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EVALUATION OF THE RELIABILITY AND REPRODUCIBILITY OF BOLTON RATIOS USING INTRAORAL SCANNER, MODEL SCANNER, AND PLASTER MODELS

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ABSTRACT

Background and Aim: Advances in digital technologies have enabled multiple methods for measuring tooth size ratios. Therefore, this study compared the reliability of manual, intraoral scanner, and model scanner techniques in determining anterior and overall Bolton ratios.

Materials and Methods: Thirty-six female subjects aged 18–25 years were included. Plaster models were obtained using silicone impressions for manual measurements. Intraoral digital models were created with an intraoral scanner, and additional digital models were produced by scanning plaster casts with a model scanner. Anterior and overall Bolton ratios were measured on all three model types by two observers. Intra- and inter-observer reliability was assessed using intraclass correlation coefficients (ICCs). Bland–Altman analyses evaluated systematic and random errors, and repeated measures ANOVA tested differences between measurement methods.

Results: Intra-observer reliability was highest for manual anterior measurements (ICC=0.914), followed by the model scanner (ICC=0.867), with intraoral scans showing lower consistency (ICC=0.826). Inter-observer agreement was lower across all methods, especially for intraoral scans. Bland–Altman analysis revealed the largest bias and widest limits of agreement in intraoral anterior measurements. Anterior Bolton ratios differed significantly between methods ($p<0.001$), with intraoral scans overestimating by 5–7 percentage points; overall Bolton ratios did not differ significantly ($p=0.601$).

Conclusions: Manual and model scanner measurements provided comparable and reliable results for anterior Bolton analysis, whereas intraoral scanning showed greater variability and overestimation. For accurate assessment of anterior tooth size discrepancies, manual or model-based methods are preferable. Overall Bolton ratios can be reliably evaluated with any of the three methods.

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INTRODUCTION

The arrangement of teeth is not only significant within each dental arch individually but also in terms of their mutual relationships, which are crucial for achieving ideal occlusion. In 1958, Bolton[1] reported that the first molars, premolars, and anterior teeth should exhibit specific dimensional ratios with one another, and he described the Bolton analysis. Bolton analysis is a fundamental diagnostic method in orthodontics, utilized to quantify tooth size discrepancies between the maxillary and mandibular arches.

With the advancement of digital technologies in orthodontics, model analyses have also become more convenient to perform. Various rapid digital analysis methods have been developed to replace the manual analyses conducted on traditional plaster models, which are considered the gold standard, and these contemporary methods are increasingly being incorporated into routine clinical practice. This is because plaster models have several limitations, including difficulty with storage, susceptibility to breakage and damage, and time-consuming production processes.[2,3] In contrast, digital systems not only yield accurate results in model analyses but also significantly reduce the application time in a statistically meaningful way.[4] Therefore, digital analyses have become an indispensable component of orthodontic diagnosis and treatment planning.

The efficiency and ease of use offered by digital modeling technology, compared to traditional orthodontic models, have also encouraged the faster and broader adoption of this technology in orthodontic clinics and educational institutions.[5,6] Numerous studies have compared measurements obtained on plaster models with those derived directly from intraoral scanners[7-9] or from digital models generated by scanning plaster casts.[10-12] In a study comparing digital models obtained using an intraoral scanner with plaster models, the manual method was found to have excellent repeatability. However, the digital models showed statistically significant differences.[7] In a systematic review comparing digital and manual methods, it was reported that the digital methods were clinically acceptable.[2] Another study indicated that although there were statistically significant differences between the digital and manual methods, these differences were not clinically significant.[13] Therefore, for digital models to be used reliably in Bolton analysis, it is essential to thoroughly understand the selected system and comprehensively evaluate it against alternative systems.

Digital models represent a strong alternative to plaster models; however, it should be noted that each software may have its own specific limitations. Therefore, the aim of the present study was to compare the Bolton ratios measured manually on plaster models with those obtained on digital models created using a model scanner and an intraoral scanner, in terms of reliability and reproducibility. The null hypothesis of the study was formulated as follows: There will be no statistically significant differences in the reliability and reproducibility of anterior and overall Bolton ratios obtained by manual measurement, model scanning, and intraoral scanning methods.

MATERIALS AND METHODS

Ethical approval for this study was obtained from the Clinical Research Ethics Committee of Hacettepe University (Approval No: KA-22051). Plaster and digital models of patients who applied to the Department of Orthodontics for treatment were included in the study. Based on the standard deviation (SD=1.16 mm) and effect size reported in a previous study, it was estimated that a minimum of 29 subjects would be required to detect a 1-mm difference with 90% power and a significance level of 0.05.[14] However, considering potential data loss, inter-individual anatomical variability, and jaw-specific measurement differences, the sample size was increased to 36 participants to ensure adequate statistical power. All participants voluntarily participated in the study and provided written informed consent.

The inclusion criteria for the study were as follows: (1) being between 18 and 25 years of age, (2) being female, and (3) having no missing teeth except for the second and third molars. The exclusion criteria were as follows: (1) having a history of previous orthodontic treatment, (2) having crowding of 5 mm or more, and (3) the presence of any restorations or defects that could affect the mesiodistal dimensions of the teeth.

All measurements were performed twice by the first investigator with an interval of 15 days. Subsequently, for inter-observer evaluation, measurements were performed once by a second investigator. On the models obtained by the three different methods, the mesiodistal widths of all teeth from the left first molar to the right first molar were measured and recorded. For the anterior Bolton ratio, the sum of the mesiodistal widths of the mandibular teeth from the right canine to the left canine (teeth 13–23) was divided by the corresponding sum of the maxillary teeth, and the result

was multiplied by 100. For the overall Bolton ratio, the sum of the mandibular teeth from the right first molar to the left first molar (teeth 16–26) was divided by the corresponding maxillary sum and multiplied by 100. The methods used to obtain the models included manual measurement, digital models obtained directly via intraoral optical scanning, and digital models obtained by scanning plaster models using a model scanner. Images of all three methods are presented in Figure 1. Patient data were recorded using coded identifiers to ensure the protection of personal information.

Manual measurement method

During the acquisition of plaster models, an A-type silicone impression material (Zhermack Elite HD putty and light body, Badia Polesine, Rovigo, Italy) was used. The impressions were taken according to the manufacturer's instructions as stated in the product prospectus. After disinfection of the impressions, models were promptly poured by a single laboratory technician using type 3 dental stone (Imistone, Imicryl, Konya, Turkey). Any excess material was carefully trimmed to avoid damage to the teeth. For measuring the tooth dimensions, a high-precision vernier digital caliper with an accuracy of 0.01 mm was used.

Intraoral Scanner Method

Records of the upper and lower arches were obtained using an intraoral scanner (3Shape Trios 3 Move Plus, Copenhagen, Denmark) and transferred to the OrthoAnalyzer software (3Shape, Copenhagen, Denmark), where the mesiodistal widths of the teeth were measured. Auto-segmentation was not used during the measurements; instead, all measurement steps were performed manually by the investigator. After completion of the measurements, the sums of the tooth dimensions required for calculating the anterior and overall Bolton ratios were recorded in the data collection form.

Model Scanner Method

Plaster models were digitized by scanning them with a model scanner (E4, 3Shape, Copenhagen, Denmark). As with the other digital method, the models were transferred to the OrthoAnalyzer software (3Shape, Copenhagen, Denmark), where the mesiodistal widths of the teeth were measured. Auto-segmentation was not used during the measurements; instead, all measurement steps were performed manually by the investigator. The total tooth dimensions required were then recorded in the data collection form.

Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 23.0 (IBM Corp., Armonk, NY, USA). Bolton ratios obtained through three different measurement methods were evaluated as anterior ratios for 6 teeth and overall ratios for 12 teeth. First, the Shapiro–Wilk test was applied to assess the normality of the data distribution. The data obtained from all measurement methods were found to be normally distributed ($p>0.05$), and therefore, parametric tests were employed. For the evaluation of intra-observer reliability, the Intraclass Correlation Coefficient (ICC) was calculated based on repeated measurements for each method. ICC values were interpreted with 95% confidence intervals and classified into 'moderate', 'good', and 'excellent' categories of reliability.[15] ICC values in the range of 0.85–0.90, which are close to the threshold, were considered to indicate reliability between good and excellent. To assess inter-observer agreement, Bland–Altman agreement analysis was performed for each method. The mean difference (bias) and the lower and upper limits of agreement with 95% confidence intervals were calculated, and corresponding plots were generated. To test whether there were statistically significant differences among the three measurement methods,

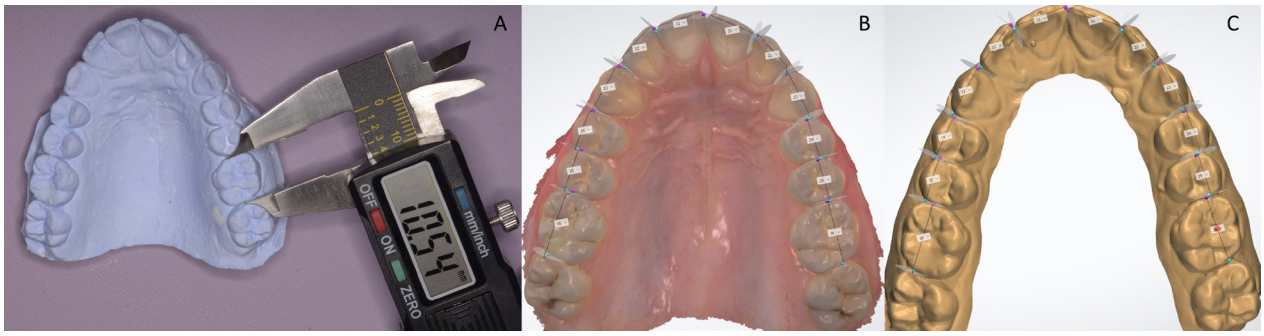

Figure 1. Measurement methods for anterior and overall Bolton ratios. (A) Manual method with caliper, (B) intraoral scanning, and (C) model scanning

Repeated Measures ANOVA was conducted separately for each tooth segment (anterior and overall). In cases where statistical significance was found, pairwise comparisons were performed using Bonferroni-adjusted post-hoc tests. A significance level of $p<0.05$ was considered statistically significant.

RESULTS

The mean age of the individuals included in the study was determined to be 22.19±3.04 years. The results of intra-observer reliability are presented in Table 1, and the findings indicated reliability ranging from good to excellent. The highest consistency was observed in the anterior Bolton ratio measured by the manual method (ICC=0.914, CI:0.832–0.956). For the other anterior ratio measurements, the model scanner demonstrated good-to-excellent reliability (ICC=0.867, CI:0.739–0.932), while the intraoral scanner showed only good reliability (ICC=0.826, CI: 0.659–0.911). Although the ICC value obtained with the intraoral scanner was within an acceptable range, it was the lowest among the anterior ratio measurements. The overall Bolton ratios exhibited good to good-to-excellent reliability. Among these, the highest ICC was observed with the model scanner (ICC=0.891, CI:0.787–0.945), followed by the intraoral scanner (ICC=0.805, CI:0.619–0.901) and the manual method (ICC=0.802, CI:0.611–0.899).

The results of the Bland–Altman analysis performed for inter-observer evaluation are presented in Table 2 and Figure 2. Based on this analysis, it can be stated that in the assessment of the anterior Bolton ratio, the manual method demonstrated low measurement bias and acceptable levels of random error. The model scanning method exhibited

Table 1 Mean ICC values and levels of reliability for different methods in the measurement of anterior and overall Bolton ratios

Method	Bolton ratio	ICC (Avg. Measures)	95% CI (Avg.)	Reliability interpretation
Intraoral scanner	Anterior	0.826	0.659-0.911	Good reliability
Manual method	Anterior	0.914	0.832-0.956	Excellent reliability
Model scanner	Anterior	0.867	0.739-0.932	Good to excellent reliability
Intraoral scanner	Overall	0.805	0.619-0.901	Good reliability
Manual method	Overall	0.802	0.611-0.899	Good reliability
Model scanner	Overall	0.891	0.787-0.945	Good to excellent reliability

Avg, average; ICC, intraclass correlation coefficient. ICC values were calculated using a two-way random-effects model for absolute agreement with average measures. All measurements were found to be statistically significant ($p<0.001$).

Table 2. Bland–Altman analysis results for different methods in the measurement of anterior and overall Bolton ratios: Bias and limits of agreement values

Method	Bolton ratio	Bias	LoA Lower	LoA Upper
Intraoral scanner	Anterior	5.89	-2.65	14.43
Manual method	Anterior	0.2	-4.7	5.1
Model scanner	Anterior	0.77	-3.43	4.98
Intraoral scanner	Overall	-0.03	-5.46	5.41
Manual method	Overall	-0.19	-3.98	3.59
Model scanner	Overall	0.39	-4.25	5.03

Bias represents the systematic deviation between different methods, while the limits of agreement (LoA) indicate the random errors between measurements taken by different observers or methods. The analyses were performed with a 95% confidence interval.

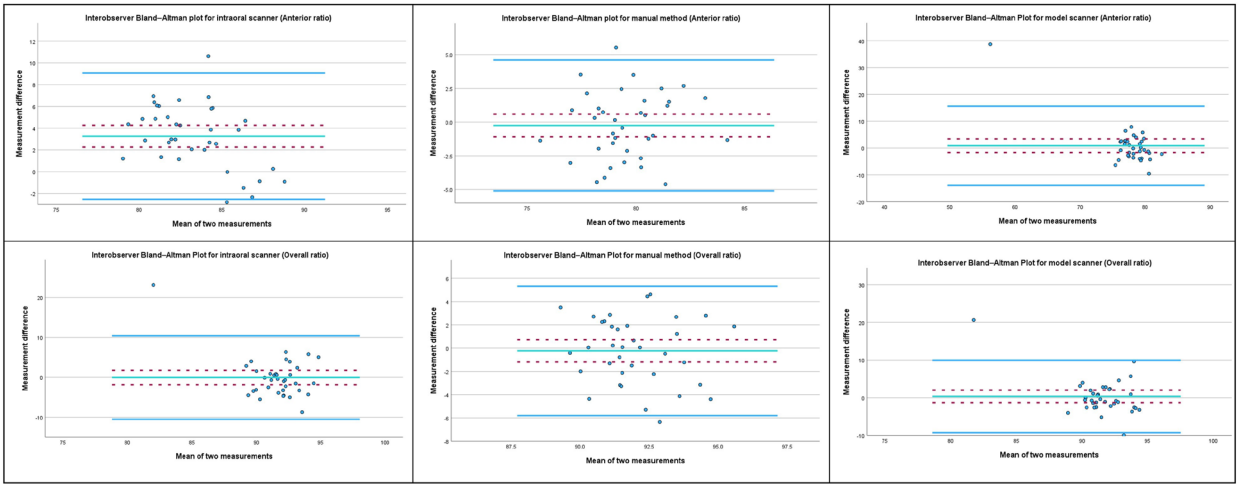

Figure 2. Bland–Altman analyses of anterior and overall Bolton ratios

greater systematic bias compared to the manual method. In the intraoral scanner measurements, significantly higher values than both other methods were observed, along with lower consistency. The lowest repeatability was observed in the anterior Bolton ratio measurements obtained using the intraoral scanner.

The most stable and consistent method was identified in the overall Bolton ratios obtained using the manual method. This result indicates that the manual method exhibited minimal systematic error and low levels of random variability in the measurements. The overall Bolton ratio data obtained with the model scanner produced results similar to those of the manual method. In the intraoral scanner measurements, the near-zero bias suggested an absence of systematic error; however, the slightly wider limits of agreement (LoA) compared to the manual and model methods indicated increased random variability. These findings demonstrate that the intraoral method provides a good level of consistency, although the random dispersion of the measurements may be somewhat greater.

When the significance of the differences among the methods for the anterior and overall Bolton ratios was examined, a statistically significant difference was found only for the anterior ratio ($F=533.863$, $p<0.001$) (Table 3). The highest mean values were observed in the models obtained using intraoral scanning, followed by those measured manually, and finally by the models obtained using model scanning. For the overall Bolton ratio, no statistically significant differences were detected among the methods ($F=0.589$, $p=0.601$).

DISCUSSION

This study was conducted to compare the reliability and reproducibility of manual measurements, intraoral scanner-derived digital models, and model scanner-derived digital models in the measurement of Bolton ratios, which hold significant importance in orthodontic diagnosis and treatment planning. The findings of the study demonstrated that all methods provided acceptable levels of intra-observer reliability. However, statistically significant differences were detected among the methods for anterior Bolton ratio measurements, with the intraoral scanner exhibiting systematic bias and a wider range of random error. In contrast, no significant differences were observed among the methods for the overall Bolton ratio. These results indicate that the manual and model scanner methods produced more consistent measurements than the intraoral scanner for the anterior segment. Based on these findings, the null hypothesis established in this study was rejected.

Only female individuals who had completed their growth and development period were included in this study. The literature reports varying results regarding the influence of sex on tooth dimensions and, consequently, on Bolton ratios. A previous study demonstrated that maxillary and mandibular tooth size ratios were larger in males.[16] Another study reported small differences in Bolton ratios between sexes,[17] whereas some studies have indicated no differences at all.[18,19] Oktay and Ulukaya[20] analyzed Bolton ratios by classifying them according to malocclusions and

Table 3. Mean percentage point differences and statistical results for the comparison of different methods in anterior bolton ratio measurements

Comparison	Mean difference	Standard error	P value	95% CI
Intraoral scanner-Manual method	5.544	0.231	<0.001*	4.963-6.125
Intraoral scanner-Model scanner	6.766	0.183	<0.001*	6.306-7.226
Manual method-Model scanner	1.222	0.243	<0.001*	0.610-1.833

*CI, confidence interval. P values were obtained using Repeated Measures ANOVA followed by Bonferroni-adjusted post-hoc tests. *P<0.001.*

showed statistically significant differences in posterior ratios between sexes across all groups. Including only female participants in the present study eliminated potential sex-related effects on tooth dimensions and Bolton ratios, allowing for a homogeneous evaluation of the results within a single-sex group.

Ensuring high precision during model acquisition is a critical factor that directly affects the accuracy and reproducibility of the results. In the manual method, an A-type silicone impression material, also known as addition silicone, was preferred due to its advantages. This material is distinguished by its high accuracy, low shrinkage rate, and excellent dimensional stability.[21] In the study by Levartovsky et al.[22], addition silicone impression material was reported to be stable enough to allow pouring to be delayed for up to 30 hours. Therefore, addition silicone was selected as the impression material for obtaining dental plaster models in our study. Furthermore, during the preparation of digital models, the auto-segmentation feature of the software was disabled, and all measurement steps were manually performed by the investigators. This approach minimized the potential impact of systematic errors associated with the software and improved measurement accuracy by leaving full control to the investigator.

Upon examining the intra-observer findings, it was observed that although the manual method is considered the gold standard, it provided the highest reliability for the anterior Bolton ratio; however, this superiority diminished as the measurement area expanded to include posterior teeth. Martin et al.[23] reported that measurement errors were greater in the molar region; similarly, Zilberman et al.[24] noted that molar tooth anatomy could increase the rate of systematic error. Although various software programs have been evaluated, a previous study reported findings consistent with ours, indicating that the Bolton ratio demonstrated high accuracy only in the anterior region.[25] Past studies have revealed that the ClinCheck software tends to underestimate tooth widths, with this tendency increasing from the anterior to the posterior teeth.[25,26] Therefore, the differences observed between anterior and overall Bolton ratios in measurement outcomes are consistent with the literature and suggest that careful assessment of measurement accuracy is particularly necessary in the posterior segments.

The intraoral scanner method demonstrated lower reliability results compared to the other methods in this study. Increased salivation and limited spacing can reduce image quality during intraoral scanning, leading to inconsistencies in tooth dimension measurements.[27,28] Moreover, in digital models obtained with both intraoral and model scanners, it can become more challenging to accurately distinguish interproximal contacts and precisely identify landmark points over larger monitoring areas. These difficulties may cause small but clinically significant measurement deviations, highlighting the need for greater caution when using digital scanning methods for segmental tooth dimension measurements compared to manual methods.[10] In a previous study comparing plaster and digital models with cone-beam computed tomography, very high levels of reliability was reported. Unlike the present study, that study found that digital models obtained via laser scanning had higher ICC values than plaster models.[11] Consistent with our findings, Stevens et al.[29] reported ICC values of 0.923 for plaster models and 0.882 for digital models when measuring various dental arch parameters, demonstrating that plaster models provided higher repeatability.

In the inter-observer evaluation, the manual method emerged as the most reliable technique for both anterior and overall Bolton measurements. In a previous study, inter-examiner concordance correlation coefficient values

were compared, and higher rates were observed with plaster models.[29] Overall, it was found that the intraoral method exhibited markedly greater systematic and random errors in anterior measurements compared to the other methods. However, in the measurements of the overall Bolton ratio, the intraoral method showed no systematic bias, although random error remained high. These findings underscore the need for careful use of intraoral scanners for segmental measurements and suggest that manual or model scanner-based methods should be preferred in clinical decision-making. The results indicate that although intraoral scanners can minimize systematic errors over larger measurement areas, random errors may still affect measurement consistency. In a previous study comparing digital models obtained by different methods, statistically significant differences were detected; however, these differences were reported to be clinically insignificant as they were smaller than 0.5 mm. It was concluded that digital models obtained from plaster model scans possessed sufficient accuracy and reliability for orthodontic diagnosis and treatment planning.[30] Consistent with these findings, the present study also showed that the model scanning method produced results comparable to the manual method in both measurements, highlighting it as a reliable digital alternative in practice.

In the present study, it was expected that inter-observer consistency would be lower than intra-observer consistency. In the manual method, small differences in the observer's determination of measurement points can lead to greater variability between observers. In the model scanning method, the challenges of performing measurements digitally on a screen can adversely affect both intra-observer and inter-observer consistency. For digital models obtained with intraoral scanners, in addition to the variations inherent to model scanning, factors such as operator scanning speed, scanner tip angulation, and scanning pattern can introduce significant differences in measurement results. Consistent with our findings, Abizadeh et al.[31] compared model analyses on plaster and digital models and reported that measurements on plaster models exhibited statistically significantly better repeatability. Furthermore, differences arising from the software used may also occur. Although both digital workflows investigated were found to be reliable, the digital workflow under examination demonstrated higher reliability and identified larger average tooth dimensions.[12]

When determining the anterior Bolton ratio, the assessment is conducted over a narrow and short area, where even small measurement differences can have a significant impact on the percentage calculation. In contrast, in total mesiodistal measurements, as the measurement area expands, the effect of small errors becomes relatively diluted within the total measurement, reducing their impact and potentially preventing differences among methods from reaching statistical significance. This suggests that over larger measurement areas, the results of digital and manual methods may converge, and different methods may provide clinically comparable accuracy in comprehensive measurements such as the overall Bolton ratio. In the present study, while statistically significant differences were detected among methods for the anterior Bolton ratio, no significant differences were observed for the overall Bolton ratio. Some studies comparing plaster models with digital models obtained by different methods have reported statistically significant differences among methods,[7,8,26,32] whereas other studies have found no significant differences and reported high accuracy and reliability among the methods.[10,11,33] In this study, the anterior Bolton ratios obtained with the intraoral scanner were found to be 5.54% higher than those obtained by the manual method and 6.77% higher than those obtained by the model scanner method. In contrast, the mean difference between the manual and model scanner methods was relatively low, at 1.22%. Amuk et al.[10] found no significant differences between plaster models and plaster model scans in their study evaluating the Bolton ratio on models obtained by different methods. Based on the findings of the present study, it appears that in clinical situations where measurement accuracy in the anterior segment is critical for treatment planning, manual or model scanner-based measurement methods may offer greater reliability.

Recent studies have demonstrated that digital models are becoming increasingly important in terms of both measurement accuracy and the time advantages they offer in clinical practice. In the literature, no significant differences have been detected in Bolton ratio measurements performed on digital versus plaster models; however, it has been reported that measurements conducted on digital models were completed, on average, five minutes faster, and this time difference was statistically significant.[34] In addition to enabling faster measurements, digital models have become indispensable tools in modern orthodontic

practice due to their advantages in data storage, ease of sharing, and three-dimensional visualization for treatment planning. These findings indicate that digital measurement technologies not only accelerate clinical workflows but also provide reliable alternatives for accurate diagnosis and treatment planning.[35]

Depending on the type of analysis to be performed and the region to be measured, orthodontists' preference for different measurement techniques is an important approach that can enable accurate decision-making in both diagnosis and treatment planning processes. The results of this study reveal the differences in the reliability of measurement methods in segmental and overall tooth size analyses, providing valuable information to support clinical decision-making. Thus, orthodontists can select the measurement technique best suited to their specific clinical requirements and treatment objectives, thereby enhancing the accuracy and effectiveness of their treatment plans. However, it should be noted that this study has several limitations. First, the sample consisted solely of female individuals within a specific age range, limiting the generalizability of the findings to male individuals and other age groups. Second, only a single intraoral scanner model and a single software program were used. Therefore, the performance of different scanners and software was not assessed. Future studies should be designed as comprehensive investigations involving broader age and sex groups, comparisons of various scanners and software, measurement of different arch parameters, and assessments of long-term repeatability data to provide more reliable and generalizable results for clinical decision-making.

CONCLUSIONS

- For intra-observer evaluations, the manual and model scanning methods demonstrated high reliability, whereas the intraoral scanning method showed lower consistency in anterior Bolton ratio measurements.
- For inter-observer evaluations, consistency decreased across all methods, with observer differences becoming more pronounced particularly in the intraoral scanning method.
- Statistically significant differences were detected among all three methods in anterior Bolton ratios, whereas no significant differences were found among the methods for overall Bolton ratios.
- Especially for anterior Bolton ratio, the use of manual or model scanning methods will provide more reliable results than the intraoral scanning method in terms of measurement accuracy and treatment planning.
- These findings indicate that although intraoral scanners offer practical advantages, their tendency to overestimate anterior Bolton ratios necessitates caution in daily orthodontic practice. Manual and model scanner methods provide more consistent results and may be preferable when accurate anterior ratio assessment is critical for treatment planning decisions.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

ETHICS STATEMENT

The study protocol was approved by the Clinical Research Ethics Committee of Hacettepe University (Approval No: KA-22051). Written informed consent was obtained from all participants prior to their inclusion in the study.

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