and inter-examiner reliability (ICC>0.97). No significant differences were found in the clinical arch length or Bolton ratios between model types. Minor, non-significant underestimations in total tooth width were observed in the digital models, particularly in maxillary teeth with moderate-to-severe crowding (maximum mean difference: 1.65 mm; $p=0.06$).

Conclusions: Both cast scans and intraoral scans are reliable alternatives to plaster casts for orthodontic measurements. While digital models slightly underestimated total tooth widths and Bolton ratios and overestimated clinical arch lengths, these variations remained within clinically acceptable limits. Operator training and scanning protocol standardization remain critical in crowded dentitions.

Keywords: accuracy, Bolton ratio, cast scan, crowding, intraoral scanner

Introduction

Accurate measurement of the arch length and tooth width is crucial in orthodontic diagnosis and treatment planning. Arch length assessments determine the space available for tooth alignment, influencing decisions such as extractions or arch expansion.(1) Similarly, the total tooth width is crucial for evaluating crowding, spacing, and arch form.(2) The Bolton ratio, which compares mesiodistal tooth widths between maxillary and mandibular teeth, is a widely accepted standard for diagnosing inter-arch tooth size discrepancies. Precise Bolton analysis facilitates the achievement of ideal overjet, overbite, and occlusal outcomes in orthodontic therapy.(3)

Plaster casts have long been considered the gold standard for dental model analysis because of their dimensional stability and high tactile accuracy.(4) They enable direct manual measurement and are widely used for visualizing occlusion, evaluating space, and constructing dental appliances. However, plaster casts are associated with several disadvantages; for example, they are susceptible to breakage, require physical storage, and are not easily duplicated or transferred between clinicians.(5) Moreover, inconsistencies in impression materials and pouring techniques can introduce errors, affecting measurement precision.(6) For these reasons, digital models obtained through cast scans or direct intraoral scanning have emerged as efficient and reliable alternatives. They offer several advantages, including enhanced data storage, easier communication, and integration with virtual treatment planning systems.(7) Both cast scans and intraoral scans produce measurements comparable to those obtained from plaster models, with high reproducibility.(8) Digital workflows also reduce chairside time and eliminate the need for physical impressions, improving patient comfort and clinical efficiency.(9)

Despite the benefits, intraoral scanners present challenges, particularly in patients with moderate-to-severe crowding. Limited access to interproximal and lingual areas, overlapping teeth, and patient movement can compromise scan accuracy.(10) In crowded cases, surface stitching errors can result in distortions, particularly in the posterior segments or narrow interproximal spaces. Jacob *et al*.,(11) reported underestimations of arch dimensions in such scenarios because of these technical limitations. Operator skill and experience are also critical factors influencing scan quality in complex cases.(12)

Numerous studies have compared the accuracy of linear measurements between digital and traditional models. Digital models offer acceptable accuracy for clinical use, especially in routine cases.(13,14) However, some investigations noted minor discrepancies in posterior tooth width measurements, attributed to scanner limitations and model curvature.(15) Overall, most studies support the clinical validity of digital methods, while acknowledging specific areas that require caution.

Few studies have specifically addressed the accuracy of digital models across varying degrees of dental crowding. Camardella *et al*.,(16) demonstrated high measurement reliability of scanned plaster casts, regardless of the severity of crowding. However, Martínez-Rodríguez *et al*.,(17) observed that measurement accuracy declined slightly in moderate-to-severe crowding, particularly in the molar regions. Therefore, this study compared the accuracy of linear measurements between plaster models and digital models across varying degrees of dental crowding to provide critical insights into their diagnostic reliability under anatomically challenging conditions. We also investigated whether the degree of dental crowding influences the accuracy of linear measurements obtained from plaster casts and digital models (cast scans and intraoral scans). In addition, we aimed to determine whether these digital models underestimate or overestimate measurements when compared with conventional methods.

The results of this study will help define clinically acceptable thresholds for measurement deviations and guide treatment planning and appliance fabrication. This study also contributes to the standardization of digital scanning protocols, particularly in crowded dentitions, and encourages further innovation in scanning technologies and software development.

Materials and Methods

This study received ethical approval (IRB No. P1-0060/2567) from the Faculty of Dentistry, Naresuan University Human Research Ethical Committee, Thailand. Fifteen subjects were selected from patients in the Department of Orthodontics at the Faculty of Dentistry, Naresuan University, Thailand, from March 2024 to September 2024, using simple random sampling. Based on a power analysis with a large effect size of 1.81, a statistical power of 0.80, and a significance level of 0.05, the minimum required sample size for this study was determined to be 12 participants. The sample size was calculated with the G*Power software version 3.1.9.7 (Heinrich-Heine-University, Düsseldorf, Germany).

Participants with permanent dentition with fully erupted first molars to the contralateral first molars in both jaws who required orthodontic treatment, and who provided informed consent, were included in this study. Any participants with cleft lip, cleft palate, craniofacial deformity, craniofacial syndrome, or a known allergy to alginate, crystalline silica, calcium sulfate, potassium titanium fluoride, latex, or nickel, or those who did not consent to this study were excluded.

The operator (Faculty of Dentistry, Naresuan University, Thailand) performed the oral examination and intraoral scanning of each participant with a Trios 3 (3Shape, Copenhagen, Denmark) scanner, then took an impression with irreversible hydrocolloid (Alginor®; LASCOD SpA, Italy).

Intra-examiner validity and reliability testing were conducted prior to initiating intraoral scanning in the study participants. Five subjects who were not included in the study were randomly selected and examined by both the expert (Faculty of Dentistry, Naresuan University, Thailand) who is an experienced orthodontist with 5 years of clinical practice, and the operator (Faculty of Dentistry, Naresuan University, Thailand) involved in the study. Intraoral scanning was carried out with the participant seated in a dental chair. A single trained operator (Faculty of Dentistry, Naresuan University, Thailand) performed all scans following the manufacturer's recommended protocol, as shown in Figure 1.

Following intraoral scanning, the irreversible hydrocolloid impression material was prepared using a 1:1 powder-to-water ratio. The estimated mixing time was 45 s, with a total working time of 105 s and an intraoral setting time of approximately 30 s. The impressions obtained were poured using type III orthodontic stone (Sirius®; Lafarge Prestia, Thailand). The stone was mixed at a powder-to-water ratio of 100 g to 31 ml (1:3.23). The mixing, working, and setting times for the stone were approximately 1 minute, 8 minutes, and 15 minutes, respectively. The plaster dental cast was called "PC" and the digital image generated from the plaster cast using a laboratory scanner (3Shape E4, 3Shape Inc., Copenhagen, Denmark) was called "CS". The data obtained by the

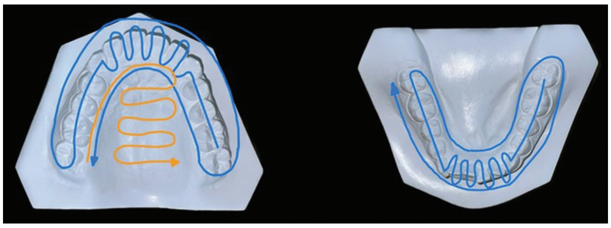

Figure 1: Scanning paths of maxillary and mandibular arches.

scanning procedure were exported as Standard Tessellation Language (STL) files and generated as digital models, which were called "IOS".

Measurement methods

The linear measurements included the following: 1) Clinical arch length: the total distance of the anterior and posterior segments (Figure 2). The anterior segment is the total distance between the distal side of the lateral incisor and the distal side of the contralateral lateral incisor. If a tooth exhibited crowding, labioversion, or linguoversion, the measurement was taken based on the tooth's ideal position within the alveolar bone. The posterior segment is the total distance between the mesial side of the first molar to the distal side of the lateral incisor. The posterior segment comprises the sum of the left and right sides of each arch. 2) Tooth widths: the largest distance between the mesiodistal point of each tooth. The tooth width was measured from the frontal view for anterior teeth and from the occlusal view for posterior teeth. 3) Bolton ratio(3): a diagnostic index used in orthodontics to assess the proportional relationship between the mesiodistal widths of maxillary and mandibular teeth. It helps identify tooth size discrepancies that may affect occlusion, alignment, and inter-arch relationships during treatment planning. There are two types of Bolton ratios: anterior Bolton ratio, which compares the combined mesiodistal widths of the six anterior mandibular teeth (canine to canine) to those of the six anterior maxillary teeth, and the overall Bolton ratio, which compares the combined widths of all 12 mandibular teeth (from first molar to first molar) to the corresponding 12 maxillary teeth. The Bolton ratios were calculated using the formulas shown in Figure 3.

The linear measurements in PC were performed using a digital Vernier caliper (Mitutoyo, Tokyo, Japan). These data are regarded as the gold standard for measuring tooth widths and were the reference data. Digital images obtained from CS and IOS were transferred to the

Ortho Analyzer™ software program (Ortho Analyzer™, 3Shape, Copenhagen, Denmark) as STL files for measuring the linear measurements (Figures 4 and 5). After all the information was collected, each arch was divided into two groups based on the severity of crowding. If the amount of crowding was ≤3.0 mm, the arch was included in the mild crowding group, and those with crowding >3.0 mm were included in the moderate-to-severe crowding group.

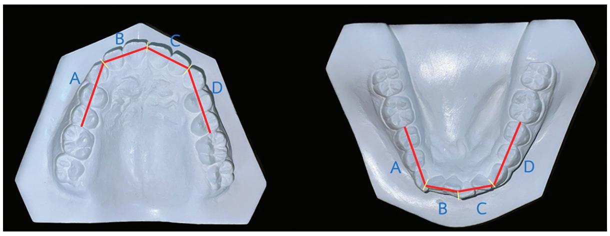

Figure 2: Clinical arch length = anterior segment (B+C) + posterior segment (A+D).

$$\text{Anterior Ratio (\%)} = \left(\frac{\text{Sum of mandibular 3−3 widths}}{\text{Sum of maxillary 3−3 widths}}\right) \text{x } 100$$

$$\text{Overall Ratio (\%)} = \left(\frac{\text{Sum of mandibular 6-6 widths}}{\text{Sum of maxillary 6-6 widths}}\right) \text{x } 100$$

Figure 3: Calculation of Bolton ratios.

Results

Intra-examiner reliability of linear measurements in plaster, scanned, and intraorally scanned models, as assessed by the two operators, showed no differences and was almost perfect for all measurements. The ICC values were 0.978 (95% CI; 0.875,0.994), 0.978 (95% CI; 0.909,0.993), 0.982 (95% CI; 0.771,0.996) for plaster models, cast scans, and intraoral scans, respectively.

The means and standard deviations (SD) of the clinical arch length (5-5) for maxillary and mandibular teeth between the mild and moderate-to-severe crowding groups are shown in Table 1. In the mild crowding group, the maxillary arch length ranged from 78.77 mm (CS) to 78.97 mm (IOS), while the mandibular arch length ranged from 67.04 mm (PC) to 67.36 mm (IOS). The mean differences between PC and IOS were minimal: -0.08 mm for maxillary arches and -0.33 mm for mandibular arches. Similarly, the mean differences between PC and CS were 0.12 mm (maxillary) and -0.26 mm (mandibular). In the moderate-to-severe crowding group, slightly larger differences were observed in the maxillary arch, with the mean clinical arch length for CS being 71.40 mm and for IOS being 71.03 mm. The mean differences reached -0.94 mm (PC-CS) and -0.57 mm (PC-IOS). In the mandibular

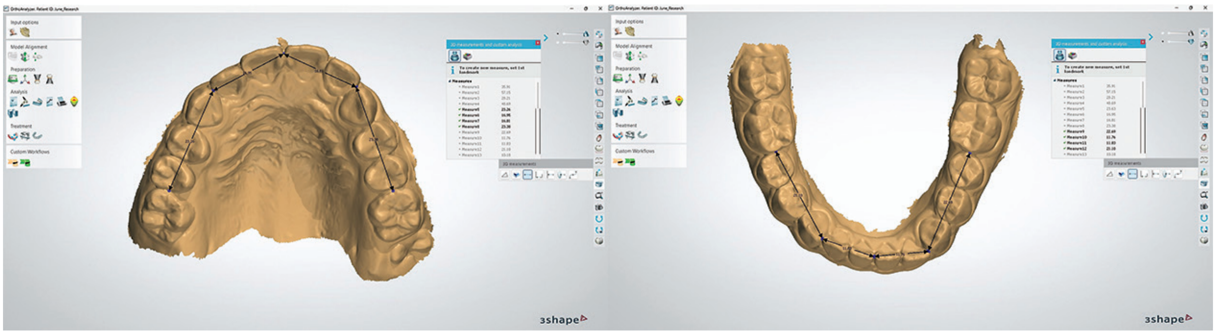

Figure 4: Clinical arch length measurement of maxillary and mandibular arches.

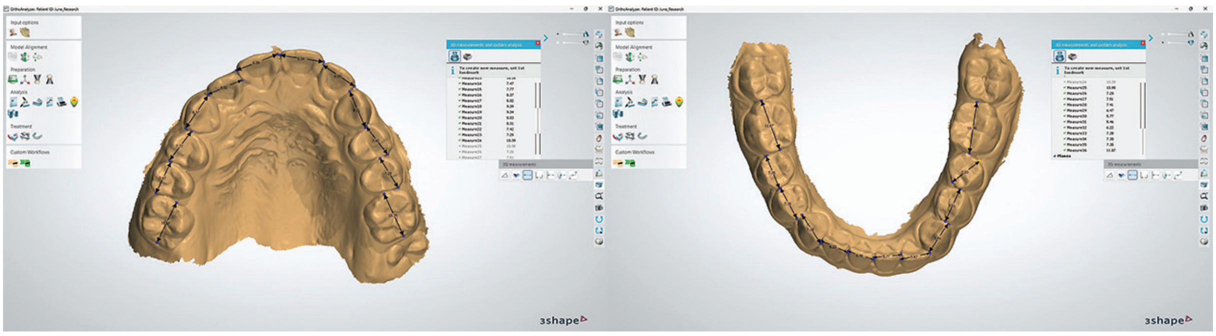

Figure 5: Tooth width measurement of maxillary and mandibular arches.

arch, values ranged from 61.82 mm (PC) to 62.08 mm (CS), with mean differences of -0.26 mm (PC-CS) and -0.18 mm (PC-IOS), closely mirroring the values of the mild crowding group.

To evaluate whether discrepancies between PC and digital models arose preferentially in the anterior or posterior portions of the arch, clinical arch length was separated into anterior and posterior segments for both mild and moderate-to-severe crowding groups (Table 1). For the anterior segment, the differences between PC and digital models were minimal in both crowding groups. In the mild group, maxillary anterior measurements showed only negligible deviations (PC-CS: +0.08 mm; PC-IOS: -0.08 mm), while the mandibular anterior segment demonstrated a uniform overestimation by both digital methods. In the moderate-to-severe group, discrepancies were slightly greater in the maxilla, with PC-CS and PC-IOS differences of -0.71 mm and -0.53 mm, respectively, whereas mandibular deviations remained small (PC-CS: -0.26 mm; PC-IOS: -0.12 mm). None of these variations reached statistical significance in pairwise comparisons (all $p>0.60$). For the posterior segment, measurements from digital models closely paralleled those from PC in both groups. In the mild group, maxillary posterior values differed only slightly (PC-CS: +0.05 mm; PC-IOS: 0.00 mm), and mandibular measurements showed similar results (PC-CS: +0.01 mm; PC-IOS: -0.06 mm). In the moderate-to-severe group, deviations were small, with the maxillary posterior segment differing by -0.23 mm (PC-CS) and -0.03 mm (PC-IOS), and the mandibular posterior segment remaining virtually unchanged (PC-CS: 0.00 mm; PC-IOS: -0.07 mm). All comparisons confirmed the absence of statistically significant differences ($p\geq0.92$).

Total tooth width (6-6) for maxillary and mandibular teeth was compared between the groups (Table 1). In the mild crowding group, the maxillary width ranged from 97.21 mm (CS) to 98.07 mm (PC), while the mandibular width ranged from 88.40 mm (IOS) to 89.09 mm (PC). Differences were minor, with mean differences between PC and IOS of 0.35 mm (maxillary) and 0.69 mm (mandibular). The mean differences between PC and CS in maxillary teeth were 0.86 mm and 0.68 mm in mandibular teeth. In the moderate-to-severe crowding group, mean differences were slightly larger in maxillary teeth: up to 1.28 mm (PC-CS) and 1.65 mm (PC-IOS). The mandibular teeth presented similar mean differences to the mild crowding group (PC-CS: 0.55 mm, PC-IOS: 0.51 mm).

Multiple comparisons using the Games-Howell test

Table 1: The difference of clinical arch length (5-5) and total tooth width (6-6) in millimeters between mild (n=10) and moderate to severe crowding groups (n=5).

			PC (mean±SD)	CS (mean±SD)	IOS (mean±SD)	Mean differences (PC-CS)	Mean differences (PC-IOS)
Anterior segment	Max	Mild	32.11±1.35	32.04±1.23	32.19±1.23	0.08	-0.08
		Mod-sev	28.13±1.28	28.85±1.36	28.67±1.19	-0.71	-0.53
	Mand	Mild	23.37±1.41	23.64±1.34	23.64±1.37	-0.27	-0.27
		Mod-sev	21.16±1.34	21.42±1.17	21.28±0.97	-0.26	-0.12
Posterior segment	Max	Mild	46.78±2.58	46.73±3.03	46.78±2.96	0.05	0.00
		Mod-sev	42.33±2.15	42.56±2.30	42.36±2.32	-0.23	-0.03
	Mand	Mild	43.66±1.93	43.65±1.97	43.72±1.98	0.01	-0.06
		Mod-sev	40.66±4.01	40.66±3.94	40.72±3.62	0.00	-0.07
Clinical arch length	Max	Mild	78.89±3.59	78.77±3.73	78.97±3.70	0.12	-0.08
		Mod-sev	70.46±1.77	71.40±2.06	71.03±2.16	-0.94	-0.57
	Mand	Mild	67.04±2.89	67.30±2.86	67.36±3.02	-0.26	-0.33
		Mod-sev	61.82±3.47	62.08±3.53	62.00±3.37	-0.26	-0.18
Total tooth width	Max	Mild	98.07±4.36	97.21±4.64	97.73±4.51	0.86	0.34
		Mod-sev	99.11±1.20	97.83±2.00	97.46±1.53	1.28	1.65
	Mand	Mild	89.09±4.09	88.41±4.12	88.40±3.66	0.68	0.69
		Mod-sev	91.00±2.32	90.45±3.40	90.49±3.24	0.55	0.51

Abbreviations: Max, maxillary arch; mand, mandibular arch; SD, standard deviation; mod-sev, moderate to severe; PC, plaster cast; CS, cast scan; IOS, intraoral scan; *p*-values were calculated by Welch ANOVA; $^{*}p<0.05$.

Table 2: Paired pairwise statistical analysis for the difference in clinical arch length and total tooth width.

			Anterior segment			Posterior segment			Clinical arch length			Total tooth width		
			PC-CS (mm)	PC-IOS (mm)	CS-IOS (mm)	PC-CS (mm)	PC-IOS (mm)	CS-IOS (mm)	PC-CS (mm)	PC-IOS (mm)	CS-IOS (mm)	PC-CS (mm)	PC-IOS (mm)	CS-IOS (mm)
Max	Mild	mean±SD	0.07±0.58	-0.80±0.58	-0.15±0.55	0.05±1.26	0.00±1.24	-0.05±1.34	0.12±0.43	-0.08±0.40	-0.20±0.58	0.86±0.64	0.35±0.43	-0.52±0.77
		95% CI	(-1.41,1.54)	(-1.55,1.39)	(-1.55,1.26)	(-3.17,3.27)	(-3.18,3.18)	(-3.47,3.37)	(-1.31,1.08)	(-1.03,1.19)	(-1.30,1.68)	(-2.66,0.93)	(-1.54,0.85)	(-1.48,2.51)
		p-value	0.99	0.99	0.96	1.00	1.00	1.00	0.96	0.98	0.94	0.41	0.71	0.78
		effect size	0.08	-0.11	-1.01	0.05	0.00	-0.13	0.09	-0.06	-0.53	0.42	0.26	-0.54
	Mod-sev	mean±SD	-0.71±0.84	-0.53±0.78	0.18±0.81	-0.23±1.41	-0.03±1.41	0.20±1.46	-0.94±0.64	-0.57±0.55	0.38±0.84	1.28±0.52	1.65±0.50	0.37±0.72
		95% CI	(-3.11,1.68)	(-2.78,1.71)	(-2.15,2.50)	(-4.26,3.80)	(-4.08,4.02)	(-3.97,4.37)	(-1.32,3.21)	(-1.40,2.53)	(-2.80,2.04)	(-3.12,0.57)	(-3.42,0.12)	(-2.42,1.68)
		p-value	0.68	0.78	0.97	0.99	1.00	0.99	0.39	0.60	0.90	0.14	0.06	0.87
		effect size	-0.59	-0.61	0.38	-0.22	-0.03	0.47	-0.66	-0.46	0.46	1.11	1.48	0.48
Mand	Mild	mean±SD	-0.27±0.62	-0.27±0.62	0.00±0.61	0.01±0.87	-0.06±0.88	-0.07±0.88	-0.26±0.27	-0.33±0.32	-0.07±0.42	0.68±0.43	0.69±0.42	0.02±0.60
		95% CI	(-1.84,1.30)	(-1.85,1.32)	(-1.54,1.55)	(-2.22,2.24)	(-2.30,2.18)	(-2.32,2.18)	(-0.49,1.01)	(-0.56,1.21)	(-1.00,1.13)	(-1.87,0.52)	(-1.86,0.47)	(-1.54,1.51)
		p-value	0.90	0.90	1.00	1.00	1.00	1.00	0.61	0.58	0.99	0.30	0.27	1.00
		effect size	-0.76	-0.66	0.01	0.01	-0.06	-0.14	-0.31	-0.33	-0.11	0.50	0.53	0.02
	Mod-sev	mean±SD	-0.26±0.80	-0.12±0.74	0.15±0.68	0.00±2.51	-0.07±2.42	-0.06±2.39	-0.26±0.12	-0.18±0.18	0.08±0.22	0.55±1.37	0.51±1.27	-0.04±1.86
		95% CI	(-2.54,2.02)	(-2.28,2.04)	(-1.80,2.10)	(-7.19,7.18)	(-6.99,6.86)	(-6.91,6.78)	(-0.15,0.68)	(-0.46,0.83)	(-0.72,0.55)	(-5.42,4.32)	(-5.02,4.00)	(-5.29,5.37)
		p-value	0.94	0.99	0.98	1.00	1.00	1.00	0.18	0.61	0.92	0.92	0.92	1.00
		effect size	-1.17	-0.25	0.56	-0.01	-0.16	-0.13	-1.01	-0.45	0.17	0.18	0.18	-0.05

Abbreviations: Max, maxillary arch; mand, mandibular arch; mm, millimeters; mod-sev, moderate to severe; PC, plaster cast; CS, cast scan; IOS, intraoral scan
Mild group (n=10); moderate to severe group (n=5); *p*-values were calculated by Welch ANOVA; *p<0.05.

Table 3: Paired pairwise statistical analysis for the differences in Bolton ratios in percentage.

	Anterior ratio			Overall ratio		
	PC-CS (percentage)	PC-IOS (percentage)	CS-IOS (percentage)	PC-CS (percentage)	PC-IOS (percentage)	CS-IOS (percentage)
mean±standard error	0.83±0.66	0.31±0.66	-0.52±0.94	0.29±0.51	0.08±0.43	-0.21±0.66
95% CI	(-0.91,2.57)	(-1.43,2.04)	(-2.84,1.80)	(-1.04,1.61)	(-1.03,1.20)	(-1.84,1.43)
p-value	0.45	0.89	0.84	0.84	0.98	0.95
effect size	-0.32	-0.12	0.30	-0.15	-0.05	0.14

Abbreviations: PC, plaster cast; CS, cast scan; IOS, intraoral scan *p*-values were calculated by Welch ANOVA; $^*p<0.05$.

revealed no significant differences in the clinical arch length of the maxillary and mandibular teeth between the methods in either the mild crowding group or the moderate-to-severe crowding group (Table 2). In the mild crowding group, *p*-values were all ≥0.58. Similar non-significant results were found in the moderate to severe group.

Comparisons for maxillary and mandibular total tooth widths also showed no statistically significant differences between methods (Table 2). In the moderate-to-severe crowding group, the PC-IOS comparison for maxillary teeth approached significance (*p*=0.06), with a mean difference of 1.65 mm.

Paired comparisons of anterior and overall Bolton ratios between methods showed minimal mean differences and no statistically significant results (Table 3). All *p*-values were >0.45 (e.g., PC-CS anterior: *p*=0.45, PC-IOS overall: *p*=0.98).

Discussion

This study supports the use of digital models (cast scans and intraoral scans) as reliable alternatives to traditional plaster casts in the assessment of clinical arch length, total tooth width, and Bolton ratios. The findings align with the growing body of evidence supporting the use of digital technologies in orthodontic diagnostics, although some minor inconsistencies highlight the need for further refinement.

From this study, the clinical arch length measurements demonstrated overall consistency across the three methods. In both mild and moderate-to-severe crowding groups, the mean differences between PC and digital scans were minimal, especially in the mild group. Across both crowding groups, the anterior segment showed larger variability than the posterior segment, particularly in the maxilla of moderate-to-severe cases, where deviations approached –0.7 mm. In contrast, posterior discrepancies remained close to zero regardless of arch or severity. This suggests a region-specific tendency toward overestimation in the anterior maxilla during digital measurement, while posterior values remained stable. However, these differences did not reach statistical significance. In evaluating total tooth width, slightly greater variability and underestimations were observed, particularly in maxillary measurements among patients with moderate-to-severe crowding. The greatest difference (PC vs. IOS: 1.65 mm) approached statistical significance (*p*=0.06), suggesting a trend toward measurement bias in complex posterior regions.

These findings are consistent with previous studies, which demonstrated that digital models offer clinically acceptable accuracy for linear measurements when compared to traditional impressions.(13,14,18) The results also support earlier studies which reported comparable linear measurements between digital and plaster models, even in cases of severe crowding.(19,20) Similarly, Lo Giudice *et al.*,(21) found that arch length values obtained from digital scans generally matched those from plaster models, but they noted slight overestimations in digital readings, especially in crowded cases. Although the maximum mean difference in total tooth width observed in this study reached 1.65 mm, this deviation is considered clinically acceptable. Prior studies have indicated that minor discrepancies in mesiodistal measurements, particularly when summed across the whole arch, typically do not compromise orthodontic diagnosis or appliance fabrication. For example, Rossini *et al.*, and Grünheid *et al.*, proposed that deviations of less than 0.25 mm per tooth are within acceptable limits, which would amount to up to 3 mm across a 12-tooth arch (from first molar to first molar).[13,14] Another study reported similar levels of overestimation in digital models, ranging from 1 to 2 mm in total arch width, but the authors concluded that these discrepancies did not significantly impact clinical outcomes.[21] Together, the observed deviation in the present study falls below the generally accepted clinical threshold of 2 mm and is consistent with the literature, thus supporting the reliability of digital models, even in crowded dentitions.

Jacob *et al.*,[11] found that intraoral scanners tend to slightly underestimate arch lengths in crowded cases, likely due to distortion or scanning artifacts in interproximal areas. This discrepancy may reflect differences in scanner type, operator experience, or patient anatomy. Similar concerns were raised by Lin *et al.*,[22] who noted deviations in IOS-derived arch length exceeding 1 mm in severe anterior crowding.

Digital models tend to underestimate tooth widths in crowded cases, primarily because of technical and anatomical challenges inherent in intraoral scanning. In moderate-to-severe crowding, teeth often overlap, rotate, or are malpositioned, which limits the scanner's ability to capture the actual mesiodistal contact points of each tooth accurately.[19,23,24] Another contributing factor is the potential distortion that can occur during cast model fabrication. Despite being considered the gold standard, plaster models created from alginate impressions are subject to dimensional changes, even when poured immediately. As such, discrepancies between digital and cast models may partially originate from inaccuracies in the plaster models themselves.[25,26] Another key issue is the difficulty in identifying exact mesiodistal contact points on digital models. This becomes more problematic in crowded dentitions, where overlapping or rotated teeth hinder accurate surface reconstruction. Digital scans, when converted into STL files, represent the surfaces as hollow structures, which can limit the fidelity of proximal surfaces. Although digital software allows for flexible point selection without physical obstruction, the underlying data interpolation and stitching algorithms may still produce underestimated values in anatomically complex areas.[27] In addition, restricted access to interproximal and lingual areas in crowded arches further impairs scan accuracy, as the scanner may not fully record the narrow spaces between teeth or may misalign surface data during the stitching process.[21,23,28] Furthermore, the curvature of the dental arch in the posterior region increases the likelihood of surface stitching errors. These stitching errors are exacerbated in crowded areas, resulting in measurement inaccuracies that are more pronounced in the posterior teeth compared with the anterior region. Patient movement, saliva, and limited mouth opening can also contribute to incomplete or distorted scans in the posterior segments. Studies have consistently reported that while digital models provide clinically acceptable accuracy overall, the reliability of measurements in the posterior teeth, particularly in crowded dentitions, can be slightly reduced because of these technical limitations.[22,28-30] Despite the noted variation in maxillary posterior segments, mandibular total tooth widths showed consistent results across methods in both crowding groups. These likely reflect the more accessible and stable morphology of the mandibular arch, which leads to less variability during scanning.[16]

The slightly greater differences in the moderate-to-severe crowding group may reflect the challenges of capturing precise anatomical contours in patients with significant crowding. Despite this, the differences were small and likely not clinically significant. The comparison of PC and IOS in the maxillary teeth of the moderate-to-severe crowding group had the lowest p-value (p=0.06), suggesting a possible trend worth investigating in larger samples.

The analysis of Bolton ratios also showed negligible differences between methods, with no statistically significant values observed. These results align with numerous studies that confirmed digital platforms can reliably calculate Bolton ratios, a critical factor in assessing inter-arch tooth size.[24,31-33] However, conflicting results from Othman and Harradine raised concerns that inaccuracies in anterior regions could lead to small, yet clinically meaningful, discrepancies in digital Bolton ratios when scans are poorly aligned or affected by light reflection errors.[34] A more recent study reiterated that IOS measurements of anterior ratios could be slightly skewed if scan resolution is inadequate or if scanning is rushed in difficult-to-access interproximal spaces.[35]

Despite minor deviations in specific measurements, the differences observed in this study remained within clinically acceptable ranges. These findings indicate that such minor discrepancies are unlikely to alter clinical decisions regarding space analysis, extraction planning, or appliance design.[14,36,37] These findings also align with those of Anh *et al*.,[38] who emphasized the influence of scan sequence and environment on IOS accuracy and recommended standardizing scanning protocols for optimal results. Beyond their demonstrated measurement reliability, digital models, including both cast scans and intraoral scans, demonstrate measurement accuracy comparable to traditional plaster casts and can be confidently used for space analysis, treatment planning, and appliance design in routine orthodontic practice. Minor deviations observed in crowded dentitions are within clinically acceptable limits and do not compromise diagnostic or therapeutic decisions. However, clinicians must remain vigilant about potential underestimations or overestimations, particularly in moderate-to-severe crowding, where anatomical and technical complexities can affect scan fidelity. Continued research and refinement of digital tools will further improve the diagnostic confidence in digital model-based orthodontic assessments.

Conclusions

This study confirms that digital models, particularly CS and IOS, offer reliable and reproducible results for most orthodontic diagnostic tasks. Nevertheless, the digital models tend to underestimate total tooth widths and Bolton ratios, while overestimating clinical arch lengths.

Implications

Digital models can be confidently used in orthodontic diagnosis and treatment planning.

However, the reliability of these models, particularly in crowded dentitions, depends on operator training and adherence to standardized scanning protocols. A limitation of the present work is that only one brand of intraoral scanner was evaluated, which may not fully represent the performance of other devices; incorporating additional scanners would strengthen the generalizability of the findings. Moreover, further studies using larger and more diverse samples may help resolve conflicting outcomes and standardize digital scanning practices across clinical settings.

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Conflict of Interest

The authors declare no conflict of interest.

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