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A pilot study to assess the feasibility and accuracy of using haptic technology to occlude digital dental models.

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Short title: The use of haptic technology to occlude digital dental models.

Key words: Haptic; digital study models, occlusion

A pilot study to assess the feasibility and accuracy of using haptic technology to occlude digital dental models.

Abstract

Objectives: The use of haptic technology as an adjunct to clinical teaching is well documented in medicine and dentistry. However its application in clinical patient care is less well documented. The aim of this pilot study was determine the feasibility and accuracy of using a haptic device to determine the occlusion of virtual dental models.

Methods: The non-occluded digital models of 20 pre-treatment individuals were chosen from the database of Faculty of Dentistry, The University of Hong Kong. Following minimal training with the haptic device (Geomagic® Touch^{TM}), the upper model was occluded with the lower model until a stable occlusion was achieved. Seven landmarks were placed on each of the corners of the original and haptically aligned upper model bases. The absolute distance between the landmarks was calculated. Intra- and inter-operator errors were assessed.

Results: The absolute distance between the 7 landmarks for each original and corresponding haptically aligned model was 0.54 ± 0.40mm in the x-direction (lateral), 0.73 ± 0.63mm in the y-direction (anterior-posterior) and 0.55 ± 0.48mm in the z-direction (inferior-superior).

Conclusion: Based on initial collision detection to prevent interpenetration of the upper and lower digital model surfaces, and contact form resistance during contact, it is possible to use a haptic device to occlude digital study models.

Clinical Significance

The use of 3D digital study models is routine, problems arise, such as the lack of "touch" in a virtual environment. Occluding study models require the sense of touch. For the first time, using haptic technology, it is possible to occlude digital study models in a virtual environment.

Introduction

Conventional plaster study models have been used in dentistry for centuries. Over the last decade there has been a drive to replace them with digital study models to overcome common problems; including storage space issues, loss, damage or degradation of the plaster models over time.[1]

The common methods of obtaining digital study models include surface scanning the plaster model or impression[2,3], direct intra-oral scanning[4,5] and volumetric scanning of plaster models or impression[6] with the ability to produce surface images at a later stage if necessary. Digital dental models have been used for crown and bridge fabrication[7], orthodontic treatment planning and appliance fabrication[8], implant planning and stent production[9], partial denture frame work manufacture[10], orthognathic surgery planning and final wafer fabrication.[11] The majority of these procedures can be performed on models of a single arch. For orthodontic aligners or pre-fabricated custom orthodontic appliances the entire upper and lower arches are imaged out of occlusion to capture all the occlusal detail and then in occlusion to obtain the correct inter-occlusal relationship. The individual teeth are segmented and moved into the desired position without being able to assess the subsequent inter-occlusal consequences. During crown and bridge fabrication often only a localised region of the arch constituting the preparation and adjacent teeth is imaged, together with the corresponding region of the opposing arch. This enables the CAD/CAM crown to be designed with the correct static inter-occlusal relationship. At present it is not possible to "feel" the final occlusion following any "virtual laboratory work" fabricated on the virtual dental models.

A possible solution is to use “haptic” technology. Haptic technology or haptics, is tactile feedback technology which recreates the sense of touch by applying forces, vibrations, or motions to the user through a haptic device. Haptics has been used in dentistry for training including cavity preparation[12], implant placement[13] and surgical simulators.[14] The outcome of its use has mainly been assessed from an educational perspective as an adjunct or alterative to actual “live” clinical exposure.[15,16] Currently physical dental models are used routinely in dentistry, by using 3D imaging the visual topological characteristics are maintained but the physical characteristics are lost. These can be re-established by printing the model and going full circle or using haptic technology and remaining in the virtual environment.

One of the simplest and commonest tasks is to occlude physical study models. Now that 3D digital models are nearly routine practice, is the same possible? Therefore, the aim of this paper is to determine the feasibility and accuracy of using a haptic device to determine the occlusion of dental models and discuss possible future uses. The null hypothesis tested was that there were no statistical significance differences between the 3D location of the landmarks in the x (medio-lateral), y (anterior-posterior) and z (inferior-superior) directions, on the original model, and on the haptically aligned upper models.

Materials and Methods

Approval was granted by the Institutional Review Board (IRB) of The University of Hong Kong and Hospital Authority Hong Kong West Cluster (UW11-385) to access this retrospective data, which formed part of a larger cohort study. The orthodontic plaster models were selected from the Faculty of Dentistry, The University of Hong

Kong. Only pre-treatment plaster models which could be hand articulated into a single position without any instability e.g. no anterior open bite were included. The correct occlusion had been determined by the inter-occlusal registration or bite that was taken during the clinical examination and recording taking session. In total 20 sets of plaster models were selected and the patient hospital numbers recorded. The patient identifier was used to download the corresponding digital models and all images were anonymous and de-identified prior to use.

The digital models had been commercially produced by laser scanning the plaster models using the following process (Modern Dental Laboratory, Cheung Sha Wan, Kowloon, Hong Kong). All dento-alveloar surfaces of the individual upper and lower models were individually scanned together with the full buccal surfaces of the teeth with the models in occlusion (3Shape, Copenhagen, Denmark). The bases of the plaster models had been previous trimmed according to the bite taken at the clinical appointment; this ensured the correct occlusal relationship during scanning. Following scanning the upper and lower models were automatically aligned to the image of the buccal teeth in occlusion (OrthoCAD®, Cadent, Carlstadt, NJ). New “orthodontically trimmed digital bases” were added to the models. Following scanning, the occlusal contacts of the upper and lower model was assessed using a colour error as well as being visually compared to the original plaster model. The final models were saved as STL files and stored.

Each set of digital study models was imported into VRMesh (VirtualGrid Company, Seattle City, U.S.A.) and decimated by 50% to reduce the number of triangles and enable faster processing (Fig. 1A). The original base of the upper model was removed leaving only the teeth and alveolar regions. The lower model was not altered and remained in the same 3D space. The upper model was moved away from the lower model, its orientation changed, (Fig. 1B) and then re-saved in its new position in 3D space.

A prototype system was implemented on a desktop PC with an Intel® CoreTM i7-3930K CPU and an NVIDIA GeForce GTX 680 display card (Santa Clara, California) connecting the Geomagic® Touch^{TM} (3D Systems, Rock Hill, South Carolina) haptic device (formerly Sensable Phantom Omni). The Geomagic® Touch^{TM} provided 6 degrees of freedom (DOF) input and 3DOF force feedback output (Fig. 2). The graphics rendering, and haptic rendering components worked in parallel. The upper dental model was manipulated through the stylus of the haptic device. As haptic interaction is not routine in clinical practice, the operator (BSK) underwent a training session based on fitting 3D shapes into each other using the haptic device. This was followed by haptically aligning 7 training sets of digital models not included in the main study. During the training, once the upper study model was manipulated into the correct position, it turned green. This provided the operator with immediate confirmation of the model position; this function was disabled during the main study.

For each set of models, the lower digital model was imported into the prototype system together with the upper model. Using the haptic device the upper model was placed onto the lower model and moved until the operator had a stable occlusion. This was tested by gently moving the haptic device in all three planes of space and feeling resistance i.e. the force feedback indicated the models were “locked” into occlusion. The upper model was then saved in its new 3D space as an STL file.

For each set of digital models, the haptically aligned upper model (teeth and alveolus only), full lower model and the corresponding original upper model were imported into VRMesh. The original upper model was then aligned to the haptically aligned upper model, which remained static. These two models are the same model but the haptically aligned model has no base; the haptically aligned upper model was deleted leaving the original model with base in its new position, this will still be referred to as the haptically aligned model. This model was then saved in STL format (Fig. 3).

Operator error

Intra-operator

To determine the intra-operator error 8 sets of models were chosen at random from the original set of 20 models and re-occluded using the 3 DoF haptic system, and re-analysed. The internal consistency of the data for the x, y and z co-ordinates was tested individually using Cronbach's alpha and the intraclass correlation coefficient (ICC) was used to assess the reproducibility of the method.

Inter-operator

To determine the inter-operator error, 7 additional sets of models were chosen at random and occluded using the 3 DoF haptic system, by a clinician and a non-clinician (student in Computing Science), and analysed. A paired Student *t*-test was used to compare the differences in mean absolute distances of the seven landmarks between the original model and haptically aligned model for the clinician and the non-clinician ($p<0.05$).

Analysis

For each individual, the original upper and lower digital study models were imported in DiView (Dimensional Imaging, Hillington, Glasgow) and 7 landmarks were placed on each of the corners of the upper model base (Fig. 4). The x, y and z co-ordinates of these landmarks were saved. The same individuals haptically aligned upper model, and unaltered lower model, were also imported into DiView. Since they occupied the same 3D space and the lower model had not moved, both lower models were exactly aligned. The same 7 landmarks were placed on each of the corners of the haptically aligned upper model and the x, y and z co-ordinates saved. If the haptically aligned model was in the correct place, both upper models would be perfectly superimposed; any discrepancy in the landmark co-ordinates would provide a measure of the error represented by the upper model displacement. Using a paired t-test, the null hypothesis tested was that there were no statistical significance differences between the 3D location of the landmarks in the x (medio-lateral), y (anterior-posterior) and z (inferior-superior) directions, on the original model, and on the haptically aligned upper models (SPSS, Chicago, IL; version 20.0).

Results

Operator error

Intra-operator

The Cronbach's alpha value for the repeated measurements for the x, y and z co-ordinates were 1.0, 1.0 and 0.8 respectively, and the ICC was 1.0, 0.9 and 0.7 for the x, y and z co-ordinates respectively. An ICC of 0.7 or above is considered to be acceptable.

The difference in the absolute distance between the x, y and z co-ordinates of each of the 7 landmarks for each pair of haptically aligned upper models was calculated. This was repeated for 8 models (56 measurements), producing a mean absolute distance (± SD) in the x, y and z co-ordinates for each landmark, Table 1. The magnitude of error (overall mean absolute distance ± SD) in model occlusion was 0.56 ± 0.54mm in the x-direction, 1.04 ± 1.09mm in the y-direction and 0.35 ± 0.24 mm in the z-direction.

Inter-operator

Using a two sample t-test should there was no statistical significant difference in the mean absolute distances of the seven landmarks between the original model, and the haptically aligned model, for the clinician and the non-clinician (p=0.878). The overall magnitude of mean absolute distances for the repeated 49 measurement was 0.50mm (±0.73mm). This was 0.68 ± 0.47mm in the x-direction, 0.67 ± 0.60mm in the y-direction and 0.85 ± 0.39 mm in the z-direction.

Main study

For each original and haptically aligned upper model, the absolute distance between each landmark in the x, y and z direction was calculated. This was repeated for all 20 models and generated 140 measurements. From this the mean absolute distance between the landmarks in the x, y and z direction for each landmark was calculated. The overall mean absolute distance between for all the landmarks in each in the x, y and z direction was also calculated, Tables 2-4.

The overall mean difference in landmark position between the original and haptically aligned models in the x, y and z-direction were -0.05 ± 0.67mm, 0.16 ± 0.95mm and 0.22 ± 0.70mm respectively. This was statistically significant in the y-direction ($p=0.007$) and z ($p=0.001$) only. The magnitude of error (overall mean absolute distance ± SD) in model occlusion was 0.54 ± 0.40mm in the x-direction, 0.73 ± 0.63mm in the y-direction and 0.55 ± 0.48mm in the z-direction

Discussion

This study set out to determine the feasibility of using a haptic device to occlude digital study models in an attempt to replicate the routine use of physical plaster models. Pre-treatment orthodontic models were chosen as they provided maximum occlusal stability and an ideal starting point to asses this technology. It was felt that the results of this study would provide a level of accuracy which would determine possible applications for haptic devices and possible areas of improvement.

Haptic feedback provides the interface between the physical and digital environment. Even though digital technology is excellent for capture and visualisation of three dimensional (3D) objects, it cannot replicate the physical properties of an object. From a hands-on clinical perspective, operative dentistry and surgery rely on a combination of depth perception, proprioception and tactile senses; any move towards a digital environment should replicate these sensations. This is demonstrated in virtual haptic cavity preparation, where there is a change in physical properties i.e. sound enamel and carious tooth substance.[17] The software is programmed to alter the resistance of the haptic device to reproduce these different physical properties encountered during cavity preparation.

Occluding virtual study models is not dependant on varying changes in physical properties, but relies on “collision detection”. Virtual models are based on 3D point cloud data, and as such two separate images can pass through each other without any resistance; collision detection will detect the intersection, or contact, of two objects. When the upper and lower digital models are in occlusion the two 3D point clouds or 3D mesh surfaces will not intersect. This is will be felt as a definite stop on the haptic device. Using a distance map (occlusionogram) to show the proximity of the upper and lower occlusal surfaces, none of the pre-treatment model meshes intersected each another.[18]

In the “real world”, clinicians search for the correct or final occlusion by moving the plaster upper and lower dental models relative to one another, generating interactive forces as a result of contact between the models. In our simulation, the lower dental model was static and the upper dental model was moved. The tendency of the motion was defined according to the normal component of the relative velocity of the lower and upper dental models. A GPU-based collision detection method was used to determine the contact triangle pairs between the upper and lower dental models.[19,20] As a consequence of contact, a force along the normal direction was applied to prevent interpenetration between the two models. Two colliding forms, the collision form or the contact form, were distinguished from the module of the normal component of the relative velocity.[21] When the upper and lower models collided (collision form), the normal impulse force at each contact point of the upper dental model was calculated based on Newton’s Impulse Law and Kinematic Impact Law. Once contact was achieved (contact form), the force at each contact point was calculated in the normal direction in order to prevent the interpenetration between the two models during the whole interval of the duration of contact.[22]. The penetration depth along the normal direction was determined by the translational motion and rotational motional of the upper dental model during the duration of contact. The tolerance zone for the interpenetration of the two meshes was set at 2 mm.

This study has shown it is possible to occlude dental models in a virtual environment using a haptic device. The mean absolute distance between landmarks placed at each corner of the original model, and a haptically aligned model, were used as the outcome measure of accuracy. The mean absolute distance was used to give an indication of the true differences between the model positions irrespective of the direction; by using the summative mean any negative values would cancel out positive values and result in underestimation of the error. The position of the teeth were not used directly as an outcome measure as reproducible landmark placement would be difficult compared to the well-defined corners of the model. Also using the model base approximately represents the boundaries of osteotomy segments i.e. maxilla and mandible providing a more clinical relevant “worst case scenario” level of accuracy for potential wider applications.

Placing the models in contact (z direction), can be achieved with a mean absolute distance of 0.55 ± 0.48mm, this represents the collision detection and interpenetration ability of the system. The anterior region of the models (landmark 1) showed the largest mean absolute distance of 0.81 ± 0.54mm with the more posteriorly sited landmarks showing less error; indicating a small error in the pitch. The error associated with medio-lateral upper model position (x direction) was similar with an error of 0.54 ± 0.40mm. There was also an error in the yaw with a rotation in the front of the model (landmark 1) showing an error 0.69 ± 0.40mm. The largest error was seen in the anterior-posterior direction (y direction), with a mean absolute distance of 0.73 ± 0.63mm. Interestingly the inter-operator error, between clinician and non-clinician, was acceptable which would tend to indicate that the technique is not related to experience or exposure to the technology.

An immediate clinical application for haptics may be during virtual planning of surgery-first cases. Over the last five years "surgery-first" orthognathic treatment has become popular as it addresses the patient's facial concerns early and accelerates post-surgical orthodontic tooth movement. [23,24] However the complexity of producing the correct soft tissue appearance first, and then the occlusion post-surgery, precludes the use of conventional 3D computerised planning. In surgery-first cases the ideal 3D planning system would allow virtual repositioning of the composite maxillary model (maxilla and digital teeth) into the desired position; followed by movement of the composite mandibular model (mandible and digital dentition) into the desired position by "feeling" for occlusal interferences and possible instabilities through the haptic device. As this process occurs in real time the clinical can continuously reposition the skeletal structures and experience immediate feedback on the occlusal consequences. At present a time-consuming iterative process of re-adjustment of the physical plaster study models on the articulator followed by re-adjustment of the virtual hard and soft tissue movement is necessary.

During planning, the anterior-posterior and medio-lateral position of the occlusion is predominately determined by the clinician, and partly based on the desired skeletal, soft tissue changes and any premature occlusal contacts. However, the inferior-superior occlusal relationship is based on the contact between the upper and lower teeth. The current haptic system can replicate this with a mean absolute distance of 0.55 ± 0.48mm. This may be clinically acceptable given the errors associated with plaster model fabrication, face bow recording and model surgery[25,26]but requires future investigation especially on the consequences of physical wafer fabrication using CAD/CAM technology. It is also anticipated that as technology advances this will improve i.e. faster GPU's and haptic devices with six degrees of freedom. However in its present state the technology would not be clinically acceptable for crown and bridge fabrication were sub-millimetre levels of accuracy are required.

The device may be further improved by changing the design of the haptic pen, which the clinician holds, as it does not represent the clinical situation. A clinician would really hold the models as a triangle with fingers at the back, front or sides of the models, providing simultaneous feedback from all region of the model. However with a pen shaped haptic device this is not possible and is far from the clinical situation. This may be improved by changing the pen-shape of the haptic device to a study model base or "D" shaped device, which the clinician would hold as if it were a study model.

This research has shown it is possible to place upper and lower digital study models in contact with minimal penetration using "collision detection" and then move them into the desired position. If this technology is integrated into commercial software, which already allows 3D orthognathic planning and orthodontic virtual set-ups, it may be possible to reduce technical laboratory time, but this requires further investigation.

Conclusions

Based on initial collision detection to prevent interpenetration of the upper and lower digital model surfaces and contact form resistance during model contact it is possible to use a haptic device to occlude digital study models. The accuracy with which this can be performed is 0.54 ± 0.40mm medio-laterally, 0.73 ± 0.63mm anterior-posteriorly and 0.55 ± 0.48mm inferior-superiorly. Whether or not this level of accuracy is clinically acceptable will depend on the clinical situation and requires further investigation.

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Tables

Table 1 Intra-operator error, the difference in the mean absolute distance and SD between the x, y and z co-ordinates of each of the 7 landmarks for each haptically aligned upper model.

Table 2 Descriptive statistics showing the difference between each of the 7 landmarks for the 20 original and haptically aligned upper models in the medio-lateral position (x-direction).

*indicates statistically significant result (p<0.05).

Table 3 Descriptive statistics showing the difference between each of the 7 landmarks for the 20 original and haptically aligned upper models in the anterior-posterior position (y-direction).

*indicates statistically significant result (p<0.05).

Table 4 Descriptive statistics showing the difference between each of the 7 landmarks for the 20 original and haptically aligned upper models in the inferior-superior position (z-direction).

*indicates statistically significant result (p<0.05).

Figures

Fig. 1 (A). Final original digital models in occlusion.

(B). Upper and lower digital models with virtual bases removed leaving only the teeth and alveolar regions. Removing the bases ensured there were no visible indications for the upper model position.

Fig. 2 Haptic prototype system in use during training session.

(A). Pen shaped haptic device (Geomagic® Touch^{TM}haptic device, formerly Sensable Phantom Omni).

Fig. 3 (A). Front view of original digital models in occlusion (grey) and same upper model following haptic alignment (red) with replacement of original virtual base.

(B). View from above showing original model (grey) and haptically aligned (red) model bases do not exactly align.

(C). Occlusal view of upper model showing original model (grey) and haptically aligned (red) model do not exactly align.

Fig. 4 Location of the landmarks placed on each of the corners of the upper model base.

Table 1 Intra-operator error, the difference in the mean absolute distance and SD between the x, y and z co-ordinates of each of the 7 landmarks for each haptically aligned upper model.

	Direction					
	x		y		z	
	Mean absolute distance (mm)	SD (mm)	Mean absolute distance (mm)	SD (mm)	Mean absolute distance (mm)	SD (mm)
Landmark						
1	0.57	0.48	0.70	0.87	0.41	0.33
2	0.34	0.39	0.98	1.14	0.33	0.23
3	0.50	0.46	1.17	1.33	0.12	0.11
4	0.73	0.70	1.10	1.23	0.24	0.17
5	0.70	0.70	0.92	1.05	0.53	0.20
6	0.49	0.48	0.96	1.10	0.44	0.20
7	0.32	0.39	0.82	0.92	0.37	0.11
Overall	**0.56**	**0.54**	**1.04**	**1.09**	**0.35**	**0.24**

Table 2 Descriptive statistics showing the difference between each of the 7 landmarks for the 20 original and haptically aligned upper models in the medio-lateral position (x-direction).

	Measurement (x-direction)					Absolute distance	
Landmark	Mean difference (mm)	SD (mm)	95% CI for the mean difference		p-value	Mean (mm)	SD (mm)
1	0.42	0.69	0.10	0.75	0.012*	0.69	0.40
2	-0.09	0.61	-0.09	0.47	0.182	0.50	0.38
3	-0.20	0.55	-0.45	-0.05	0.112	0.48	0.33
4	-0.44	0.59	-0.72	-0.16	0.004*	0.56	0.48
5	-0.39	0.63	-0.68	-0.10	0.013*	0.54	0.50
6	-0.21	0.54	-0.47	0.05	0.105	0.48	0.33
7	0.27	0.58	-0.01	0.54	0.055	0.52	0.37
Overall	**-0.05**	**0.67**	**-0.16**	**0.06**	**0.363**	**0.54**	**0.40**

*indicates statistically significant result (p<0.05).

Table 3 Descriptive statistics showing the difference between each of the 7 landmarks for the 20 original and haptically aligned upper models in the anterior-posterior position (y-direction).

	Measurement (y-direction)					Absolute distance	
Landmark	Mean difference (mm)	SD (mm)	95% CI for the mean difference		p-value	Mean (mm)	SD (mm)
1	0.13	0.72	-0.20	0.47	0.419	0.58	0.43
2	-0.24	0.86	-0.65	0.16	0.277	0.66	0.59
3	-0.46	0.91	-0.89	-0.03	0.039*	0.76	0.67
4	-0.36	0.89	0.78	0.05	0.083	0.72	0.61
5	0.69	0.83	0.30	1.08	0.001*	0.80	0.72
6	0.77	0.87	0.36	1.18	0.001*	0.88	0.75
7	0.56	0.79	0.19	0.93	0.005*	0.73	0.62
Overall	**0.16**	**0.95**	**-0.01**	**0.32**	**0.056**	**0.73**	**0.63**

*indicates statistically significant result ($p<0.05$).

Table 4 Descriptive statistics showing the difference between each of the 7 landmarks for the 20 original and haptically aligned upper models in the inferior-superior position (z-direction).

	Measurement (z-direction)					Absolute distance	
Landmark	Mean difference (mm)	SD (mm)	95% CI for the mean difference		p-value	Mean (mm)	SD (mm)
1	0.80	0.56	0.54	1.06	0.001*	0.81	0.54
2	0.55	0.57	0.28	0.82	0.001*	0.61	0.50
3	0.10	0.56	-0.16	0.36	0.431	0.40	0.39
4	-0.15	0.53	-0.39	0.10	0.238	0.40	0.37
5	-0.22	0.73	-0.56	0.12	0.184	0.58	0.48
6	0.01	0.70	-0.33	0.32	0.975	0.51	0.46
7	0.05	0.54	0.25	0.75	0.001*	0.51	0.52
Overall	**0.22**	**0.70**	**0.11**	**0.34**	**0.001***	**0.55**	**0.48**

*indicates statistically significant result (p<0.05).

Figure 1

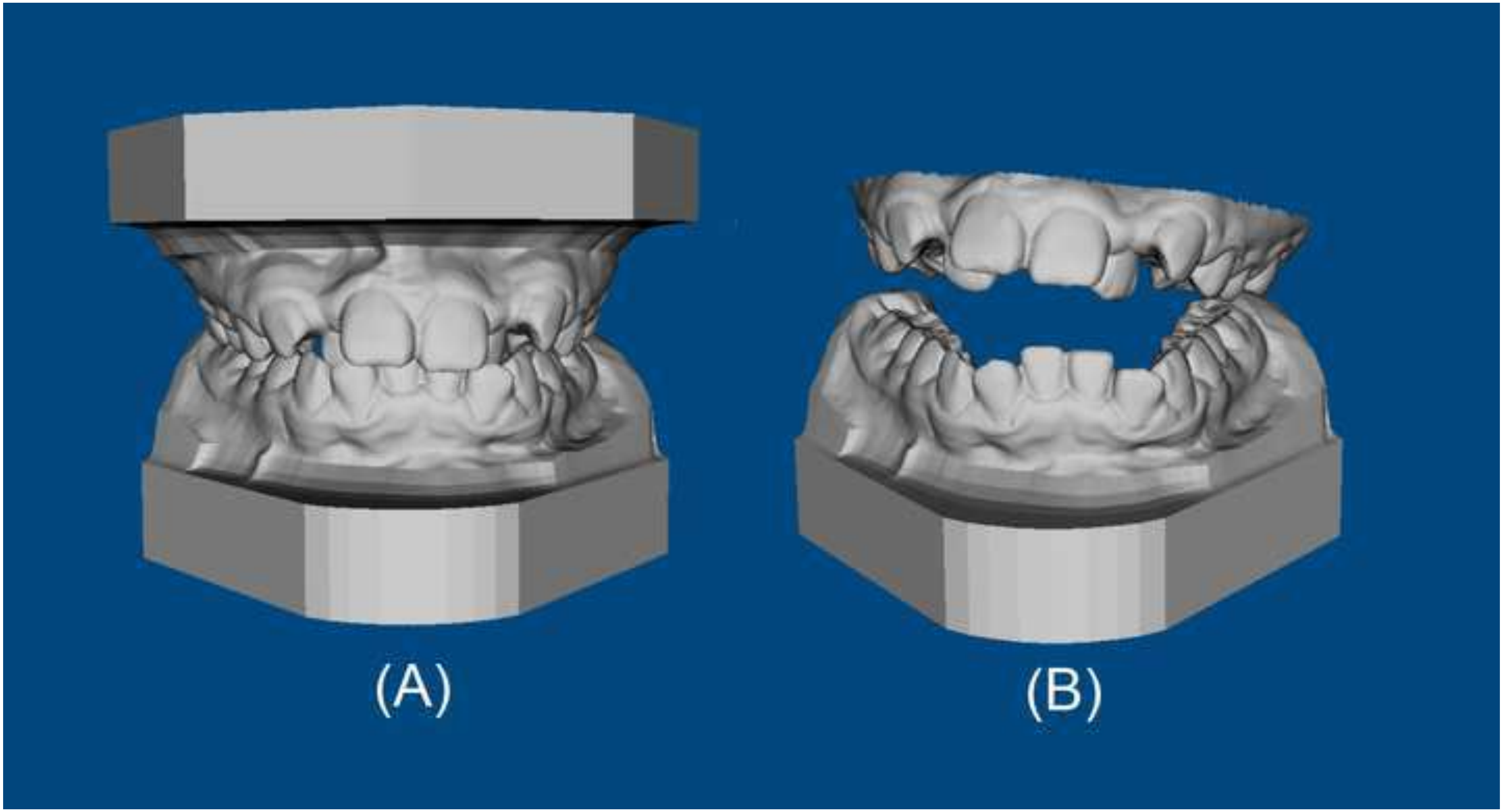


Figure 2

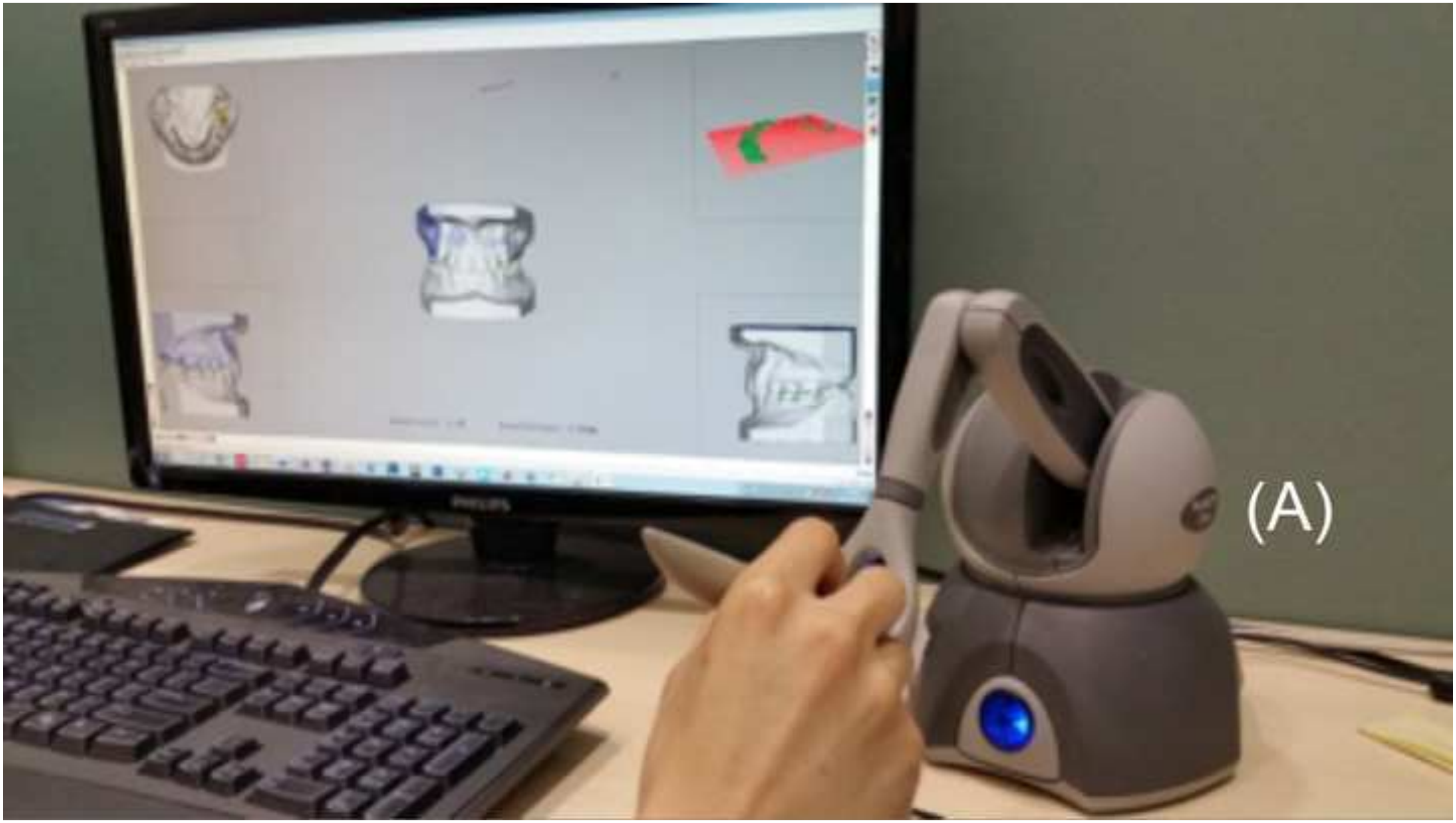


Figure 3

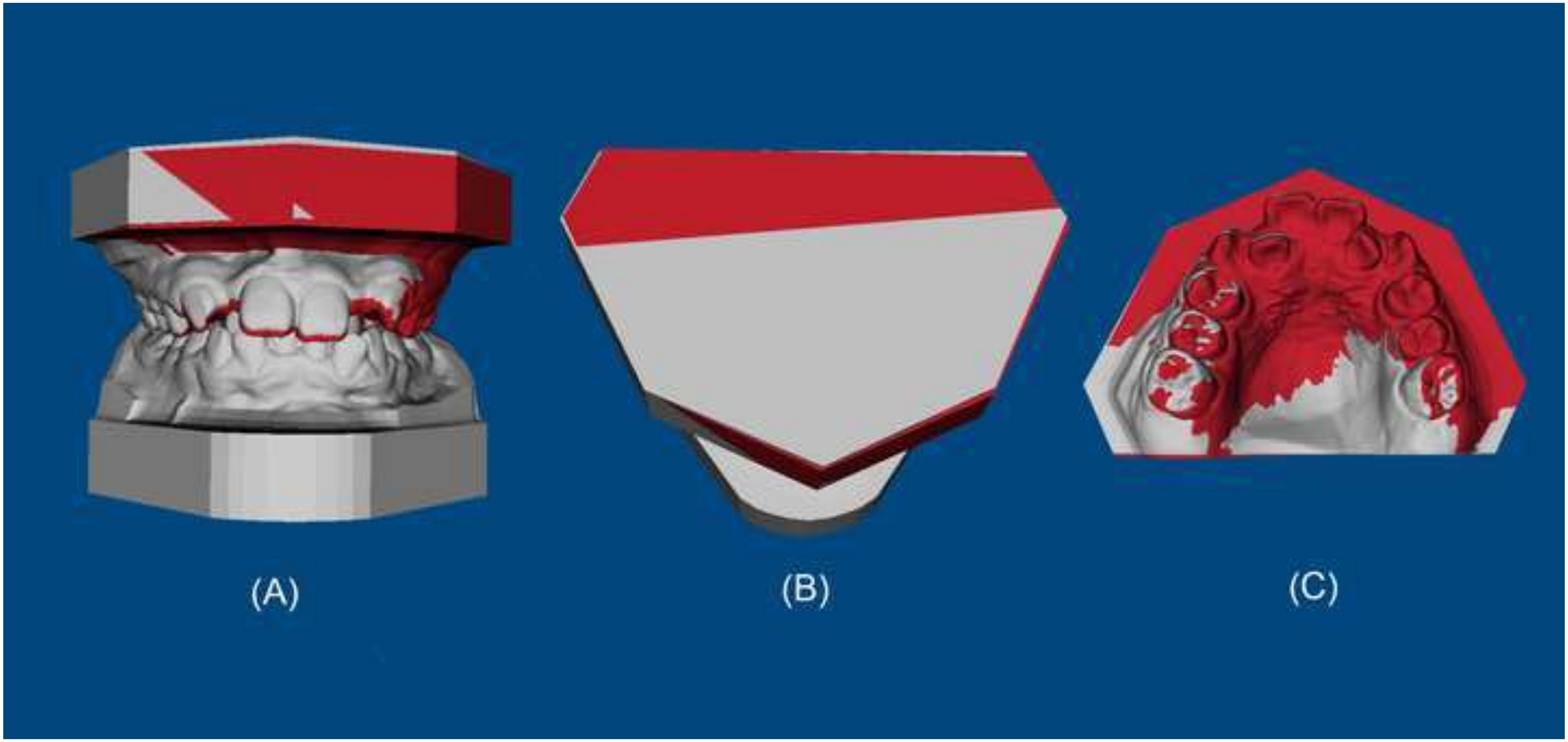
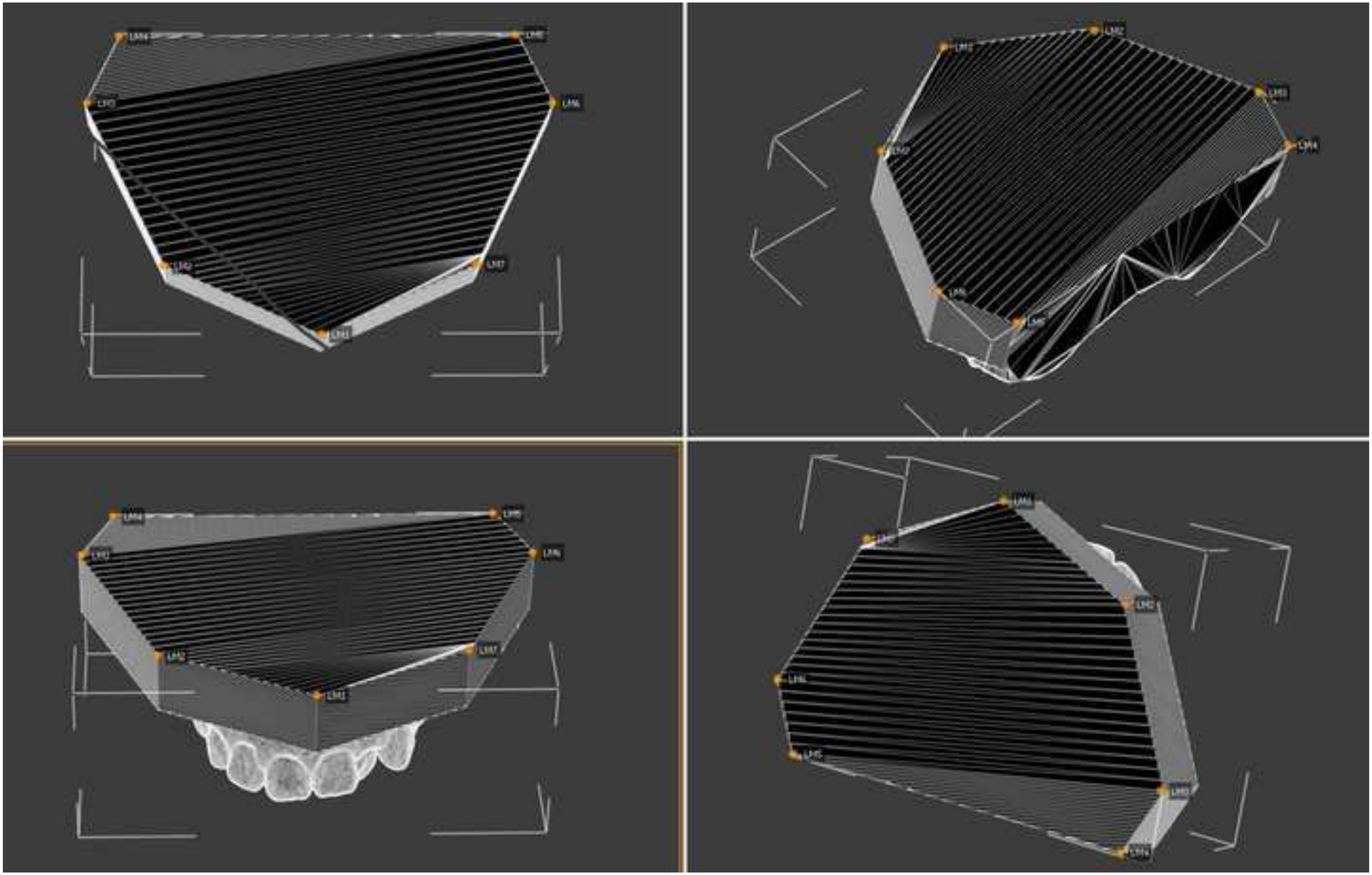


Figure 4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