



Influence of digital crown design software on morphology, occlusal characteristics, fracture force and marginal fit

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ABSTRACT

Objectives: The study evaluated the influence of digital design software on crown morphology, occlusal characteristics, fracture force, and marginal fit across varying preparation designs for an identical target tooth.

Methods: A resin-based tooth (tooth 36) was digitized, manufactured ($n = 8$), individually prepared and re-digitized. Five design groups were established using conventional software proposals, technician designs, two AI-based software solutions, and natural tooth-based reference designs. All systems employed consistent parameters. Crown designs were digitally assessed using quantitative morphological and occlusal metrics in reference to the original tooth. Crowns were milled, marginal fit was measured via digital microscopy, and fracture resistance was determined after thermal cycling and mechanical loading.

Results: Morphological metrics revealed statistically significant deviations across groups, with the technician design achieving the best performance. Occlusal metrics showed high deviations in the positional accuracy of the contact points across all groups. Technician and AI-based designs exhibited comparable functional results. None of the design groups were able to achieve contact with all relevant antagonist teeth, due to high deviations in the mesiolingual cusp. Conventional software designs exhibited the lowest fracture forces. Significant improvements were achieved through technician intervention. Vertical marginal discrepancies remained comparable across groups.

Significance: Improved functional and morphological design combined with high fracture resistance can reduce the need for clinical adjustments, minimize wear, and enhance crown longevity. Digital design software significantly influences crown morphology, occlusal characteristics and fracture forces. Vertical marginal discrepancies remain similar. AI-driven approaches demonstrate comparability with technician designs in terms of fracture forces, functional performance, and marginal fit.

1. Introduction

The design phase of dental crowns is a critical stage in restorative dentistry, as it directly impacts the functional and aesthetic outcomes of the restoration. Digital technologies have transformed the crown design process, enabling precise and efficient workflows. Nevertheless, the choice of design software remains a critical factor, as each system employs unique algorithms and design strategies that can influence the final result [1].

Previous studies have investigated the accuracy and efficiency of various AI-based crown design software solutions across groups of patients [1–3]. The studies found that AI approaches can enhance either

efficiency or morphological accuracy compared to conventional software, with overall shape accuracy similar to that achieved by experienced technicians. However, the comparative performance of diverse software solutions in reconstructing a single target tooth across various preparation designs remains under-investigated. Consequently, potential findings could not only show the differences between software solutions, but also demonstrate the expected variability resulting from diverse preparation-specific design constraints.

While time efficiency and morphological accuracy remain important aspects in dental crown evaluation, restorative outcomes can be evaluated using a broad range of methods [4]. Quantitative morphological metrics allow for a generalized assessment of crown geometry and its

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integration within the existing dentition. Occlusion specific metrics, such as the position and number of contact points, are critical for both static and dynamic function, directly affecting the distribution of chewing forces on the restoration [5].

The marginal fit of a crown is a key factor influencing clinical performance. Marginal gaps can be crucial for the fit of the restoration as they influence the sealing of tooth substance, which in turn impacts long-term durability of the restoration [6]. Clinically acceptable vertical marginal discrepancies generally range between 25 μm and 200 μm [7, 8].

The stability of the crowns is not only determined by the materials used but also by the wall thicknesses, which can vary based on software specific design strategies [9]. No scientific in vivo information is available for the performance of crowns designed based on varying preparation designs and different software systems. Prior to routine clinical application, in vitro tests may facilitate a contemporary evaluation of these systems. Thermal cycling and mechanical loading (TCML) can provide an initial prediction of the long-term mechanical performance of crowns, comparing the influences of preparation design and design software [10]. In cases where no visible failures during the simulation are observable, the effects of aging and deterioration can manifest, leading to a reduction in strength and fracture resistance. In such cases, a final static fracture test can identify potential weak points in the restoration.

Prior research has addressed morphological accuracy and time efficiency. This study broadens the analytical framework to encompass quantitative assessments of morphology and function, in addition to evaluating fracture resistance and vertical marginal discrepancies.

This study hypothesizes that design software significantly influences the crown morphology, occlusal characteristics, the marginal fit as well as the in-vitro performance and fracture force of digitally designed crowns for an identical target tooth based on different preparations.

2. Methods

2.1. Study design

A resin-based tooth (tooth 36, anatomical model i21D-400C, Morita, D) was digitized (CEREC Omnicam, Dentsply Sirona, USA) and identical

teeth (Shaded PMMA Disc, Dentsply Sirona, USA; Lot. 0000210477) were milled (inLab MC X5, Dentsply Sirona, USA). The model was selected as the reference to guarantee optimal conditions for the validity of the reference data and the existing occlusal contact situation. The milled teeth ($n = 8$) were individually prepared by a single dentist (M. S.) using a shoulder preparation with a circular reduction of 1.5 mm, 6° angulation, occlusal reduction of 1.5 mm, and a minimum cervical to occlusal height of 4 mm.

As illustrated in Fig. 1, all preparations (prep) were digitized (CEREC Omnicam, Dentsply Sirona, USA) including their roots. The full anatomical dental model (i21D-400C, Morita, D) was digitized with a laboratory scanner (inEos X5, Dentsply Sirona, USA). Upper and lower jaws were scanned as separate entities with full dentition and no inter jaw alignment (lower-full, upper-full). The lower jaw was additionally scanned with the reconstruction target tooth 36 extracted (lower-ext). The reconstruction target was separately scanned including its roots (target).

The full jaw scans were aligned using AI-based dental occlusion software (Bite-Finder, Bite-Finder AG, CHE) (lower-full-occl, upper-full-occl). The “lower-ext” model was aligned with “lower-full-occl” based on the data of the remaining teeth using Iterative Closest Point (ICP) registration [11] (lower-ext-occl). The “target” tooth was aligned with “lower-full-occl” based on the occlusal surface of “target” (target-occl). All “prep” objects were aligned with “target-occl” based on the morphology of the roots yielding the aligned preparations (prep-occl). The “prep-occl” objects were then merged with “lower-ext-occl” to create the final lower jaw input data for the crown design (lower-ext-occl-prep). The software input data included the aligned and processed jaws “lower-ext-occl-prep” and “upper-full-occl”.

2.2. Group definitions

Crown design was performed with ExoCAD software (ExoCAD, D), Automate (3Shape, DK) and Dentbird (Imageworks, KOR). ExoCAD was selected to represent conventional software solutions, while Automate and Dentbird exemplify AI-based solutions with varying levels of automation. Five design groups were established based on the software and the design strategy. The design groups were:

(cs) Conventional software (cs) proposal based on template library

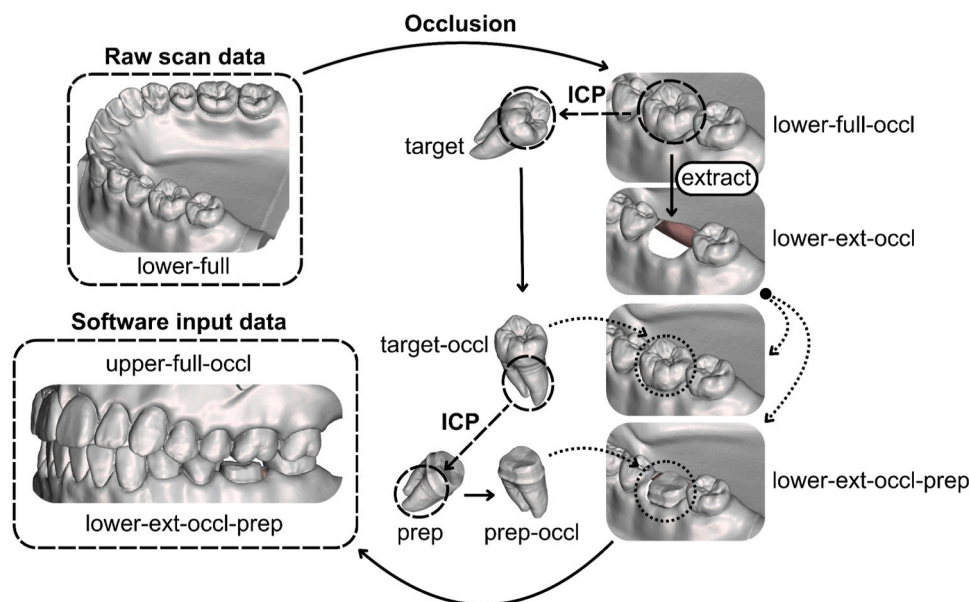


Fig. 1. Visualization of the data digitalization and preparation process. Dental preparations and models were digitized using CEREC Omnicam (Dentsply Sirona, USA) and inEos X5 (Dentsply Sirona, USA). Upper and lower jaws were scanned separately with full dentition and after extraction of tooth 36. AI-based occlusion software (Bite-Finder, Bite-Finder AG, CHE) and ICP registration were used to digitally align the scans, yielding the final jaw models for the crown design process.

(mindforms) with minimal manual intervention (ExoCAD).

(cs/gt) Ground truth (GT) situ design based on margin line data and design parameters from (cs) and the original tooth (ExoCAD).

(cs/ai) AI software (ai) proposal based on margin line data and design parameters from conventional software (cs) (Automate).

(cs/dt) Conventional software (cs) with user intervention and design completion through a dental technician (dt; J.R.) (ExoCAD).

(ai) Full AI software (ai) proposal with minimal manual intervention (Dentbird).

Comparable design parameters were selected across all groups. The margin width (0.15 mm), cement gap (0.08 mm), and minimum thickness (0.8 mm) were consistent parameters between Dentbird and ExoCAD software. Automate software was based on the margin line data and design parameters of the ExoCAD group (cs) and did not offer comparable user parameters. The designs were exported as STL files in the initial coordinate system, eliminating the need for further spatial transformations of the crown data.

2.3. Morphological and occlusal evaluation metrics

The generated occlusal surfaces were evaluated using a set of metrics assessing both overall morphology and functional occlusal relationships (Table 1) [12]. Widely adopted metrics such as Chamfer Distance (CD) [13] and Intersection over Union (IoU) [14] are effective for evaluating the similarity between two point clouds [15]. The CD is a bidirectional point cloud comparison metric that assesses the similarity between two objects by averaging the nearest-neighbor distances from each point in one object to the other. The IoU is defined as the volumetric intersection of two objects divided by their union. The CD was employed to measure the 3D similarity between the generated crown surfaces and the GT. The distances in the metric were defined as the lengths of the difference vectors, computed using the Euclidean (L2) norm. To align with the remaining metrics, the IoU was complemented ($\text{cloU} = 1 - \text{IoU}$) such that lower values indicate better performance. The metric assessed the spatial characteristics and pose of the generated tooth within the patient's existing dentition, helping to ensure accurate positioning and alignment.

However, general 3D object comparison metrics lack specificity for assessing occlusal surfaces in relation to patient-specific contact points. To address this limitation, additional occlusal metrics were employed to quantify the quality of the contact situation between the target tooth and its antagonist teeth.

All metrics were calculated as deviations from the original tooth, providing a consistent reference for comparison.

To capture functional aspects, a set of occlusal metrics was evaluated. In the following context, a contact point refers to the center of a cluster of occluded points, representing functional contact between the target tooth and its antagonist teeth. A point is considered occluded if the normal vector of this point and its nearest neighbor in the antagonist point cloud are pointing in opposite directions. Due to potential automatic cropping of high penetration contact areas in the crown design software, the conditional distance threshold for a point to be considered occluded was set to $d_{\text{occl}} < 200 \mu\text{m}$. This ensures correct identification of the anticipated contact points and aligns with the visual depictions of

the contact situations. The employed metrics were as follows:

- **Contact point number loss:** quantifies the difference in the total number of contact points between the crown and the GT.
- **Contact point position loss:** assesses inter-positional deviations by comparing the distance of each contact point on the generated crown to the nearest contact point on the GT using CD.
- **Contact point distance loss:** evaluates intra-positional contact point relationships by measuring the mean distance between all contact points in the generated crown compared to the GT.
- **Penetration loss:** quantifies the mean penetration depth of all occluded points between the target tooth and its antagonist teeth in reference to the GT.

2.4. Visual evaluation

The mean contact points for every group were visually depicted for better interpretability of the quantitative results. This representation is calculated as the mean distance of every occluded point on the antagonist teeth to its nearest neighbors in the target crowns of the respective group. Analog to the quantitative evaluation, the conditional distance threshold for a point to be considered occluded was set to $d_{\text{occl}} < 200 \mu\text{m}$. To enhance visual clarity, values below the 1st percentile of the occluded GT points were capped.

Heatmaps of the mean deviations from the GT were generated for each group to enable a visual and qualitative assessment of the reconstruction results. Deviations were computed between each point on the GT and its nearest neighbor on the reconstructed tooth. To enhance the interpretability and resolution of the heatmaps, deviation values were capped at the global 99th percentile.

All distances were calculated using the absolute L1 norm.

2.5. Determination of marginal fit

Eight fully anatomical crowns per group (nano-hybrid composite, Grandio disc, Voco, Germany) were milled (inLab MC X5, Dentsply Sirona, USA) based on the generated 3D files. Milling was performed with high level of detail (0.5 mm, 1.0 mm and 2.5 mm burs for composite) under “normal processing speed” out of a standard 98 mm disc.

Each crown was firmly seated on its corresponding preparation and the margins of all crowns were digitized using a digital microscope (VK-X100 series, Keyence, Japan) to evaluate the vertical marginal discrepancy. This parameter is a commonly used measurement to assess marginal fit [16]. It is defined as the distance measured parallel to the crown's insertion direction between the prepared tooth margin and the

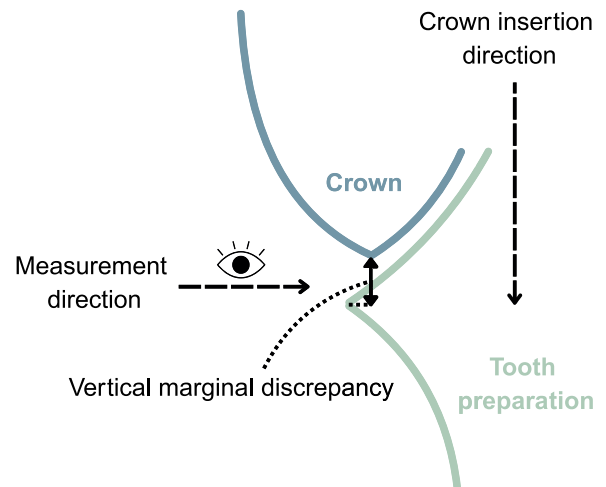


Fig. 2. Schematic representation of the vertical marginal discrepancy [16].

Table 1

Overview of the evaluation metrics. ↓↑ indicate whether lower or higher values are preferable for the metric.

Metric	Purpose
Chamfer Distance ($L_{\text{chamfer},1,2}$) ↓	General morphological accuracy.
Complemented Intersection over Union (L_{cloU}) ↓	Spatial alignment and fit in the tooth gap.
Contact point number loss ($L_{\text{cp,num}}$) ↓	Number of contact points.
Contact point position loss ($L_{\text{cp,pos}}$) ↓	Shape of the contact point pattern.
Contact point distance loss ($L_{\text{cp,dist}}$) ↓	Spatial spread of the contact points.
Penetration loss (L_{pen}) ↓	Contact strength.

restoration margin (Fig. 2). In this study, the vertical marginal discrepancy was recorded at 12 predefined locations between the crown and the preparation margins resulting in $n = 96$ measuring points per group.

2.6. TCML and fracture testing

To simulate periodontal resilience, the roots of the teeth were coated with polyether [17]. The inner surfaces of the crowns and the teeth were sandblasted with Al_2O_3 (50 μm , 1.5 bar), steam-cleaned, and dried with oil-free air. The crowns were fixed using a dual-curing bonding composite (Bifix QM, Voco, Germany). During the setting, a 2.9 kg occlusal load was applied. Final polymerization was performed with Elipar Tri-light (3 M, USA, 4×40 s).

Eight crowns per group underwent chewing simulation with thermal cycling and mechanical loading (TCML; chewing simulator, EGO, Regensburg, Germany; 1.2×10^6 cycles at 50 N; 3000 thermal cycles at 5°C alternating with 3000 thermal loads at 55°C ; H_2O , 2 min cycle duration) to simulate five years of oral service [10,18,19]. The crowns were centrally loaded using a steatite sphere ($d = 12$ mm), serving as the antagonist to simulate a four-point molar contact situation. The crowns were monitored during testing. Following TCML, the fracture force was determined by applying a quasi-static load (Z010, Zwick-Roell, Ulm, Germany, $v = 1$ mm/min, steel sphere with tin foil and $d = 12$ mm). The fracture patterns were subsequently documented and categorized into chipping, crown fracture, or combined crown-tooth fracture.

2.7. Statistical evaluation

The statistical evaluation was performed in Python (3.8.10) using the packages SciPy (1.6.3) [20] and Statsmodels (0.14.1) [21]. Normality of all outcome variables was assessed using the Shapiro-Wilk test.

Evaluation of the morphological ($L_{\text{chamfer,L2}}$, L_{cIoU}) and occlusal metrics ($L_{\text{cp,num}}$, $L_{\text{cp,pos}}$, $L_{\text{cp,dist}}$, L_{pen}) (Table 1) was conducted using non-parametric tests on medians due to their non-normal distribution, as determined by Shapiro-Wilk tests ($p < 0.05$). For these metrics, Friedman Chi-Squared tests were used to identify statistically significant differences across groups followed by two-sided Wilcoxon signed-rank tests for post hoc pairwise comparisons of median values.

To ensure comparability across metrics, the results were normalized to a range of $[0, 1]$ based on the maximum and minimum values across all

groups for each metric. Cases with failed occlusion establishment were assigned a value of 1.1 for the respective occlusal metrics, highlighting potential limitations of the crown design process. A post hoc power analysis was performed using $n_{\text{sim}} = 1000$ bootstrap iterations to estimate the statistical power of the significant non-parametric tests of the morphological and occlusal metrics.

While morphological and occlusal metrics were evaluated relative to the GT, fracture force and vertical marginal discrepancy were assessed using their absolute values. Normality was determined using Shapiro-Wilk tests ($p > 0.05$) and Levene's test was used to evaluate homogeneity of variance ($p > 0.05$). Since both assumptions were met, these outcome variables were compared using repeated measures ANOVA and post hoc pairwise dependent T-tests.

Benjamini-Hochberg correction was applied to control the false discovery rate of all metrics including fracture force, vertical marginal discrepancy, morphological and occlusal metrics.

Kendall's τ was used to assess the correlation between all metrics. The level of significance was set to $\alpha = 0.05$ for all tests.

3. Results

3.1. Morphological and occlusal metrics

Fig. 3 presents the normalized results of the evaluation metrics for the different groups, with the corresponding real value ranges provided in Table 2. Statistically significant differences (p ; power) were found in Friedman Chi-Square tests for all metrics: $L_{\text{chamfer,L2}}$ (< 0.001 ; 1.00), L_{cIoU} (< 0.001 ; 1.00), $L_{\text{cp,num}}$ (0.001; 1.00), $L_{\text{cp,pos}}$ (< 0.001 ; 1.00), $L_{\text{cp,dist}}$ (0.038; 1.00), L_{pen} (0.003; 1.00).

Apart from the situ crowns (cs/gt), the technician group (cs/dt)

Table 2

Ranges of real values for the evaluation metrics in Fig. 3. The min and max values correspond to 0 and 1 in the normalized results, respectively.

Metric	min	max
$L_{\text{chamfer,L2}}$ /mm	0.109	0.334
L_{cIoU}	0.143	0.434
$L_{\text{cp,num}}$	0.000	4.000
$L_{\text{cp,pos}}$ /mm	0.077	2.783
$L_{\text{cp,dist}}$ /mm	0.020	1.909
L_{pen} /mm	0.000	0.027

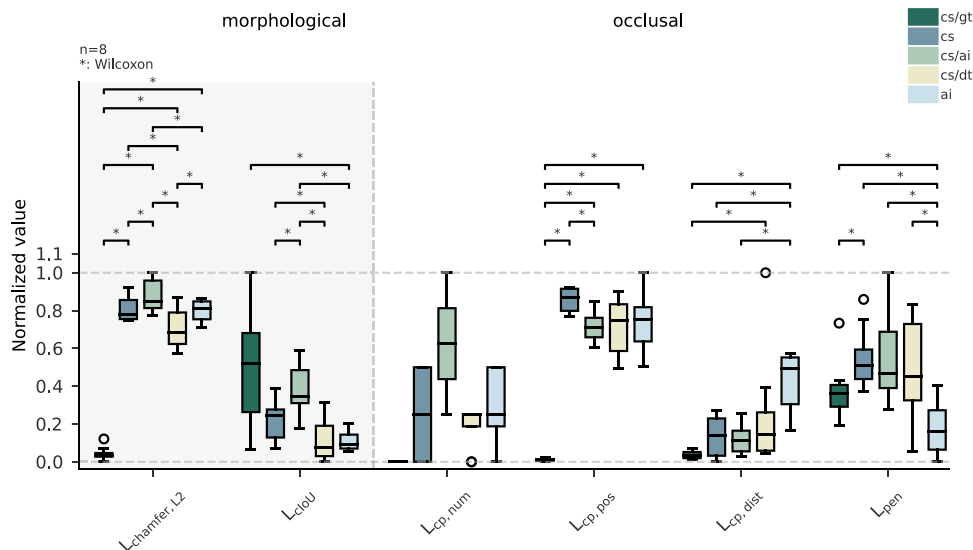


Fig. 3. Normalized results of the evaluation for the different groups with $n = 8$. The significance level is set to $\alpha = 0.05$. Asterisks refer to statistically significant deviations according to Wilcoxon signed rank tests. Lower values indicate better performance.

exhibited the best median performance in the morphological metrics with significant differences to all groups in $L_{\text{chamfer},L2}$ (< 0.043 ; > 0.67). However, (cs/dt) showed higher variances compared to the software-only groups. As anticipated, the situ design crowns (cs/gt) performed best for CD showing statistically significant median differences to the remaining groups (< 0.014 ; 1.00). Notably, in L_{cloU} the performance of (cs/gt) decreased in terms of both median and variance compared to the other groups. Further statistically significant median differences in L_{cloU} were detected between groups (cs/ai) and (cs, cs/dt, ai) (< 0.027 ; 1.00). The technician intervention significantly (0.047 ; 0.78) improved the L_{cloU} compared to the conventional software proposal (cs). The AI-group (ai) showed the lowest overall variance with significantly (0.039 ; 0.95) lower values than (cs/gt).

For better interpretability of the following results, Fig. 4 shows a visual representation of the mean contact points for each group. The initial contact situation of the natural tooth is depicted as a separate group (gt). Consistent with the morphological metrics, (cs/gt) outperformed the other groups in $L_{\text{cp,num}}$, $L_{\text{cp,pos}}$, and $L_{\text{cp,dist}}$. No statistically significant pairwise differences in $L_{\text{cp,num}}$ were observed. Although, (cs/dt) yielded borderline results compared to (ai, cs/ai, cs/gt) with $p = 0.068$. $L_{\text{cp,pos}}$ showed statistically significant differences between (cs/gt) and the remaining groups (< 0.02 ; 1.00) as well as between (cs) and (cs/ai) (0.047 ; 0.78). The pairwise comparison between (cs) and (cs/dt) showed a borderline result with $p = 0.065$. The (cs) group showed the highest deviations in positional accuracy $L_{\text{cp,pos}}$. Apart from (cs/gt), (cs/ai) yielded the best positional accuracy ($L_{\text{cp,pos}}$) and spatial spread ($L_{\text{cp,dist}}$) of the contact points. The AI group (ai) showed the highest deviations in $L_{\text{cp,dist}}$ with significant differences to (cs/ai, cs, cs/gt) (< 0.040 ; 1.00). The (cs/*)-based groups performed on similar levels. The AI group (ai) showed the lowest deviation in L_{pen} from the GT with significant differences to groups (cs/dt, cs/ai, cs, cs/gt) (< 0.040 ; > 0.93) and the overall highest penetration in the crown designs. The (cs/*)-based groups again performed on similar levels.

3.2. Visual deviations

The heatmaps in Fig. 5 illustrate the mean deviations of the crowns for each group in reference to the GT using absolute L1 distances. They highlight the distinct occlusal characteristics of each group. The mesiolingual cusp region, extending slightly toward the distolingual cusp, exhibited the highest deviation across all groups with (cs) showing the least pronounced deviation especially in the distolingual cusp area. Additionally, groups (cs), (cs/ai), (cs/dt) demonstrate significant deviations in the buccal groove area, with (cs) extending toward the mesiobuccal cusp. AI groups (cs/ai) and (ai) exhibit similar deviation patterns to the technician design group (cs/dt) regarding the lingual cusp area. Noteworthy, group (cs/ai) also adapts the deviation pattern of group (cs/dt) in the buccal groove area. As anticipated, the situ design

crowns (cs/gt) exhibit the lowest mean deviations across all occlusal regions. The remaining deviations in this group were primarily localized in the central groove area, confirming its close alignment with the GT anatomy.

3.3. Vertical marginal discrepancy

The median vertical marginal discrepancy varied between $223 \mu\text{m}$ (cs) and $293 \mu\text{m}$ (cs/dt). The repeated measures ANOVA did not detect any statistically significant differences (0.77 ; 0.69). Due to the moderate power of the ANOVA, post hoc pairwise comparisons were conducted. No statistically significant differences could be found. Groups (cs), (cs/ai), (cs/gt) show similar median values as well as groups (cs/dt) and (ai), although with higher overall values. The corresponding values are shown in Fig. 6. As suggested by the figure, the groups with the highest median values (cs/dt, ai) showed borderline statistical results compared to (cs) with (cs-cs/dt: 0.06 ; 0.79) and (cs-ai: 0.09 ; 0.67), respectively.

3.4. Fracture force

No crown failure was observed during the chewing simulation. The median fracture forces ranged from 1186 N (cs) to 1983 N (ai) (Fig. 7). Although repeated measures ANOVA did not reveal statistically significant differences (0.06 ; 0.89), the borderline result warranted post hoc pairwise comparisons, which identified statistically significant differences between groups ($p \leq 0.038$).

Group (cs) showed significantly lower fracture forces compared to all other groups except (cs/ai) (0.038 ; > 0.95). The failure patterns observed during fracture testing were comparable across all systems, predominantly involving partial to complete crown fractures or combined crown-tooth fractures (Fig. 8).

3.5. Correlation analysis

Fig. 9 displays the correlations between the metrics. For clarity, L_{fracture} is defined as the negative fracture force value (lower is better), while the margin width loss L_{margin} directly corresponds to the measured margin widths. Significant ($p < 0.05$) correlations between the metrics were found. $L_{\text{chamfer},L2}$ exhibited moderate positive correlations with the occlusion metrics $L_{\text{cp,num}}$ (0.51) and $L_{\text{cp,pos}}$ (0.45). The contact point position loss $L_{\text{cp,pos}}$ showed significant weak correlations with $L_{\text{cp,num}}$ (0.27) and L_{cloU} (-0.26).

4. Discussion

The partial hypothesis that design software significantly influences the morphology, occlusal characteristics and fracture resistance of a

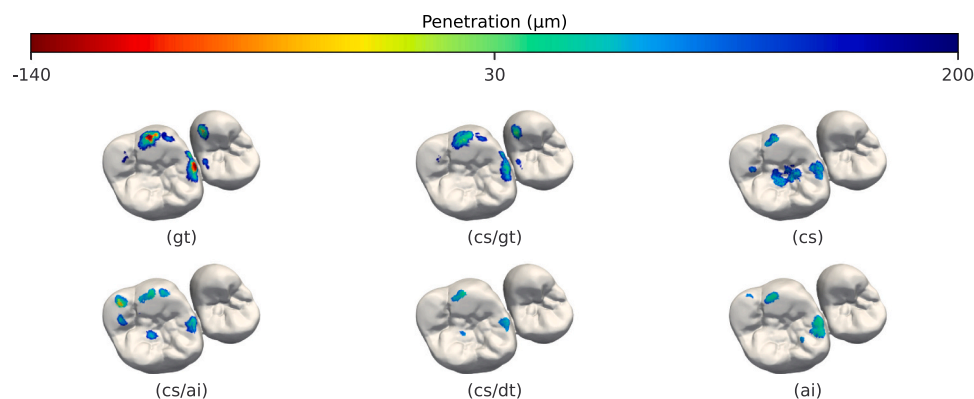


Fig. 4. Heatmaps of the mean contact points for each group. Smaller values indicate stronger contact. The (gt) group shows the contact situation of the natural tooth. Values below the 1st percentile of the occluded GT points are capped.

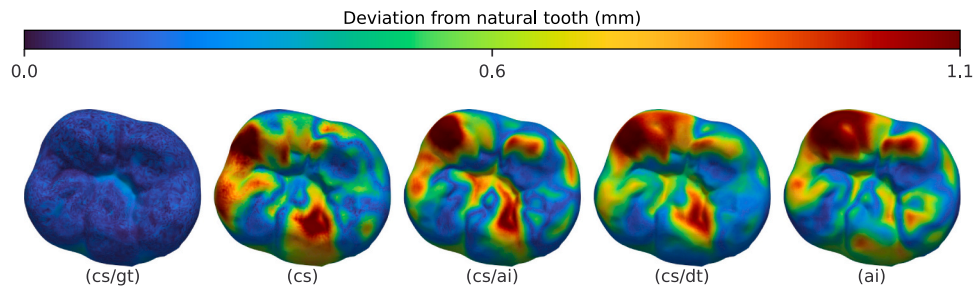


Fig. 5. Heatmaps of the mean deviations for each group relative to the GT. The deviations are calculated as the absolute L1 distance of every point on the GT to its nearest neighbor on the reconstructed crown. All distances are capped at the global 99th percentile.

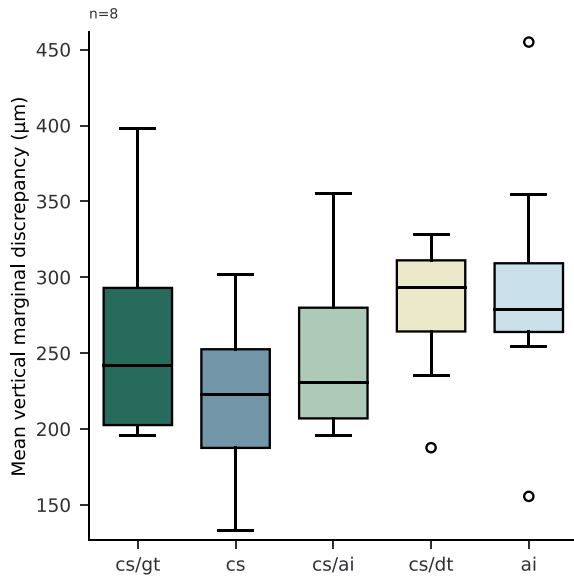


Fig. 6. Mean vertical marginal discrepancies at all measured positions across the different groups. Lower values indicate better performance.

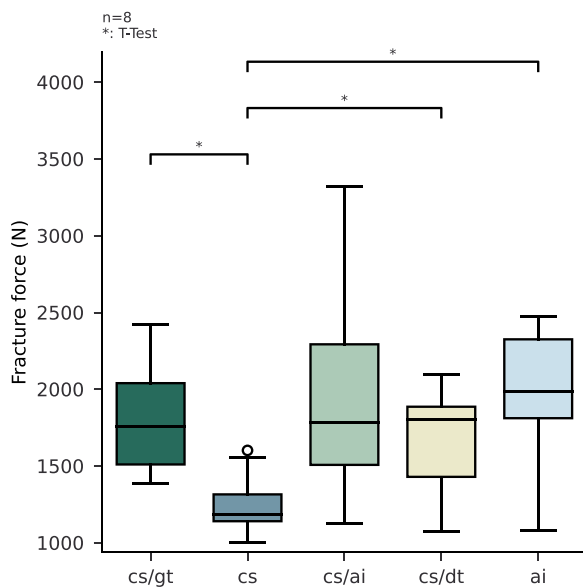


Fig. 7. Fracture forces after TCML. The significance level for the two-sided T-tests was set to $\alpha = 0.05$. Higher values indicate better performance.



Fig. 8. Typical pattern after fracture testing.

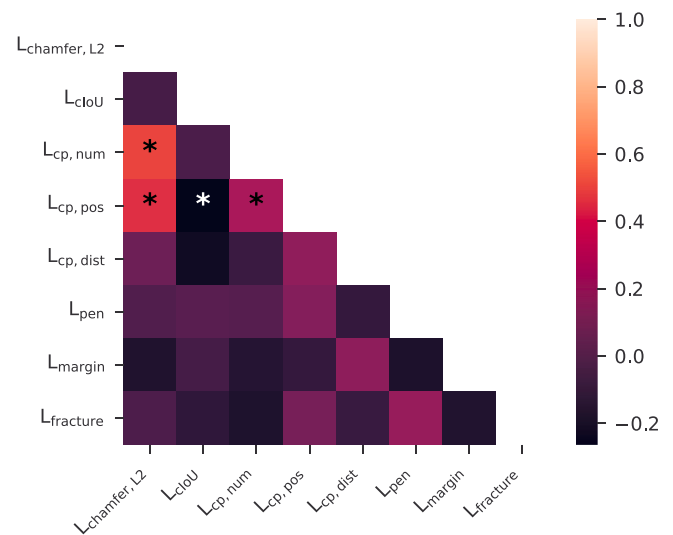


Fig. 9. Kendall's τ correlations between all metrics with $-1 \leq \tau \leq 1$. Significant values ($p < 0.05$) are marked with asterisks.

digitally designed crown is supported by the results. The choice of software does not seem to significantly affect the vertical marginal discrepancies.

The findings underscore the impact of varying crown design strategies for different preparations on crown morphology, occlusal contact point characteristics and fracture resistance. The morphological evaluation metrics indicate that, although automated design methods produce more consistent outcomes with reduced overall variability, manual refinement significantly enhances the median morphological accuracy. Notably, (cs/dt) showed the lowest median values in $L_{\text{chamfer}, L2}$ with significant improvements compared to the software proposal (cs) and

both AI groups (cs/ai, ai). The superior CD performance of the situ design crowns (cs/gt) aligns with expectations, given their reliance on GT data. However, the high variability in L_{cloU} suggests that while the mean point-to-point distances of the occlusal surfaces closely match the GT, other methods better preserve the overall spatial characteristics of the crowns. A visual inspection of the crown designs combined with the low deviations in $L_{\text{chamfer},L2}$ and the occlusion metrics indicate comparably high deviations in the circumferential areas of the (cs/gt) crowns.

As illustrated in Fig. 4 and Fig. 5, none of the design systems were able to accurately recreate the natural contact situation. The natural tooth (36) contacts the antagonist tooth (25) at the mesiolingual cusp. All design systems showed substantial deviations from the GT in this region (Fig. 5), resulting in gaps of up to 1.1 mm between the mesiolingual cusp and the antagonist tooth. This is further supported by the high values in the positional accuracy of the contact points ($L_{\text{cp,pos}}$) compared to the GT-based design (cs/gt). In contrast to the high positional deviations, all (cs/*)-based groups (cs, cs/ai, cs/dt) exhibited similarly low deviations in the spatial spread of the contact points ($L_{\text{cp,dist}}$). While the overall spatial spread of the contact points was comparable, the individual contact points did not align with the GT positions. Notably, while the AI group (ai) demonstrated similar deviations to the other groups in the positional accuracy ($L_{\text{cp,pos}}$) and the number of contact points ($L_{\text{cp,num}}$), the spatial spread of the contact points ($L_{\text{cp,dist}}$) was significantly higher. This underscores the need for a comprehensive set of occlusal metrics that captures all functional aspects of the occlusion, enabling a full quantitative assessment of the crown's occlusal performance.

Although (cs/ai) exhibited the highest deviations in the morphological metrics ($L_{\text{chamfer},L2}$, L_{cloU}) and the number of contact points ($L_{\text{cp,num}}$) (Fig. 4), it showed the best overall performance in the positional accuracy and the spatial spread of the contact points ($L_{\text{cp,pos}}$, $L_{\text{cp,dist}}$). This highlights the importance of using two distinct sets of evaluation metrics. While overall morphological aspects are essential, the functional area of the tooth represents only a small part of the entire crown. Therefore, morphological metrics alone cannot fully reflect the crown's functional performance, requiring a more detailed analysis to capture the nuances of functional behavior.

The $L_{\text{cp,pen}}$ values were similarly high across all (cs/*)-based groups. This observation, further supported by Fig. 4, suggests a reduction of high penetration areas in the digital crown design software to avoid excessive contact. In contrast, the AI group (ai) applied a more aggressive approach to handling high penetration areas, leading to significantly higher contact point strength compared to the other groups and thus lower overall deviations from the GT.

While the (cs/gt) group demonstrated that consistent functional performance is achievable for varying preparation types, the remaining design groups exhibited higher variability in the occlusion metrics. This is particularly evident in the variability of the contact point strength ($L_{\text{cp,pen}}$). Variations in tooth preparation can influence the crown's morphology and contact dynamics due to potential software restrictions or adherence to minimum material thicknesses. This highlights the importance of considering final material thickness and the position of potentially occurring contact points during tooth preparation to ensure optimal occlusal functionality.

Overall, groups (cs/ai) and (cs/dt) showed similar functional performance, as indicated by the visual results in Fig. 4 and Fig. 5 as well as the occlusion metrics in Fig. 3.

The vertical marginal discrepancy exhibited considerable variability, with median values exceeding 200 μm , indicating a compromised edge quality. This may result from omitting the cementation process to facilitate multiple measurements on a single preparation. In clinical practice, appropriate fixation could yield improved outcomes for identical crowns. No statistically significant differences between the groups could be detected using repeated measures ANOVA. The moderate statistical power suggests that the sample size may have been insufficient to reliably detect small to moderate effects in the vertical marginal

discrepancy across the groups.

While the margin quality is affected by material selection (minimum wall thickness) and manufacturing technology (drill size, feed rates), the choice of design software and preparation design does not seem to have a crucial impact. All (cs/*)-based groups (cs, cs/gt, cs/ai) performed on similar levels. Additional technician intervention (cs/dt) increased vertical marginal discrepancies by approximately 25%, resulting in performance comparable to the (ai) group. Consequently, manual adjustments did not improve the margin quality of the initial software proposal (cs), which showed the best performance across all groups.

The fracture forces for all crowns were at clinically acceptable levels, aligning with the magnitudes reported in previous studies [9,22]. The AI-designed crowns exhibited the highest median fracture forces. Crowns generated based on a conventional software approach without user intervention (cs) showed the lowest overall values with significantly lower values compared to (cs/gt, cs/dt, ai). The manual technician intervention (cs/dt) significantly increased the fracture resistance of the crowns.

The visual representation of the contact points (Fig. 4) revealed a distinct contact point in the central fossa of the antagonist tooth 26 for group (cs). This contact is attributed to an altered mesiobuccal cusp (Fig. 5). A potential increase in the buccal-lingual component of the resulting force vector may explain the observed fracture patterns (Fig. 8). None of the groups with significantly higher fracture forces established this particular contact. Group (cs/ai) showed a similar but weaker contact in this region. Fracture forces between these groups did not significantly deviate.

Crown designs based on natural tooth morphology (cs/gt) exhibited results comparable to groups (cs/ai, cs/dt, ai), indicating that current design software can achieve fracture resistance similar to natural tooth morphology. Aligning with [5], design software can significantly influence the measured fracture forces.

5. Conclusion

The following conclusions can be drawn from the study:

- Morphological metrics revealed statistically significant deviations across groups.
- Automated design methods can produce more consistent results with reduced variability, whereas manual refinement can improve overall morphological quality.
- None of the design groups were able to establish contact with the antagonist tooth 25 due to high deviations in the mesiolingual cusp.
- All groups exhibited high deviations in the positional accuracy of the contact points.
- Digital tooth evaluation metrics provide a robust and sensitive framework for crown evaluation.
- The vertical marginal discrepancy was comparable for the investigated systems.
- Conventional design software proposals (cs) exhibited significantly lower fracture forces compared to all groups except (cs/ai).
- AI-designed crowns (cs/ai) demonstrated comparability with technician designs (cs/dt) in terms of fracture forces, functional performance, and marginal fit.

Declaration of Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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