Virtual bite registration using intraoral digital scanning, CT and CBCT: 
In vitro evaluation of a new method and its implication for 
orthognathic surgery

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A B S T R A C T

Three-dimensional (3D) computer-assisted planning requires detailed visualisation of the cranio-maxillofacial region and interocclusal relationship. The aim of this study was to establish and evaluate a method to create a 3D model of the cranio-maxillofacial region and to adopt intraoral digital scanning to place the lower jaw into a centric relation (CR) without the need of additional plaster casts and model surgery.

A standard plastic skull modified by metallic dental wires and brackets was subjected to computed tomography (CT), cone beam computed tomography (CBCT), and intraoral digital scanning. We evaluated two different virtual bite registrations, a digital scan of the buccal dental surfaces and scanning of the wax bites to position the lower jaw into a CR, and intraoral digital scanning. We evaluated the mean registration error of corresponding mesh points for the CT and intraoral scanned images was 0.15 ± 0.12 mm, while this error was 0.18 ± 0.13 mm for the CBCT and intraoral scanned images. The mean accuracy of the two virtual bite registrations ranged from 0.41 to 0.49 mm (buccal scan technique) and from 0.65 to 1.3 mm (virtualised wax bite technique).

A method for virtual bite registration was developed. It has the potential to eliminate plaster casts and model surgery and may facilitate 3D computer-assisted planning of orthognathic surgery cases.

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1. Introduction

In the field of cranio-maxillofacial surgery, three-dimensional (3D) computer-assisted planning requires detailed, spatial information to be acquired and different image data and imaging modalities processed in a computerised fashion (Plooij et al., 2011). Recent advances in computer technologies offer the surgeon the possibility to integrate all relevant 3D planning information in one single multi-modality imaging model. A clinical advantage can be seen when studying complex asymmetric deformities within orthognathic surgery (Stokbro et al., 2014; Uribe et al., 2013a).

CT scans and particularly CBCT scans processed within available software solutions have significantly simplified diagnosis, analysis, and preoperative planning (Scarfie and Farman, 2008; Sukovic, 2003; Schulze et al., 2004). Both CT and CBCT scans are considered to be appropriate imaging modalities for the 3D visualisation and analysis of bone. However, computer modelling of the dental occlusion requires more precise computer models and cannot be obtained from image data, such CT or CBCT scans (Plooij et al., 2011). Limited image resolution, creation of streak artefacts from metal dental restorations and orthodontic brackets, difficult image segmentation, and separation of the upper from the lower teeth in a closed bite position inhibit accurate 3D modelling and visualisation.
of the teeth (Nkenke et al., 2004). Additionally, during CT or CBCT scanning, the patient is usually positioned with the jaws and teeth in a closed, habitual bite position and not in a centric relation (CR), as commonly used for treatment planning. The definition of a CR has been controversial and has undergone multiple changes over the past years (Keshvad and Winstanley, 2000a, b, 2001). Truitt et al. agreed to the definition of CR as when the condyles are in their most posterior–superior position within their fossa (Truitt et al., 2009). Regardless of the definition, appropriate surgery requires a position of the mandible that is reproducible both pre- and intraoperatively (Ellis, 1990).

Currently, different advanced 3D imaging techniques are available that can display separate parts of the facial structures with high accuracy. To date, none of the present craniomaxillofacial imaging techniques can capture a competent 3D model of all structures (i.e., facial skeleton, dentition, and soft tissue) with the quality required for orthognathic surgery. Hence, there is a need for combining and merging different 3D imaging techniques to establish a multi-modality imaging model for 3D orthognathic surgery planning.

Numerous attempts have been made to combine CT or CBCT images with a digital model of the teeth to present an accurate 3D model of the region in question (Gateno et al., 2003; Swennen et al., 2007, 2009a, b; Nkenke et al., 2004).

Currently, intraoral digital scanners have the ability to obtain image information of a full dental arch scan with the same accuracy as conventional impressions (Patzelt et al., 2014). Attempts have been made to merge the intraoral optical scan information into the CBCT image for fabrication of surgical splints (Hernandez-Alfaro and Guijarro-Martinez, 2013). Despite the advantages, there is a lack of a clinical method describing the use of intraoral digital scanning as an accurate means for bite registrations.

This study describes an in vitro method and evaluates the techniques for the virtual bite registration required to manufacture a single 3D planning model with the bone and teeth properly visualised and with the lower jaw positioned into a CR. It introduces computational procedures without the need for any traditional laboratory work.

2. Materials and methods

A standard, commercially available plastic skull (SOMSO®. Coburg, Germany) with detailed dental surfaces was used for the evaluation. Orthodontic brackets with arch wires were placed on the buccal surfaces of the teeth. The lower jaw of the plastic skull model was placed into a simulated CR, and a wax bite registration (Alminax, Kemdent, Purton, UK) was obtained. Dental plaster casts (COECA™ Type III Dental Stone, GC America Inc., Alsip, IL, USA) were created from impressions taken with alginate (Blueprint X-cement, Dentsply (York, PA, USA). A face-bow transfer with Artex® face-bow (Amann Girrbach, Charlotte, NC, USA) was made, and the plaster casts were mounted onto a standard articulator (Artex® CR, Amann Girrbach, Charlotte, NC, USA). The occlusion pattern was evaluated with occlusion paper (Arti-Fol, Bausch, Köln, Germany).

The plastic skull was positioned into the gantry of a standard clinical CT scanner (Somatom Definition AS, Siemens, Erlangen, Germany). A routine CT head protocol was acquired (convolution kernel U75, 120 kV, and isotropic voxel size: 0.4 × 0.4 × 0.4 mm). One CT scan was performed with the wax bite in place with the mandible positioned in a CR; a second CT scan was performed without the wax bite in the maximum intercuspation position (MIP). Two different scans were also obtained with the skull positioned in a standard CBCT scanner (NewTom 5G, QR, Verona, Italy) using a standard CBCT protocol (110 kV, voxel size: 0.3 × 0.3 × 0.3 mm). Optical information of the plastic skull's dentition was acquired by scanning all of the dental surfaces of the upper and lower jaws using a TRIOS intraoral digital scanner (3Shape, Copenhagen, Denmark) (Fig. 1).

Virtual bite registration. Using the same optical scanning device, two different types of virtual bite registrations were performed with the wax bite in situ. In the first technique, the virtual bite registration was performed with optical scanning of the buccal surfaces of the teeth in a CR. In the second technique, the optical scanner was used to scan the wax bite, creating a computer model of the wax bite (Fig. 2). The procedures were repeated twice. The scan information was exported in a standard image data format (i.e., Standard Tessellation Language [STL] files).

The CT and CBCT images were exported as Digital Imaging and Communication in Medicine (DICOM) information, and the optical scan images from the intraoral scanner were exported as STL files. The files were transferred to a desktop computer running Windows XP (Microsoft Corporation, Redmond, CA, USA) and post-processed in Amira (Amira Version 5.5.0, FEI Visualisation Sciences Group, Bordeaux, France), a commercial software package for image visualisation and data analysis. The CT and CBCT scans were reconstructed to 3D images, generating 3D computer models with a triangular mesh structure. The mandible was segmented from the cranium by standard semi-automated threshold procedures.

The 3D models of the dentition were cropped to restrict the volumes being considered for subsequent registration. The intraoral optical scan data of the dental surfaces were pre-aligned with the CT/CBCT models by manually placing three landmarks onto corresponding regions. Then, the surface-based registration was implemented using an iterative closest point (ICP) algorithm. The ICP uses corresponding surfaces from two data sets, which are represented by two point clouds. This algorithm is designed to minimise the distances. In the process, a point cloud, which is the reference (i.e., the dentition of CT/CBCT scans), is kept fixed, while the other one, which is the surface to be aligned (i.e., the dentition of optical scanning), is transformed and rotated to best match the reference. This procedure was performed for the CT and CBCT scans separately. Hence, a 3D CT/CBCT reference model of the jaws was generated while considering the two different imaging modalities and CR.

A duplicate model of the lower jaw, having an identical mesh structure, was computed and moved away from its original position. This model was repositioned according to the information of the two virtual bite registration procedures. The result of the registration between the different imaging modalities was evaluated using the colour-coded distance mapping technique as given in Amira (Fig. 3).

By placing a rotational axis passing through the centre of the condylar head, the mandible was rotated into dental contact, and the contact pattern was evaluated by graphical demonstration of the distance between the upper and lower teeth. The virtual contact pattern was compared to the conventional articulator model (Fig. 4).

Fig. 1. Digital scanning of teeth of the upper and lower jaws. A virtual bite registration in a CR is performed by scanning the buccal surfaces of the teeth with a wax bite in situ.
3. Results

We elaborated a technical workflow to merge different 3D-digitised information of the craniomaxillofacial skeleton and of the dental surfaces and to position the mandible in a CR. The procedure consisted of image acquisition and image processing, in particular of CT or CBCT imaging, intraoral optical scanning, standard manual image segmentation, and registrations. The workflow included the mandible to be rotated according to an axis passing through the condylar heads with a virtual occlusal contact pattern obtained. The final computer model was available in a standard image format, like the STL format, and might be transferred to another application (e.g., used for CT-/CBCT-based software planning) (Fig. 5).

After each registration of the intraoral scanned image into the CT/CBCT image, the differences between the two 3D models were expressed in a colour-coded distance map. Most of the regions showed a blue colour, indicating a distance close to 0 mm (i.e., a good fit). The maximum deviations appeared around the orthodontic brackets and third molars, showing a red colour indicating a distance close to 1 mm (Fig. 6). The absolute mean distance of the corresponding mesh points of the registration of the surface model of the teeth ranged from $0.14 \pm 0.12$ mm to $0.15 \pm 0.12$ mm.

![Fig. 2.](image1)

**Fig. 2.** The result of the two virtual bite registration techniques. The yellow model (left) represents the buccal scan technique, and the green model (right) represents the scanned wax bite.

![Fig. 3.](image2)

**Fig. 3.** Evaluation of the virtual bite registration, as illustrated for the buccal scan technique (a–c). The distance (mm) between the corresponding vertex points of the meshes is represented in a colour-coded distance map. The unmoved mandible is used as a reference for the registration.

![Fig. 4.](image3)

**Fig. 4.** Landmarks are placed on the condylar head to create a rotational axis. The mandible can be rotated into dental contact (left). Virtual contact pattern after rotation of the mandible into dental contact (middle). Contact pattern after conventional articulator modelling (right).
for the CT and from 0.17 ± 0.13 mm to 0.18 ± 0.13 mm for the CBCT scan (Table 1).

Registration into CR. Two different approaches for virtual bite registration techniques were evaluated. The buccal scanning technique, with the wax bite in situ, was performed twice for both the CT and CBCT scans, and the differences between the two copies of the mandibles were expressed in a colour-coded distance map. The buccal scan technique showed a lower mean distance than the virtualised wax bite technique (Table 2). The mean accuracy was 0.41 mm for CT, while the mean accuracy for CBCT was 0.45 mm and 0.49 mm. For the virtualised wax index technique, the results were 1.3 mm, 1.0 mm, 0.65 mm and 1.0 mm, respectively.

The accuracy of the virtual bite registration was also evaluated by visual judgement of the virtual occlusion pattern in comparison to the dental contacts in the conventional articulator model. This accuracy showed a similar representation in both models (Fig. 4).

The analysis of the cranio-maxillofacial skeleton and dental occlusion represents a key planning step in craniomaxillofacial surgery. Individual plaster casts mounted to an articulator assist the surgeon in the preoperative assessment; however, these casts limit the analysis to the dental surfaces and interocclusal relationship. The procedure is laborious, requiring dental impressions, plaster cast modelling, wax bite registration, and face-bow transfer. It has been reported to be inaccurate and unreliable (Ellis et al., 1992; Sharifi et al., 2008). While the traditional approach allows

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**Table 1**

Differences in the distance (mm) between the mesh overlap following the registration of CT/CBCT data and surface data from intraoral optical scanning.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT maxillary arch</td>
<td>0.15</td>
<td>0.12</td>
<td>0.13</td>
<td>0.99</td>
</tr>
<tr>
<td>CT mandibular arch</td>
<td>0.14</td>
<td>0.12</td>
<td>0.11</td>
<td>0.98</td>
</tr>
<tr>
<td>CBCT maxillary arch</td>
<td>0.18</td>
<td>0.13</td>
<td>0.15</td>
<td>0.93</td>
</tr>
<tr>
<td>CBCT mandibular arch</td>
<td>0.17</td>
<td>0.13</td>
<td>0.14</td>
<td>0.87</td>
</tr>
</tbody>
</table>

**Table 2**

Differences in the distance (mm) between the lower jaw positioned with guidance of the two different virtual bite registration approaches using the unmoved lower jaw as a reference.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT buccal scan 1</td>
<td>0.41</td>
<td>0.077</td>
<td>0.37</td>
<td>0.69</td>
</tr>
<tr>
<td>CT buccal scan 2</td>
<td>0.41</td>
<td>0.13</td>
<td>0.39</td>
<td>0.73</td>
</tr>
<tr>
<td>CT wax bite scan 1</td>
<td>1.3</td>
<td>0.32</td>
<td>1.3</td>
<td>1.8</td>
</tr>
<tr>
<td>CT wax bite scan 2</td>
<td>1.0</td>
<td>0.23</td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td>CBCT buccal scan 1</td>
<td>0.45</td>
<td>0.15</td>
<td>0.44</td>
<td>0.84</td>
</tr>
<tr>
<td>CBCT buccal scan 2</td>
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<td>0.19</td>
<td>0.50</td>
<td>0.97</td>
</tr>
<tr>
<td>CBCT wax bite scan 1</td>
<td>0.65</td>
<td>0.16</td>
<td>0.67</td>
<td>0.91</td>
</tr>
<tr>
<td>CBCT wax bite scan 2</td>
<td>1.0</td>
<td>0.30</td>
<td>0.69</td>
<td>1.6</td>
</tr>
</tbody>
</table>

4. Discussion

Fig. 5. Technical workflow for merging the different 3D models. The final computer model is available in a standard image format, such as the STL format, and might be transferred to another application (e.g., used for CT/CBCT-based software planning).

Fig. 6. The accuracy of merging the digital impressions with the 3D models generated from the CT/CBCT scans is represented in a colour-coded distance map. Blue represents an accuracy close to 0 mm, and red represents an accuracy close to 1 mm.
the dentition in its CR to be assessed, it does not provide any information about the facial soft tissue or bone. Radiographic assessment can be performed in parallel to the articulator model but cannot be performed simultaneously. Current 3D imaging modalities allow different tissues (i.e., dentition, facial bone or soft tissue) to be visualised, creating a multi-modality model available for computer-assisted planning (Plooij et al., 2011; Swennen et al., 2009a,b; Gatenò et al., 2003).

Our main observation was that there was no possible way to create an accurate 3D model using just one single imaging source (Plooij et al., 2011). Additionally, there was a lack of CR consideration in the computer-assisted planning. Hence, there was a need for 3D multi-modality imaging and registration. Our study was initiated to elaborate on a method to accomplish 3D computer-assisted planning of cranio-maxillofacial surgery procedures without the need for traditional approaches.

The results of this study demonstrated a novel method for unifying CT or CBCT image data with intraoral optical scans of the dentition and for positioning the 3D model of the lower jaw into a CR with minimal error. CT or CBCT scans may be used to visualise the cranio- or maxillofacial skeleton in multiplanar views or in three dimensions. In addition, intraoral optical scanning might be adopted to properly visualise the dentition of the upper and lower jaws. Registration of the two 3D imaging sources was performed first to merge the different imaging modalities and second to position the 3D jaw model into a CR. Hence, the method provides a unique technique to create a novel 3D model of the cranio- or maxillofacial region with all of the relevant bony and dental structures in the same field of vision, with the lower jaw positioned in a CR and without the need of any additional, traditional work. Such a model may be readily transferred into a 3D computer-assisted planning environment.

The intraoral optical scanning system that was used directly captured the detailed morphology of the entire upper and lower dental surfaces of the modified plastic skull and represented them via a high number of surface mesh points per area. However, proper image data could not be obtained at specific dental sites, such as the undercuts created by dental brackets. Intraoral optical scanning proved to be a rather fast procedure, and a scan of a full dental arch took no longer than 3–4 min (Yuzbasioglu et al., 2014).

Both CT and CBCT scanning signify another type of 3D imaging sources and require image segmentation. Hence, computer meshes created via CT/CBCT scanning cannot be generated with the same quality due to the limited image resolution restricting the number of mesh points per area. Most often, CT and CBCT scans are acquired with the patient in the MIP (i.e., in a habitual bite position). An option might be to achieve CBCT scanning with the patient directly scanned in a CR, particularly when the CBCT scanner is available in the clinical setting (Sun et al., 2013). The virtual bite registration technique, on the other hand, offers the option to relocate a 3D model of the lower jaw at any assessment or treatment stage using both CT and CBCT scans.

Image segmentation signifies a technical step in which a threshold is selected to label single volume units (voxels) within CT or CBCT scans, sharing the same characteristic (e.g., bone, soft tissue or teeth). Since CT and CBCT scans are often obtained in the MIP, segmentation is a challenging and time-consuming task because it requires the separation of the upper teeth from the lower teeth in order to obtain a separate 3D model of the lower jaw. Therefore, care should be taken to avoid additional time-consuming image segmentation by scanning the patient with the wax index between the teeth.

Registration characterises the process of transforming different sets of image data into one coordinate system. In this study, a surface-based registration was used after a pre-alignment using a set of paired landmarks. Other authors have demonstrated the feasibility of obtaining digital models of the dentition and of integrating it into a CBCT model via ICP registration (Nkenke et al., 2004; Noh et al., 2011). Our method required ICP registration made twice: First, to register the optical scans to CT or CBCT, and second, to obtain a virtual bite registration to place the lower jaw in a CR. The investigation unavoidably faced several technical challenges when using the ICP-based registration. Compared to the registration of a set of paired landmarks, which can be manually set by the user, ICP is a state-of-the-art registration technique, and its main parts were computed automatically. It does not rely on only a few landmarks, but it necessitates the definition of corresponding surfaces and pre-alignment and may even take into account several ten thousands of mesh points (Lin et al., 2015). As expected, the procedure proved technically demanding and may be significantly disturbed by non-matching surfaces, such as those surfaces created by dental streak artefacts, undercuts created during intraoral optical scanning, or the unavailability of the occlusal surfaces when performing CT/CBCT scanning in the MIP.

Our results indicated that the registration between the CT/CBCT scans and intraoral optical scan is technically demanding but can be performed with minimal error. The buccal scans showed better accuracy than the virtualised wax bite. A possible explanation might be that the accuracy increases when a broad area (e.g., the buccal scan technique) is used for registration (Noh et al., 2011). Another reason for the decreased precision of the virtualised wax bite can be the image acquisition process. The accuracy of scanning a wax bite index was technically more demanding. This was likely due to the index representing a flat object. Our results of the registration between the CT/CBCT scans and intraoral optical scanning were similar to previous studies in which dental casts were scanned with a 3D laser scanner (Noh et al., 2011; Nkenke et al., 2004). However, it has to be considered that both CT and CBCT imaging offer only limited image resolution and require image segmentation, which in turn may have a significant impact on the accuracy of the final result. There are several steps in creating an adequate model of the desired structures for orthognathic surgery planning. The first part, the image acquisition, is essential. The further workflow with inherent image-processing step cannot compensate for unsatisfactory resolution in the original data (Varga et al., 2013).

Evaluations were made by distance measurements between the superimposed surfaces to evaluate the registration by computing 3D colour-coded distance maps. These maps represent graphical representations of the distance differences between two superimposed surfaces (Jayaratne et al., 2010). It is relevant to know how to interpret this information and to be aware of how the calculations have been made. One must note that while comparing different models from different image modalities, it is merely possible to show the deviation between the nearest neighbouring surface points. First, the distance may be calculated in different directions depending on which surface is defined as the reference surface. Second, when calculating the distance between two exact 3D copies, which in this case was the position and repositioning of the 3D mandible models, we were able to analyse the deviation between the exact matching mesh points. This representation is closer to a true measurement and therefore will create other types of 3D colour-coded distance maps. We were able to apply the mapping technique onto two identical 3D models with identically numbered and located mesh points.

In the field of orthognathic surgery, 3D computer-assisted planning has already become a widespread clinical application. Several authors have reported on this topic (Aboul-Hosn Centenero and Hernandez-Alfaro, 2012; Swennen et al., 2009a). It has the potential to make postoperative outcomes more accurate, reduce
operation time, and improve the communication between the patient and clinical team (Xia et al., 2011). Similar to traditional planning, our method represents a technical approach integrating modern 3D-imaging concepts into the same planning, our method represents a technical approach integrating operation time, and improve the communication between the patient and clinical team. It may be used to virtually model and to assess more complex asymmetric cases in 3D, such as syndromic craniofacial deformities. There is a great advantage to a 3D approach for computer-assisted planning, because it provides all of the relevant information about the cranio-maxillofacial hard tissue (Uribe et al., 2013a,b). Another benefit of creating such detailed 3D planning models is the possibility of evaluating the outcome of the surgery in three dimensions.

The strength of this study is the novelty and usefulness of the method, as this skeletal site exclusively allows for noninvasive registration of the two bones (i.e., cranium and mandible) via dental surfaces; therefore, it permits computerised planning models to be repositioned accordingly. Registration represents a standard and important diagnostic procedure in orthognathic surgery. Both proper 3D imaging and image registration techniques are required to enhance the preoperative assessment, particularly of the bone and dental structures. They help to avoid the use of traditional plaster modelling and radiographs, which are techniques that require additional efforts prior to surgery and still provide only limited information.

There are two main limitations of this study. First, it does not compare the difference between the CR and MIP. A comparative analysis of the differences between the CR and MIP within computer models, plaster cast models, and clinical cases would be highly valuable and could also give a hint to the reproducibility of the methods. However, we are also aware of the technical difficulties to compare these methods. Second, virtual bite registration is still considered to be a time-consuming and technically demanding procedure. This is particularly true when performing ICP-based registration in cases with a significant amount of streak artefacts from metallic dental restorations. We consider an automated virtual bite registration to be a clinically relevant and technically feasible procedure.

The development of the described method required several demanding steps to be tested. The use of an in vivo model proved to be highly advantageous, since it was very easy to handle during image acquisition, processing, and testing. However, it still requires the transfer into the clinical setup. This study experienced the advantages and limitations of 3D imaging, registration, and evaluation techniques, and the method demonstrated the potential use for orthognathic surgery. Imaging of the facial soft tissue was not a subject of this study.

5. Conclusion

In conclusion, we described a new method for virtual bite registration using intraoral optical, CT, and CBCT scanning in order to create a 3D computer model of the cranio-maxillofacial region without the need for any additional, traditional laboratory work. The method suggests the use of intraoral optical scanning to first capture the detailed morphology of the dental surfaces and then to place the 3D model of the lower jaw into a CR. The buccal scan technique demonstrated to be more accurate than the virtualised wax bite to position the mandible into a CR. In particular, image resolution, image segmentation, registration, and appropriate 3D evaluation techniques required careful considerations. The method and 3D model created may serve as a foundation for improving and facilitating 3D computer-assisted planning of orthognathic surgery procedures. Comparative analyses between a virtual CR, MIP, and clinical cases, along with more efforts, are required for the automated registration of CT/CBCT scans and intraoral optical scans with the lower jaw positioned in a CR.

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