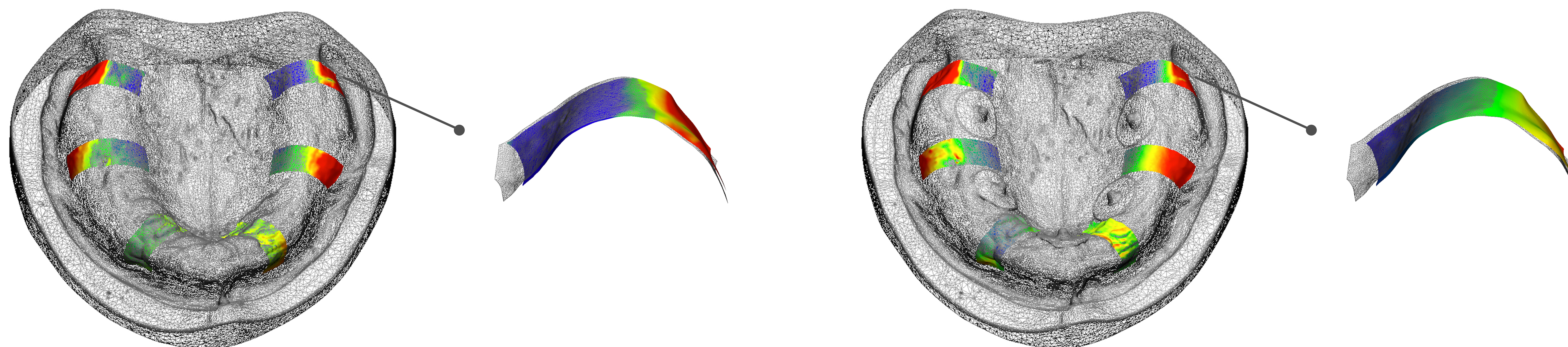


IN VITRO STUDY ON ACCURACY OF COMPLETE-ARCH INTRAORAL SCANS: THE CONTRIBUTION OF TRANSLOCATION ERRORS TO OVERALL SURFACE INACCURACY

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Introduction

Digital impressions derived from intraoral optical scanning (IOS) obtain surface data that are used to replicate the intraoral hard and soft tissues. IOS excludes material defects such as voids, inadequate polymerization and distortions involved in conventional impression-taking procedures. However digital impressions have shown increasing deviations in trueness as the scanned area expands.^{1, 2} This error is generally recognized, but there is a lack of evidence to characterize the nature of such inaccuracy.

Herein, the authors seek to further investigate the contributors to surface inaccuracies of digital casts produced by IOS. The field of statistical shape analysis states that differences between geometries arise from three main components: position, scale, and shape.³ Scale-and-shape analysis, employed here, compares all the geometric information remaining when location and rotational effects are removed from an object.⁴

The purpose of this in vitro, non-clinical investigation is to evaluate the extent to which deviations in position, scale, and shape contribute to the overall surface deviation observed in complete-arch digital impressions.

Materials and Methods

Digital Impression

An edentulous stone cast was scanned on a laboratory scanner (Planmeca Planscan Lab, Planmeca, Helsinki, Finland) as reference-scan-cast (RSC1), and with an IOS (Emerald S, Planmeca, Helsinki, Finland) as test-scan-cast 1 (TSC1). Five fiducial markers (VF-20, Suremark, Simi Valley, CA) were positioned on the cast palatal to the mid-crestal position, and scanned with laboratory scanner and IOS as reference-scan-cast (RSC2) and test-scan-cast 2 (TSC2). Test scans were repeated 50 times. Throughout all scans, the scanning pattern and scanner settings were held constant. The first 5 scans were deleted from each group for intra-operator calibration and the following 45 scans were used for evaluation. All scans were processed to generate a standard tessellation language (STL) mesh.

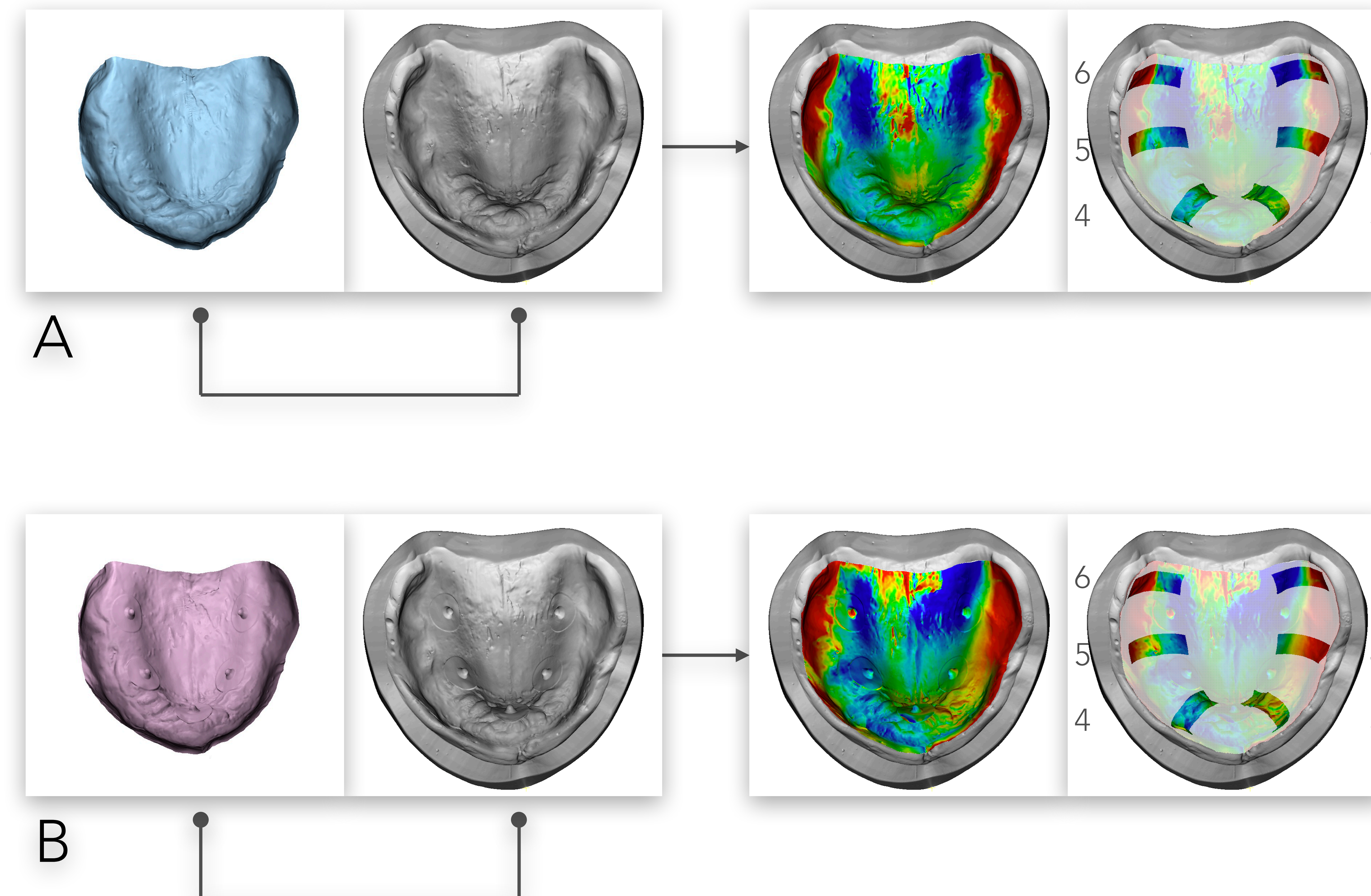


Figure 1. Digital impression, alignment surface deviation calculation, and ROI segmentation workflow. A, TSC1 is aligned to RSC1 and a surface deviation heat map is shown for both the entire TSC and isolated ROIs; B, the same process defined in part A is applied to TSC2 and RSC2, which includes fiducial markers. ROI numeration is shown for both TSC1 and TSC2.

Materials and Methods

Initial Alignment and Segmentation

TSC1 and TSC2 were aligned to RSC1 and RSC2 respectively using iterative closest point (ICP) registration algorithm⁵ to find a “best-fit” position using a 3-D metrology software (CloudCompare v2.10.3, GPL). All TSCs were translated and rotated during ICP registration but scale was held constant. Subsequently all TSCs were trimmed using a fixed boundary relative to RSCs to create a consistent boundary for all TSCs using a 3-D graphics software toolset (Blender v2.79, Blender Foundation, GPLv2+). In this initial alignment the surface deviation measurement was calculated (Fig. 1).

Six region-of-interest (ROI) with dimensions of 18x6 mm (18 mm buccolingual, 6 mm mesiodistal) were centered mid-crestal and evenly distributed across the curve of the arch of RSCs. These ROIs were segmented using a 3-D graphics software toolset (Blender v2.79, Blender Foundation, GPLv2+) from each TSCs and used for subsequent analysis (Fig. 1).

Secondary Alignment with ROI Position Correction

Following initial alignment and segmentation, each ROI was translated and rotated to find its own “best-fit” position in accordance with RSC while holding the ROI’s scale constant. The translocation error was defined as the combined translational and angular discrepancy of each ROI to reach its “best-fit” position. After position correction, a new surface deviation measurement was calculated (Fig. 2).

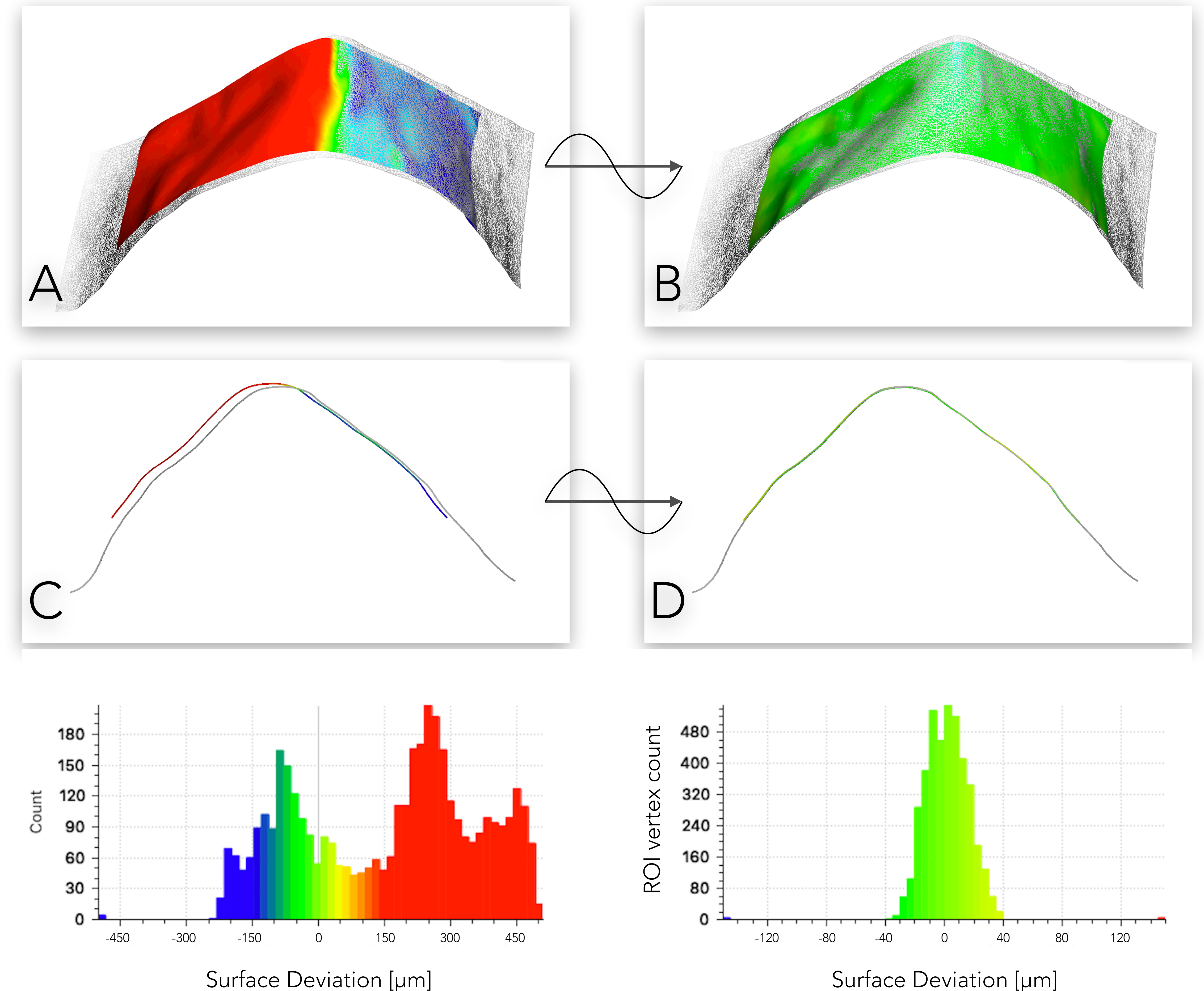


Figure 2. ROI position correction workflow, each ROI is translated and rotated to obtain “best-fit” position in accordance with RSC. A, heat map of ROI initial alignment relative to wireframe RSC (grey); B, heat map of ROI following position correction of translocation (translational, angular) error correction; C, cross-sectional view of ROI initial alignment; D, cross-sectional view of ROI following position correction of translocation (translational, angular) error. Histogram of surface deviation (µm) of each point in the ROI.



Materials and Methods

Data Collection

Surface deviation was numerically reported as mean, and standard deviation of pre- and post-correction root mean square error (RMSE) for each ROI. RMSE is a standard method to measure the error of a model in predicting quantitative data. The formula is $RMSE = \sqrt{(f - o)^2}$ whereas f is forecasts (expected values or unknown results) and o is observed values (known results).

$$\%RMSE_{position} = (\Delta RMSE / RMSE_{pre-correction}) \times 100 = (RMSE_{pre-correction} - RMSE_{post-correction}) / RMSE_{pre-correction} \times 100$$

Equation 1. The contribution of positional error to the ROI surface deviation RMSE is calculated above. The ROI starts at an initial position (pre-correction) and is translated and rotated to a "best-fit" position (post-correction) during the position correction. The change in surface deviation RMSE during the position correction represents the portion of the pre-correction RMSE attributable to positional misalignment of the ROI.

$$\%RMSE_{non-position} = (RMSE_{post-correction} / RMSE_{pre-correction}) \times 100$$

Equation 2. The post-correction RMSE represents the residual deviations of the ROI following application of position correction to the ROI. The residual RMSE quantifies the effect of scale and shape discrepancies on the ROI surface deviation.

Statistical Analysis

The Shapiro-Wilk test was used to assess whether the data were normally distributed. As a result, since there was no normal distribution, the differences between segments were analyzed using Kruskal-Wallis ($\alpha = 0.05$) and Bonferroni correction method as post-hoc tests ($\alpha = 0.004167$).

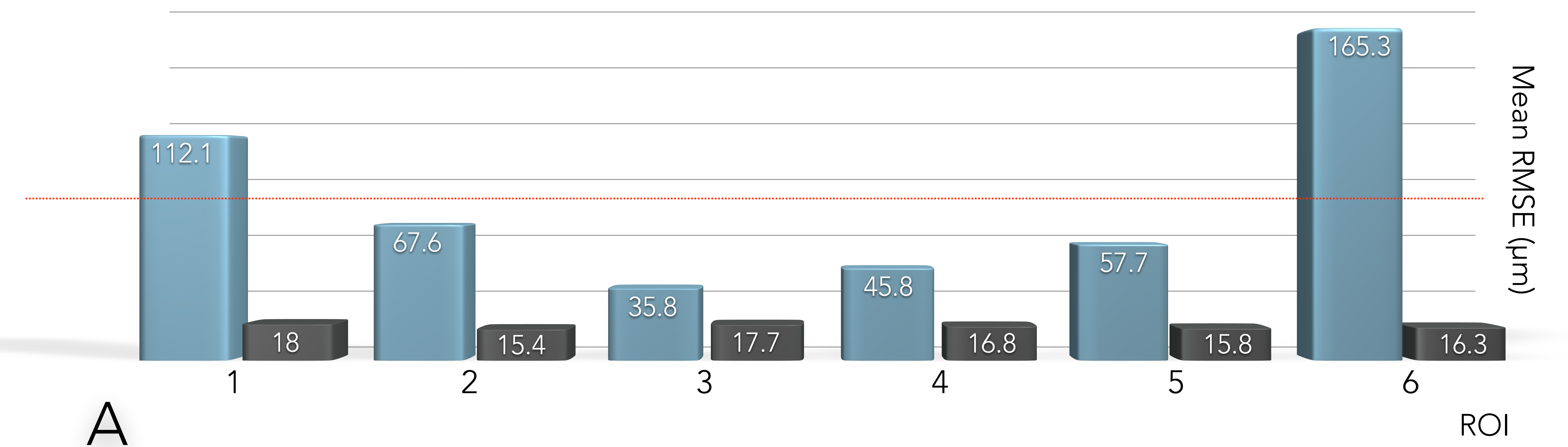
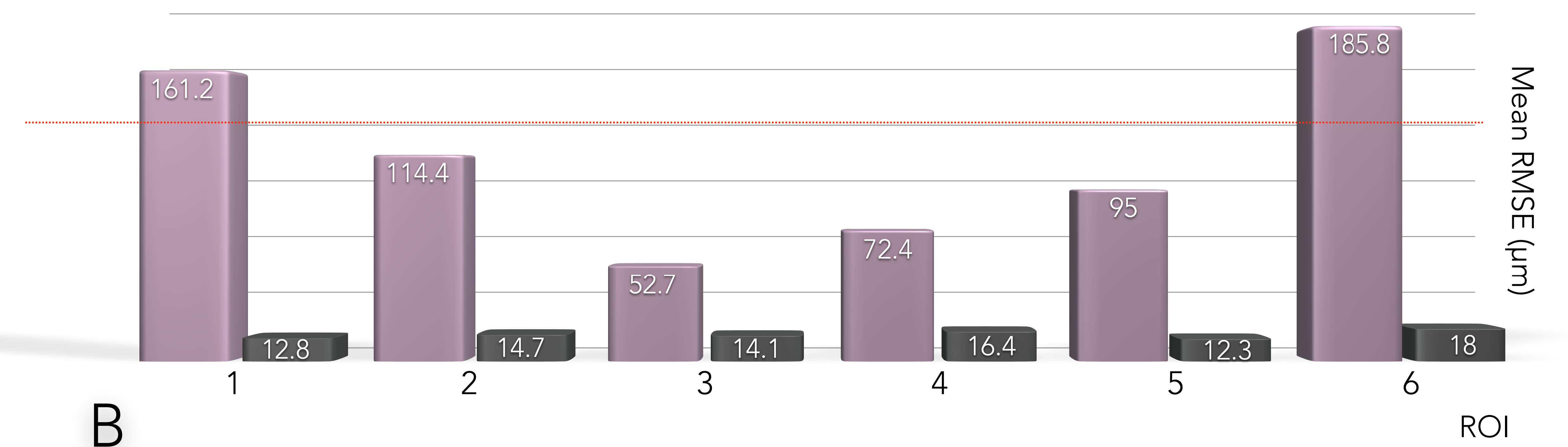


Figure 3. Mean RMSE values for each ROI in pre- and post-correction positions. A, TSC1 pre-correction ROI RMSE in blue, post-correction ROI RMSE in grey; B, TSC2 pre-correction ROI RMSE in pink, post-correction ROI RMSE in grey. Red dot line denotes complete-arch RMSE.

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Results

Δ RMSE for TSC1 was 70.3 $\pm$ 17.2% (p=.000) with a pre-correction RMSE absolute value (AV) of 80.7 $\pm$ 58.0 μ m and post-correction RMSE (AV) of 16.7 $\pm$ 5.5 μ m (Table 1). Δ RMSE for TSC2 was 81.8 $\pm$ 13.4% (p=.000) with a pre-correction RMSE (AV) of 113.6 $\pm$ 71.6 μ m and post-correction RMSE (AV) of 14.7 $\pm$ 12.0 μ m (Table 1). Following position correction via secondary alignment, the residual RMSE (TSC1 - 16.7 $\pm$ 5.5 μ m; TSC2 - 14.7 $\pm$ 12.0 μ m) value can be attributed to scale and shape discrepancies. However, with the present study method, fractionating scale and shape contributions was not possible. During the process of creating virtual casts with IOS 3-D displacement may occur, and the mean value of the distance of all point clouds cannot represent the error in specific areas.⁶ Segments were used as an analysis unit for that purpose and the result of the present study indicates a significant difference in accuracy from the anterior to posterior segments ($P < 0.001$) (Fig. 3, Table 2). The utilization of fiducial markers did not aid in improved surface trueness (Table 2). This is in contrast to recently reported studies^{7, 8} and would require further investigation.

Conclusions

The present study suggests translocation as a prominent source of inaccuracy in complete-arch digital impressions acquired via IOS. Comparison between scans with and without fiducial markers indicated such reference markers failed to aid in improved accuracy. Trueness and precision were sub-optimal for both test scans. Error distribution pattern analysis indicated increased inaccuracy in posterior segments compared to anterior segments.

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		ROI 1	ROI 2	ROI 3	ROI 4	ROI 5	ROI 6	mean
Δ RMSE post-correction	TSC1	81.7 $\pm$ 7.6	74.5 $\pm$ 13.5	47.6 $\pm$ 15.3	61.8 $\pm$ 8.9	69.0 $\pm$ 11.5	87.3 $\pm$ 8.8	70.3 $\pm$ 17.2
	TSC2	89.1 $\pm$ 9.2	86.1 $\pm$ 13.0	69.8 $\pm$ 12.9	72.2 $\pm$ 11.9	84.4 $\pm$ 10.0	88.2 $\pm$ 8.2	81.6 $\pm$ 13.4

Table 1. TSC1 and TSC2 Δ RMSE (%) after application of position correction to each ROI.

		ROI 1	ROI 2	ROI 3	ROI 4	ROI 5	ROI 6
Pre-Correction	TSC1	112.1 $\pm$ 40.3 ^a	67.6 $\pm$ 29.4 ^b	35.8 $\pm$ 9.2 ^e	45.8 $\pm$ 9.9 ^c	57.7 $\pm$ 23.3 ^b	165.3 $\pm$ 73.6 ^d
	TSC2	158.9 $\pm$ 71.5 ^d	113.9 $\pm$ 42.3 ^a	55.2 $\pm$ 26.7 ^{bc}	72.8 $\pm$ 37.8 ^b	94.4 $\pm$ 36.8 ^a	183.3 $\pm$ 88.4 ^d
Post-Correction	TSC1	18.0 $\pm$ 2.4 ^f	13.7 $\pm$ 2.3 ^g	17.17 $\pm$ 3.4 ^{fh}	16.8 $\pm$ 3.0 ^{fhi}	15.8 $\pm$ 2.7 ⁱ	16.3 $\pm$ 2.5 ^{hi}
	TSC2	12.5 $\pm$ 3.9 ^j	12.0 $\pm$ 4.3 ^j	14.1 $\pm$ 3.2 ^g	16.8 $\pm$ 4.2 ^{hi}	12.5 $\pm$ 3.2 ^{gj}	15.3 $\pm$ 3.0 ⁱ

Table 2. TSC1 and TSC2 RMSE (μ m) pre-correction and post-correction delineated in mean and standard deviation for individual ROI. Significant by Kruskal-Wallis test; $P < 0.05$. Different letters indicate the significant differences among the ROI by Bonferroni correction method ($P < 0.004167$).