Accuracy comparison of digital occlusal registration according to scanning methods, trimming range, and clinical crown height

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This certifies that the Master's Thesis of BATJARGAL ENKHJARGAL is Approved

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2025년 6월

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ABSTRACT

Accuracy comparison of digital occlusal registration according to scanning methods, trimming range, and clinical crown height

Purpose: The purpose of this study was to evaluate the accuracy of digital occlusal registration according to scanning methods, trimming range, and clinical crown height, and to assess the influence of these factors on angular deviation and surface-based occlusal clearance.

Methods: A total of 80 STL datasets were generated using 3D-printed general and attrition dental models. Each model type was subjected to two scan methods (standard unilateral and occlusal-buccal) and two trimming range (narrow and wide range), with 10 repetitions per group. Accuracy was assessed by measuring angular deviation (occlusal, buccal, proximal directions) and surface distance at a defined area of interest using CAD analysis software. Statistical comparisons were made using one-way ANOVA and Tukey's HSD test.

Results: Angular deviation was significantly greater in attrition models and when narrow trimming range was applied. The standard unilateral scan combined with wide trimming yielded the most consistent and accurate results. Differences in surface-based occlusal clearance among groups were minimal and not statistically significant ($p > 0.05$).

Conclusion: The findings suggest that both scanning strategy and trimming range influence digital occlusal registration accuracy. Standard unilateral scanning with wider surface retention may be preferred for enhanced inter-arch alignment, particularly in cases of reduced anatomical landmarks. However, these results must be interpreted with caution due to the study's in vitro nature, operator

consistency, and fixed scan direction.

Key words: intraoral scanner, scanning method, trimming range, digital occlusal registration, angular deviation, surface-based occlusal clearance, attrition model

1. Introduction

A critical aspect of restorative dental procedures is the accurate recording of the patient's occlusion (Solaberrieta et al., 2015; Ender et al., 2016; Wong et al., 2018; Lee et al., 2022; Ries et al., 2022; Kakali & Halazonetis, 2023). Traditionally, this has been achieved using conventional impression techniques, which involve materials such as wax or silicones to capture the occlusal relationship (Lee et al., 2022; Ries et al., 2022). However, the advent of intraoral scanners (IOS) in dental practice has introduced a digital alternative to these conventional methods, offering a more streamlined and potentially more accurate approach to impression-taking (Boeddinghaus et al., 2015; Muller et al., 2016; Ender.A; et al., 2019; Diker & Tak, 2020).

Digital impressions can be categorized into two main methods: indirect and direct. The indirect method combines conventional and digital workflows (Boeddinghaus et al., 2015; Ender.A; et al., 2019; Diker & Tak, 2020; Zarone et al., 2020). It involves taking a traditional impression using materials like alginate or silicone, followed by the fabrication of stone casts, which are subsequently digitized using laboratory scanners (Zarone et al., 2020). In contrast, the direct method is entirely digital, utilizing intraoral scanners to capture the patient's intraoral condition directly. A wide range of intraoral scanners is now available on the market, each with varying features and capabilities (Muller et al., 2016; Ender.A; et al., 2019; Ammoun et al., 2020; Zarone et al., 2020).

The increasing adoption of intraoral scanners has significantly influenced both clinical practice and research. Studies have demonstrated that the accuracy of certain intraoral scanners is comparable to, and in some cases exceeds, that of conventional impression techniques (Boeddinghaus et al., 2015; Jeong et al., 2016; Muller et al., 2016; Ender.A; et al., 2019;

Diker & Tak, 2020; Yazigi et al., 2023; Rutkunas et al., 2024). The use of intraoral scanners offers several advantages for both clinicians and patients (Emir Yuzbasioglu et al., 2014; Boeddinghaus et al., 2015; Ender.A; et al., 2019; Latham et al., 2020; Zimmermann et al., 2020).

For clinicians, digital impressions eliminate the need for physical impression materials and allow for the selective rescanning of unclear areas, improving efficiency and precision (Ender.A; et al., 2019; Diker & Tak, 2020). For patients, this method is particularly beneficial for those with a strong gag reflex, as it avoids the discomfort associated with traditional impression materials (Anh et al., 2016). Additionally, digital impressions enable the storage of patient data for future use, enhancing long-term treatment planning and record-keeping.

The digital impression process mirrors the conventional workflow in many respects. It begins with capturing the patient's intraoral condition, followed by the occlusal registration of both arches. In digital workflows, occlusal registration is achieved by scanning the buccal surfaces of both arches, after which the software aligns the occlusal data with the complete intraoral scan (Ortensi et al., 2024). However, as the occlusal registration relies solely on the buccal surfaces, alignment inaccuracies between the upper and lower arches can occasionally occur (Muller et al., 2016).

This limitation becomes even more critical in patients with reduced anatomical references, such as those with severe tooth wear or attrition, where occlusal morphology is diminished. These anatomical challenges can compromise the accuracy of digital inter-arch alignment.

To address this limitation, recent advancements in intraoral scanner technology have introduced enhanced occlusal registration features (Wong et al., 2018). These include the ability to superimpose the lower arch onto the upper arch at multiple levels, allowing clinicians to verify the intraoral condition in real time. This feature enables a direct comparison of the scanned data, facilitating the selection of the most accurate representation of the patient's occlusion. Nonetheless, further research is needed to validate the efficacy and reliability of these features.

In clinical practice, patients exhibit diverse occlusal patterns and conditions, such as attrition, which can influence the accuracy of occlusal registration (Camci & Salmanpour, 2021). Excessive coverage of the maxillary teeth, for instance, may result in insufficient mandibular data, leading to occlusal alignment errors and potentially compromising the fit and accuracy of the final restoration (Kakali & Halazonetis, 2023). In such cases, the loss of occlusal landmarks complicates the software's ability to match upper and lower scans reliably.

Although some studies have evaluated scanner performance under normal conditions, limited evidence is available regarding the impact of scan strategy and surface coverage in anatomically compromised scenarios, particularly in evaluating how different scan methods and trimming extents influence angular deviation and interocclusal clearance in models simulating clinical conditions such as attrition. This represents a gap in current literature requiring focused investigation. A focused investigation is warranted to determine how scanning method and trimming range affect registration accuracy in such cases.

A trimming range refers to the extent of surface data retained during the scan alignment process, typically categorized as wide or narrow.

Therefore, this study aims to compare the accuracy of the standard unilateral scan and the occlusal-buccal scan, while assessing their clinical relevance through a trimming range. Additionally, the study seeks to determine which scanning method is more effective in improving accuracy under varying clinical conditions and to evaluate the impact of combining different scanning methods and ranges on overall accuracy. Understanding these factors can contribute to more predictable digital occlusion protocols, especially in patients with compromised dentition or reduced anatomical landmarks. To ensure objective comparison, accuracy will be assessed based on angular deviation of embedded reference cubes and interocclusal clearance at a defined area of interest (maxillary first molar).

2. Material and methods

2.1. Digital design of Maxillary and Mandibular full arches

The maxillary and mandibular full-arch models were designed using a computer-aided design (CAD) software (Meshmixer, Autodesk). The digital design process focused on creating anatomically accurate full-arch models, ensuring that the occlusal surfaces, interproximal contacts, and overall morphology adhered to clinical standards (Figure 1 and 2).

To enhance the analysis process, the first mandibular molar was digitally prepared for a full-coverage crown. This preparation was performed to establish a defined Area of Interest (AOI), which allowed for a more focused and precise evaluation of the occlusal registration and trimming range.

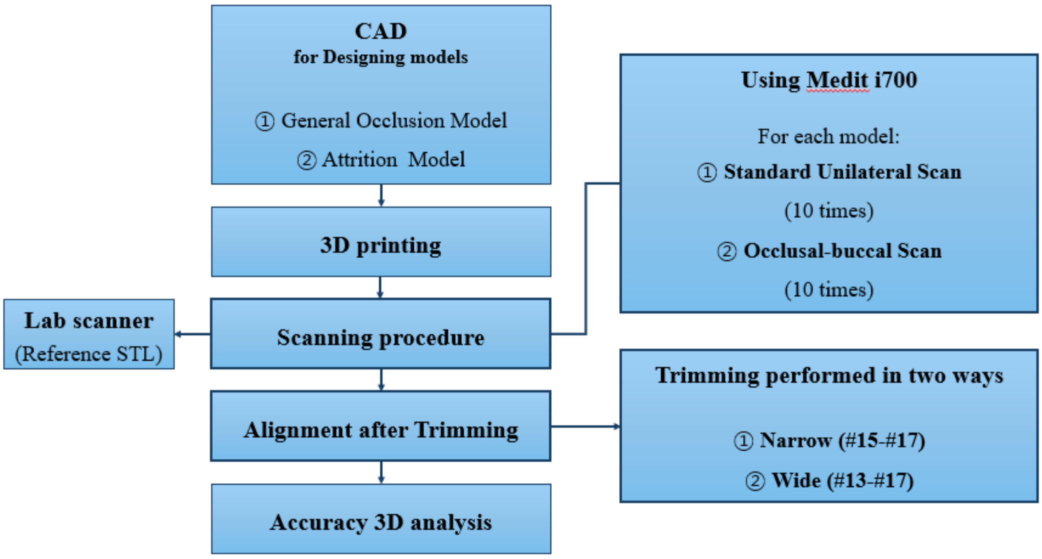

Figure 1. Workflow of model preparation, scanning, and accuracy 3D analysis.

CAD-designed models (general occlusion and attrition types) were 3D printed and scanned using a lab scanner (reference STL) and an intraoral scanner (Medit i700) with two scan methods (Standard Unilateral and Occlusal-Buccal). Scanned data were trimmed in narrow and wide ranges, followed by alignment and 3D deviation analysis.

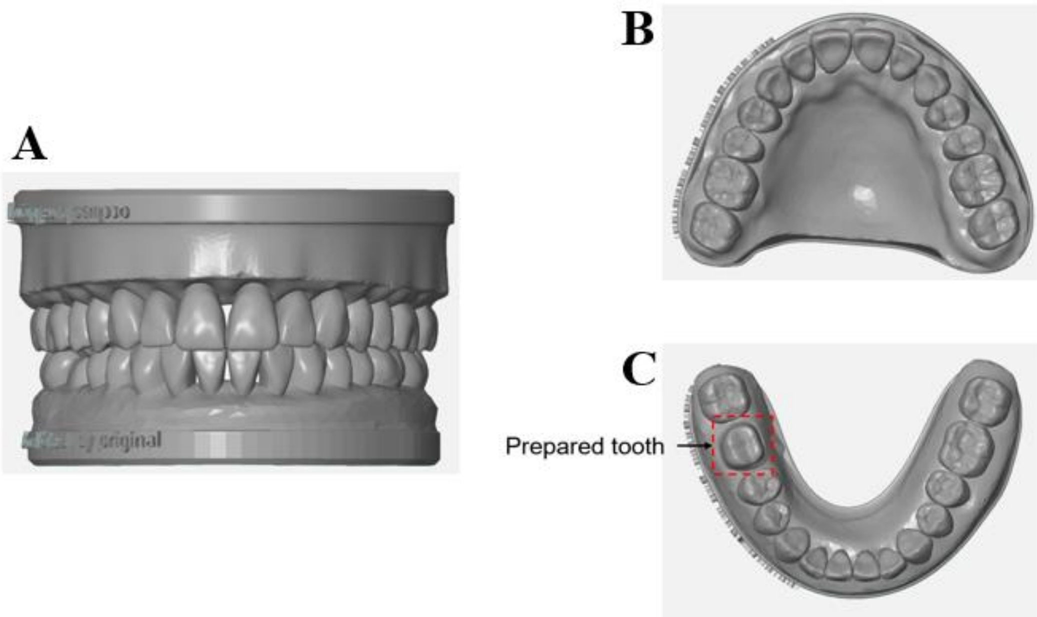

Figure 2. Digital design of full-arch models and preparation site.

A. Maxillary and mandibular full-arch models were digitally designed and aligned in maximum intercuspation to simulate a clinical occlusal relationship. **B.** Occlusal view of the maxillary full-arch design, demonstrating the overall dental arch form. **C.** Occlusal view of the mandibular model, showing the digitally prepared first molar (indicated by red box and label). This preparation served as the opposing reference surface for evaluating inter-arch alignment accuracy, although the defined Area of Interest (AOI) was located on the maxillary arch.

2.2. Digital mounting of models

The digitally designed maxillary and mandibular arches were mounted using two distinct methods to simulate different occlusal relationships (Figure 3):

- Maximum Intercuspation (MI): In this method, the models were aligned to achieve occlusal contacts that represented the natural position of maximum intercuspation. This postiion is characterized by the optimal interdigitation of the maxillary and mandibular teeth, which is commonly used as a reference point in restorative and prosthodontic procedures (Figure 3A).

- Attrition: For the second method, the models were digitally adjusted to simulate an occlusal relationship with attrition. This condition was defined as an exaggerated vertical overlap of the maxillary anterior teeth over the mandibular anterior teeth, beyond the normal range. The attrition was intentionally introduced to evaluate its impact on the accuracy of the digital occlusal registration. (Figure 3B).

The digital mounting process was performed within the CAD sofware.

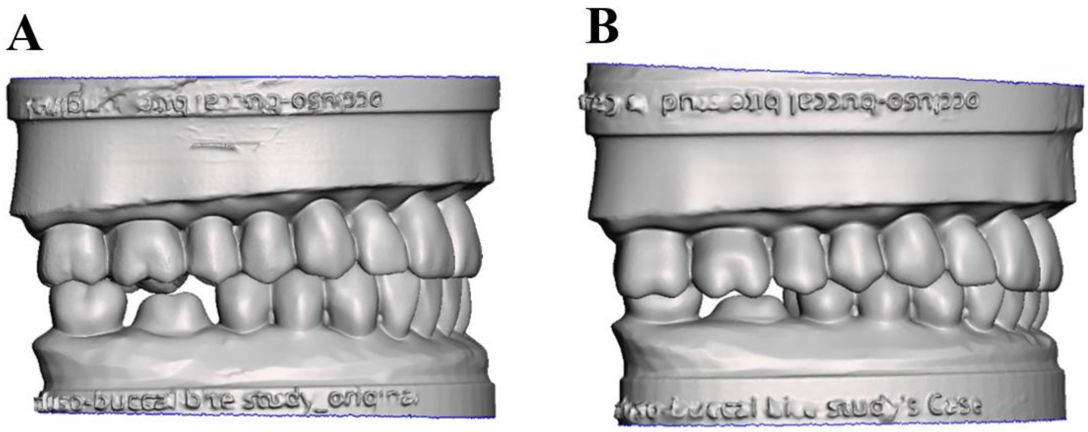

Figure 3. Digital mounting methods used to simulate occlusal relationships:

A. Maximum intercuspation model with full occlusal contact (right side). **B.** Attrition model showing deep anterior overlap (right side).

2.3. 3D Printing of models

A total of four models were fabricated usign a high-resoulution 3D printer (NextDent5100, 3D SYSTEMS). This printer utilizes Digital Light Processing (DLP) technology, which is know for its ability to produce highly accurate and detailed dental models. The printing parameters, including layer thickness, exposure time, and post-processing protocols, were optimized according to the manufacturer's recommendations to achieve the highest quality output.

2.4. Scanning and Establishment of Reference Data

The fabricated maxillary and mandibular full-arch models were scanned using a laboratory scanner (DOF, DOF Inc.). The scanning process generated three-dimensional (3D) data of the models, which were exported in the standard tessellation language (STL) file format. The STL format was choosen due to its compatibility with various CAD and analysis software. The STL files obtained from the laboratory scanner were imported into Medit software (Medit link, Medit Corp.) to serve as the reference data for subsequent scanning and analysis procedures.

2.5. Scanning procedure with Intraoral scanner

To ensure consistent inter-arch positioning during intraoral scanning, the 3D-printed maxillary and mandibular models were manually placed on a non-adjustable articulator, following the digitally pre-established occlusal relationship. No additional bite jig or stabilization material was used, and care was taken to replicate the positioning for all repeated scans. (Figure 4, 5)

Following the establishment of the reference data, the scanning procedure was performed using an intraoral scanner (i700, Medit Corp.). The intraoral scanner was employed exclusively for the occlusal registration process, where in two distinct scanning methods were performed to evaluate their accuracy and consistency. For each method, the same maxillary and mandibular arches from the reference data were used in all cases. Each scanning method was repeated 10 times. All intraoral scans were performed exclusively on the right side of the dental arch to maintain consistency across all trials.

- Standard Unilateral Scan: this method involved scanning the buccal surfaces of both the maxillary and mandibular models. The scanner was positioned to capture the lateral aspects of the arches, focusing solely on the buccal surfaces without including the occlusal surfaces (Figure 6).

- Occlusal-Buccal Scan: in this method, the scanning process began with the occlusal surfaces of the mandibular posterior teeth. The scanner was first positioned to capture the occlusal surfaces. Following the occlusal scan, the buccal surfaces of the mandibular teeth were scanned to complete the dataset. This method provided a more comprehensive capture of the both the occlusal and buccal surfaces. (Figure 7)

Both scanning methods were performed under standardized conditions by the same operator. The scanning speed, angulation, and distance from the models were carefully controlled to minimize variability.

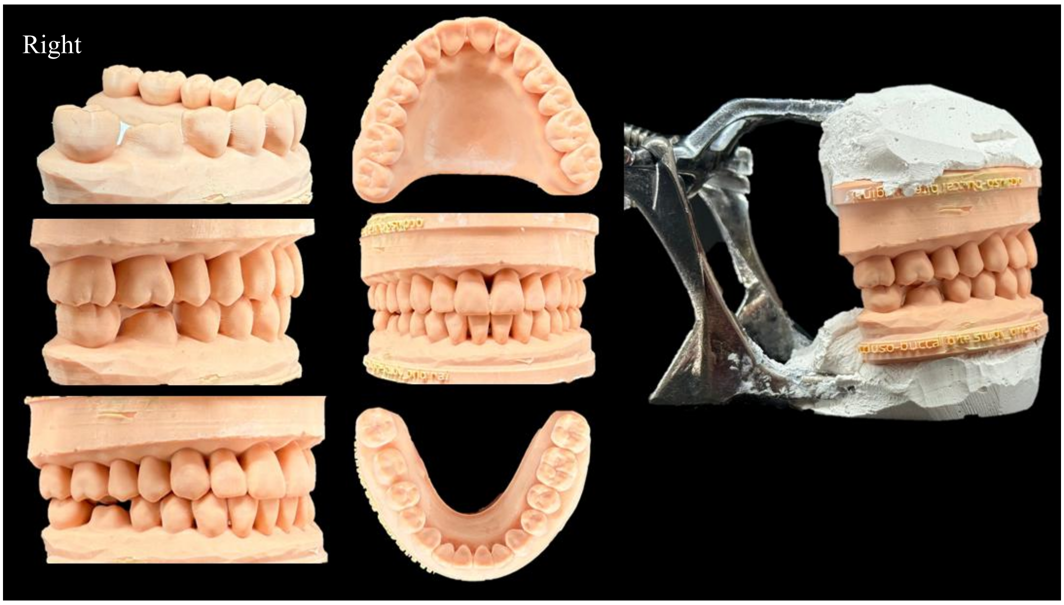

Figure 4. A fully 3D-printed general occlusal model was mounted on a non-adjustable articulator using dental stone.

Figure 5. A fully 3D-printed attrition model was mounted on a non-adjustable articulator using dental stone.

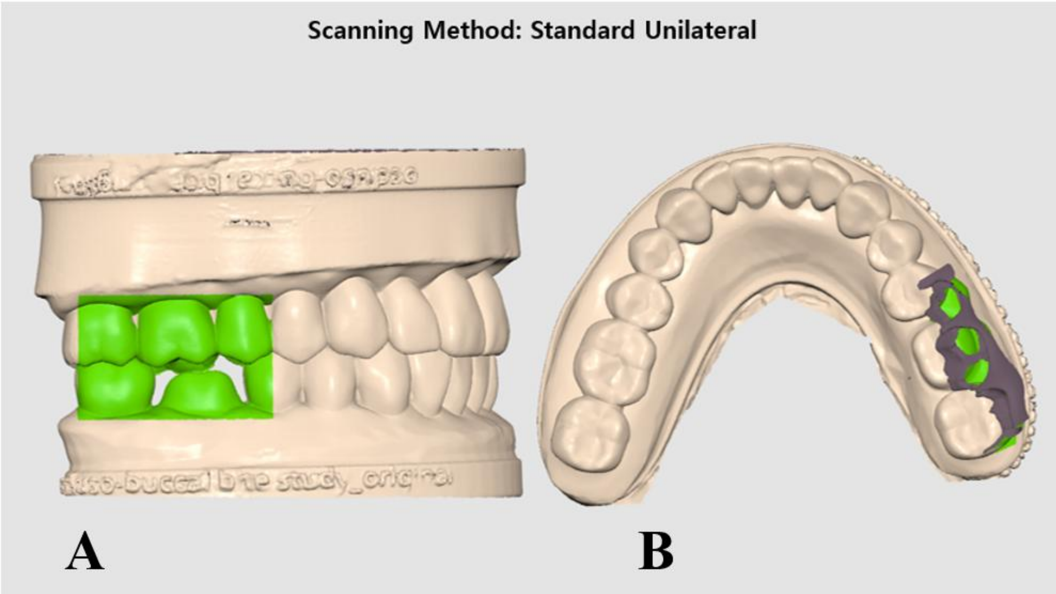

Figure 6. Indicated narrow trimming range in the Standard Unilateral Scan method on general scanning model.

A. Buccal view showing the area proposed for retention during narrow trimming range, limited to the buccal surfaces of the posterior teeth. **B.** Occlusal view highlighting the intended trimming range from the second premolar to the second molar. The green-highlighted surfaces represent the region designated to be preserved for alignment and accuracy evaluation.

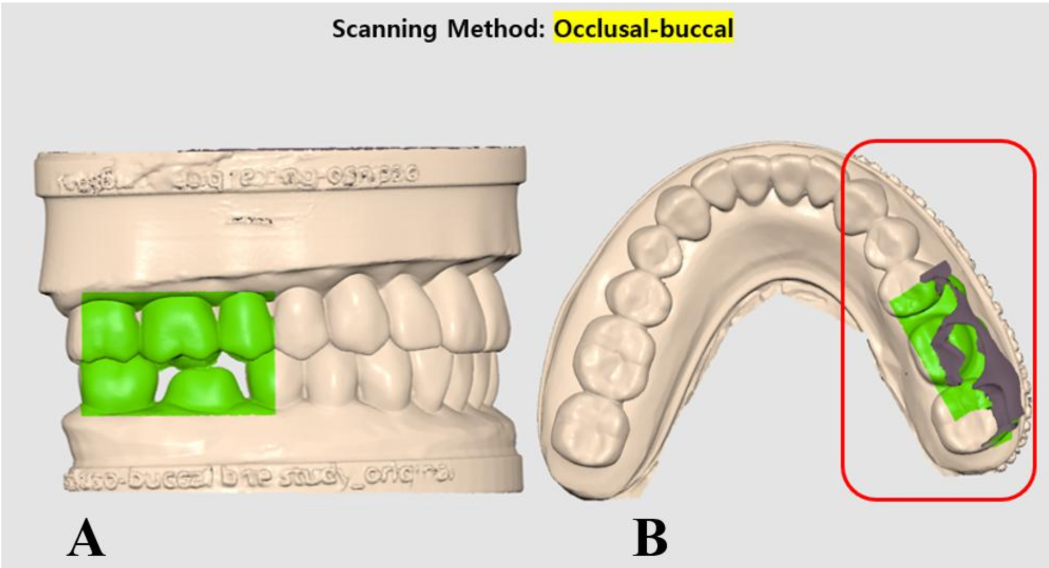

Figure 7. Indicated narrow trimming range in the Occlusal-Buccal Scan method on general scanning method (green-highlighted surfaces represent the narrow trimming range).

A. Buccal view showing the area proposed for retention during narrow trimming, including both the occlusal and buccal surfaces of the posterior teeth. **B.** Occlusal view highlighting the intended trimming range. The green-highlighted surfaces represent the region designated to be preserved for accuracy evaluation.

2.6. Trimming range

Trimming range in this study, the term ‘trimming range’ refers to the amount and extent of occlusal surface data retained for alignment and analysis. It involves digitally selecting specific regions of the scanned occlusal data. Following the acquisition of 20 occlusal registrations (10 from the standard unilateral scan and 10 from the occlusal-buccal scan), two trimming range were applied using CAD software to assess how varying occlusal surface coverage influences registration accuracy. The two trimming range were defined as follows:

- Narrow range: in this strategy, the occlusal registration data were trimmed to include only the region spanning from the second premolar to the second molar. This range focused on the posterior segment of the dental arches. The narrow trimming range was designed to assess the accuracy of occlusal registrations when limited to a smalled, posterior-focused data (Figure 8A, B).

- Wide range: the wide trimming range included a broader range of occlusal registration data, extending from the canine to the second molar. This range incorporated both anterior and posterior segments of the dental arches. The wide trimming range was intended to evaluate the impact of including additional data (Figure 8C, D).

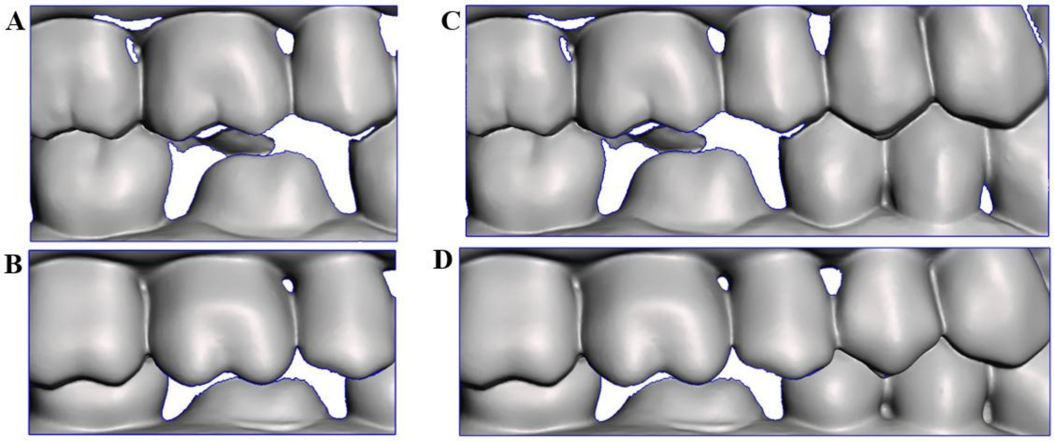

Figure 8. Narrow and wide trimming range applied to different occlusal models.

A. Occlusal contact alignment in the general occlusion model, demonstrating proper intercuspation with retained data from the second premolar to the second molar. **B.** Occlusal contact alignment in the attrition model, showing altered inter-arch relationship despite the same trimming range. These images illustrate the influence of anatomical variation on registration accuracy under narrow data conditions. **C.** General occlusion model showing occlusal alignment after trimming from the canine to the second molar. **D.** Attrition model displaying altered inter-arch contact despite using the same wide trimming range. These images illustrate how anatomical differences affect occlusal registration outcomes when a broader data range is retained.

2.7. Analysis procedure

1. Alignment of Reference data: The analysis of the scanned data was conducted using a CAD analysis software (GOM Inspect 2018, Autodesk). To ensure consistency and accuracy in the evaluation process, all datasets were aligned and centered on the prepared mandibular first molar. This alignment served as a reference point, allowing for a standardized and reproducible analysis across all groups. The alignment process was based on the embedded cube geometry, which provided a fixed spatial reference for orienting the models consistently. In this coordinate system, the X-axis represented the buccolingual direction (buccal), the Y-axis the mesiodistal (proximal) direction, and the Z-axis the occluso-gingival (occlusion) direction (Figure 9A).

2. To evaluate the tilting effect of occlusal registration, a geometry cube with 3mm dimensions was digitally embedded into the occlusal surfaces of the maxillary and mandibular first molars using CAD software (Figure 9B). The embedding was performed prior to analysis and applied consistently across all reference and test STL datasets, including different trimming ranges and scanning conditions. This standardized reference geometry enabled precise alignment and direct comparison between datasets by minimizing variability and ensuring reproducibility (Figure 9C).

3. An Area of Interest (AOI) was established to facilitate precise measurement of occlusal registration accuracy between the occlusal surface of the first maxillary molar and the prepared first mandibular molar. The maxillary first molar was chosen due to its anatomical stability, central location in the arch, and consistent morphology across models. As the maxillary arch served as the reference during alignment, this site enabled reproducible and accurate measurement of inter-arch deviations (Figure 9D) and (Figure 10).

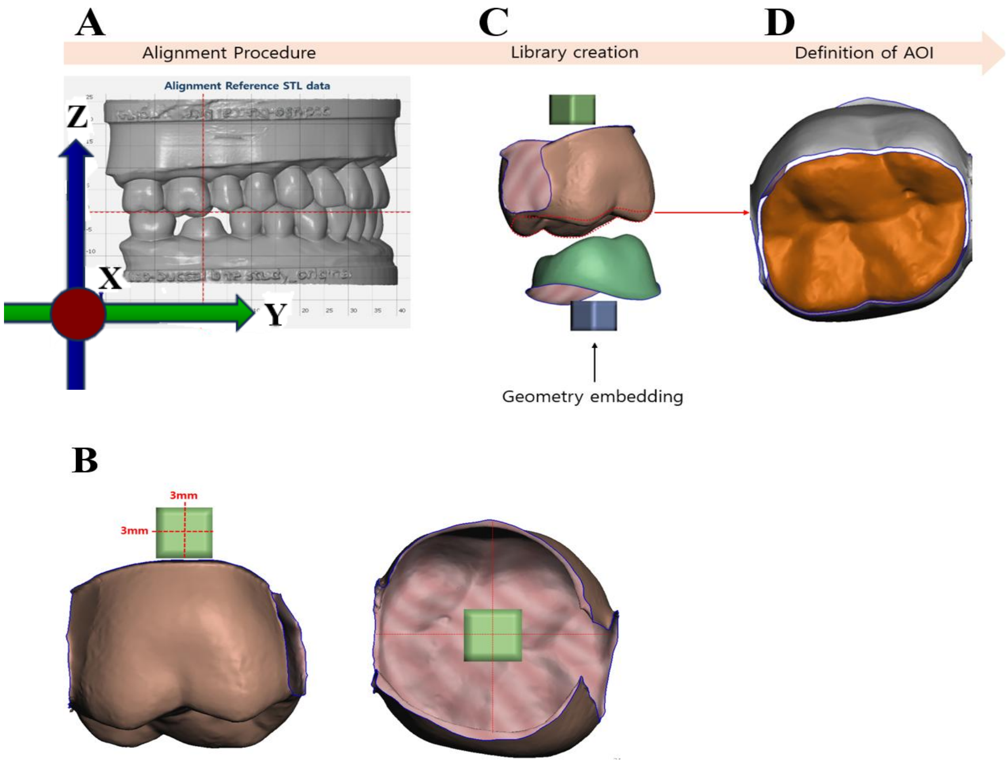

Figure 9. Workflow of the alignment and analysis procedure for occlusal registration evaluation.

A. Reference data alignment using embedded coordinate axes, centered on the prepared mandibular first molar in GOM Inspect. These axis directions were used consistently to evaluate angular deviations in occlusal (Z), buccal (X), and proximal (Y) dimensions. **B.** Geometry cube (3×3×3mm) digitally embedded into the occlusal surfaces of both maxillary and mandibular first molars to serve as standardized reference geometry. **C.** Library model creation with embedded cubes for alignment consistency across all groups. **D.** Definition of the Area of Interest (AOI) on the occlusal surface of the maxillary first molar, used for measuring registration accuracy relative to the opposing mandibular molar.

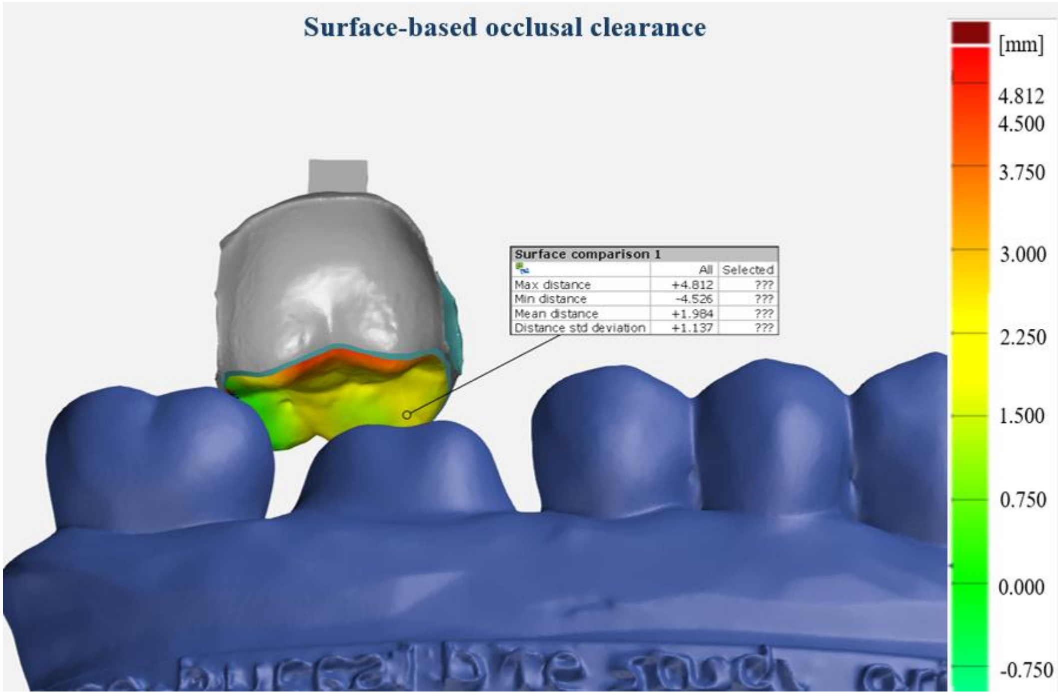

Figure 10. Representative surface deviation map at the Area of Interest (AOI)

Representative surface comparison map of the maxillary first molar (AOI) showing the spatial deviation between the test and reference models in one sample case. Color coding represents deviation magnitude from green (minimal deviation) to red (positive deviation) and blue (negative). The surface-based occlusal clearance of +1.984mm in this image corresponds to a single analysis instance, not to be confused with group means reported in the Results section.

2.8. Statistical analysis

Statistical analysis was performed using SPSS version 25.0 (IBM Corp., Armonk, NY, USA). The normality of data distribution was assessed using the Shapiro–Wilk test. After confirming the normal distribution of the data, one-way analysis of variance (ANOVA) was conducted to evaluate differences among the eight groups (n = 10 per group). A total of 80 STL datasets were generated and analyzed, resulting from 2 model types (general and attrition), 2 scanning methods (standard unilateral and occlusal-buccal), 2 trimming ranges (narrow and wide range), and 10 repetitions per group. Post hoc comparisons were performed using Tukey's honestly significant difference (HSD) test. A significance level of 0.05 was set for all statistical tests (Figure 11).

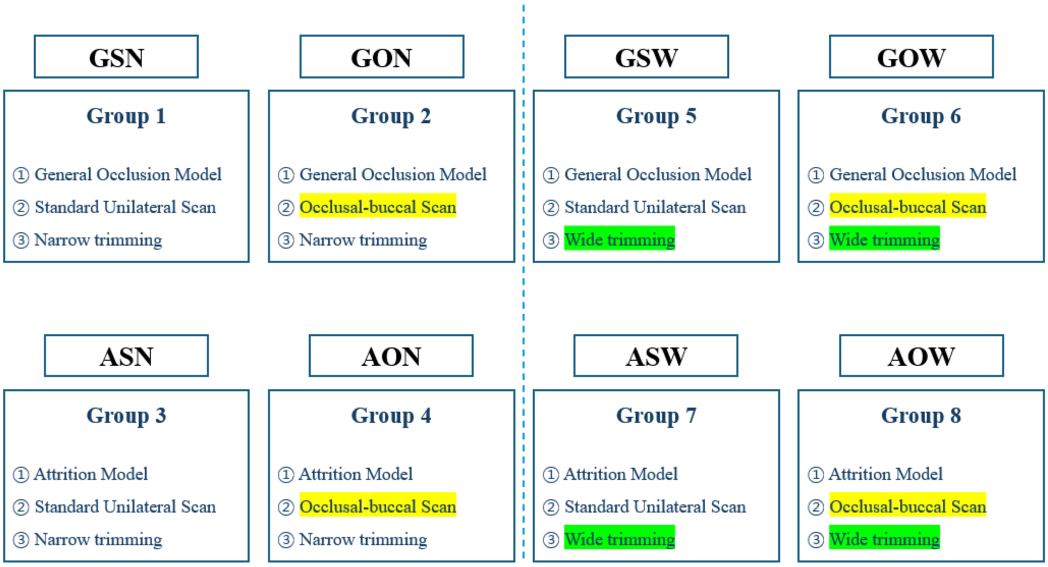

Figure 11. Angular deviation across experimental groups categorized by model type, scanning method, and trimming range.

Bar graph illustrating the angular deviation (in degrees) for each experimental group across three spatial directions: occlusion (Z-axis), buccal (X-axis), and proximal (Y-axis). The data compares eight groups based on model type (general vs. attrition), scanning method (standard unilateral vs. occlusal-buccal), and trimming range (narrow vs. wide). Each group name is a three-letter code representing:1st letter (G/A): Model type — G: General, A: Attrition. 2nd letter (S/O): Scanning method — S: Standard Unilateral, O: Occlusal-Buccal. 3rd letter (N/W): Trimming range — N: Narrow, W: Wide. For example, GSN refers to the General model with Standard scan and Narrow trimming range.

3. Results

This study evaluated the accuracy of digital occlusal registration across different scanning ranges and clinical conditions. The results were categorized into angular deviation (in degrees) and surface-based occlusal clearance (in mm), analyzed in relation to trimming ranges, scan method, and model type. Statistical analysis was performed using one-way ANOVA with Tukey's HSD post hoc test, and differences with p-values less than the predetermined significance level of 0.05 were considered statistically significant.

3.1. Angular deviation

Angular deviation was (°) assessed in three spatial directions (occlusion, buccal, and proximal) for all eight experimental groups. The results revealed that both anatomical condition and scan strategy significantly influenced alignment accuracy.

Among the narrow trimming groups, the general model with standard scan (GSN) recorded the lowest angular deviation values: 0.060 ± 0.022° (occlusion), 0.063 ± 0.020° (buccal), and 0.051 ± 0.014° (proximal). The general model with occlusal-buccal scan (GON) showed moderately higher values of 0.109 ± 0.057°, 0.103 ± 0.057°, and 0.041 ± 0.021°, respectively.

In contrast, attrition models showed substantially higher deviation. The ASN group (attrition, standard scan, narrow range) exhibited deviations of 0.257 ± 0.108° (occlusion), 0.245 ± 0.098° (buccal), and 0.106 ± 0.066° (proximal), while the AON group (attrition, occlusal-buccal scan, narrow range) recorded the highest values: 0.388 ± 0.032°, 0.387 ± 0.032°, and 0.061 ± 0.034°, respectively. The difference between GSN and AON was statistically highly significant ($p < 0.001$), indicating that both anatomical wear and scan method had a compounded negative impact on registration accuracy.

Among the wide trimming groups, GSW (general model, standard unilateral scan, wide range) achieved the most accurate alignment: 0.054 ± 0.024° (occlusion), 0.091 ± 0.018° (buccal), and 0.086 ± 0.021° (proximal). In comparison, GOW (general model, occlusal-buccal scan, wide range) showed slightly higher deviation in occlusion and buccal directions (0.103 ± 0.051° and 0.101 ± 0.050°), while its proximal deviation remained low at 0.050 ± 0.018°.

In attrition models with wide range, ASW yielded values of 0.130 ± 0.030° (occlusion), 0.147 ± 0.028° (buccal), and 0.073 ± 0.017° (proximal), whereas AOW presented 0.346 ± 0.066° (occlusion), 0.354 ± 0.060° (buccal), and 0.093 ± 0.033° (proximal). The comparison between ASN and ASW demonstrated that expanding the trimming range significantly reduced angular deviation ($p < 0.05$), even in cases of compromised occlusal morphology.

Overall, wide trimming range consistently produced lower deviation across all scan methods and models, underscoring its benefit in improving occlusion alignment. These results are detailed in Table I and visualized in Figure 12.

Table I. Angular deviation values in degrees (°) across all experimental groups by spatial direction Z-axis/Occlusion, X-axis/Buccal, Y-axis/Proximal

Groups	**Model type**	**Scan method**	**Trimming range**	**Z-axis (Occlusion)**	**X-axis (Buccal)**	**Y-axis (Proximal)**
GSN	General	Standard unilateral	Narrow	0.060 ± 0.022°	0.063 ± 0.020°	0.051 ± 0.014°
GON	General	Occlusal-buccal	Narrow	0.109 ± 0.057°	0.103 ± 0.057°	0.041 ± 0.021°
GSW	General	Standard unilateral	Wide	0.054 ± 0.024°	0.091 ± 0.018°	0.086 ± 0.021°
GOW	General	Occlusal-buccal	Wide	0.103 ± 0.051°	0.101 ± 0.050°	0.050 ± 0.018°
ASN	Attrition	Standard unilateral	Narrow	0.257 ± 0.108°	0.245 ± 0.098°	0.106 ± 0.066°
AON	Attrition	Occlusal-buccal	Narrow	0.388 ± 0.032°	0.387 ± 0.032°	0.061 ± 0.034°
ASW	Attrition	Standard unilateral	Wide	0.130 ± 0.030°	0.147 ± 0.028°	0.073 ± 0.017°
AOW	Attrition	Occlusal-buccal	Wide	0.346 ± 0.066°	0.354 ± 0.060°	0.093 ± 0.033°

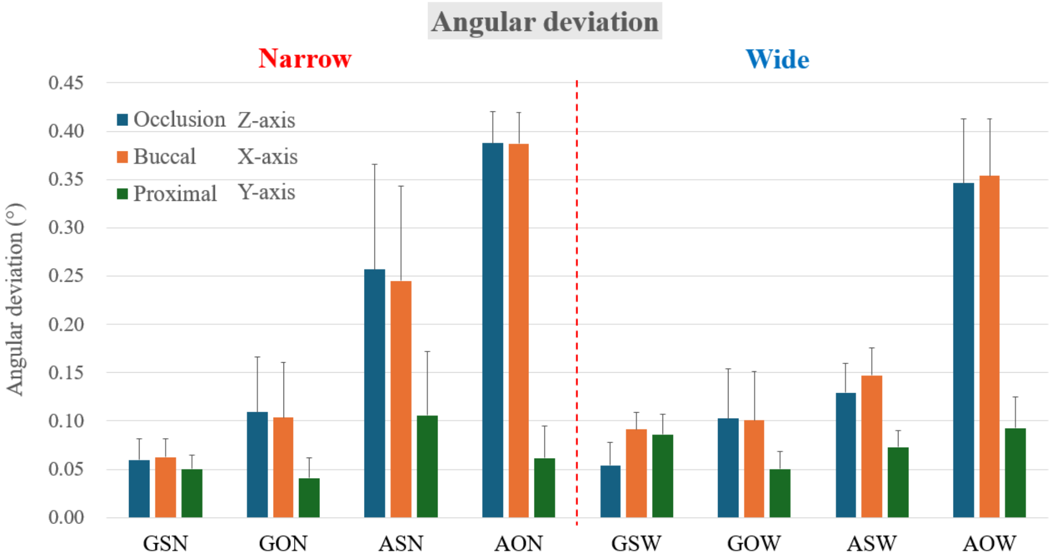

Figure 12. Bar graph illustrating angular deviation (in degrees) by group, trimming ranges (Narrow vs. Wide), and measurement direction (Occlusion, Buccal, Proximal).

3.2. Surface-Based Occlusal clearance

The surface-based occlusal clearance was analyzed to evaluate the spatial discrepancy between the occlusal surfaces after different scan and trimming combinations. The surface-based occlusal clearance and standard deviation (STD) for each group are summarized below showing in Table II.

Across the general model groups, the surface-based occlusal clearance demonstrated minimal variation between the narrow and wide trimming ranges, as well as between scanning methods. Specifically, the GSN group (general model, standard unilateral scan, narrow trimming range) exhibited a mean clearance of -0.250 ± 0.010 mm, while the GON group (general model, occlusal-buccal scan, narrow trimming range) showed -0.247 ± 0.011 mm. In the wide trimming groups, the GSW group recorded a mean clearance of 0.016 ± 0.013 mm, and the GOW group presented -0.006 ± 0.023 mm. Statistical analysis indicated no significant difference among these general model groups ($p > 0.05$).

Similarly, in the attrition model groups, surface clearance values remained within a narrow range regardless of the scanning and trimming variations. The ASN group (attrition model, standard unilateral scan, narrow trimming range) displayed a clearance of -0.041 ± 0.011 mm, while the AON group (attrition model, occlusal-buccal scan, narrow trimming range) showed -0.047 ± 0.023 mm. Under the wide trimming condition, ASW yielded -0.037 ± 0.010 mm, and AOW demonstrated -0.072 ± 0.040 mm. As with the general models, no statistically significant differences were observed among the attrition model groups ($p > 0.05$). Complete data are illustrated in Figure 13.

Table II. Standard deviation and surface-based occlusal clearance (*mm*) across experimental groups.

Groups	**Surface-based occlusal clearance (*mm*)**	**Standard deviation (*mm*)**
GSN	-0.250	± 0.010
GON	-0.247	± 0.011
GSW	0.016	± 0.013
GOW	-0.006	± 0.023
ASN	-0.041	± 0.011
AON	-0.047	± 0.023
ASW	-0.037	± 0.010
AOW	-0.072	± 0.040

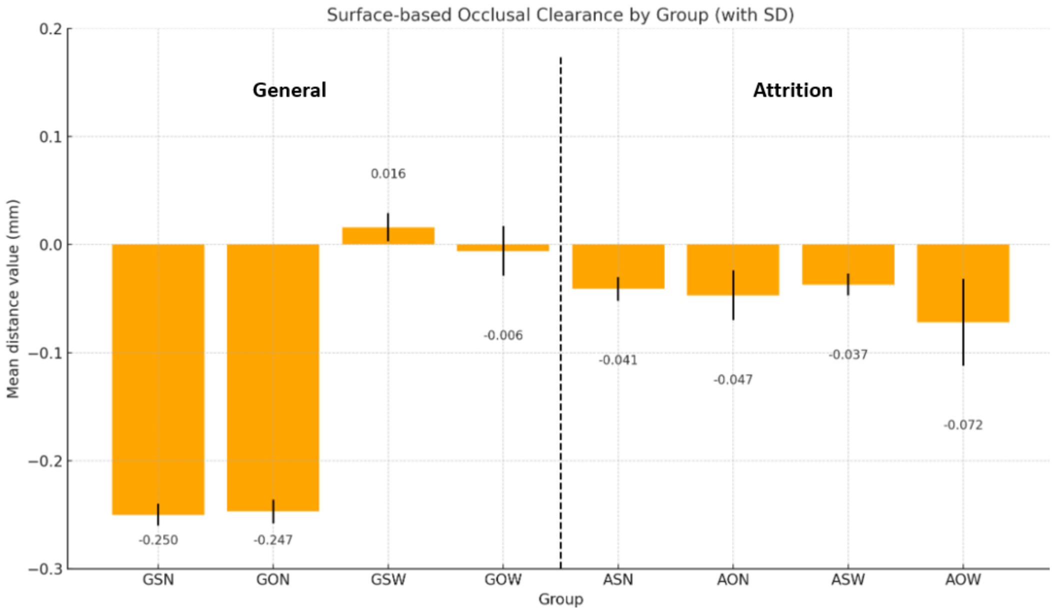

Figure 13. Bar chart showing mean distance of surface-based occlusal clearance (*mm*) for each group.

Error bars indicate standard deviations. No statistically significant differences were found between trimming range within each model type ($p > 0.05$).

4. Discussion

This study aimed to evaluate the impact of scanning method and trimming strategy on the accuracy of digital occlusal registration under different anatomical conditions. A total of eight experimental groups, categorized by model type (general or attrition), scan method (standard unilateral or occlusal-buccal), and trimming range (narrow or wide), were assessed. The results were interpreted through angular deviation and overall surface comparison, providing insights into clinical implications, methodological relevance, and areas for further research.

The angular deviation data revealed that both anatomical condition and scanning strategy significantly influence alignment accuracy. In particular, the occlusal-buccal scan method exhibited higher angular deviations compared to the standard unilateral scan, especially in attrition models where occlusal morphology was compromised. This outcome supports findings from (Ender et al., 2016; Mei et al., 2022),who reported increased variability in scan data when more complex anatomical or scanning variables were introduced.

Narrow trimming range were also associated with greater angular deviation than wide trimming approaches. The comparison between ASN and ASW groups illustrated a statistically significant improvement in accuracy when the trimming range was expanded ($p < 0.05$). This aligns with observations from (Ortensi et al., 2024), who found that increased surface coverage enhances the reliability of digital bite registration.

Despite the observed variability, the general model groups consistently showed lower angular deviation than the attrition groups. This trend highlights the role of anatomical stability in facilitating accurate occlusal alignment, as also noted by (Wong et al., 2018; Ries et al., 2022). Loss of occlusal landmarks in attrition models likely hindered the scanner software's ability to accurately match the opposing arches.

Interestingly, the surface-based occlusal clearance showed minimal statistical difference between the groups, with all deviations falling within a narrow range. This suggests that while angular orientation may vary with scan strategy and trimming, surface-level congruency can remain relatively consistent. It reflects previous findings by (Jeong et al., 2016; Botsford et al., 2019), who observed minor surface discrepancies despite different scan techniques.

However, it should be noted that the surface analysis focused primarily on vertical clearance at a defined Area of Interest (AOI), and thus may not fully capture rotational misalignments. Therefore, angular deviation remains a more sensitive indicator of registration fidelity, particularly under anatomically challenging conditions.

The methodological design of this study—using embedded geometric cubes and consistent AOIs—allowed for objective, reproducible comparison across all experimental conditions. This approach is in line with recommendations by (Lee et al., 2022; Kakali & Halazonetis, 2023), who emphasized the value of standardizing scan evaluation protocols in digital dentistry.

This in vitro study employed 3D-printed resin models mounted on non-adjustable articulators to simulate clinical occlusion. While this setup ensured high standardization and reproducibility, it does not fully replicate intraoral conditions such as saliva, soft tissue movement, or patient variability, which are known to influence scan quality and occlusal contact accuracy. Additionally, all scans were performed using a single intraoral scanner (Medit i700) and by a single operator on the right side only, which may introduce directional and operator bias into the results.

Although this reduced intra-operator variability, it limits generalizability to broader clinical contexts, as previous studies have suggested that multi-operator trials may yield different outcomes (Edher et al., 2018; Yazigi et al., 2023).

Furthermore, the exclusion of resin bite registration and reliance on the articulator's preset occlusion omit real-time occlusal adjustments, which may affect inter-arch alignment accuracy. Future research should incorporate multiple scanner systems, operators, and in vivo conditions to validate and expand upon these findings. Comparative studies using conventional materials and real-time registration tools could also enhance clinical applicability of digital occlusion workflows.

However, the results should be interpreted with caution, as all scans were performed on 3D-printed models by a single operator using one scanner and a fixed scan direction. These factors may introduce potential bias and limit generalizability to clinical settings. Future in vivo studies involving various scanner systems, operators, and scanning angles are recommended to further validate these findings. Environments and to optimize digital bite registration protocols

5. Conclusion

Within the limitations of this in vitro study, the findings suggest that both the scanning method and trimming range significantly influence the accuracy of digital occlusal registration. Standard unilateral scanning combined with wide trimming range yielded the most consistent results, particularly in anatomically compromised models. These insights highlight the importance of scan path planning and data retention in enhancing digital occlusion protocols.

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Abstract in Korean

스캐닝 방법, 트리밍 범위 및 임상적 치관 높이에 따른 디지털 교합 등록 정확도 비교

목적: 본 연구의 목적은 스캐닝 방법, 절단 범위, 임상적 치관 길이에 따른 디지털 교합 기록의 정확도를 평가하고, 이러한 요인들이 각도 편차 및 표면 기반 교합 간격에 미치는 영향을 분석하는 것이다.

방법: 3D 프린터로 제작한 일반 모델과 마모 모델을 사용하여 총 80 개의 STL 데이터를 생성하였다. 각 모델은 스탠다드 유니레터럴 스캔과 교합-협측 스캔의 두 가지 스캔 방법 및 협소 절단과 광범위 절단의 두 가지 절단 범위로 스캔하였으며, 각 군마다 10 회씩 반복 측정하였다. 정확도 평가는 CAD 분석 소프트웨어를 활용하여 정의된 관심 영역에서의 각도 편차(교합, 협측, 근원심 방향)와 표면 거리 차이를 측정하여 수행하였다. 통계 분석은 일원 분산분석(ANOVA)과 Tukey 의 HSD 검정을 이용하였다.

결과: 마모 모델 및 협소 절단 범위에서 각도 편차가 유의하게 증가하였다. 스탠다드 유니레터럴 스캔과 광범위 절단 범위를 조합한 경우 가장 일관되고 정확한 결과를 보였다. 표면 기반 교합 간격의 군 간 차이는 미미하였으며 통계적으로 유의하지 않았다($p > 0.05$).

결론: 스캔 방법과 절단 범위 모두 디지털 교합 기록의 정확도에 영향을 미치는 것으로 나타났다. 해부학적 지표가 감소된 경우에는 표면 보존을 넓게 적용한 스탠다드 유니레터럴 스캔이 교합간 정렬을 향상시키는 데 더 적합할 수 있다. 다만 본 연구의 실험실 환경, 조작자 일관성 및 고정된 스캔 방향을 고려하여 결과를 해석해야 한다.

주요어: 구강내 스캐너, 스캐닝 방법, 절단 범위, 디지털 교합 기록, 각도 편차, 표면 기반 교합 간격, 마모 모델