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Research Paper
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Reproducibility and reliability of digital occlusal planning for orthognathic surgery

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Abstract. The digital articulation of dental models is gradually replacing the conventional physical approach for occlusal prediction planning. This study was performed to compare the accuracy and reproducibility of free-hand articulation of two groups of digital and physical dental models, 12 Class I (group 1) and 12 Class III (group 2). The models were scanned using an intraoral scanner. The physical and digital models were independently articulated 2 weeks apart by three orthodontists to achieve the maximum inter-digitation, with coincident midlines and a positive overjet and overbite. The occlusal contacts provided by the software color-coded maps were assessed and the differences in the pitch, roll, and yaw were measured. The reproducibility of the achieved occlusion of both the physical and digital articulation was excellent. The z-axis displayed the smallest absolute mean differences of 0.10 ± 0.08 mm and 0.27 ± 0.24 mm in the repeated physical and repeated digital articulations, respectively, both in group 2. The largest discrepancies between the two methods of articulation were in the y-axis (0.76 ± 0.60 mm, $P = 0.010$) and in roll ($1.83° \pm 1.72°$, $P = 0.005$). The overall measured differences were < 0.8 mm and $< 2°$. Despite the steep learning curve, digital occlusal planning is accurate enough for clinical applications.

Keywords: Dental occlusion; Dental models; Computer-aided design; Orthognathic surgery; Orthodontics.

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Conventionally, orthognathic occlusal planning is performed by physically articulating the study models until a well inter-digitated occlusion is achieved.[1] This is undertaken in conjunction with the analysis of the face and jaw bones for surgical planning.

Computer-assisted planning now allows digital planning of orthognathic surgery, including assessment of the quality of the final occlusion and printing of the guiding occlusal wafers.[2,3] This can be achieved through the replacement of the defective images of the dentition produced by the cone beam computed tomography (CBCT) scan with accurate digital images of the study models, captured using CBCT or laser scanning.[4–10]

Digital planning of the postoperative occlusion using virtual models with current software packages lacks the haptic feedback that is present with

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physical models, and this could potentially affect the accuracy of digital articulation. A number of studies have attempted to evaluate the difference between physical and digital articulation. Baan et al.[11] assessed 17 cases using IPS Case Designer (v. 2.0.4.2; KLS Martin, Tuttlingen, Germany), which provides a tool to allow the user to achieve a virtual occlusion. They reported 0.20 mm difference between the conventional and virtual occlusion groups, which was larger than the intra-observer variability of the gold standard (physical occlusion).

Nadjmi et al.[1] developed a visual occlusal planning tool that produces a change in the color of the three-dimensional (3D) model upon collision. Using this, they reported a difference of 0.60 mm between the conventional and virtual occlusion groups. Ho et al.[2] demonstrated the application of color-coded distance maps for the detection of occlusal penetration, or overlap, to guide the clinician to adjust the occlusion and maximize occlusal contact, using Dolphin Imaging software (Dolphin Imaging and Management Solutions, Chatsworth, CA., USA). However, the pre-determined overjet and overbite used in their study did not allow the assessment of the operator's ability to freely select the most appropriate occlusion according to the required surgical correction, which is case-specific and should be guided by clinical judgment rather than pre-determined criteria.

Wu et al.[12] proposed a physically based haptic simulation method to manually articulate digital models. Their method was based on the dynamic and collision properties of the dental models during alignment, although its broad clinical application has not been tested. A software tool and workflow were developed by Liu et al.[13] to achieve a virtual occlusal definition. The accuracy of digital articulation was limited to the Euclidean distances between 37 corresponding points, marked on the maxillary and mandibular dental models. However, this did not take into consideration the digital planning errors in the pitch, roll, and yaw, where the correction of an occlusal cant, or posterior maxillary impaction, was required.

The studies conducted to date have all attempted to apply pre-determined criteria to the process of digital articulation, but there is a lack of studies comparing the ability of clinicians to articulate digital dental models using free-hand manipulation of the images on the computer screen with free-hand articulation of physical models. The aim of this study was therefore to compare the accuracy and reproducibility of free-hand articulation of two groups of digital and physical dental models.

Materials and methods

Ethical approval was obtained from the local National Health Service Clinical Governance Committee, Greater Glasgow & Clyde Health Board (03/02/21). Based on the sample size calculation, a total of 24 sets of upper and lower dental study models were required to detect a mean difference of 0.21 mm (standard deviation 0.18 mm), with a power of 0.8 and a level of significance of 0.05.[14] The 24 cases selected for the study were divided into two equal groups. Group 1 consisted of post-treatment study models with well-aligned dental arches and well inter-digitated Class I occlusions. Group 2 consisted of pre-treatment study models from patients with Class III malocclusions, who would require orthognathic surgery for occlusal correction.

Cases were excluded if they had any of the following: one or more missing central incisors, canines, and/or first molars; retained primary teeth; large non-anatomic restorations on the first molars; moderate to severe attrition; posterior bite-raising resin placed on the occlusal surfaces of teeth; or if they required a segmental osteotomy.

Determining the threshold of occlusal contacts for digital articulation

Ten randomly selected sets of study models, with varied malocclusions, were articulated and retained in occlusion by placing melted utility wax across the lingual surfaces of the upper and lower posterior teeth. The models were then scanned using an intraoral scanner (Trios; 3Shape, Copenhagen, Denmark) and imported in stereolithography (STL) format into VRMesh version 11.2 software (VirtualGrid, Bellevue, WA, USA) for the manipulation of the 3D images. This software is readily available, is not linked to any commercial orthognathic prediction planning package, and allows the free manipulation of digital models. The occlusal contact areas were then clinically evaluated and simultaneously assessed using the color-coded maps supplied by the software.

The contact areas were visualized within the color-coded distance map threshold of −0.05–0.25. This threshold was extended to −0.15–0.5 to allow the detection of occlusal penetration at one end of the scale and occlusal separation at the other end.

Digital articulation of the maxillary models

Three experienced orthodontic clinicians were trained to manipulate the digital models and evaluate the quality of the occlusions in real time using the VRMesh software.

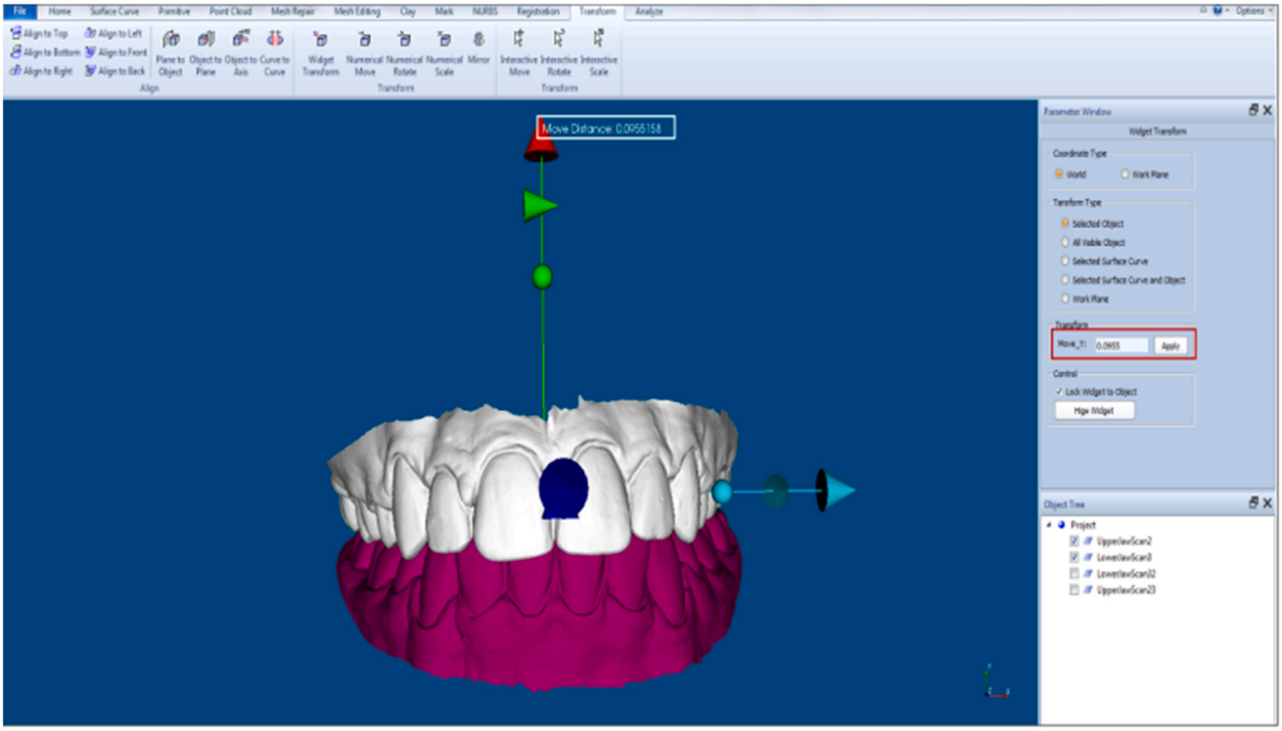
Two exercises were subsequently conducted. The first was aimed at assessing the ability of the clinicians to digitally articulate the sets of post-treatment dental models with well interdigitated Class I occlusions. This was aimed at testing the hypothesis that clinicians are able to articulate digital models with an optimal occlusion as accurately as they are able to articulate the same physical models. The objective was to eliminate as much uncertainty as possible regarding the best occlusion by using models where the occlusion was as clearly defined and unambiguous as possible.

The second exercise was aimed at simulating the process of orthognathic occlusal planning for Class III patients. This is the most common group of patients treated at the authors' clinic. The models were scanned in their Class III pre-treatment occlusions before the clinicians were instructed to digitally articulate them into the position that they considered to achieve the maximum degree of inter-digitation, with coincident midlines and a positive overjet and overbite.

The maxillary models could be manipulated on the computer screen in six degrees of freedom and the standard occlusal color map showed the site and magnitude of separation or penetration of the opposing occlusal surfaces. A time limit of 10 min was set for each set of models (Fig. 1). The procedure was then repeated after 2 weeks.

Physical articulation of the maxillary models

The three examiners were asked to manually articulate the same sets of physical dental models to achieve the



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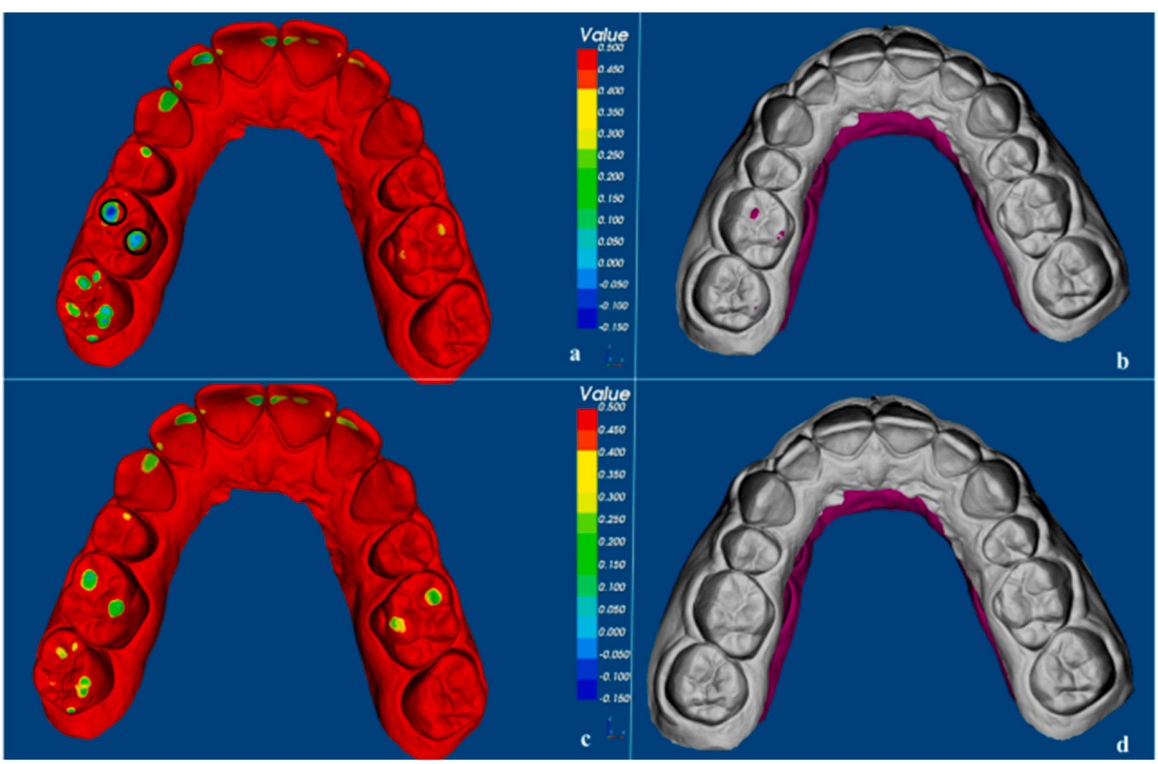

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Fig. 1. (A) Digital articulation using the 'Widget Transform' tool in VRMesh software. The white box was automatically displayed, indicating the magnitude of the free-hand movement undertaken using the arrows. The red box on the right of the display permitted the manual insertion of the required movements. (B) Color-coded distance map with simultaneous view of the occlusal surface of the digitally articulated maxillary model. Occlusal penetrations greater than −0.05 mm were illustrated as dark blue areas on the occlusal surface, as seen here on the right maxillary first molar. Yellow spots indicated a lack of penetration on the occlusal surface of the maxillary models.

Table 1. Differences between the repeated physically articulated cases and between the repeated digitally articulated cases in groups 1 and 2, showing the absolute mean ± standard deviation values in millimeters and degrees.

	Translation (mm)			Rotation (°)		
	x-axis Horizontal	*y*-axis Vertical	*z*-axis Antero-posterior	Roll	Pitch	Yaw
Repeated physical articulation						
Group 1	0.19 ± 0.23	0.22 ± 0.20	0.12 ± 0.11	0.51 ± 0.39	0.33 ± 0.27	0.69 ± 0.66
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Group 2	0.22 ± 0.21	0.29 ± 0.38	0.10 ± 0.08	0.55 ± 0.58	0.24 ± 0.24	0.88 ± 1.11
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Repeated digital articulation						
Group 1	0.47 ± 0.41	0.75 ± 0.79	0.33 ± 0.26	1.06 ± 0.88	0.55 ± 0.37	1.33 ± 1.23
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Group 2	0.50 ± 0.45	0.67 ± 0.76	0.27 ± 0.24	1.08 ± 0.90	0.42 ± 0.32	1.45 ± 1.41
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Group 1, post-treatment study models with well-aligned dental arches and well inter-digitated Class I occlusions; group 2, pre-treatment study models from patients with Class III malocclusions, who would require orthognathic surgery for occlusal correction.

best fit occlusion according to the same guidelines (positive overjet and overbite, coincident dental midlines, and maximum occlusal contact). This process was also repeated after 2 weeks.

Reproducibility and accuracy of physical and digital articulation

Model registration

The physically articulated models were considered the gold standard and were scanned and imported into the VRMesh software. Three points were used to define the x and y axes: the mesiobuccal cusp tip of the right and left mandibular first molars and the mesio-incisal edge of the right mandibular central incisor. The x–y plane was in the plane of the three points, with the x-axis being defined as the line between the mesiobuccal cusp tips of the left and right mandibular first molars. The origin of the y-axis was defined as the mid-point of the x-axis, and the z-axis was then defined as a line perpendicular to the point of intersection of the x and y axes. To measure the differences between the physical and digital models, these models were aligned based on the mandibular models. The mandibular models were registered and the related differences in the position of the maxillary models were measured. The digital mandibular models were rigidly registered to the physical mandibular models using three landmarks initially and the corresponding 3D models were superimposed using the iterative closest point (ICP) algorithm. Three occlusal landmarks were also selected on all maxillary models to determine the achieved movements in six degrees of freedom (x-axis, y-axis, z-axis, pitch, roll, and yaw): the mesiobuccal cusp tip of the right and left maxillary first molars and the mesio-incisal corner of the right maxillary central incisor.

Differences between physical and digital maxillary landmarks

To assess the differences between the landmarks on the physical and digital models in the x, y, and z axes, as well as pitch, roll, and yaw, the following formula was used to calculate the magnitude of translation and rotation across the x-axis, y-axis, and z-axis:

$$\begin{bmatrix} P1phys \\ P2phys \\ P3phys \end{bmatrix} = R \begin{bmatrix} P1dig \\ P2dig \\ P3dig \end{bmatrix} + \begin{bmatrix} tx \\ ty \\ tz \end{bmatrix}.$$

$P1_{phys}$, $P2_{phys}$, and $P3_{phys}$ each represented a maxillary landmark of the physically articulated model with coordinates (x, y, z). Similarly, $P1_{dig}$, $P2_{dig}$, and $P3_{dig}$ represented the coordinates of the designated maxillary landmarks on the digitally articulated model.

The magnitude of rotation ‘R′ in all three planes of space was derived from a 3 × 3 rotational matrix. The magnitude of translation in all three axes was represented by the values t_x, t_y, and t_z. This permitted the assessment of the differences in translation and rotation between the physically and digitally articulated models.

Statistical analysis

The one-sample Student t-test was used to assess the mean differences in repeated physical and digital articulations. The lower tailed t-test was used to evaluate the mean differences in translation and rotational movements between the physically and digitally articulated models less than 0.5 mm and 1°, respectively. The mean overjet and mean number of occlusal contact areas were measured. The intra- and inter-examiner reliability were assessed using the intra-class correlation coefficient (ICC). The statistical analysis was performed using IBM SPSS Statistics version 28.0 (IBM Corp., Armonk, NY, USA) at a level of significance of 0.05.

Results

The mean non-directional landmarking error was 0.11 mm. The mean landmarking errors in the x-axis, y-axis, and z-axis were 0.1 mm, 0.1 mm, and 0.2 mm, respectively. Excellent intra-examiner (ICC = 0.999) and inter-examiner (ICC = 0.999) reliability was found for both groups, digitally and physically articulated.

Regarding translation, the smallest absolute mean differences in the repeated physical and repeated digital articulations were found for the z-axis in group 2: 0.10 ± 0.08 mm and 0.27 ± 0.24 mm, respectively. Similarly, the smallest discrepancy among the rotations was for pitch in group 2, as shown in the repeated physical articulation (0.24° ± 0.24°) and repeated digital articulation (0.42° ± 0.32°) (Table 1).

The largest absolute mean differences in the repeated physical articulation were demonstrated in the y-axis (0.29 ± 0.38 mm) and yaw (0.88° ± 1.11°) in group 2. The greatest absolute mean differences in the repeated digital articulation were found in group 1 in the y-axis (0.75 ± 0.79 mm) and group 2 in yaw (1.45° ± 1.41°) (Table 1).

Table 2. The absolute mean ± standard deviation differences between the digital and physical articulations.

	Translation (mm)			Rotation (°)		
	x-axis Horizontal	*y*-axis Vertical	*z*-axis Antero-posterior	Roll	Pitch	Yaw
Group 1						
Digital vs physical	0.39 ± 0.35	0.76 ± 0.60	0.36 ± 0.27	1.83 ± 1.72	0.51 ± 0.39	1.02 ± 0.87
P-value (< 0.8 mm or < 2°)	0.035	0.010	0.003	0.005	< 0.001	0.461
Group 2						
Digital vs physical	0.40 ± 0.37	0.61 ± 0.56	0.41 ± 0.30	1.22 ± 0.90	0.51 ± 0.42	1.43 ± 1.27
P-value (< 0.8 mm or < 2°)	0.051	0.122	0.045	0.197	< 0.001	0.032

Group 1, post-treatment study models with well-aligned dental arches and well inter-digitated Class I occlusions; group 2, pre-treatment study models from patients with Class III malocclusions, who would require orthognathic surgery for occlusal correction.

In both groups, the main error in the digital articulation, compared with the physical articulation, was across the *y*-axis in the vertical direction (group 1, 0.76 ± 0.60 mm, $P = 0.010$; group 2, 0.61 ± 0.56 mm, $P = 0.122$), but its impact on the pitch of the maxillary plane was limited. Similarly, the errors in the digital articulation of the models in both groups were mainly in the roll (group 1, 1.83° ± 1.72°, $P = 0.005$) and yaw (group 2, 1.43° ± 1.27°, $P = 0.032$) (Table 2).

The measured differences between the digitally and physically articulated maxillary models were less than 0.8 mm in each of the *x*, *y*, and *z* directions and less than 2° in each of the roll, pitch, and yaw.

The number of occlusal contacts for the physically articulated dental models was greater than for the digitally articulated ones, but the contact distribution was similar, as shown in Table 3 and Fig. 2.

The examiners were asked to repeat 14 digital articulations, for which they had exceeded the 10-minute time limit at their first attempt. All the physically articulated cases required only one attempt. The average time taken for physical articulation was 7 s (range 2–18 s) for group 1 and 20 s (range 5–50 s) for group 2. The average time taken for digital articulation was 6 min (range 1–10 min) for group 1 and 8 min (range 3–10 min) for group 2.

Discussion

The findings of this study confirm the reproducibility of the free digital articulation of occlusal surfaces for prediction planning of orthognathic surgery. It was possible to overcome the limitations of the previous studies that necessitated the digitization of several corresponding points of the maxillary and mandibular occlusal surfaces to allow the spring force to guide the articulation.[1,11] The application of corresponding points is subjective and the software automated approach of minimizing the distances between these points may not be required in some clinical scenarios. This particularly applies to posterior maxillary impaction and the deliberate creation of occlusal spaces in cases planned for the surgery-first approach.[3,15] In an attempt to resolve this dilemma, Nadjmi et al.[1] proposed a method using a ‘spring connection’, which requires the user to first move the maxillary dental model to a satisfactory position. This is followed by a built-in force (spring connection) to bring the upper and lower teeth together. The method provides a hybrid mix of manual articulation, which is dependent on the initial position and the accuracy of three occlusal points, digitized by the operator. The method assumes that maximum occlusal contact is required in all cases for orthognathic surgery, but this may not be the case in certain clinical scenarios.

Deng et al.,[3] and subsequently Wong et al.,[15] provided an automated approach for the digital articulation of dental study models, where the mesiobuccal cusp of the upper first molar was seated into the central fossa of the corresponding lower first molar, and the distobuccal cusp of the lower first molar was seated into the central fossa of the corresponding upper first molar, both with maximum contact. Based on a set of linear distances between the corresponding three vertical maxillary lines of the digitally and physically mounted models, they reported a mean error of 0.22 mm in the digital articulation. The impact of the errors in the automated articulation on the roll, pitch, and yaw of the maxillary plane was not investigated. However, the methodology was very complex for routine clinical use, with 24 dental points and six vertical lines having to be identified prior to the automated creation of a 200-point fitting curve. This was followed by a complex mathematical process to extract the occlusal plane.

Despite the convenience of the automatic occlusal articulation, there is still a need for the operator to use intuitive clinical judgment in adjusting the occlusal contacts. This is desirable to allow the correct movements of the bony segments in order to achieve

Table 3. Number of contact areas in the digitally and physically articulated models; mean ± standard deviation values.

	Right posterior sextant	Right anterior sextant	Left anterior sextant	Left posterior sextant
Group 1				
Digital articulation	3.36 ± 1.91	1.67 ± 1.47	1.88 ± 1.32	3.57 ± 1.61
Physical articulation	5.76 ± 2.17	3.10 ± 1.45	2.82 ± 1.32	5.01 ± 2.23
Group 2				
Digital articulation	2.36 ± 1.09	0.71 ± 0.66	0.78 ± 0.70	1.67 ± 0.78
Physical articulation	3.74 ± 1.33	1.10 ± 0.818	1.63 ± 1.30	3.19 ± 1.23

Group 1, post-treatment study models with well-aligned dental arches and well inter-digitated Class I occlusions; group 2, pre-treatment study models from patients with Class III malocclusions, who would require orthognathic surgery for occlusal correction.

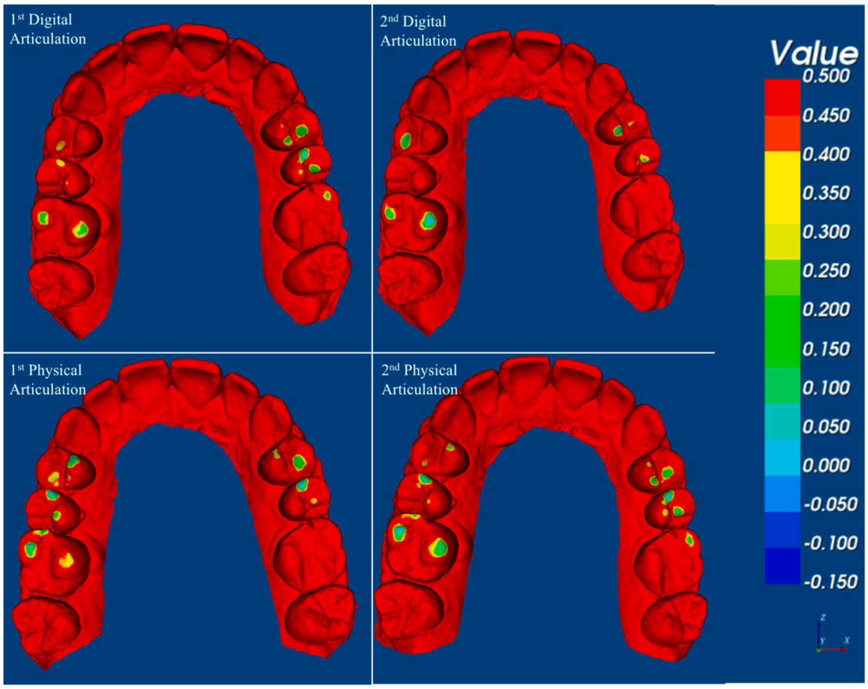

Fig. 2. Digitally and physically articulated study model from group 2, displaying similar contact distribution with less contact on the digital models.

optimal facial harmony, which is the main objective of orthognathic surgery.

The results of this study are comparable to those of Nadjmi et al.[1] and Baan et al.,[11] who reported an average difference of 0.6 mm of the digital articulation when compared to the gold standard physical articulation. In the present study, the highest levels of discrepancy between the digital and physical articulation were in the *y*-axis and the roll of the maxillary plane. The relative increased error of the roll of the maxillary plane with digital articulation can be explained by the fact that the examiners may have had different interpretations of what constituted the ideal occlusion following surgery.

Nevertheless, the overall digital articulation errors did not exceed 0.76 mm in translation and 1.83° in rotation, which are of limited clinical significance. Therefore, it is not unreasonable to confirm that the free-hand digital articulation of the maxillary and mandibular occlusal surfaces is accurate, and the reproducibility of the operators is satisfactory for the clinical applications. According to a systematic review by Alkhayer et al.,[16] an accuracy of less than 2 mm and 2° was considered clinically acceptable for orthognathic surgical planning. Ritto et al.[17] and Tonin et al.[18] regarded 2 mm and 4° as adequate cut-off values. Similarly, Hsu et al.[19] demonstrated surgical planning accuracy with a maximum mandibular root mean square deviation of 1.1 mm and 1.8°. Zhang et al.[20] also assessed orthognathic surgical accuracy and reported satisfactory mean values of 0.81 mm and 0.95°.

A limitation of this study was the lack of collision detection using a rigid motion engine. This was partially compensated for with the color-coded map, which allowed real-time detection of any occlusal penetrations, or lack of contact. The color-coded distance map also permitted assessment of the magnitude and location of the overlap. Another limitation is the lag time between the manipulation of the digital model and the display of the color map that was evident when using the VRMesh software. Clinicians should be aware of the steep learning curve involved when replacing the physical articulation of study models with the digital manipulation of the corresponding 3D images. Nevertheless, in this study, the operators were able to achieve a satisfactory digital occlusion within 10 min, with excellent inter- and intra-examiner reproducibility. Further studies are needed to assess the reproducibility of digital articulation in segmental osteotomies. A prospective randomized controlled trial to assess its reliability in clinical practice is also recommended. Further studies may consider asymmetric and Class II malocclusion cases.

In conclusion, a satisfactory level of accuracy and reliability was achieved with the digital articulation of virtual dental study models. The detected inaccuracies were of limited clinical significance. The digital articulation of study models for orthognathic surgical planning using VRMesh software is reliable and reproducible and should be applicable in clinical practice.

Competing interests

None.

Ethical approval

The local National Health Service Clinical Governance Committee, Greater Glasgow & Clyde Health Board (03/02/21) provided the necessary ethical approval to conduct the study.

Patient consent

Not applicable.

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