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RESEARCH AND EDUCATION

In vitro evaluation of accuracy and precision of automated robotic tooth preparation system for porcelain laminate veneers

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ABSTRACT

Statement of problem. Controlling tooth reduction for porcelain laminate veneers (PLVs) in fractions of millimeters is challenging.

Purpose. The purpose of this study was to assess an automated robotic tooth preparation system for PLVs for accuracy and precision compared with conventional freehand tooth preparation.

Material and methods. Twenty maxillary central incisor tooth models were divided into 2 groups. Ten were assigned to a veneer preparation with a robotic arm according to preoperative preparation design-specific guidelines (experimental group). Ten were assigned to conventional tooth preparation by a clinician (control group). Initially, all tooth models were scanned with a 3-dimensional (3D) laser scanner, and a tooth preparation for PLVs was designed on a 3D image. Each tooth model was attached to a typodont. For the experimental group, an electric high-speed handpiece with a 0.9-mm-diameter round diamond rotary cutting instrument was mounted on the robotic arm. The teeth were prepared automatically according to the designed image. For the control group, several diamond rotary cutting instruments were used to prepare the tooth models according to preoperative preparation design guidelines. All prepared tooth models were scanned. The preoperative preparation design image and scanned postoperative preparation images were superimposed. The dimensional difference between those 2 images was measured on the facial aspect, finish line, and incisal edge. Differences between the experimental and the control groups from the 3D design image were computed. Accuracy and precision were compared for all sites and separately for each tooth surface (facial, finish line, incisal). Statistical analyses were conducted with a permutation test for accuracy and with a modified robust Brown-Forsythe Levene-type test for precision (α=.05).

Results. For accuracy for all sites, the mean absolute deviation was 0.112 mm in the control group and 0.133 mm in the experimental group. No significant difference was found between the 2 (P=.15). For precision of all sites, the standard deviation was 0.141 mm in the control group and 0.185 mm in the experimental group. The standard deviation in the control group was significantly lower (P=.030). In terms of accuracy for the finish line, the control group was significantly less accurate (P=.038). For precision, the standard deviation in the control group was significantly higher at the finish line (P=.034).

Conclusions. For the data from all sites, the experimental procedure was able to prepare the tooth model as accurately as the control, and the control procedure was able to prepare the tooth model with better precision. The experimental group showed better accuracy and precision at the finish line. (J Prosthet Dent 2015;114:229-235)

Porcelain laminate veneers (PLVs) have become a popular conservative treatment for fulfilling esthetic demands and restorative needs. The clinical long-term success and survival of PLVs is directly correlated with having sufficient enamel for bonding.[1-6] Multiple clinical studies have demonstrated that when PLVs are bonded to enamel (at least 50% bonding surface is enamel) and when the finish-line is placed supragingivally on enamel, these restorations are extremely successful.[7-10] The enamel thickness of anterior teeth varies according to area and tooth type.[11,12] Clinically, the average enamel thickness has been used as one of the references for the tooth preparation of PLVs.[10,11,13] However, controlling the amount of tooth reduction in one tenth of millimeter increments is challenging and technique sensitive because of the thinness of the enamel. Therefore, tooth preparation for PLVs needs to be performed

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Clinical Implications

The development of a robotic system for preparing teeth for PLVs may allow clinicians to provide better accuracy and precision at the finish line, which is a critical area in terms of residual enamel for predictable adhesive cementation, than freehand conventional tooth preparation procedures. This may further facilitate longevity of such restorations.

carefully to preserve enamel for successful bonding. One of the most common veneer preparation methods for preserving enamel is the use of a preoperative diagnostic arrangement with direct composite resin.[13-15]

In the medical field, robotic surgery has been used in a broad array of applications.[16-18] The advantages of robotic surgery over conventional surgery include increased precision and accuracy, shortened healing period, reduced morbidity, and the ability to accurately import, integrate, and apply the presurgical planning data to the surgery.[16-18] Moreover, robotic surgery improves the ergonomics for the surgeon, in that the robot can sustain indefinitely the desired position for performing the surgical procedures accurately and with precision.[16-18]

Tooth preparation is one of the most common dental procedures, and the high accuracy and precision of robotic technology may be beneficial for such a procedure. Successful, consistent results with high accuracy and high precision may be expected for the application of robotics to tooth preparation. Such an application may be especially beneficial for the high accuracy and precision required by clinicians for a technique-sensitive procedure such as tooth preparation for PLVs. However, currently no studies have been published on the use of robotic technology for such a clinical dental application simulating conventional tooth preparation techniques.

Therefore, the purpose of this in vitro study was to develop an automated dental robotic tooth preparation system for PLVs in order to assess the accuracy and precision of robotic tooth preparation compared with conventional freehand tooth preparation by a dental clinician. The null hypotheses of this study were that no significant difference would be found in accuracy or precision of tooth preparation between the automated robotic tooth preparation system and conventional freehand tooth preparation.

MATERIAL AND METHODS

Twenty right maxillary central incisor tooth models with mean natural tooth dimensions and made out of composite resin and epoxy-resin to simulate enamel and underlying dentin (2-Layered Tooth Model; Nissin Dental Products Inc) were divided into 2 groups (Fig. 1). Ten tooth models were assigned for tooth preparation with dental robotics as an experimental group, and 10 tooth models were assigned for tooth preparation with the conventional free-hand method as a control group.

For the experimental group, 3 indentations were made on the facial surface of the tooth model with 0.9-mm-diameter round diamond rotary cutting instrument (801.31.009 FG Medium Round Diamond; Brasseler USA) (Fig. 2). These indentations were placed at the incisal and middle thirds, with a depth of half of the 0.9-mm-diameter round diamond rotary cutting instrument. These indentations were used to calibrate the robotic arm.

Twenty tooth models were digitally scanned with 3-dimensional (3D) laser scanner (D700L; 3Shape A/S). Scanned data were exported as a stereolithography (STL) file, and the STL file was 3D reconstructed with 3D computer-aided design (CAD) software (SolidWorks; Dassault Systemes SolidWorks Corp). A tooth preparation for a PLV was designed on the 3D-reconstructed image of a tooth model (Fig. 3). The facial tooth reduction was designed with a dimension of 0.5 mm at the incisal third, 0.5 mm at the middle third, and 0.3 mm at the cervical third. A shallow chamfer finish line (0.3 mm wide) was designed and placed 1 mm above the free gingival margins. The incisal reduction was designed with a dimension of 1.5 mm and a butt joint design. All line angles and corners were designed to be rounded. Designed tooth preparation data were exported to computational software (MATLAB; The MathWorks Inc), and transformed data were exported to programming software (WINCAPS III; Denso Intl America Inc). The robotic arm was controlled with this programming software.

Ten model teeth were mounted on a typodont (Prosthetic Restoration Jaw Model; Nissin Dental Products Inc) with a screw. The typodont was attached to the custom mounting unit on a table and stabilized. An electric high-speed handpiece (Ti-Max Z95L; NSK) was attached to the robotic arm (VM-60B1G [http://densorobotics.com/products/vm-g-series/spec]; Denso Intl America Inc) with a custom attachment, and a 0.9-mm-diameter round diamond rotary cutting instrument was attached to the handpiece (Fig. 4). The robotic arm was calibrated by fitting the round diamond rotary cutting instrument into each facial indentation. The rotation speed of the diamond rotary cutting instrument was controlled at 25 000 rpm, and the speed of the robotic arm movement was controlled at 2 mm/s. The teeth were prepared according to the preoperative preparation design under air-waterspray cooling (Fig. 5).

The same experimental settings as for the robotic tooth preparation were used, and the teeth were prepared in a conventional freehand method according to the same preparation design with the same electric

Figure 1. Maxillary central incisor tooth model with mean natural tooth dimension made out of composite resin and epoxy resin to simulate enamel and underlying dentin (2-Layered Tooth Model; Nissin Dental Products Inc).

Figure 2. Tooth model with 3 indentations for experimental group. These were used for robotic arm calibration.

Figure 3. Tooth preparation design for PLV on 3D reconstructed image of tooth model.

handpiece and the same rotational speed. Facial depth grooves (0.5 mm) were placed on the incisal and middle thirds with a depth cutting diamond rotary cutting instrument (828.31.026 FG Medium Depth Cutting Diamond; Brasseler USA), and a 0.3-mm facial depth groove was placed on the cervical third with a 0.3-mm depth cutting diamond rotary cutting instrument (828.31.022 FG Medium Depth Cutting Diamond; Brasseler USA). All of the grooves were connected with a double grit diamond rotary cutting instrument (6844.31.016 LVS3; Brasseler USA). Incisal depth grooves were placed with a 0.5-mm depth cutting diamond rotary cutting instrument, and all of the grooves were connected with the same diamond rotary cutting instrument. This procedure was repeated 2 times to achieve a 1.5-mm incisal reduction, and a silicone matrix (Panasil Lab Putty; Kettenbach GmbH & Co KG) was used to confirm a 1.5-mm incisal reduction. A 0.3-mm wide finish line was placed 1 mm supragingivally with the fine tip of a double

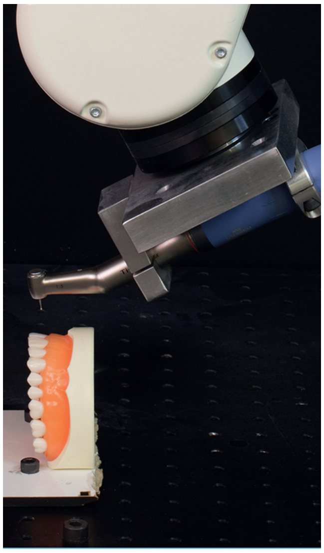

Figure 4. Experimental setting: Typodont (Prosthetic Restoration Jaw Model; Nissin Dental Products Inc) attached to table; Robotic arm (VM-60B1G; Denso International America Inc) with custom attachment and electric high-speed handpiece (Ti-Max Z95L; NSK) attached to robotic arm; 0.9-mm-diameter round diamond rotary cutting instrument (801.31.009 FG Medium Round Diamond; Brasseler USA).

grit diamond rotary cutting instrument, and all the line angles on the tooth preparation were rounded (Fig. 6).

For both the robotic preparation and conventional freehand preparation, the prepared tooth models were detached from the typodont and digitally scanned with a 3D laser scanner (D700L; 3Shape A/S). Scanned data were exported as an STL file, and the STL file was 3D reconstructed with 3D CAD design software. The postoperative scan image was superimposed on the preoperative preparation design image with computational

Figure 5. Prepared tooth model made with robotic tooth preparation system.

Figure 6. Prepared tooth model made with conventional freehand tooth preparation.

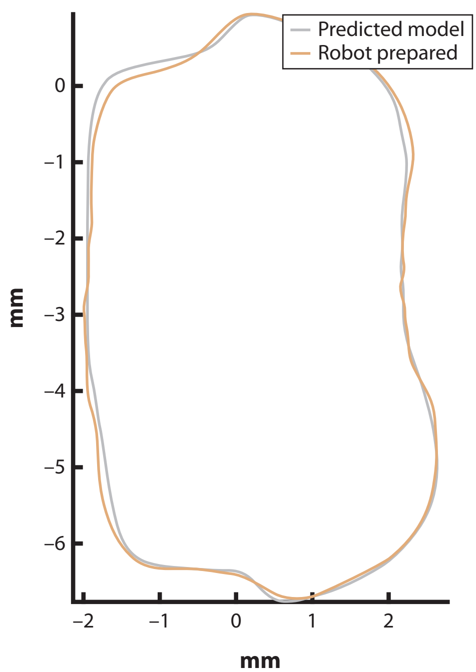

Figure 7. Superimposition of cross-sectional images of preoperative scan image (orange was robot) and postoperative scan image (predicted was grey) of tooth preparation made with robotic arm.

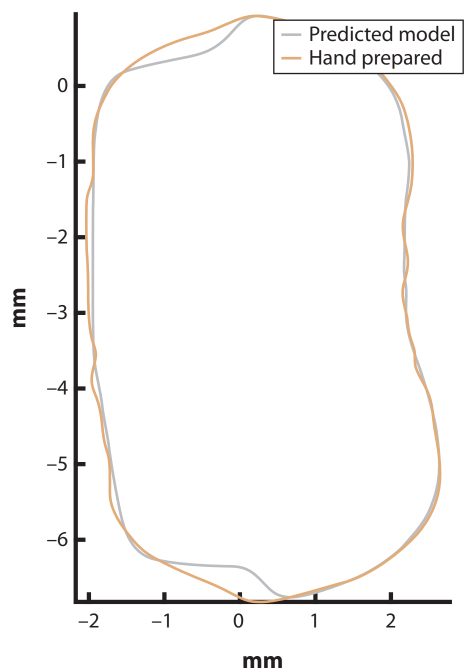

Figure 8. Superimposition of cross-sectional images of preoperative scan image (orange was hand) and postoperative scan image (grey was predicted) of tooth preparation made with conventional free hand tooth preparation.

software (Figs. 7, 8), and the dimensional differences between these 2 images was measured with the software at 9 points to measure the facial reduction, at 6 points to measure the finish-line width, and at 3 points to measure the incisal reduction (Fig. 9).

To determine the accuracy and precision of the 2 groups, the difference between the robotic tooth preparation system and the manual freehand tooth preparation from the preoperative preparation design on the 3D image was computed. The accuracy and precision of the 2-tooth preparation methods were summarized from all sites and separately for each tooth surface (facial, finish-line, incisal).

Accuracy was measured by the mean absolute difference and the 95% confidence for the mean. For each tooth preparation, the mean absolute difference was given by the average based on all sites or the average

Figure 9. Measurement points: 9 points for measuring facial reduction (red), 6 points for measuring finish-line width (blue), 3 points for measuring incisal reduction (green).

of the sites associated with a specific tooth surface. Bias-corrected accelerated bootstrap methods were used to compute 95% confidence intervals for the mean absolute difference based on 10 000 replications.[19,20] A permutation test was used to compare the mean absolute difference between the methods.[21] Precision was measured by the standard deviation of the differences and 95% confidence for the standard.[22] For each tooth preparation the standard deviation of the differences was calculated based on all sites or sites associated with a specific tooth surface. A modified robust Brown-Forsythe Levene-type test based on the absolute deviations from the median was used to compare the standard deviation between the 2 methods.[23-25] The robust Brown-Forsythe version of the Levene-type test substitutes the group mean with the group median in the classicl Levene statistic for the homogeneity of variances. Computer statistical software was used to perform all analyses (R v3.1.0; Free Software Foundations).[26]

RESULTS

Over all sites, the mean absolute deviation was 0.112 mm in the control group (95% CI 0.096 to 0.125) and 0.133 mm in the experimental group (95% CI 0.115 to 0.161; bias-corrected bootstrap P=.15) (Table 1). By surface location, the mean deviation in the control group was 0.076 mm (95% CI 0.063 to 0.104) at the facial region, 0.125 mm (95% CI 0.097 to 0.157) at the finish line, 0.195 mm (95% CI 0.148 to 0.245) at the incisal region. The mean deviation in the experimental group was 0.092 mm (95% CI 0.079 to 0.104) at the facial region, 0.087 mm (95% CI 0.069 to 0.112) at the finish line, 0.350 mm (95% CI 0.266 to 0.445) at the incisal region. A permutation test showed a statistically significant difference between the 2 groups in terms of accuracy of the finish line, while the control group was less accurate (P=.038) and for the incisal reduction, while the experimental group was less accurate (P=.016) (Table 2).

Table 1. Accuracy and precision of freehand and robotic preparations for all sites

		Accuracy			Precision		
Method	N	Mean	95% CI[a]	P[b]	SD[c]	95% CI[d]	P[e]
Hand	10	0.112	0.096, 0.125	.15	0.141	0.128, 0.157	.030
Robot	10	0.133	0.115, 0.161		0.185	0.168, 0.207	

[a]Bias-corrected accelerate bootstrap 95% confidence for accuracy (absolute mean difference).
[b]Permutation test, P value for comparing accuracy (absolute mean difference).
[c]Standard deviation (SD).
[d]95% confidence for standard deviation.
[e]Modified robust Brown-Forsythe Levene-type test based on absolute deviations from median for comparing precision (SD).

Table 2. Accuracy and precision of freehand and robotic preparations for each tooth surface

			Accuracy			Precision		
Location	Method	N	Mean	95% CI[a]	P[b]	SD[c]	95% CI[d]	P[e]
Chamfer	Hand	10	0.125	0.097, 0.157	.038	0.155	0.131, 0.189	.034
	Robot	10	0.087	0.069, 0.112		0.123	0.104, 0.150	
Facial	Hand	10	0.076	0.063, 0.104	.19	0.083	0.072, 0.097	.008
	Robot	10	0.092	0.079, 0.104		0.108	0.095, 0.127	
Incisal	Hand	10	0.195	0.148, 0.245	.016	0.205	0.163, 0.275	.34
	Robot	10	0.350	0.266, 0.445		0.173	0.137, 0.232	

[a]Bias-corrected accelerate bootstrap 95% confidence for accuracy (absolute mean difference).
[b]Permutation test, P value for comparing accuracy (absolute mean difference).
[c]Standard deviation (SD).
[d]95% confidence for standard deviation.
[e]Modified robust Brown-Forsythe Levene-type test based on absolute deviations from median for comparing precision (SD).

Based on all sites, the standard deviation for precision was 0.141 mm (95% CI 0.128 to 0.157) in the control group and 0.185 mm (95% CI 0.168 to 0.207) in the experimental group. A modified robust Brown-Forsythe Levene-type test indicated the standard deviation in the control group was significantly lower than in the experimental group (P=.030) (Table 1, Fig. 10).

By surface location, the standard deviation in the control group was 0.083 mm (95% CI 0.072 to 0.097) in the facial region, 0.155 mm (95% CI 0.131 to 0.189) at the finish line, and 0.205 mm (95% CI 0.163 to 0.275) in the incisal region. The standard deviation in the experimental group was 0.108 mm (95% CI 0.095 to 0.127) in the facial region, 0.123 mm (95% CI 0.104 to 0.150) at the finish line, and 0.173 mm (95% CI 0.137 to 0.232) in the incisal region. A modified robust Brown-Forsythe Levene-type test indicated the standard deviation in the control group was significantly lower than that of the experimental group in the facial region (P=.008), and significantly higher at the finish line (P=.034) (Table 2, Fig. 10).

DISCUSSION

This study assessed how accurately and precisely an automated robotic tooth preparation system can perform tooth

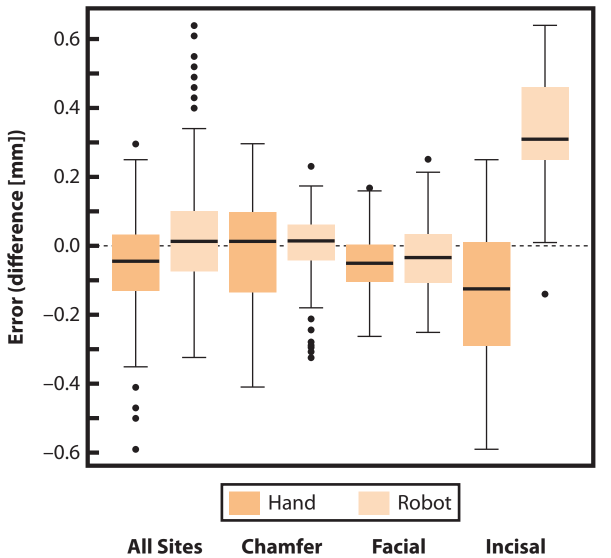

Figure 10. Boxplots of accuracy and precision of freehand and robotic tooth preparations for all sites and for each tooth surface.

preparation for PLVs. The null hypothesis of this study was that no difference would be found in the accuracy and precision of the tooth preparation between the 2 groups. This hypothesis was partially rejected because of the statistically significant difference in accuracy at the finish line and in the incisal region and in precision in the facial region and at the finish-line. Integrated data from all the sites showed that robotic tooth preparation system had a similar level of accuracy but less precision than conventional freehand tooth preparation. In the context of accuracy, a significantly lower level of accuracy in the incisal region was shown. When the robotic system prepared the incisal edge, it tended to generate more pressure on the tooth model, and that pressure may have moved the tooth model, resulting in less accuracy. This may also happen in the clinical setting because of the periodontal ligament, especially when teeth exhibit increased mobility. However, the result of the robotic tooth preparation system showed a significantly higher level of both accuracy and precision at the finish line. The preparation of the finish line is most challenging and critical for the long-term clinical success of PLVs because of the limited amount of enamel in the cervical area[8,11,12] and the risk of traumatizing gingival tissue. These results suggest that the application of robotic technology for tooth preparation for PLVs is beneficial. The rotational speed of the diamond rotary cutting instrument and the speed of the robotic arm movement may need to be constantly modified with the location of the instrument on the tooth so as not to create excessive pressure.

The robotic preparation system showed less precision; however, this may be a result of the innate position repeatability of the robotic arm. The position repeatability of the robotic arm used in this study was ±0.07 mm according to the manufacturer's data sheet. This error may be the reason for less accuracy than with conventional freehand tooth preparation. Therefore, results in the future may be improved by using a robot with better position repeatability.

A preoperative intraoral composite resin arrangement may be beneficial in additive situations. In subtractive situations, however, a diagnostic waxing may be scanned with digital dental impression systems,[27,28] because in such a situation performing an intraoral arrangement without reducing tooth structure is challenging. Subsequently, a robotic arm may prepare the tooth automatically according to the confirmed virtual preparation design. Thus, a robotic tooth preparation system may facilitate the preservation of tooth structure with high accuracy and precision even for subtractive situations. Concurrently, adequate space for the restorative material may be secured to enhance the dental technician's ability to fabricate conservative and esthetic definitive PLVs. Consequently, a predictable adhesion of the restoration to the enamel, through the composite-resin cement, will lead to long-term clinical success and to satisfactory esthetic and functional clinical outcomes.

Another benefit of using a robotic tooth preparation system is the prospect of the preoperative fabrication of a definitive or interim restoration. Because tooth reduction is designed on a 3D image, the 3D data of the tooth reduction part can be sent to the manufacturing machine, and definitive or interim restorations can easily be manufactured and delivered immediately after the tooth preparation. Digital dentistry with a robotic tooth preparation system may save time in terms of the number of visits to the dental practice and may also facilitate gingival health with well-fitting interim PLVs. Therefore, such a novel automated robotic tooth preparation system may be beneficial, especially for a highly technique-sensitive tooth preparation, for PLVs, with multiple restorative options, and may serve as the last piece of the puzzle in completing the digital dentistry circle.

One limitation of this study is that the calibration of the robotic arm was performed by a clinician touching the three 0.45-mm-deep indentations on the tooth model freehand with a 0.9-mm-round diamond rotary cutting instrument. When the robotic arm touches those indentations, it calibrates the position of the tooth model on the premise that the depth of the indentation is exactly 0.45 mm. However, making an indentation exactly 0.45 mm deep freehand is challenging, and any calibration error would affect the accuracy and precision of the robotic tooth preparation to some extent. Moreover, if the jaw model moves after the facial tooth preparation of the incisal and middle third with 3 indentations, there would be no reference points for calibration and recalibration would be impossible. To calibrate the robotic arm more accurately, attaching machine-made calibration instruments to the jaw arch instead of making indentations on the tooth surface would be beneficial.

In addition, in this study, only 1 operator prepared the tooth for the conventional freehand tooth preparation (control group). Since tooth preparation for PLVs is highly technique sensitive, results may differ if multiple clinicians with different skill levels perform this procedure. Another limitation is that the tooth model used for this study was fabricated from composite-resin and epoxy-resin. The hardness of these tooth models is different from that of natural dentition, which may also affect the study results. In addition, the tooth model was inserted into a typodont and stabilized with screw, which is different from natural dentition in terms of tooth mobility. For those reasons, different rotation speeds of the handpiece and the speed of the robotic arm movement need to be assessed for the preparation of the natural dentition. The time required to prepare a natural tooth may differ from the time required for the tooth model.

Further developments in the use of robotic technology for tooth preparation should consider including the ability to follow the patient's movement by applying a tracking system or attaching the device to the dental arch in a way similar to a surgical template; this would reduce the likelihood of any adverse incidents caused by a patient's movement or jaw closure. The evaluation of the accuracy of prefabricated CAD/CAM restorations may also be useful for further assessing the clinical application of dental robotic systems in dentistry. Moreover, measuring enamel thickness preoperatively may make it possible to design the tooth preparation considering the enamel thickness for each patient, facilitating a predictable clinical outcome.

CONCLUSIONS

Within the limitation of this study, the following conclusions may be drawn:

1. In terms of accuracy, for the integrated data from all the sites, automated robotic tooth preparation system prepared the tooth model as accurately as the conventional freehand tooth preparation. For each independent tooth surface, the system showed significantly better accuracy at the finish line, and conventional freehand tooth preparation showed significantly better accuracy in terms of incisal reduction.
2. In terms of precision, for the integrated data from all the sites, conventional freehand tooth preparation was able to prepare tooth models with significantly better precision. For each independent tooth surface, the robotic tooth preparation system showed significantly better precision at the finish line, and conventional freehand tooth preparation showed significantly better precision in the facial region.

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