Dimensional Accuracy and Slot Angulation of 3D-Printed Zirconia Nanohybrid Orthodontic Brackets

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INTRODUCTION

Bracket slot dimensions and orientation contribute to archwire–slot play and potential third-order expression. Additive-manufacturing accuracy is workflow-specific and depends on the printer, material, orientation, support strategy, and post-processing; findings therefore cannot be generalized across workflows.

This in vitro study evaluated whether a custom zirconia-nanohybrid bracket produced with LCD-masked vat photopolymerization could reproduce four CAD features: slot height, slot depth, base height, and 7.00° slot-wall angulation.

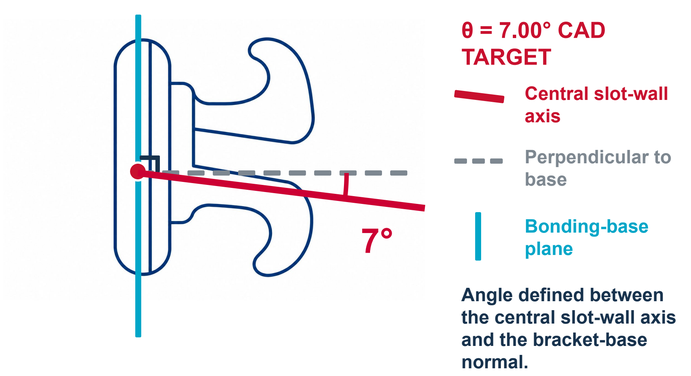
OBJECTIVE

Evaluate the dimensional and angular accuracy of 50 zirconia-nanohybrid orthodontic brackets by comparing measured slot height, slot depth, base height, and slot-wall angulation with their CAD targets.

METHODS AND MATERIALS

- 50 custom brackets printed together from one CAD design
- Rodin Sculpture 2.0 zirconia-nanohybrid resin
- Phrozen Sonic Mini 8K S LCD-masked printer; 0.05-mm layers
- Flat 90° orientation with slot and tie wings facing upward
- One 5-minute wash in 95% IPA; 405-nm post-cure for 10 minutes
- Keyence VHX-7000 optical microscopy at 10×, 30×, and up to 100×
- ImageJ 1.54p and Geomagic Control X 2026.1
- Two blinded examiners × two software packages × three repetitions = 12 readings per bracket per parameter

SLOT-WALL ANGULATION DIAGRAM



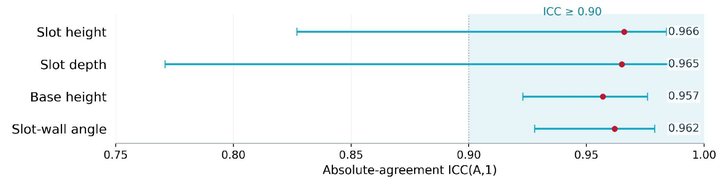
Angle defined between the central slot-wall axis and the bracket-base normal.

Slot-wall angulation was measured between the central slot-wall axis and the line perpendicular to the bonding-base plane. The CAD target was 7.00°.

STATISTICAL ANALYSIS

- Descriptive statistics included means, standard deviations, 95% confidence intervals, and ranges.
- Specimen-level agreement used prespecified margins of ±0.05 mm for linear dimensions and ±0.35° for angulation.
- TOST equivalence testing evaluated mean differences with 90% confidence intervals.
- Bias-corrected and accelerated bootstrap 90% confidence intervals used 100,000 resamples.

ICC RELIABILITY ANALYSIS



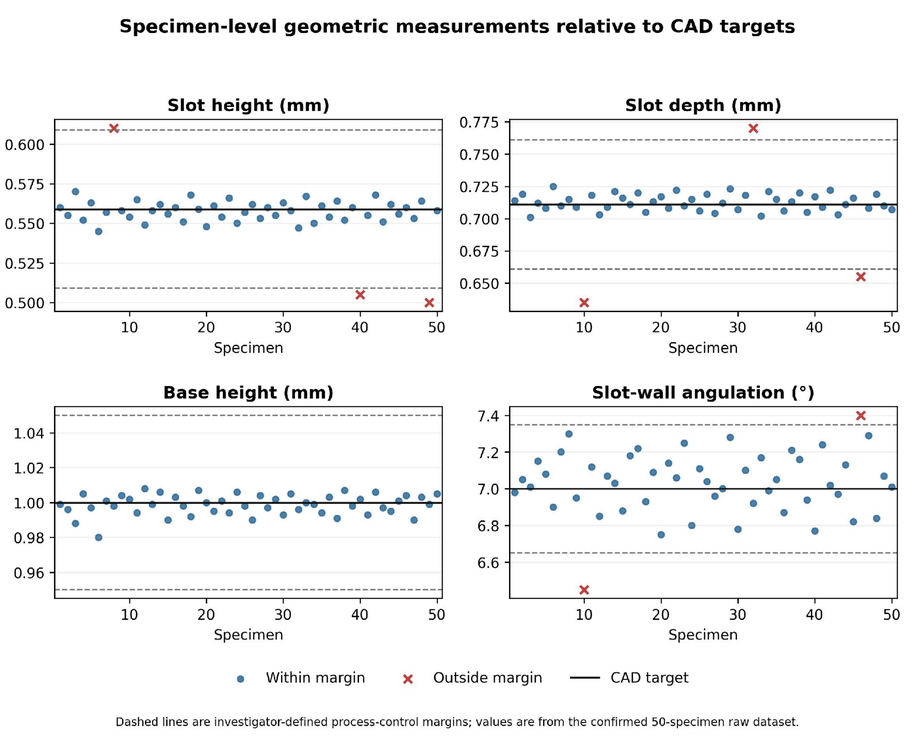
Interexaminer ICC(A,1): two-way absolute agreement between each examiner's mean of three readings (50 brackets). Bars: percentile 95% CIs from 20,000 paired bracket bootstrap resamples.

RESULTS

All 50 brackets passed visual inspection and were analyzed.

Outcome	CAD target	Mean (SD)	Within margin
Slot height	0.559 mm	0.557 (0.015)	47/50 (94%)
Slot depth	0.711 mm	0.711 (0.017)	47/50 (94%)
Base height	1.000 mm	0.999 (0.006)	50/50 (100%)
Slot-wall angle	7.00°	7.032° (0.174°)	48/50 (96%)

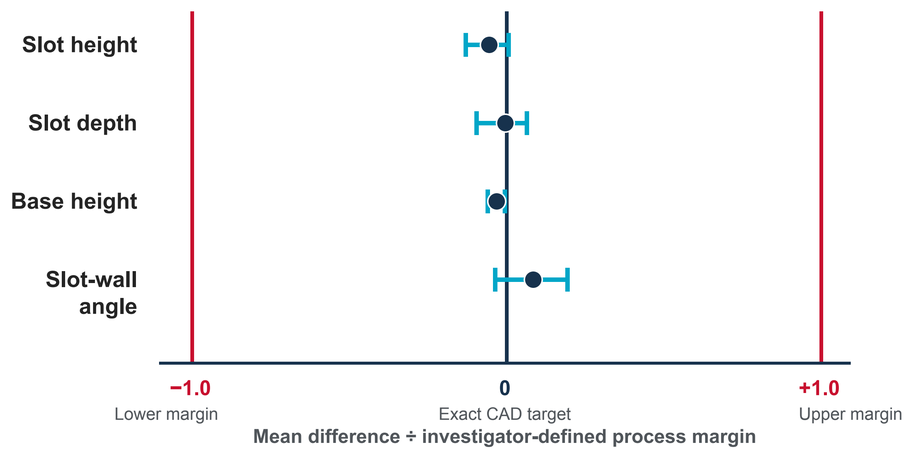
DIMENSIONAL AND ANGULAR RESULTS



Solid lines show CAD targets. Dashed lines show the prespecified accuracy margins. Red symbols identify measurements outside a margin.

BOOTSTRAP ANALYSIS

All four 90% confidence intervals remained within the prespecified accuracy margins.



BCa bootstrap 90% confidence intervals supported the equivalence findings for slot height, slot depth, base height, and slot-wall angulation.

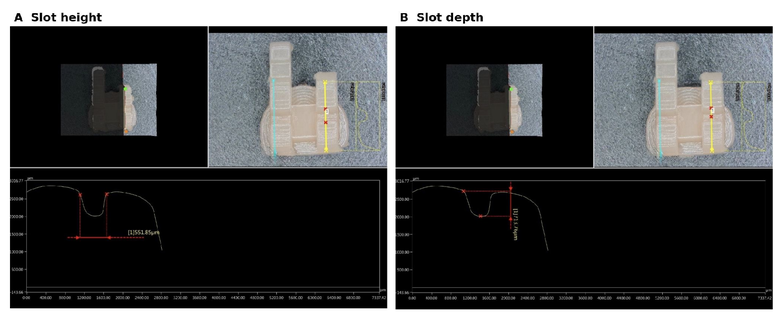
KEY RESULT

The printing workflow reproduced all four CAD features with high mean agreement and 94% to 100% specimen-level conformity.

DISCUSSION

The measured dimensions closely matched the CAD design. Mean slot depth equaled its 0.711-mm target, while mean slot height and base height differed by only 0.002 mm and 0.001 mm, respectively. Mean slot-wall angulation differed from the 7.00° target by 0.032°. The bootstrap analysis supported the same conclusion despite non-normal slot-height and slot-depth distributions. **These results demonstrate precise geometric reproduction within the evaluated zirconia-nanohybrid printing workflow.**

OPTICAL MEASUREMENT



Representative Keyence outputs for slot height and slot depth. Panels show different brackets; exported image identifiers were not retained.

LIMITATIONS

- All specimens came from one printer run using one bracket design and one manufacturing protocol.
- The study evaluated geometric accuracy; mechanical and clinical performance require separate testing.

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CONCLUSION

LCD-masked vat photopolymerization produced zirconia-nanohybrid brackets with mean linear dimensions and slot-wall angulation closely matching the custom CAD targets.

Conflicts of interest: None declared.