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Accuracy analysis of all-ceramic crowns with different materials in CAD/CAM digital replication mode

Haoyang Wang[1], Wenli Qu[1], Ting Wang[1], Xuan Wu[1*] and Hao Sun[1*]

Abstract

Background The study aimed to evaluate the three-dimensional accuracy of computer-aided design and computer-aided manufacturing (CAD/CAM) in fabricating all-ceramic crowns using various cuttable materials, assessed through reverse engineering.

Methods The original resin tooth morphology of the left maxillary mesial incisor and left maxillary first molar from a standard resin tooth model, along with the two corresponding prepared teeth, were scanned and imported into exocad software. The digitally reproduced crown morphology was utilized to fabricate crowns from cut porcelain-reinforced resin ceramic (Uh group, Upcera Hyramic), lithium disilicate glass-ceramic (e.max group, IPS e.max Cad), and zirconia ceramic (*Ue* group, Upcera Explore). All specimens were subsequently rescanned, and the root mean square (RMS) values were calculated after overlaying with the original crown CAD data using the 3D analysis software Geomagic Studio 2013 to compare the dimensional accuracy.

Results Among the mesial incisor and first molar specimens, the e.max group demonstrated the highest dimensional accuracy of the all-ceramic crowns, followed by the *Ue* group, while the Uh group exhibited the lowest accuracy. The differences in dimensional accuracy among the three groups were statistically significant ($P < 0.05$).

Conclusion The digital replication technique effectively restored the original crown morphology with a high degree of accuracy. For the same CAM pattern, the dimensional accuracy of all-ceramic crowns varied depending on the CAD/CAM porcelain material, with lithium disilicate glass-ceramic showing the superior results.

Keywords Computer-aided design and fabrication, All-ceramic crowns, Three-dimensional deviation, Accuracy

*Correspondence:
Xuan Wu
787725399@qq.com
Hao Sun
shuano@126.com
[1]Department of Prosthodontics, Dalian Stomatological Hospital, Dalian 116000, China

Background

With the progression of digital technology, intraoral digital scanning has emerged as a widely adopted approach for fabricating all-ceramic crown restorations, attributed to its advantages in enhancing patient comfort, ensuring high accuracy, and improving time efficiency during clinical visits [1]. Unlike traditional restorative methods, computer-aided design and computer-aided manufacturing (CAD/CAM) technology employs specialized software to design the restoration model based on intraoral 3D scans. The cuttable porcelain material is subsequently shaped using a computer numerical control (CNC) machine to generate the final restoration [2]. Currently, the most commonly utilized restorative materials in chairside CAD/CAM applications include resin ceramics, feldspathic porcelains, glass ceramics, and zirconia ceramics [3]. These ceramics, known for their superior translucency and abrasion resistance, have played a pivotal role in restorative dentistry, aligning with the increasing demand for restorations that meet both aesthetic and functional requirements.

The commonly employed restoration design methods in CAD/CAM systems include the database method, the mirror method, and the replication method, with the database method being the most frequently utilized in clinical settings. The database method relies on the design and generation of restorations using a standard tooth database embedded in the design software. However, this approach often requires extensive manual adjustments, making the process labor-intensive and resulting in restorations that lack a personalized anatomical profile [4]. The replication method, in contrast, involves scanning and replicating the shape of the lower crown or a diagnostic wax-up before tooth preparation. This method aims to preserve the original crown's morphology, reduce clinical adjustment and grinding time, and improve diagnostic and treatment efficiency. Moreover, it is critical to restore the occlusal surface of restorations in a manner that is both natural and harmonious to support a stable occlusal contact relationship, which contributes to the overall stability of the stomatognathic system. Research by Ender et al. [5] demonstrated that restorations produced using the replication method exhibited superior restoration of the crown's HE surface morphology. Similar findings were reported by Kollmuss et al. [6], who noted that the occlusal surfaces of restorations created via the replication method closely resembled natural teeth compared to those fabricated through the traditional stacking wax-up method. However, the replication method requires the integrity of the abutment teeth in their original form or the creation of a diagnostic wax pattern or finish before proceeding.

The evaluation of the accuracy of full crowns involves assessing both the precision of the crown surface and the fit of the crown's interior and margin. Extensive research has indicated that restoration accuracy plays a critical role in determining the long-term clinical success of restorations [7, 8]. Accuracy is defined as the dimensional discrepancy between the fabricated crown's measured data and the original CAD data, with smaller discrepancies reflecting higher accuracy. Highly accurate crown restorations minimize the risk of damage induced by modifications and reduce the time required for clinical adjustments. Several techniques are currently employed to evaluate the suitability of crown restorations, including direct examination of the restoration margin gap using probes or microscopes, the triple scanning method, micro-computed tomography, and silicone rubber replicas followed by cross-sectional analysis. However, methods for assessing the accuracy of occlusal and axial crown surfaces remain limited [9, 10]. These conventional methods have inherent drawbacks, such as their destructive nature, restricted measurement sites, and susceptibility to inaccuracies, especially for internal and marginal fit assessments. The advent of oral scanners has enabled the use of three-dimensional technology for evaluating restoration accuracy [11]. The 3D deviation method offers a rapid, precise, and non-destructive approach to quantitatively assess a larger number of samples while qualitatively analyzing overall fitness and 3D accuracy using deviation chromatograms. This method eliminates the need for silicone rubber replicas, thereby avoiding potential errors associated with their breakage. In this study, resin ceramic, glass ceramic, and zirconia ceramic all-ceramic crowns were fabricated using digital replication techniques to evaluate their three-dimensional accuracy, providing a reference for the selection of materials for clinical all-ceramic crown restorations.

Materials and methods

Materials and equipment

The study utilized a standard jaw model (Nissin, Japan) along with resin-based tooth substitutes (models 11 and 26) from Nissin, Japan. The Trios oral scanner (3Shape, Copenhagen, Denmark) was employed for digital scanning, and the exocad® Dental CAD software (Germany) was used for crown design. Materials included Eltron Runner Ceramics, a cutting porcelain-reinforced resin (UPCERA, China), lithium disilicate glass ceramics (IPS e.max Cad, Ivoclar Vivadent), and zirconia (UPCERA, China). Fabrication of the crowns was carried out using a CNC cutting machine (ARUM 5X-200, Korea).

Methods

Preparation and digital data acquisition of resin-based tooth substitute full crowns

The Nissin standard denture model was utilized in this study, and the model was pre-scanned using an extra-oral scanner. The pre-scanned data were exported in STL format to serve as a reference standard for subsequent analyses, with this dataset designated as the control group. Resin-based tooth substitutes (models 21 and 26) were prepared on the model according to clinical preparation standards for all-ceramic crowns. For the 21 resin teeth, preparation involved removing 1.5–2.0 mm of the tangential end, 1.2–1.4 mm of the labial surface, 1.0 mm of the adjacent surface, 1.0 mm of the lingual surface, and 0.5 mm of the cervical margin, incorporating a deep grooved shoulder 0.5 mm wide. The preparation of the 26 resin teeth entailed removing 1.0–1.5 mm of the HE surface, 1.0 mm of the axial surface, and 0.5 mm of the shoulder, also with a 0.5 mm wide deep grooved shoulder, and a degree of polymerization of 2–5 degrees. Both the 21 and 26 prepared resin-based teeth were designed with rounded corners and smooth, continuous surfaces. Following preparation, the 21 and 26 resin substitutes were scanned using an extra-oral scanner, and the resulting scans were saved in STL format for further analysis.

Design and fabrication of inner crowns

The pre-scanned 21 and 26 STL files were imported into exocad® Dental CAD software to design the final restorative inner crown parameters using the scanned data. The vertical and horizontal bonding gaps were set at 30 mm. Both STL files were imported simultaneously, and the full crowns were fabricated using a reverse engineering approach. The *Uh* group consisted of porcelain-reinforced resin crowns ($n = 10$) fabricated via CNC cutting. The e.max group included lithium disilicate glass-ceramic crowns ($n = 10$) produced through CNC cutting. The *Ue* group comprised zirconia all-ceramic crowns ($n = 10$), also prepared using CNC cutting. Zirconia crowns were sintered at 1450 °C for 2 h following fabrication. All the all-ceramic crowns underwent optical magnification examination to confirm the absence of defects and ensure that no surface retouching had occurred. A single operator conducted the entire fabrication process to maintain consistency and eliminate inter-operator variability.

Accuracy study of all-ceramic crowns

The all-ceramic crowns from each group were individually cleaned and dried using ultrasonic vibration. Following this, they were stored in a dry, opaque box and scanned within 48 h. A uniform layer of developer was sprayed onto the outer surfaces of the crowns before scanning with an oral scanner. The scanner was calibrated under consistent ambient lighting conditions, and the same operator performed the spraying of the developer and the scanning of all crowns to ensure uniformity. The resulting scanning data was exported in STL format to serve as the experimental group dataset.

The scanned STL files were imported into reverse engineering software Geomagic Studio 2013 (Raindrop, NC, USA). A manual alignment using n-point alignment was conducted by selecting corresponding points on the experimental and control models, followed by a best-fit alignment to assess the dimensional accuracy of all-ceramic crowns made from different materials. The outer surface of the 21 crowns was divided into three regions: overall crown outer surface, labial surface, and lingual surface. The outer surfaces of 26 crowns were segmented into four regions: the overall crown outer surface, the labial surface, the HE surface, and the lingual surface. Three-dimensional deviations of these regions were evaluated for both the experimental and control groups. The variations between the models of the experimental groups and the control group model were analyzed along the x-axis, y-axis, and z-axis. Root-mean-square (RMS) values were calculated using the formula provided in the following figure, where n denotes the total number of measurement points, X1,i represents measurement point i in the control group scanning data, and X2,i represents the corresponding measurement point in the experimental group scanning data. The standard deviation of RMS values was derived by selecting 10 points each on the labial, HE, and lingual surfaces of the final restorations to represent the precision of the crowns. Higher RMS values indicated greater deviations, implying lower accuracy of the experimental crowns compared to the control crowns. A three-dimensional surface deviation color map was generated for visualization. Red areas on the map indicated positive deviations, signifying that experimental crowns were larger than control crowns, while blue areas represented negative deviations, indicating smaller experimental crowns.

$$\mathrm{RMS} = \frac{\sqrt{\sum_{i=1}^{n}(X_{1,i} - X_{2,i})^2}}{\sqrt{n}}$$

Statistical analysis

The experimental data were analyzed using GraphPad Prism 10. Levene's test was applied to assess the chi-square distribution. One-way ANOVA was conducted to evaluate the differences in three-dimensional deviation among the different groups of all-ceramic crowns.

Results

Qualitative analysis of the suitability of the replica method for fabricating all-ceramic crowns of different cuttable materials in three positions

The color difference maps of the labial and lingual surfaces for the three groups of 21 all-ceramic crowns (Uh, e.max, and *Ue*) are presented in Fig. 1. The labial and lingual surfaces of all-ceramic crowns in all groups

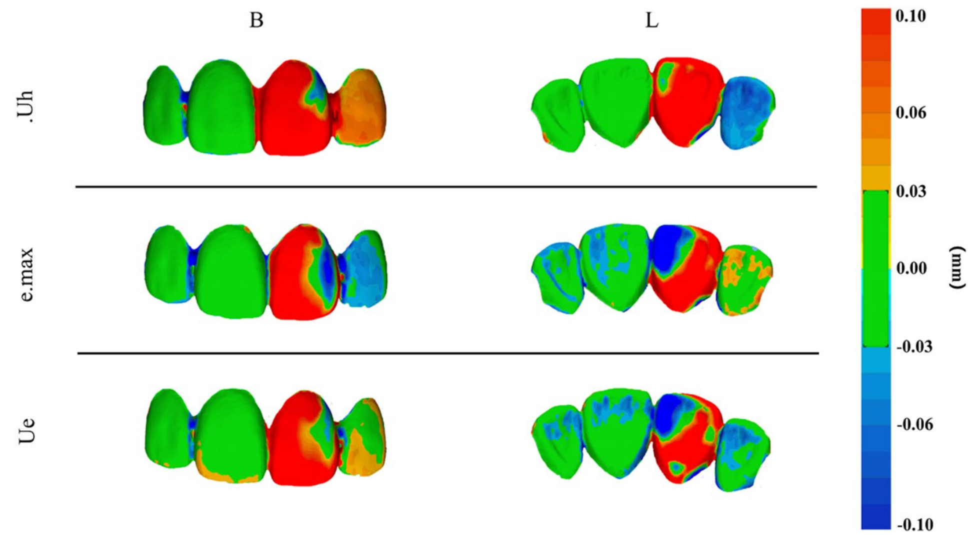

Fig. 1 Chromatograms of the labial and lingual deviations of three 21 all-ceramic crowns

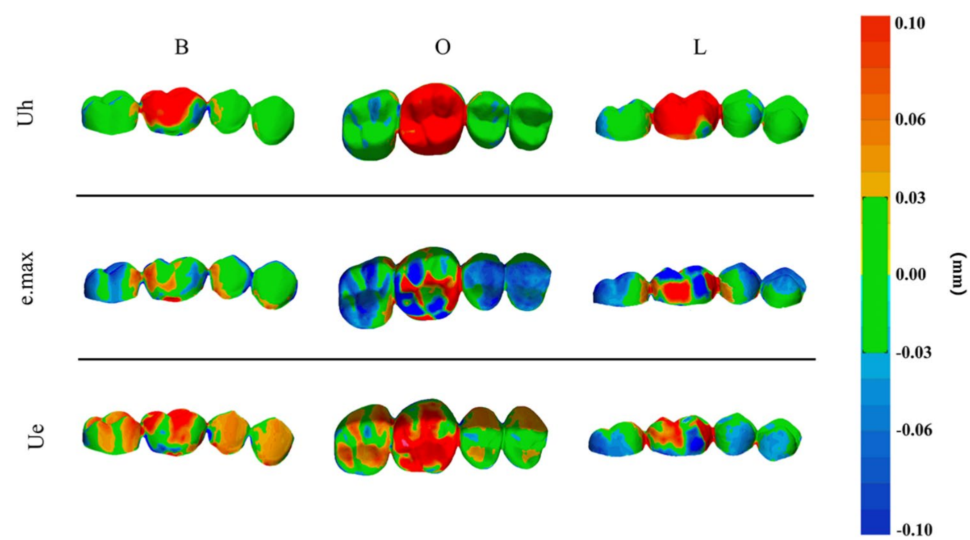

Fig. 2 Chromatograms of the labial, HE and lingual deviations of three 26 all-ceramic crowns

displayed extensive positive red areas, indicating deviation values of ≥ 100 μm. Dark blue negative areas, representing deviation values of ≤ 100 μm, were observed near the mesial lingual incisal edge in the e.max and *Ue* groups.

Figure 2 presents the color difference maps of the labial, HE, and lingual regions of all-ceramic crowns in the Uh, e.max, and *Ue* groups. The maps indicate that the all-ceramic crowns in the Uh group exhibited a higher prevalence of positive red areas (deviation values ≥ 100 μm) across the labial, HE, and lingual regions compared to the other two groups, suggesting greater deviations in these regions. The e.max and *Ue* groups showed reduced deviations in the labial and lingual regions relative to the Uh group. However, within the e.max and *Ue* groups, significant heterogeneity was observed between the fossa and cusp regions compared to the axial region. This was particularly pronounced in the HE surface of the e.max group, where both red positive and blue negative areas were present. These findings suggest that higher machining accuracy is achievable in flat regions such as the labial and lingual surfaces. Conversely, the fossa region exhibited reduced accuracy due to limitations in the size and shape of the milling cutter head, which affects the ability to precisely machine detailed areas.

Quantitative analysis of the suitability of the replica method for the fabrication of all-ceramic crowns of different cuttable materials in three positions

Figure 3 displays the comparison of regional RMS values for the labial, lingual, and overall labio-lingual surfaces of all-ceramic crowns in the Uh, e.max, and

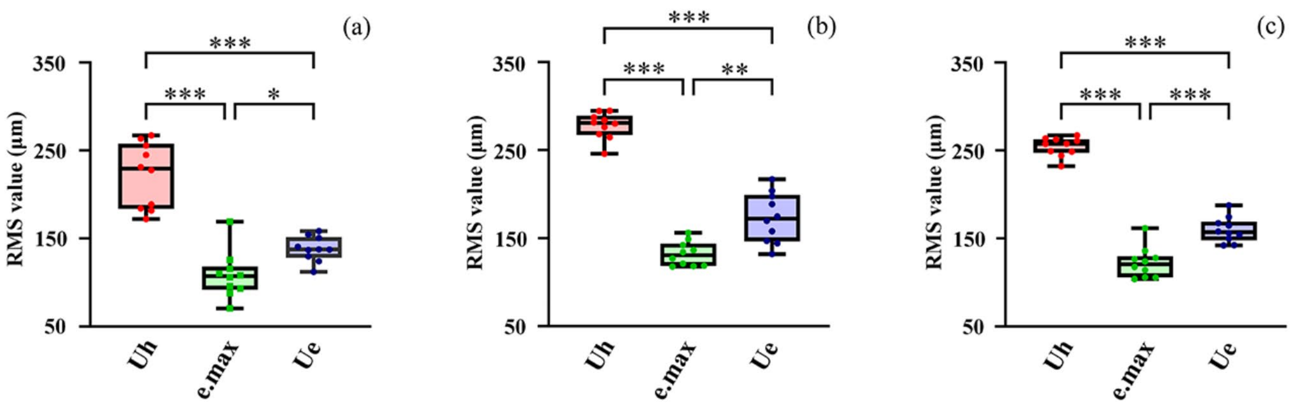

Fig. 3 Statistical results of RMS values in the different regions of three types of 21 all-ceramic crowns, (**a**) Labial surface, (**b**) Lingual surface, (**c**) Labiolingual surface, '*' represents $P < 0.05$, '**' represents $P < 0.01$, '****' represents $P < 0.001$

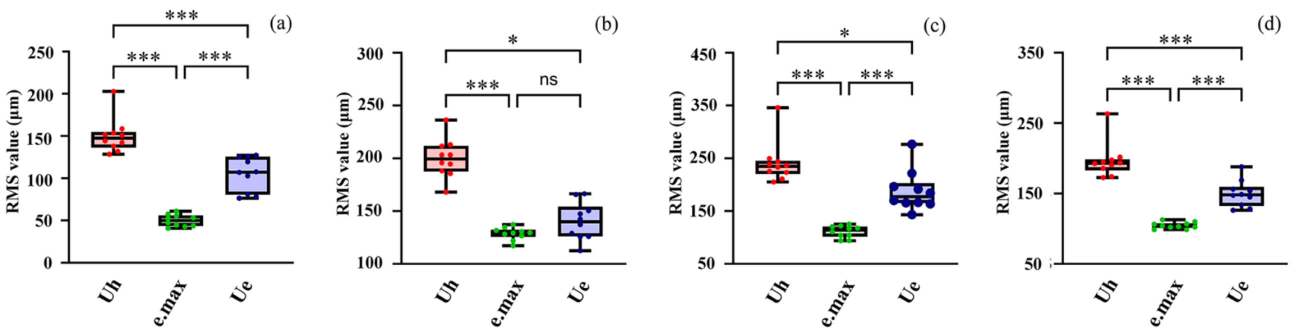

Fig. 4 Statistical results of RMS values in different areas of the three 26 all-ceramic crowns, (**a**) Labial surface, (**b**) Lingual surface, (**c**) HE surface, and (**d**) Labial and lingual HE surfaces, '*' represents $P < 0.05$, '**' represents $P < 0.01$, and '***' represents $P < 0.001$

Ue groups for the 26 samples. The deviation values for the Uh group were (221.64 ± 36.76 μm) for the labial surface, (277.60 ± 14.91 μm) for the lingual surface, and (254.69 ± 10.69 μm) for the overall labio-lingual surface. For the *Ue* group, the deviation values were (108.21 ± 26.40 μm) for the labial surface, (132.02 ± 13.84 μm) for the lingual surface, and (122.32 ± 17.47 μm) for the overall labio-lingual surface. In the e.max group, the deviation values for the labial, HE, and lingual surfaces were (138.17 ± 14.07 μm), (173.18 ± 28.21 μm), and (159.67 ± 14.22 μm), respectively. These differences were statistically significant, demonstrating that among the three groups of all-ceramic crowns fabricated using the replica CAD/CAM method, the e.max group exhibited the highest accuracy, followed by the *Ue* group. The Uh group displayed the poorest accuracy across all measured regions.

Figure 4 presents a comparison of the regional root mean square (RMS) values for the labial, lingual, and HE surfaces, as well as the overall labial and lingual HE surfaces, of all-ceramic crowns from the Uh, e.max, and *Ue* groups. Similar outcomes were observed with the same 21 all-ceramic crowns. However, the deviation values for the various regions of the all-ceramic crowns in the Uh group were significantly higher compared to those in the e.max and *Ue* groups. In contrast, the deviation values in the e.max group were lower than those in the *Ue* group, confirming that the all-ceramic crowns in the e.max group demonstrated superior accuracy.

Figure 5 compares the root mean square (RMS) values for the labial, lingual, and HE facial regions of all-ceramic crowns in the 26 Uh, e.max, and *Ue* specimens. The results indicate that the deviation values for the HE surface were consistently larger across all three groups. Statistical analysis further revealed that achieving high precision for the HE surface of restorations remains challenging when using the CAD/CAM replication method.

Discussion

In recent years, the prevalence of dental defects, characterized by the destruction of tooth morphology in the hard tissues, has increased, with causes including caries and tooth fractures. Restoring the ideal anatomical and physiological morphology of teeth is crucial in treating these defects, as dental morphology is closely linked to oral physiological function. Incisal guidance, the process by which the lingual lateral contact surfaces of maxillary anterior teeth guide the incisal point during mandibular anterior movement, plays a vital role in occlusal dynamics. During non-central movements,

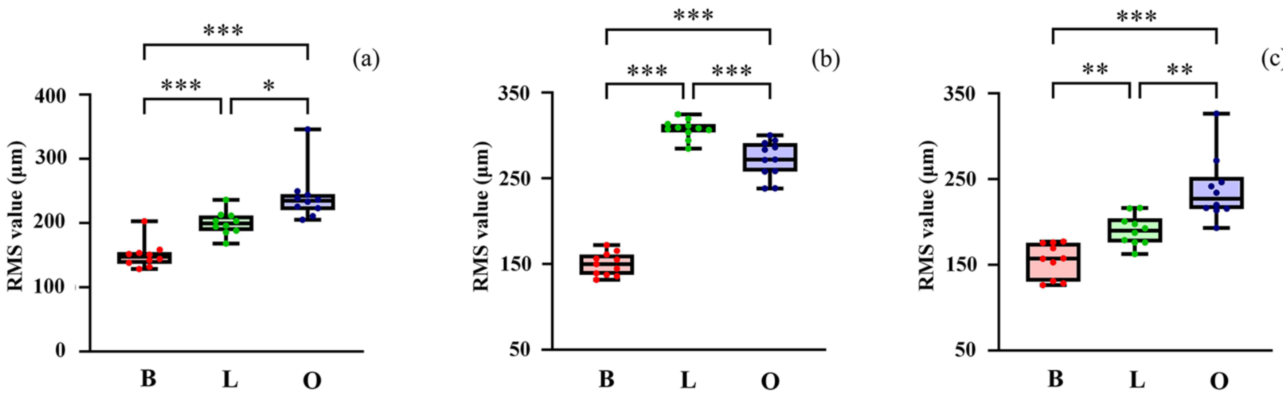

Fig. 5 Statistical results of RMS values of lip, tongue and HE regions of three types of 26 all-ceramic crowns, (**a**) Uh, (**b**) e.max, (**c**) Ue, '*' represents $P<0.05$, '**' represents $P<0.01$, and '***' for $P<0.001$

incisal guidance facilitates occlusal separation of posterior teeth, reducing lateral forces on them and minimizing the risk of overloading the temporomandibular joint [12, 13]. The absence of incisal guidance following anterior restorations can increase stress on adjacent teeth, while HE interference in restorations may elevate forces on the restored tooth, leading to potential displacement or fracture. Severe HE interference can also affect anterior displacement of the condyles, compressing the tissues behind the articular disc and causing TMJ discomfort [14]. Thus, restoring optimal lingual contact surface morphology in anterior teeth is essential. Similarly, in posterior teeth, the occlusal cuspal-fossa morphology influences masticatory function, and axial convexity affects food spillage flow. Evidence suggests that restorations replicating original crown morphology provide superior occlusal function, comfort, and reduced wear. For teeth with more intact HE surface morphology, it is recommended to restore the shape of the restoration to closely match the original tooth morphology before preparation. This practice reduces HE interference and supports the coordinated stability of the stomatognathic system, contributing to long-term restorative success [15].

All-ceramic crown restorations are widely used for the treatment of significant dental defects. With advancements in digital technology within restorative dentistry, all-ceramic restorations produced using CAD/CAM technology have become a common clinical practice due to their benefits of accurate processing and ease of use. The choice of CAD/CAM crown restorations is typically influenced by the inherent properties of the materials. For example, glass ceramics are commonly selected for their aesthetic qualities in anterior teeth, while zirconia ceramics are considered the preferred choice for posterior teeth, which endure greater chewing forces and offer enhanced wear resistance. However, previous research has often overlooked the morphological defects of restorations arising from the material's workability. The aim of this study was to evaluate the three-dimensional accuracy of resin ceramics, lithium disilicate glass ceramics, and zirconia ceramics in vitro. The results revealed that the three-dimensional accuracy of all-ceramic crowns made from different materials using the CAD/CAM replication method showed variation across all surfaces. Lithium disilicate glass ceramics from the e.max group demonstrated superior performance compared to zirconia ceramics from the Uh group, and more so compared to resin ceramics from the *Ue* group. The study by Khaled et al. [16] aligns with the findings of the current experiments, which also revealed that the precision of cut glass ceramic crowns exceeded that of cut zirconia ceramic crowns. The precise cause of this result remains unclear, though several studies have suggested it may be linked to the machinability characteristics of the materials and their respective machining methods. Furthermore, differences in the hardness of the materials, milling procedures, and the type of turning needle used can influence the dimensional accuracy of each crown. In contrast, zirconia ceramics undergo a sintering shrinkage of around 25% during the sintering process, making it challenging to control the accuracy of the final restoration, even if this shrinkage is accounted for before cutting [17]. Resin ceramics and lithium disilicate glass ceramics, however, do not undergo sintering, contributing to the morphological differences among the three types of all-ceramic crowns. The study by Moritz et al. [18], however, presented different results from those observed in this study. The authors argued that the composite resin ceramic crystals and brittleness were smaller than those of glass ceramics, facilitating better edge precision in CAM mode. The disparity in these results may be due to the higher hardness of glass ceramics, which can lead to wear and shedding of diamonds from milling and turning pins, causing the milling cutter heads to dull and affecting the surface accuracy of the final restoration. In the present study, the milling needle was not replaced during the cutting process. As the cutting time increased, the wear on the needle became more pronounced, diminishing the machining accuracy of the restorations. Additionally, failing to remove residual porcelain material promptly can negatively affect the lifespan of the milling tool [19]. The milling angle of the spindle also varies depending on the specific porcelain material, influencing the precision of porcelain full crowns. However, the precise impact of this variability on the accuracy of the crowns is not well understood and requires further study.

In this study, all crown restorations were fabricated using a 5-axis selective cutting machine, which was found to provide superior machining accuracy compared to 3-axis and 4-axis milling machines. Previous studies have suggested that the surface accuracy of crowns can be evaluated using root-mean-square (RMS) values of less than 50 μm, which is considered a standard reference for assessing surface quality [20, 21]. In this study, the RMS values for each surface of the crowns ranged from 43.7 μm to 345.7 μm, showing considerable fluctuation. This variability may be attributed to the semi-transparent nature of the material, which causes a sub-surface scattering phenomenon that affects the accuracy of extraoral scans. Factors such as the crystal content and size of glass-based ceramics, the crystal phase size of zirconia ceramics, the thickness of the porcelain material, and whether it has been polished can influence the translucency of the material, thereby affecting the accuracy of digital scanning [22]. Additionally, although the experiment aimed to ensure that the sprayed powdered developer was thin and uniform to minimize errors, achieving this consistently is challenging. The presence of uneven or thick layers of developer can lead to the acquisition of significantly higher RMS values [23]. The results presented in Fig. 2 indicate that the occlusal surfaces of the crowns produced from different materials show considerably lower accuracy compared to the lip and tongue surfaces. This is due to the limitations imposed by the turning needle dimensions. When the needle diameter exceeds the fossa morphology, it leads to over-milling or incomplete milling of the fossa, which ultimately reduces the accuracy at this site [24].

While this study demonstrated that lithium disilicate (e.max) crowns exhibited superior dimensional accuracy compared to zirconia and resin-reinforced ceramics, it is important to note that accuracy alone does not fully determine clinical performance. Other mechanical properties, such as fracture toughness, flexural strength, and wear resistance, play essential roles in long-term clinical success. For example, zirconia ceramics, despite exhibiting slightly lower machining accuracy in this study, possess higher fracture toughness and superior mechanical stability, making them more suitable for high-load-bearing posterior restorations. In contrast, lithium disilicate offers a favorable balance of esthetics and adequate mechanical properties, making it an ideal choice for anterior crowns where esthetic demands are higher and functional stresses are relatively lower. Therefore, clinical material selection should consider both the accuracy of CAD/CAM fabrication and the material's mechanical behavior under functional loads to optimize restoration performance.

Although this study provides valuable insights into the dimensional accuracy of all-ceramic crowns using different CAD/CAM materials, it is important to note that the findings are based on in vitro conditions. In actual clinical settings, additional factors such as cement thickness, adhesive protocols, and intraoral environmental variables (e.g., saliva contamination, occlusal dynamics) may further influence the final fit and performance of restorations. Variations in cementation technique could potentially alter marginal integrity and internal adaptation, thereby affecting clinical outcomes. Therefore, while the current study highlights material-dependent differences in pre-cementation accuracy, further in vivo investigations incorporating cementation steps and adhesive processes are necessary to fully translate these findings into clinical recommendations.

In addition, it is important to acknowledge that this study assessed crown accuracy prior to cementation. The cementation process, including the thickness and shrinkage of the cement layer as well as variations in adhesive protocols, can significantly influence the final internal and marginal fit of restorations. These clinical procedures introduce additional variables that were not simulated under the current in vitro conditions. Therefore, the absence of cementation in this experimental setup should be regarded as a limitation of the study. Future research incorporating cementation variables is recommended to better approximate real-world clinical outcomes and further validate the present findings.

Conclusion

In conclusion, this study evaluated the dimensional precision discrepancies of all-ceramic crowns made from three different materials using CAD/CAM replication, employing the three-dimensional deviation method. The results indicate that the accuracy of all-ceramic crowns varies depending on the material used in the replication process. Crowns fabricated from e.max lithium disilicate glass demonstrate the highest dimensional precision. The three-dimensional deviation method utilized in this study effectively captures the three-dimensional features of the crowns by employing a large number of paired points for calculation and quantitative analysis. However, the method has certain limitations: (1) Despite the large sample size, which approximates real-world results, human errors, such as those associated with the scanning process and developer application, cannot be entirely eliminated; (2) The experiment did not include precise measurements of the proximal and distal mesial surfaces of the crowns or the inner surfaces; (3) As an in vitro study, it does not fully replicate the actual occlusal conditions in the mouth. Further in vivo experiments, such as the evaluation of intraoral crown wear time and occlusal contact, are needed to provide additional insights for the selection of clinical all-ceramic crown materials.

Abbreviations

CAD	Computer-aided design
CAM	Computer-aided manufacturing
CNC	Computer numerical control
RMS	Root-mean-square

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Not applicable.

Author contributions
Haoyang Wang designed and completed the experiment, and was the main author of the manuscript. Wenli Qu completed the experiment. Ting Wang revised the manuscript. Hao Sun reviewed the manuscript. Xuan Wu designed the experiment, and was the main reviewer of the manuscript, and was responsible for project administration and funding acquisition. All authors approved the final manuscript.

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Data availability
The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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