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ORIGINAL RESEARCH

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Agreement of digital and conventional maxillary arch-length and intermolar-width measurements in children aged 7 to 12

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Abstract

Background: Digital dental models are increasingly used in children, but their agreement with conventional cast measurements for arch-length and intermolar-width assessment remains unclear. This study compared conventional and digital workflows for intermolar width and arch-length assessment in maxillary models and evaluated workflow-level agreement between them. **Methods**: Maxillary models from 60 untreated children aged 7–12 years with Angle Class I molar relationships were evaluated. On plaster casts, intermolar width and arch length were measured with a digital caliper. The same casts were then digitized and analyzed using dedicated software. Intraobserver repeatability of conventional measurements was assessed with intraclass correlation coefficients and Dahlberg's formula. Agreement between conventional and digital measurements was evaluated using Bland–Altman analysis. **Results**: The mean difference in arch length was 1.46 mm with 95% limits of agreement ranging from −6.5 to +9.5 mm, while the mean difference in intermolar width was 0.67 mm with 95% limits of agreement ranging from −3.1 to +4.4 mm. **Conclusions**: The digital workflow showed closer agreement with the conventional workflow for intermolar width than for arch length; however, the observed limits of agreement indicate that the two workflows should not be assumed to be interchangeable for individual patient-level decisions without clinical caution. For arch length, the wider limits of agreement likely reflect, at least in part, the non-equivalent geometric definitions used by the two workflows.

Keywords

Mixed dentition; Digital dental model; Arch length; Intermolar width; Bland–Altman analysis

1. Introduction

Orthodontic model analysis plays an important role in the evaluation of developing malocclusions and in treatment planning during the mixed dentition period. In children, measurements such as arch length and intermolar width are clinically relevant for the assessment of space conditions, monitoring of arch development, and decisions related to space maintenance, guidance of eruption, expansion, or extraction [1]. Accurate assessment of arch-length discrepancies is important for orthodontic diagnosis and treatment planning in children with mixed dentition [2].

Conventional plaster models have traditionally been regarded as the gold-standard for orthodontic measurements [3]. However, they have practical disadvantages, including the risk of fracture or deterioration, storage burden, and difficulties in transport, duplication, and long-term archiving. In addition, impression taking and cast fabrication are technique-sensitive procedures that may introduce distortion or require repetition when errors occur [4, 5].

Advances in digital technology have led to the increasing use of digital orthodontic models as an alternative to conventional plaster casts. Digital models eliminate physical degradation, facilitate long-term storage without space constraints, and allow rapid data transfer between clinics and laboratories. Digital datasets can also be archived for the reproduction of lost or damaged appliances. These models may be generated directly via intraoral scanning or indirectly by scanning impressions or plaster models, with data commonly stored in stereolithography (STL) format for analysis using specialized software [6]. However, the relatively high cost of digital systems continues to limit their accessibility in some clinical settings [7].

Numerous studies have evaluated the accuracy and reliability of digital orthodontic models. Investigations comparing indirectly obtained STL models with plaster models have generally reported small differences that are often considered clinically negligible [8, 9]. A systematic review by Rossini *et*

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al. [10], including 35 studies, concluded that digital models are as reliable as conventional plaster models for orthodontic analysis. Evidence regarding digital and conventional model agreement in mixed dentition remains limited, particularly for specific linear measurements such as arch length and intermolar width [11, 12].

Although correlation coefficients and mean differences are informative, they do not adequately address whether two measurement workflows can be used interchangeably in clinical practice. Evaluation of interchangeability requires assessment of agreement and identification of potential systematic bias. In digital model analysis, reference points are frequently identified manually, introducing potential observer-related variability. As conventional measurements serve as the reference standard for comparison, assessment of their intraobserver repeatability is essential to ensure valid method comparison.

In this context, differences between digital and conventional model analyses should be interpreted not only in terms of statistical significance, but also with respect to clinical acceptability. Bland–Altman analysis provides a robust framework for evaluating agreement between measurement methods by quantifying mean differences and limits of agreement, thereby facilitating assessment of clinical interchangeability.

Therefore, the aim of the present study was to compare conventional and digital workflows for maxillary arch-length and intermolar-width assessment in children with mixed dentition, to assess the intraobserver repeatability of conventional measurements, and to evaluate workflow-level agreement using Bland–Altman analysis. The study hypothesis was that digital and conventional measurements would show closer agreement for the simple linear transverse measurement than for the composite arch-length measurement.

2. Materials and methods

2.1 Study design and participants

This observational workflow-comparison study evaluated agreement between conventional and digital measurements obtained from maxillary models of children in the mixed dentition stage. The sample size was calculated a priori using G*Power version 3.1 (Heinrich Heine University Düsseldorf, Düsseldorf, NRW, Germany) for a paired means comparison. To determine the required sample size, the mean differences (MD) and standard deviations (SD) reported in a highly cited method-comparison study by Stevens *et al*. [13] were utilized to establish an expected effect size. Based on their findings, a moderate effect size 0.50 was assumed to detect clinically meaningful measurement differences between the conventional and digital modalities. When computed with a two-sided alpha level of 0.05 and 90% statistical power, the analysis indicated that a minimum sample size of 44 subjects was required. To improve the precision of the agreement estimates and to compensate for possible exclusions, 60 children were included.

A consecutive sample of 60 children who attended the clinic between September 2023 and September 2024 and fulfilled the eligibility criteria was included. The inclusion criteria were age between 7 and 12 years, good general health, untreated dentition, Angle Class I molar relationship, and eruption of the maxillary permanent first molars and central incisors sufficient to permit identification of the reference landmarks used in the measurements. Children were eligible only if they were in the mixed dentition stage; those who had completely transitioned into permanent dentition were excluded.

Exclusion criteria were craniofacial syndromes, cleft lip and/or palate, previous orthodontic treatment, extensive restorations or structural defects affecting the reference teeth, and poor-quality impressions or casts. One maxillary plaster cast was obtained from each participant and then digitized to generate the corresponding digital model.

2.2 Procedures

All maxillary impressions were obtained by a single examiner using perforated plastic trays selected according to arch size and alginate impression material (Tropicalgin®, Zhermack S.p.A., Italy). Impressions were poured within 30 minutes with Type III dental stone according to the manufacturer's instructions. The resulting casts were used for both conventional measurements and digitization.

The plaster casts were digitized extraorally using a Helios 600 intraoral scanner (Eighteeth, Changzhou Sifary Medical Technology Co., Ltd., Changzhou, Jiangsu, China) in an indirect cast-scanning workflow [14]. Calibration was performed according to the manufacturer's recommendations at the beginning of each scanning session. The casts were scanned under clean and dry conditions, and the digital files were exported in stereolithography (STL) format.

Conventional measurements were performed on the plaster casts using a digital caliper with 0.01-mm resolution. All measurements were recorded in millimeters by the same examiner; therefore, intraobserver repeatability was assessed, whereas interobserver reliability was not evaluated.

Intermolar width was defined as the linear distance between the mesiobuccal cusp tips of the maxillary permanent first molars. For arch-length assessment, a segmental approach was used. Each hemi-arch was measured from the mesial contact point of the maxillary permanent first molar to the contact point between the maxillary central incisors, using the mesial aspect of the canine as an intermediate landmark. The total arch length was calculated as the sum of the right and left hemi-arch measurements. This measurement represented available arch length or arch perimeter; individual tooth widths and final space discrepancy were not calculated, as the present study focused on agreement between conventional and digital workflows for arch-length measurement rather than on comprehensive mixed-dentition space analysis. The measured parameters and reference points are illustrated in Fig. 1.

The study was not designed to compare identical geometric measurement paths for all variables. Intermolar width was measured as a linear distance in both workflows, whereas arch length was assessed using the routinely applied segmental linear method on plaster casts and the software-generated curved-path measurement in the digital workflow.

To ensure consistency between measurement methods, the corresponding reference points were marked on the plaster models and used in both conventional and digital analyses.

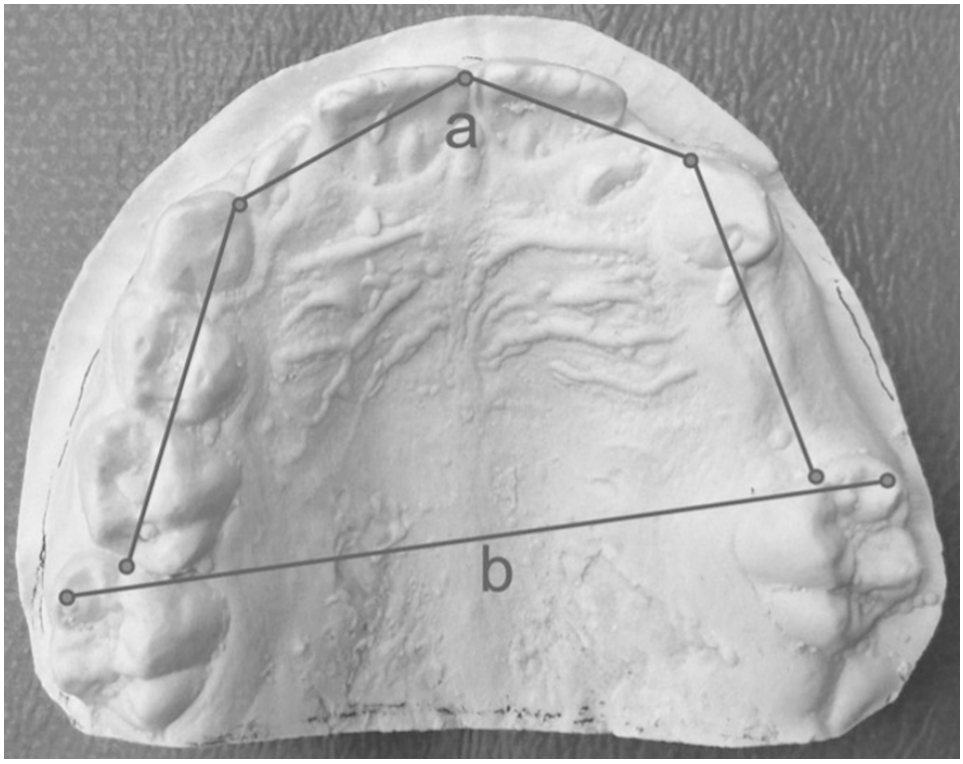


FIGURE 1. Measurement parameters used in the study; a: arch length, b: intermolar width.

To assess intraobserver repeatability, all conventional measurements were repeated by the same examiner on all 60 plaster models after a one-week interval. The mean of the two measurements was used for subsequent analyses. Intraclass correlation coefficient (ICC) values were calculated using a two-way mixed-effects model with absolute agreement.

The STL files were imported into Maestro 3D Dental Studio version 5.1 (AGE Solutions S.r.l., Pontedera, Italy), and all digital measurements were performed by the same examiner. To maximize anatomical correspondence between workflows, the same anatomical regions used in the conventional analysis were identified on the digital models.

Intermolar width was measured as the linear distance between the mesiobuccal cusp tips of the maxillary permanent first molars using the software's distance tool.

For arch-length assessment in the digital workflow, the mesial contact areas of the maxillary right and left permanent first molars and the contact region between the maxillary central incisors were identified on the digital model, and the software-generated arch curve was used to calculate arch length. This digital workflow was selected because it represents the routine measurement approach provided by the software for dental arch analysis.

2.3 Statistical analysis

Statistical analyses were performed using SPSS version 23.0 (IBM Corp., Armonk, NY, USA) and MedCalc version 23.0.8 (MedCalc Software, Ostend, Belgium). Continuous variables were summarized as mean and SD. Intraobserver repeatability of conventional measurements was evaluated using ICC (two-way mixed-effects model, absolute agreement) and Dahlberg's formula. Dahlberg's formula was used to quantify random intraobserver measurement error between repeated conventional measurements, whereas MD between repeated measurements were used to indicate the direction of any systematic tendency.

Agreement between conventional and digital workflows for arch length and intermolar width was assessed using Bland–Altman analysis. For each variable, the difference between methods (conventional minus digital) was plotted against the corresponding mean of the two measurements. MD and 95% limits of agreement were calculated to evaluate workflow-level agreement and the clinical relevance of differences between workflows. All tests were two-sided, and a p value < 0.05 was considered statistically significant. Proportional bias was assessed by linear regression analysis, in which the difference between workflows was entered as the dependent variable and the mean of the two workflows was entered as the independent variable. This analysis was performed separately for arch length and intermolar width.

3. Results

3.1 Sample characteristics

A total of 60 children in the mixed dentition stage were included in the study. The mean age of the participants was 9.42 $\pm$ 1.58 years, with an age range of 7–12 years. The sample included 20 girls (33.3%) and 40 boys (66.7%).

To assess whether age moderated the differences between workflows, additional linear regression analyses were performed with the difference between workflows as the dependent variable and age in years as the independent variable. This analysis was performed separately for arch length and intermolar width.

Age did not significantly moderate the difference between

workflows for either variable. For arch length, the regression coefficient for age was −0.105 mm/year (95% confidence interval (CI), −0.783 to 0.573; $p = 0.757$; $R^2 = 0.002$). For intermolar width, the regression coefficient for age was −0.130 mm/year (95% CI, −0.446 to 0.186; $p = 0.413$; $R^2 = 0.012$).

3.2 Intraobserver repeatability of conventional measurements

Intraobserver repeatability of the conventional measurements was excellent for both intermolar width and arch length (Table 1). For intermolar width, the ICC was 0.919 for single measurements and 0.958 for the mean of two measurements. The Dahlberg error was 0.87 mm, and the MD between the first and second measurements was 0.39 mm. For arch length, the intraclass correlation coefficient was 0.971 for single measurements and 0.985 for the mean of two measurements. The Dahlberg error was 1.01 mm, and the MD between repeated measurements was −0.49 mm.

The MD between repeated conventional measurements were 0.39 mm for intermolar width and −0.49 mm for arch length, indicating slight directional tendencies, whereas the Dahlberg errors reflected random intraobserver measurement error.

3.3 Agreement between conventional and digital measurements

Agreement between conventional and digital measurements is presented in Table 2 and illustrated in the Bland–Altman plots (Figs. 2,3). For arch length, the conventional measurements were greater than the digital measurements by a mean of 1.46 mm. The 95% limits of agreement ranged from −6.5 to 9.5 mm, indicating substantial variability between the two workflows at the individual level.

For intermolar width, the MD between conventional and digital measurements was 0.67 mm, with conventional values again being slightly greater. The 95% limits of agreement ranged from −3.1 to 4.4 mm, showing narrower dispersion than that observed for arch length.

Overall, the digital and conventional workflows showed closer agreement for intermolar width than for arch length, consistent with the simpler and geometrically equivalent linear definition used for intermolar width in both workflows. Whereas the MD for intermolar width was small and the spread of differences was relatively limited, arch-length measurements demonstrated wider limits of agreement, which should be interpreted in light of the different geometric definitions used by the conventional and digital workflows.

Proportional bias analysis showed a significant positive association between the mean value and the difference between workflows for arch length (slope = 0.226; 95% CI, 0.005 to 0.447; $p = 0.045$; $R^2 = 0.067$). This indicates that the difference between workflows tended to increase as the mean arch length increased. In contrast, no significant proportional bias was detected for intermolar width (slope = 0.028; 95% CI, −0.162 to 0.218; $p = 0.768$; $R^2 = 0.002$).

4. Discussion

Previous studies have consistently shown that digital dental models can provide accurate and reliable measurements when compared with conventional plaster models for many orthodontic variables. A systematic review reported that measurements obtained from laser-scanned digital models were generally comparable with direct plaster-model measurements and that reported differences were unlikely to be clinically relevant [15]. In that review, differences below 0.5 mm for individual tooth-width measurements and below 1.0 mm for crowding estimates were considered unlikely to alter clinical treatment-planning decisions [15]. Similarly, Nawi *et al.* [16] reported no significant differences between manual and digital measurements of arch width, arch length, and space analysis, with MD between 0.01 and 0.45 mm and narrow Bland–Altman limits for maxillary intermolar width and arch length.

More recent studies using Bland–Altman analysis have suggested that agreement between digital and conventional methods may vary according to the type of measurement assessed. Transverse dimensions, such as intercanine and intermolar widths, generally demonstrate smaller discrepancies and nar-

TABLE 1. Intraobserver repeatability and measurement error of conventional maxillary plaster-cast measurements (n = 60).

Measurement	1st measurement mean ± SD	2nd measurement mean ± SD	Mean difference (MD)*	Range of differences	Dahlberg error	ICC (3,1)	ICC (3,2)
Intermolar width	51.72 ± 2.93	51.33 ± 2.89	+0.39	−2.40 to +3.00	0.87	0.919	0.958
Arch length	72.43 ± 5.45	72.92 ± 5.79	−0.49	−2.60 to +2.60	1.01	0.971	0.985

*SD, Standard deviation; Dahlberg error, Dahlberg's formula for method error; ICC, intraclass correlation coefficient. *Mean difference = (1st measurement) − (2nd measurement).*

TABLE 2. Agreement between conventional and digital measurements (Bland–Altman analysis, n = 60).

Measurement	Conventional mean ± SD	Digital mean ± SD	Mean difference (conventional − digital)	SD of differences	95% limits of agreement
Arch length	72.67 ± 5.58	71.21 ± 4.60	1.46	4.09	−6.5 to 9.5
Intermolar width	51.52 ± 2.85	50.86 ± 2.78	0.67	1.91	−3.1 to 4.4

SD, Standard deviation.

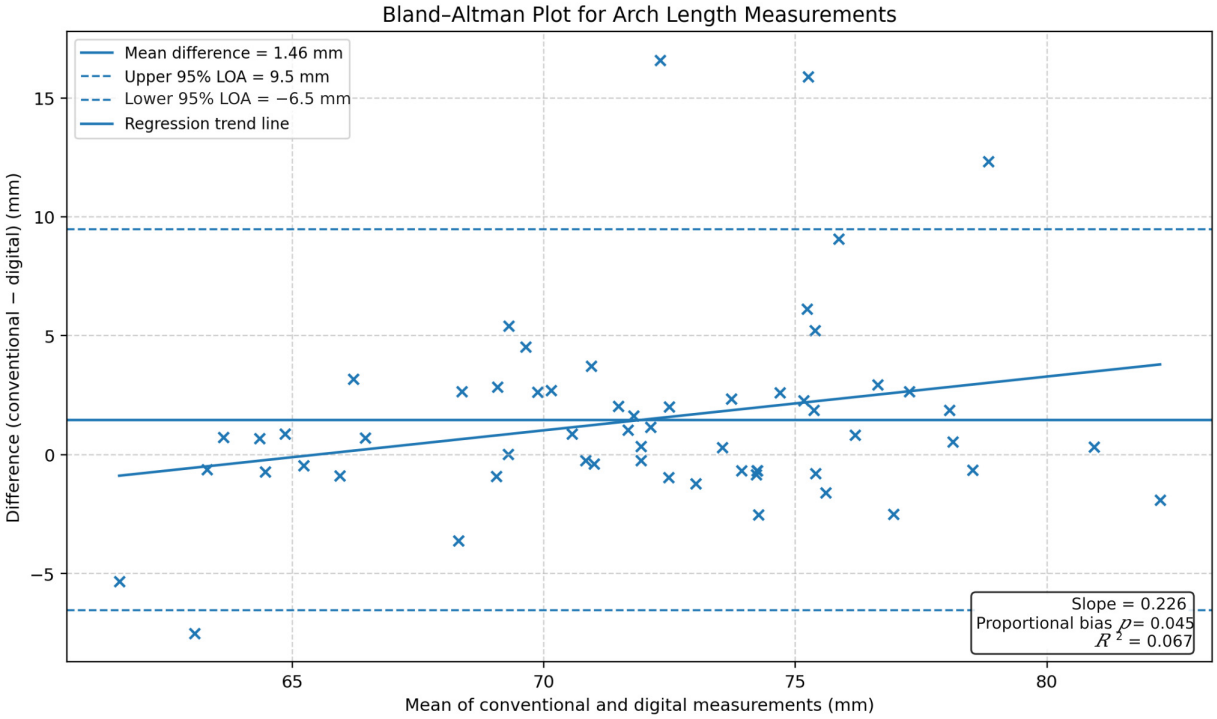


FIGURE 2. Bland–Altman plot for arch length measurements. Bland–Altman plot showing agreement between conventional and digital measurements of maxillary arch length. The x-axis represents the mean of conventional and digital measurements for each subject, and the y-axis represents the difference between methods (conventional − digital). The solid horizontal line indicates the mean difference (1.46 mm), the dashed lines indicate the 95% limits of agreement (−6.5 to 9.5 mm) and the oblique solid line indicates the regression trend line. LOA, limits of agreement.

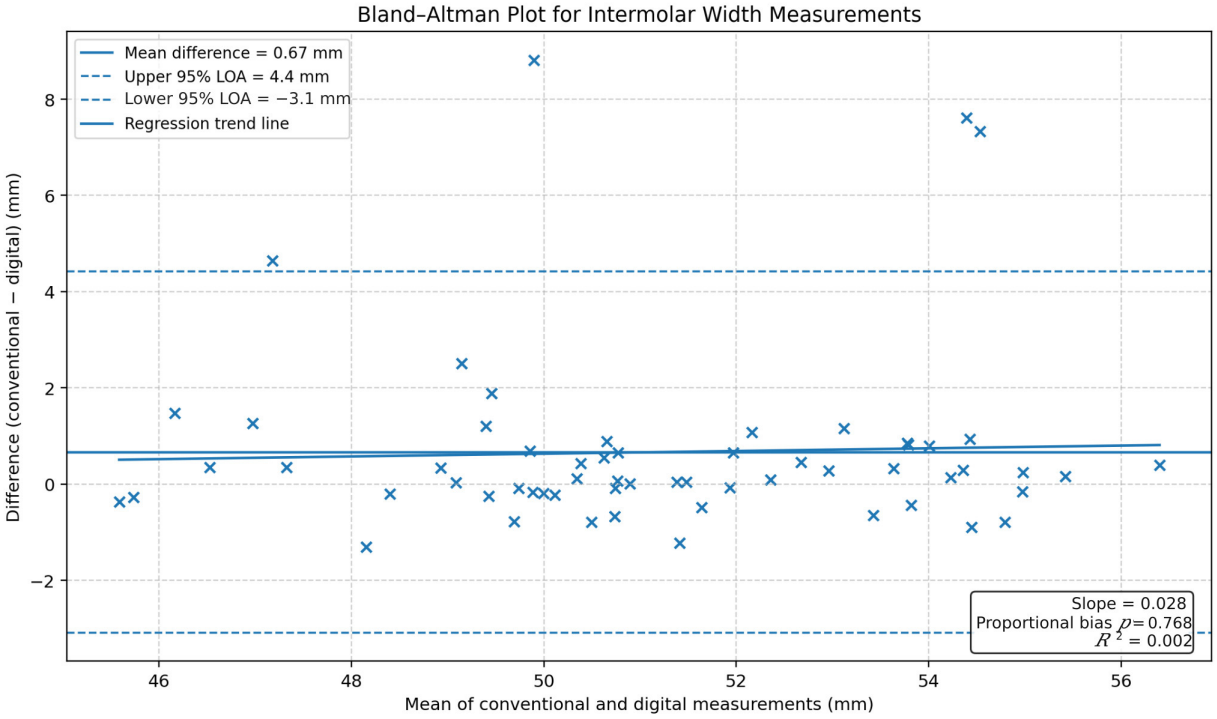


FIGURE 3. Bland–Altman plot for intermolar width measurements. Bland–Altman plot showing agreement between conventional and digital measurements of intermolar width. The x-axis represents the mean of conventional and digital measurements, and the y-axis represents the difference between methods (conventional − digital). The solid horizontal line indicates the mean difference (0.67 mm), the dashed lines indicate the 95% limits of agreement (−3.1 to 4.4 mm) and the oblique solid line indicates the regression trend line. LOA, limits of agreement.

rower limits of agreement, whereas arch-length measurements tend to show greater variability [9, 11]. Similar patterns have been reported across different digital systems, with simple linear measurements often regarded as clinically acceptable, while curved or segmental parameters appear to be more sensitive to methodological variation [17, 18]. In pediatric populations, particularly during mixed dentition, previous studies have also reported high agreement at the group level, with relatively small MD for several dental measurements [19].

In line with these findings, the present study demonstrated closer agreement between digital and conventional methods for intermolar width than for arch length. For intermolar width, conventional measurements were on average 0.67 mm greater than digital measurements, and the 95% limits of agreement ranged from −3.1 to +4.4 mm. Although this MD was small, indicating limited average systematic bias between the two workflows, the 95% limits of agreement indicate that larger differences may occur at the individual patient level. Therefore, the small mean bias should not be interpreted alone as evidence of clinical interchangeability. Because transverse orthodontic decisions may be influenced by discrepancies of only a few millimetres, the observed limits of agreement may still be clinically relevant for individual patient-level decisions.

In contrast, arch length showed a larger MD of 1.46 mm and wider 95% limits of agreement (−6.5 to +9.5 mm). This degree of variability exceeds what is generally considered clinically negligible and appears greater than that reported in some previous investigations [9, 20]. Therefore, although digital and conventional methods may show similar tendencies at the group level, the present findings suggest that they should not be considered directly interchangeable for arch-length assessment at the individual patient level.

Although an MD of 1.0 mm was used as a reference value for sample size estimation, this value should not be interpreted as a prospectively defined clinically acceptable limit of agreement. Previous studies have generally interpreted small MD, particularly those below approximately 0.5–1.0 mm, as unlikely to be clinically relevant for orthodontic model analysis. However, limits of agreement are more informative than mean bias when evaluating whether two workflows may be used interchangeably for individual patients. In the present study, the 95% limits of agreement were wider than those reported in several previous digital–conventional model comparisons, particularly for arch length. Therefore, the observed findings were interpreted cautiously and were not considered sufficient to support direct interchangeability at the individual patient level.

An important methodological issue in the interpretation of the present findings is the use of an indirect digitization workflow. In this study, digital models were generated by scanning plaster casts rather than by direct intraoral scanning. Although indirect digitization reduces patient-related variables such as saliva, movement, and limited intraoral access, it does not fully represent the clinical conditions associated with direct intraoral scanning. Therefore, the present results should be interpreted as applying specifically to the cast-digitization workflow used in this study.

The greater variability observed for arch length compared with intermolar width is also methodologically plausible. Arch length is a composite measurement that depends on multiple anatomical landmarks and on the path used to represent the dental arch. In the mixed dentition period, tooth eruption stage, rotations, contact-point definition, and axial inclination may all affect landmark identification and contribute to cumulative measurement error. In addition, the conventional and digital arch-length assessments in the present study were based on different measurement workflows: the conventional method used a segmental linear approach, whereas the digital method relied on a software-generated arch curve based on manually selected points. This difference is central to the interpretation of the findings and likely contributed to the broader limits of agreement observed for arch length; therefore, the arch-length results should be regarded as a comparison of two clinically used workflows rather than as a pure comparison of identical measurement workflows.

Most differences between the two workflows were distributed around the mean bias and fell within the 95% limits of agreement. However, the relatively wide limits of agreement for arch length and the presence of occasional outlying values indicate that the two workflows cannot be assumed to be fully equivalent in all clinical situations, particularly when precise arch-length assessment is required.

The proportional bias detected for arch length further supports this cautious interpretation, as it indicates that the difference between workflows was not constant across the measurement range. In contrast, no proportional bias was detected for intermolar width, suggesting that the agreement pattern for this variable was more stable across the observed measurement range.

Several limitations of the present study should be acknowledged. The study was conducted at a single center using an indirect digitization protocol and a single scanner–software combination; different scanning systems, software algorithms, or direct intraoral scanning workflows may yield different levels of agreement. Although recent evidence has reported clinically acceptable trueness values for the Helios 600 scanner under pediatric intraoral scanning conditions, scanner-specific validation evidence for indirect digitization of plaster casts remains limited. Therefore, the use of a single scanner–software combination should be considered when interpreting the generalizability of the present findings [14].

The inclusion of patients in the mixed dentition stage, while clinically relevant, likely increased variability in arch-length measurements and may limit direct comparison with studies conducted exclusively in permanent dentitions. In addition, all measurements were performed by a single examiner. Although this approach enhanced intraobserver consistency, it precluded assessment of interobserver reliability. This limits the external validity and generalizability of the findings, because landmark identification and use of digital measurement tools may vary among clinicians in routine clinical practice.

It should also be noted that caliper-based measurements on plaster casts, commonly regarded as the reference standard, are themselves subject to potential inaccuracies related to impression materials, plaster expansion, and operator-dependent factors. These limitations may be particularly relevant for composite measurements, such as arch length, in which cumulative errors inherent to conventional segmental measurement

techniques could contribute to the observed discrepancies between the methods.

Age was evaluated as a potential moderator of the differences between workflows, eruption-stage subgroups were not recorded separately. Therefore, potential differences in workflow agreement between early and late mixed dentition could not be evaluated. This should be considered when interpreting the findings, particularly for arch-length assessment.

From a clinical perspective, the present findings suggest that digital models may provide closer agreement with conventional casts for transverse assessment than for arch-length assessment in mixed dentition; however, caution is required when either measurement may influence individual treatment decisions. When clinical decisions depend on small differences in available space, digital and conventional measurements should not automatically be assumed to be interchangeable.

Overall, the present findings indicate closer workflow-level agreement for maxillary intermolar width than for arch length in mixed dentition. However, the observed limits of agreement, particularly for arch length, do not support direct interchangeability of the two workflows for individual patient-level decisions. Further studies with larger samples, standardized measurement definitions, different dentition stages, and alternative scanner–software combinations are needed to better define the clinical validity of digital arch-length assessment in pediatric patients.

5. Conclusions

Digital and conventional maxillary model workflows showed closer agreement for intermolar width than for arch length in mixed dentition. However, the observed limits of agreement indicate that the two workflows should not be assumed to be interchangeable for individual patient-level decisions, particularly when small dimensional differences may influence transverse assessment or arch-length-based treatment planning. Further studies using standardized measurement definitions and different scanner–software combinations are needed to clarify the clinical validity of digital arch-length assessment in pediatric patients.

AVAILABILITY OF DATA AND MATERIALS

The data supporting this study's findings are available upon request from the corresponding author.

AUTHOR CONTRIBUTIONS

BNG—contributed to concept, design, data collection, processing, analysis, interpretation, literature search, and writing. AYG—contributed to design and data collection. OEG—contributed to concept, design, analysis, interpretation, and writing. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study protocol was approved by the Ethics Committee of Akdeniz University and by the Turkish Ministry of Health, Turkish Medicines and Medical Devices Agency (Ref. No. E-68869993-511.06.01.01-1195871). The study was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from the parents or legal guardians of all participants for participation in the study and for publication of the collected data.

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CONFLICT OF INTEREST

There is no conflict of interest.

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