Geometric accuracy of 3D-printed vs. milled dental crowns: A surface-partitioned analysis of occlusal, intaglio and marginal regions

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Overview

1. Background and objectives
2. Materials
3. Methods
4. Results
5. Discussion
6. Conclusions and future work

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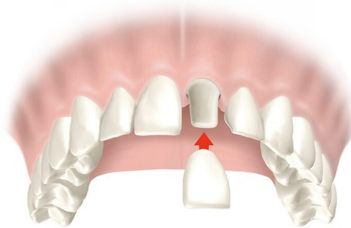
Dental crowns: what they are why they are used

Custom-made caps that permanently cover a damaged, weak or decayed tooth

Functions:

- Restoration (to restore a damaged or worn-down tooth)
- Protection (to protect a weak or partially broken tooth)
- Cosmetics (to cover a misshapen tooth or an implant)



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Dental crowns: how they are made (1/2)

Traditional (analogue) methods

- Lost-wax casting
- Heat pressing

Subtractive methods

- CAD/CAM milling

Additive manufacturing (3D printing)

- Digital light processing (DLP)
- Lithography-based ceramic manuf. technology (LCM)
- Stereolithography (SLT/TSLA)

Dental crowns: how they are made (2/2)

Subtractive manufacturing

- High geometric accuracy
- Good mechanical strength

Additive manufacturing

- Less material waste compared to milling
- Intricate geometries possible

Dental crowns: functional regions

Occlusal region (blue):

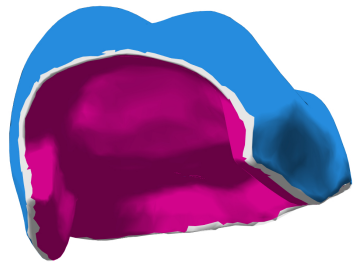
- Chewing (external) surface of the crown
- Touches the opposing teeth when biting

Intaglio region (purple):

- Inside (internal) surface of the crown
- Adheres to the prepared tooth

Marginal region (white):

- Boundary between the intaglio and occlusal
- Guarantees sealing



Dental crowns: why precision matters

For the occlusal region:

- Maintains bite and jaw alignment
- Improves masticatory efficiency

For the intaglio region:

- Determines fit and retention

For the marginal region:

- Prevents micro-leakage and bacteria infiltration

Objectives

- To investigate geometric accuracy (trueness) of milled vs. additive manufactured dental crowns
  - Global accuracy analysis
  - Separate analysis for the occlusal, intaglio and marginal regions

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4. Results

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Reference geometry–virtual model

Physical starting sample:

- Intact upper molar, extracted for periodontal reasons

Acquisition:

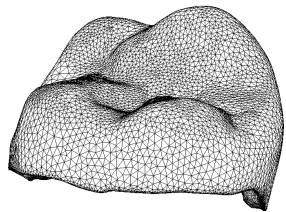
- Intraoral 3D scanner Trios 3 (3Shape)

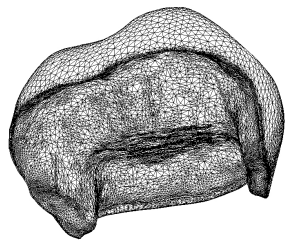
Generation of the crown model:

- Dental system CAD software (3Shape)
- Uniform thickness offset (1.5 mm)

Virtual sample generated:

- Triangulated STL model (34374 faces)





Physical samples

Six groups of specimens:

- Milled samples (two groups, M1–M2)
- 3D-printed samples (four groups, A1–A4)

Group	Material	Technique	Num. samples
M1	Composite	Milling	7
M2	Ceramic	Milling	8
A1	Composite	AM/DLP	7
A2	Ceramic/composite	AM/TSLA	6
A3	Ceramic	AM/LCM	9
A4	Ceramic	AM/LCM	16

Milled samples

Group M1

- Material: BRILLIANT Crios (Coltene Group)
- Milling machine: inLab MC XL (Dentsply Sirona)

Group M2

- Material: KATANA Zirconia STML (Kuraray Noritake Dental Inc.)
- Milling machine: inLab MC XL (Dentsply Sirona)

3D-printed samples (1/2)

Group A1

- Material: VarseoSmile Crown plus (BEGO GmbH & Co.)
- Printer: SprintRay Pro S (SprintRay Inc.)
- Thickness: 50 μm

Group A2

- Material: Irix Max (DFAB)
- Printer: DFAB Desktop 3D (DWS Systems)
- Thickness: 50 μm

3D-printed samples (2/2)

Group A3

- Material: 5Y-TZP zirconia (Tosoh Corporation)
- Printer: LCM (Admatec Admaflex 130)
- Thickness: 50 μm

Group A4

- Material: 8Y-TZP zirconia (Tosoh Corporation)
- Printer: LCM (Admatec Admaflex 130)
- Thickness: 30 μm

1. Background and objectives
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Accuracy estimation procedure

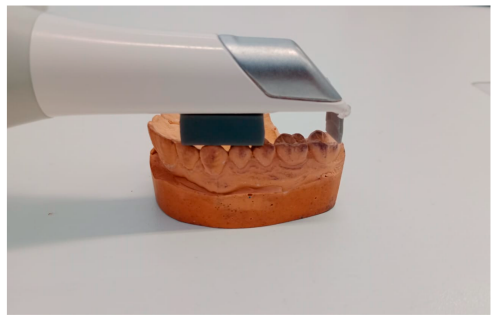
1. Sample digitalisation
2. Shape registration
3. Surface segmentation
4. Evaluation of the goodness-of-fit
5. Statistical analysis

Sample digitalisation

3Shape Trios 3 system (same used for generating the reference geometry)

Declared specs:

- Weight: 340 g
- Capture rate: 1875 images/sec
- Precision: 4.5 ± 0.9 μm
- Trueness: 6.9 ± 0.9 μm



Source: Hokayem et al., 2025
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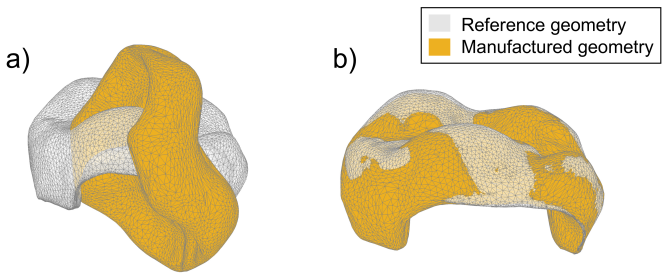
Shape registration

Performed with CloudCompare (Open Source Project)

a. Preliminary manual alignment (translation and rotation)

b. Fine registration by iterative closest point (ICP)

- Stopping criterion: < 15 μm diff. between two consecutive iterations



Evaluation of the goodness-of-fit (trueness)

Local performance metric (node level):

- Signed distance δ between each node of the sample's mesh and the closest triangle in the reference geometry
  - Positive for deviations in the same direction as the surface normal (angle between 0° and 90°)
  - Negative for deviations in direction opposite to the surface normal (angle between 90° and 180°)

Global performance metric (surface level):

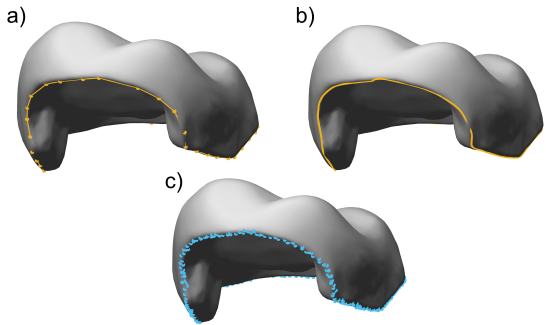
- Root mean square (RMS) of δ

Segments analysed:

- Whole surface
- Occlusal, intaglio and marginal regions separately

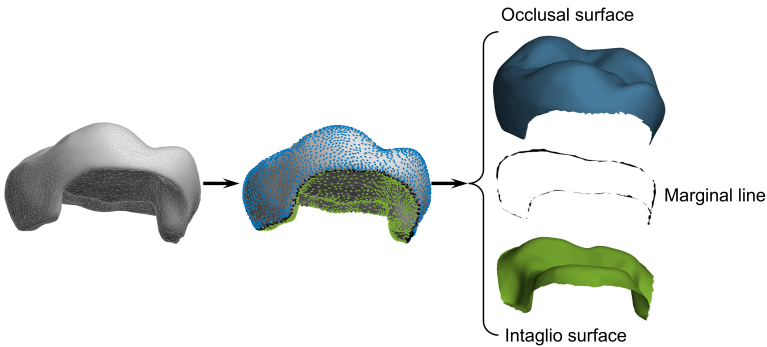
Surface segmentation: identification of the marginal region

a. Manual generation of an approximating closed polyline (CloudCompare)
b. Polyline over-sampling (Matlab–custom routine)
c. Identification of the closest nodes on the mesh (Matlab–custom routine)



Surface segmentation: occlusal and intaglio regions

- Occlusal: all nodes not belonging to the marginal line and with the normal vectors pointing outward
- Intaglio: all nodes not belonging to the marginal line and with the normal vectors pointing inward



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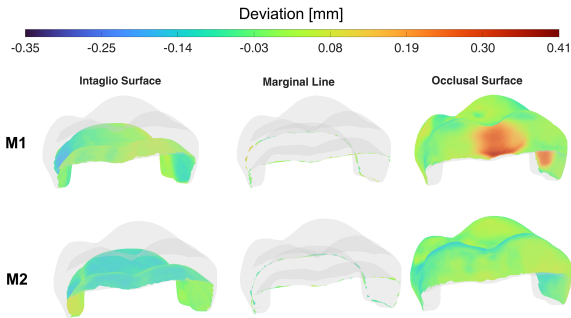
Trueness

Group	Surface segment			
	Overall	Intaglio	Occlusal	Marginal
M1	**79.4** ± 4.74	**47.0** ± 8.97	95.7 ± 9.33	**41.2** ± 5.76
M2	94.3 ± 63.3	125.6 ± 105.9	**55.5** ± 19.2	83.5 ± 45.3
A1	112.0 ± 12.5	156.4 ± 23.8	72.9 ± 16.1	83.2 ± 19.4
A2	**78.2** ± 25.6	100.6 ± 44.1	**56.3** ± 14.1	74.5 ± 35.7
A3	111.6 ± 11.1	127.8 ± 13.7	98.3 ± 18.7	110.6 ± 27.0
A4	118.1 ± 13.2	121.6 ± 22.9	115.1 ± 13.0	114.9 ± 25.1

- RMS values for δ pooled by group (mean ± std., μm)

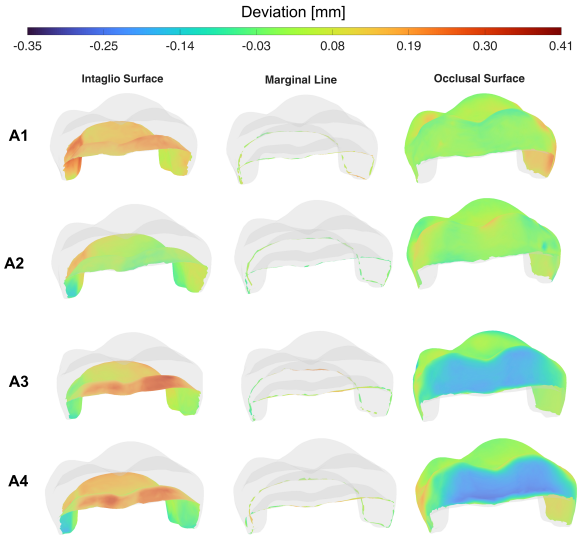
Deviation colourmaps: milled samples

- Intaglio surface:
  - General material deficiency
- Occlusal surface:
  - Fairly contained overall deviation
  - Concentrated material excess (M1)



Deviation colourmaps: 3D-printed samples

- Intaglio surface:
  - General material excess
- Occlusal surface:
  - Material deficiency in large areas of A3–A4
  - No clear trend for A1–A2



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Clinical fitness of the samples

- Cut-off values for trueness:
  - 100–150 μm generally considered acceptable
  - 50–100 μm generally considered good

- Results aligns well with the current literature
- Nearly all groups (except A1) achieved acceptable values for all the surface segments
- Group M1 attained good values for all the surface segments

Comparing methods

- All 3D-printed groups resulted in material deficiency at the intaglio surface
- A3-A4 yielded material excess on the occlusal surface
- M1 generated localised material notches at the occlusal surface

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Conclusions

- The accuracy of 3D-printed crowns was clinically acceptable on the whole
- Milling on composite (M1) was good for the intaglio and marginal regions, however milling on ceramics (M2) performed better at the occlusal region
- The intaglio surface was more critical for AM than the occlusal region

Future work

- Further validate the results on larger datasets
  - More reference teeth
  - Larger number of physical samples
- Investigate reasons behind material excess/deficiency in specific zones

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Thank you for your attention

Any questions?