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A Simulator for Maxillofacial Surgery Integrating 3D Cephalometry and Orthodontia

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ABSTRACT Objectives: This paper presents a new simulator for maxillofacial surgery that gathers the dental and maxillofacial analyses together into a single computer-assisted procedure. The idea is to first propose a repositioning of the maxilla via the introduction of 3D cephalometry applied to a 3D virtual model of the patient's skull. Orthodontic data are then integrated into this model, using optical measurements of plaster casts of the teeth.

Materials and Methods: The feasibility of the maxillofacial demonstrator was first evaluated on a dry skull. To simulate malformations (and thus simulate a "real" patient), the skull was modified and manually cut by the surgeon to generate a given maxillofacial malformation (with asymmetries in the sagittal, frontal, and axial planes).

Results: The validation of our simulator consisted of evaluating its ability to propose a bone repositioning diagnosis that would restore the skull to its original configuration. An initial qualitative validation is provided in this paper, with a 1.5-mm error in the repositioning diagnosis.

Conclusions: These results mainly validate the concept of a maxillofacial numerical simulator that integrates 3D cephalometry and guarantees a correct dental occlusion. Comp Aid Surg 5:156–165 (2000). ©2000 Wiley-Liss, Inc.

Key words: **maxillofacial surgery, simulator, orthodontia, cephalometry**

INTRODUCTION

Planning craniofacial surgical procedures, particularly orthognathic surgery, requires the integration of multiple and complex data gathered from different sources: clinical examination (anthropometry), orthodontic (dental models), radiological (cephalometry), and intra-operative data (constraints and position information). This heterogeneity makes the therapeutic decision difficult, particularly in asymmetrical dysmorphoses. For this reason, several types of three-dimensional (3D) surgical analysis, simulation software, and methods have been developed.[3,7,9–11,13–15,17–20] The pioneers in this field were Marsh and Vannier.[13,18,19] According to Cutting,[7] a surgical simulation program must be built with three functions. First, one must be able to cut a model of the skull in ways that reflect actual surgical procedures. Second, mobilization of the bone segments with six degrees of freedom must be

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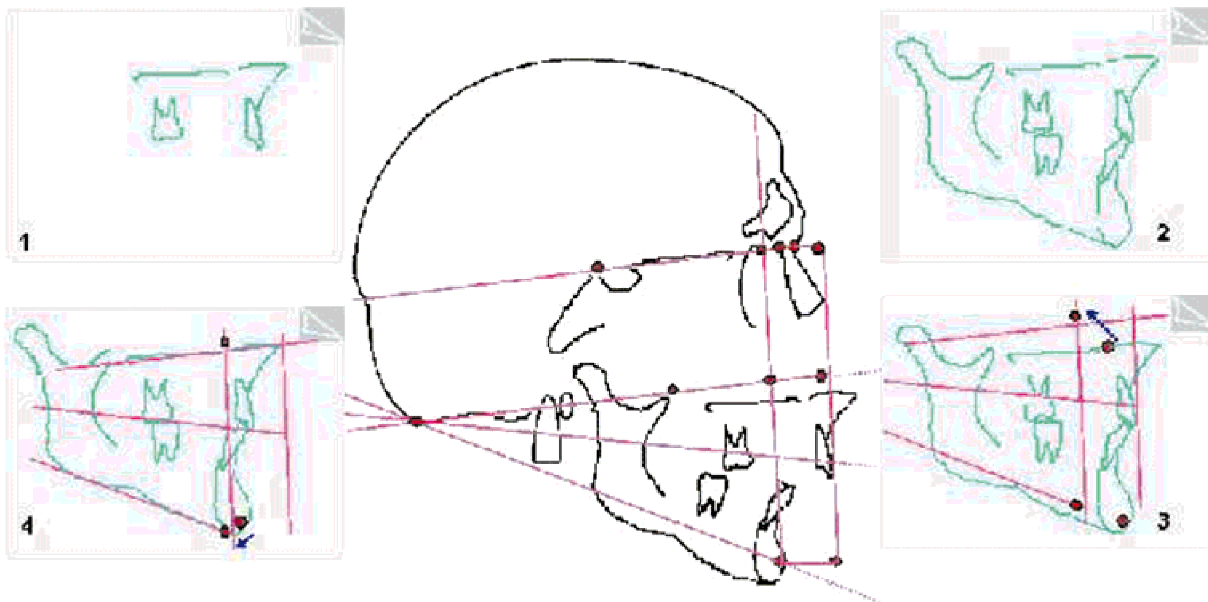

Fig. 1. Delaire cephalometry on sagittal radiographic tracings: computation of maxilla and mandible repositioning achieved with tracing paper.

possible. The third function is to create a 3D cephalometric analysis. To these functions, one must add the necessity of being able to adapt to the limitations imposed by the anatomical or physiological characteristics of the area (thereby preserving vessels, nerves, etc.). It is also important to integrate a soft-tissue simulation in this bone analysis.

Another important challenge is transferring these 3D data to the operating room in order to simplify the surgical procedure with the aid of the computer.[4,5] Even though the technology is rapidly improving, the simulations proposed are still rudimentary[17] and do not take into account previous 3D cephalometric analyses. Three-dimensional cephalometric analysis is a real problem and very few relevant publications are available. The major difficulties are the large volume of data that has to be processed by the computer and the lack of craniofacial normative 3D data. Altobelli[1] has discussed the use of anthropometric data or the extrapolation of two-dimensional (2D) data. Marsh[13] considers that this extrapolation is adequate in cases of symmetrical dysmorphosis, but cannot be applied to craniofacial problems or asymmetrical abnormalities.

Surgical simulation is usually performed in two environments: digital graphics workstations and solid life-size skull facsimiles. Digital graphics workstations allow multiple simulated operations without degradation of the database, and theoretically allow combination of osseous and soft-tissue simulation. The digital data format facilitates quantitative analysis of the simulation and outcome, but it is very difficult to define the dental occlusion with sufficient accuracy. From this point of view, stereolithographic models are more concrete for the surgeon;[6] the occlusal problem can be solved, and implants can be prepared prior to surgery. However, the manipulation is destructive, and the cost and fabrication time of the model are shortcomings of this procedure.

This paper deals with a 3D cephalometric analysis system and a surgical simulator for orthognathic surgery that integrates the advantages of

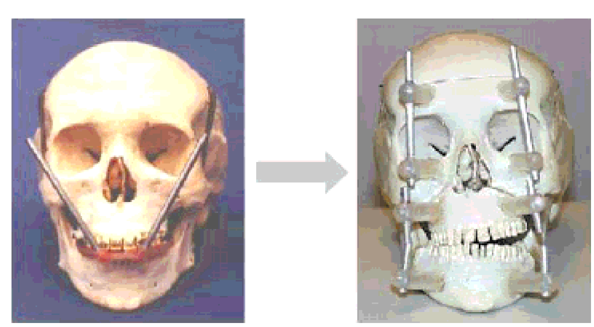

Fig. 2. A "standard" dry skull (left) manually cut to simulate malformations (right).

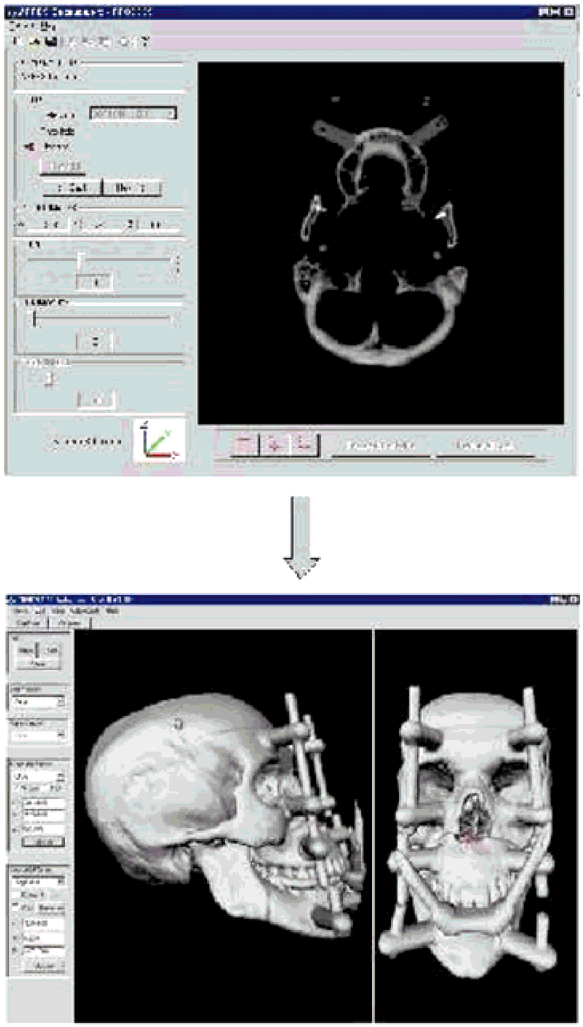

Fig. 3. Software interface: horizontal CT slices (top) and the corresponding reconstructed 3D model of the patient's skull (bottom).

both environments (graphic and facsimiles). The simulator is based on the integration of dental models and 3D cephalometry.

OBJECTIVES

State of the Art

Orthognathic surgery deals with face dysmorphosis arising from congenital malformations or accidents.[16] For example, in the case of mandibular prognathism (a dentofacial deformity of the lower third of the face resulting from excess mandibular growth), orthognathic surgical treatment is required to correct the occlusion (dental position) by means of an osteotomy of the mandible.[2] For this treatment, and for many other orthognathic surgical procedures, surgeons usually start from (1) plaster casts of the teeth and (2) sagittal, frontal, and/or axial 2D radiographs of the patient's head.

Plaster casts of the teeth are used to plan the osteotomy phase: both casts (of the mandible and maxilla) are manually cut to simulate (1) a correct positioning of the maxilla in relation to some specific facial anatomical landmarks (by means of a facial bow study), and (2) a correct positioning of the mandible in relation to the maxilla that guarantees normal dental occlusion. During this cutting procedure, resin splints (called *intercuspidation splints*) are built from the plaster casts, providing dental occlusion prints for the initial (actual maxilla and mandible), intermediary (actual mandible and cut maxilla) and final (cut maxilla and mandible) plaster cast positions. These splints are used during surgery as references for maxillary and mandibular osteotomies.

In parallel to this dental planning, surgeons can make a simplified 2D Delaire cephalometry,[8] i.e., compute from sagittal and/or facial radiographic tracings the desired displacements of the maxilla and the mandible. This is achieved by first placing specific anatomical landmarks onto the radiography, then, using tracing paper, suitable displacements of mandibular and maxillary landmarks in relation to the rest of the skull are measured manually (Fig. 1). This cephalometric diagnosis is then compared to the displacements provided by the orthodontic facial bow study.

As may be deduced from the above, two parallel procedures are required for the planning of orthognathic surgery: dental analysis and maxillofacial analysis, both working on different principles. Moreover, the decision phase only occurs at the end of each procedure, which means that the undertaking has been a waste of time if the two plans are not compatible and the procedures have to be run again.

The aim of the work presented in this paper is to combine the two surgical planning procedures into a single computer-assisted procedure that integrates information from surgeons about repositioning of the bone structures, and information from orthodontists about optimal dental occlusion. The idea is first to use orthopedic knowledge to propose a repositioning of the maxilla via the introduction of a 3D cephalometry applied to a 3D virtual model of the patient skull. Then, orthodontic data obtained by measurements of plaster casts of the teeth are integrated into this model using a 3D localizing system. For this approach, only the final desired position of the mandible, in relation to the

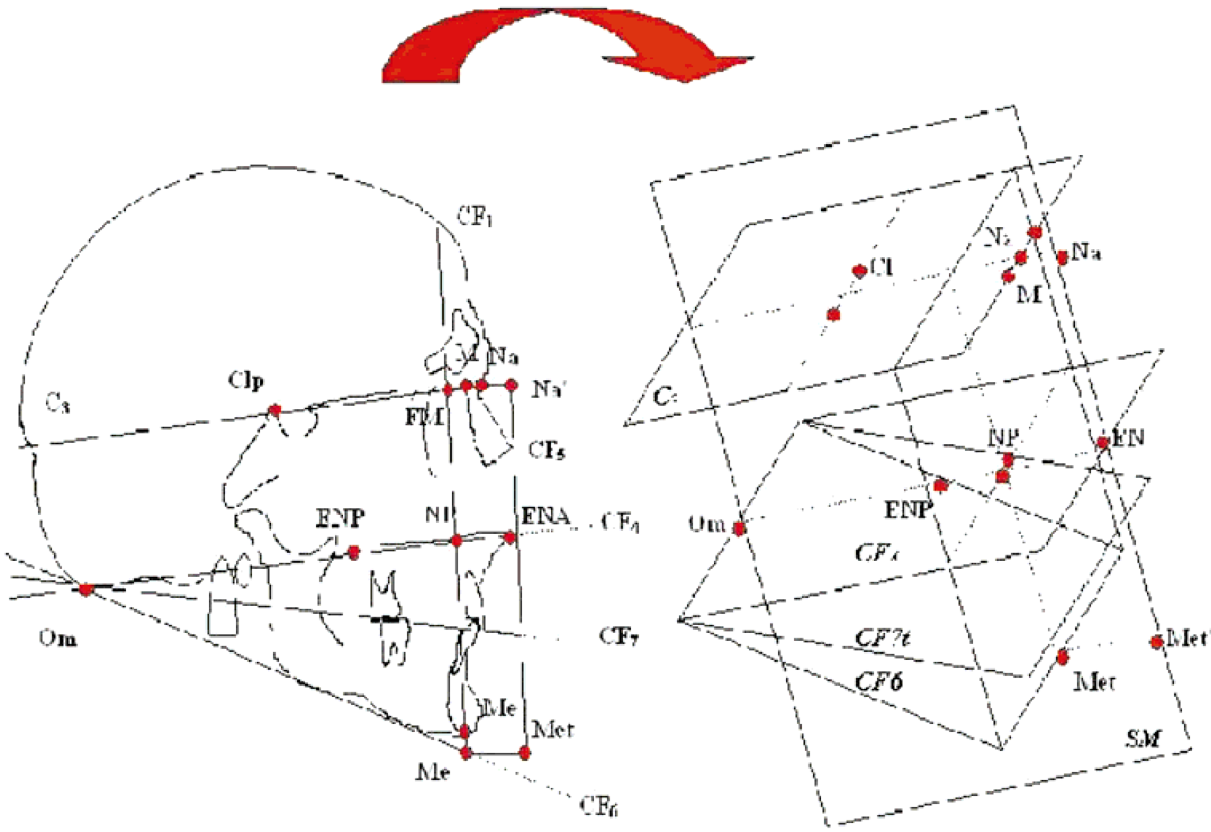

Fig. 4. 3D extrapolation (right) of the simplified Delaire analysis (left).

maxilla, is taken into account. Therefore, no cast-cutting phase is required, which makes the procedure easier.

MATERIALS AND METHODS

Choice of Patient

The feasibility of our demonstrator was first evaluated on a dry skull. This skull was a "standard" one without any noticeable maxillofacial dysmorphosis (Fig. 2, left). This choice was motivated by our wish to be able to quantify the repositioning diagnosis proposed by the simulator, which necessitates having knowledge of the "normal" maxillary and mandibular positions. To simulate malformations (and thus a "real" patient), the skull was modified and manually cut by the surgeon (Fig. 2, right) to generate a given maxillofacial dysmorphosis (with asymmetries in the sagittal, frontal, and axial planes). Before this cutting phase, two parallel tubes were fixed between the forehead and the mandible.

As can be seen in Figure 2 (right panel), each tube had to be cut into three parts in order to allow the manual bone-structure cutting phase. The validation of our simulator would thus consist of evaluating its ability to propose a repositioning diagnosis that re-aligned each part of the two tubes, as in the original skull configuration.

Data Acquisition and 3D Reconstruction of the Patient's Skull

Horizontal Computer Tomography (CT) slices were collected for the whole skull (helical scan with a 3-mm pitch and slices reconstructed every 1.5-mm). The Marching Cubes algorithm[12] has been implemented to reconstruct the skull from CT slices. Before running this reconstruction process, tools (erasers) can be used to clean specific slices, and a threshold value for the reconstructed isosurface must be chosen (the top panel in Figure 3 shows a snapshot of the PC platform software). Then, the process automatically builds the virtual 3D model (Figure 3, lower panel).

3D Cephalometry

The third dimension brings to cephalometric analysis the advantage of taking into account the data

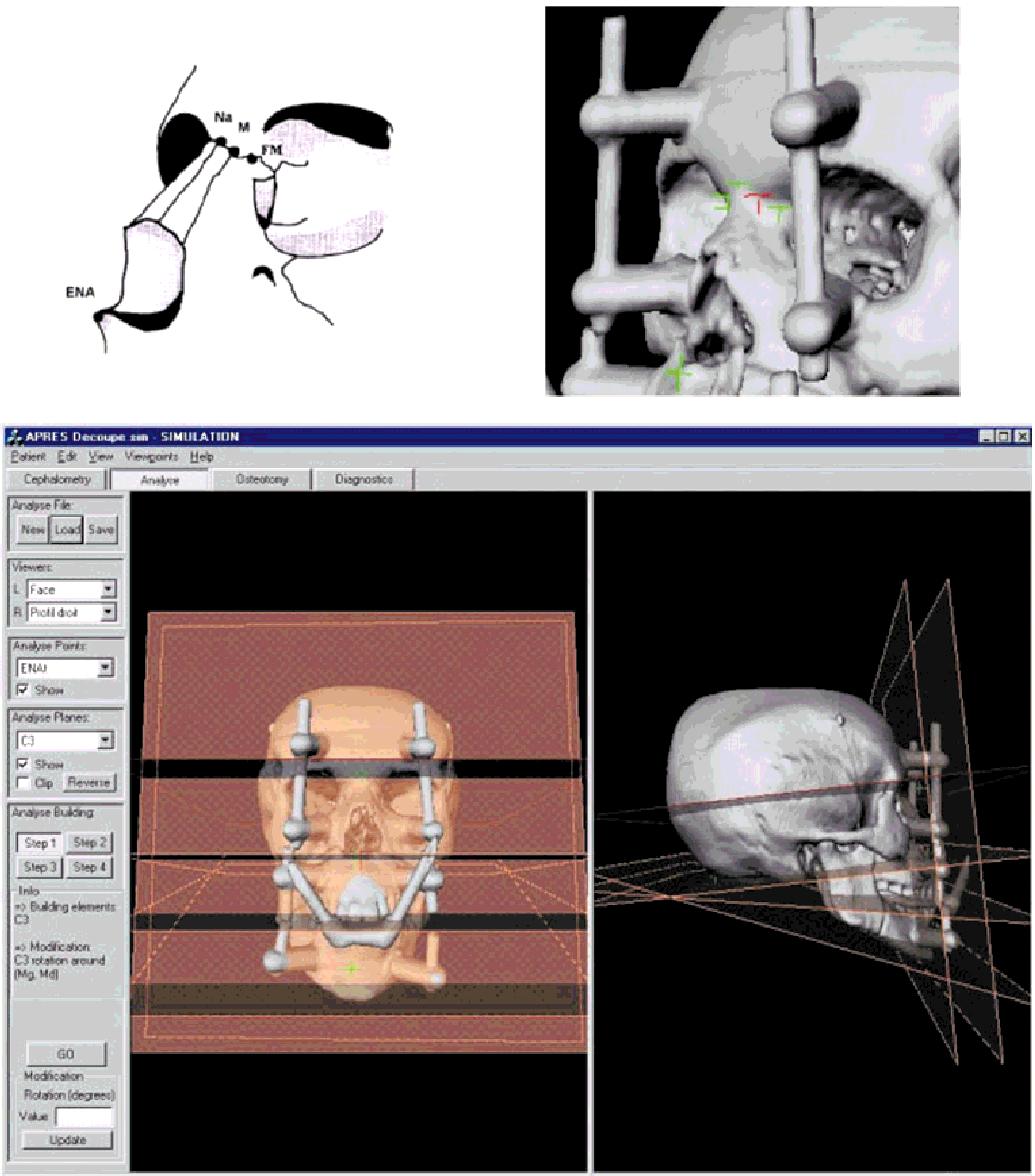

Fig. 5. Positioning of the anatomical landmarks (upper panels) and the corresponding 3D cephalometric analysis (lower panel).

provided by frontal, sagittal, and axial studies in a single step. It allows the integration of the problems of facial asymmetry and occlusal plane horizontality into the profile analysis. Apart from the implementation, the main problem in 3D cephalometry is the standardization and reference to the norms that exist in 2D cephalometries. Instead of creating a new 3D analysis, the idea was to transpose the data from 2D cephalometry in the third dimension. Our approach consists of a 3D extrapolation of the simplified Delaire analysis and is illustrated in Figure 4.

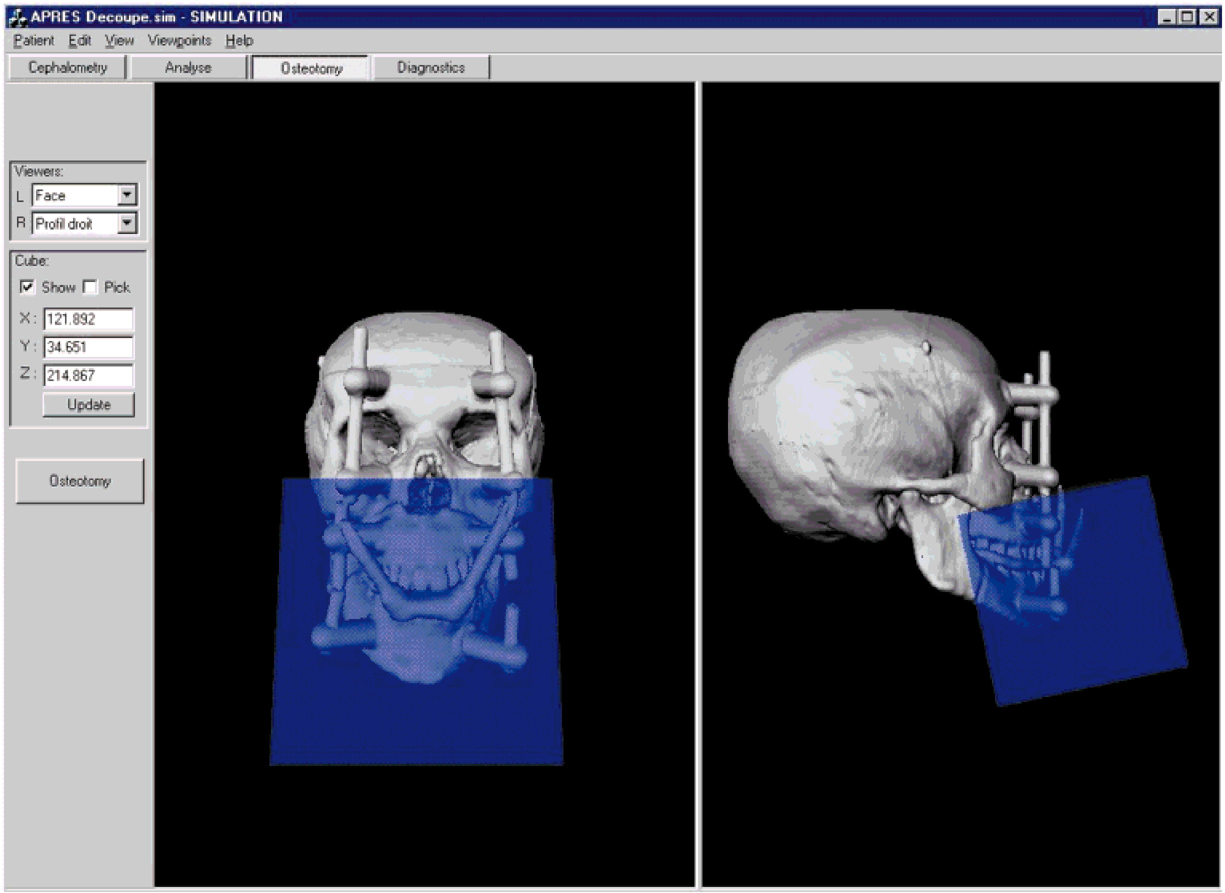

Fig. 6. A cube for simulating a virtual osteotomy that separates the maxilla/mandible block from the rest of the skull.

This analysis is adapted to the third dimension so that the reference standards existing in the sagittal plane are respected. The norms in the other dimensions are theoretically easy to define: it is simply a matter of respecting the horizontality in the frontal plane and the symmetry in relation to the sagittal median plane.

The surgeon is therefore asked to manually position each of the points listed in Figure 4 onto the virtual model of the patient's skull (Fig. 5, top panels). Starting from these cephalometric points, an automatic analysis procedure provides specific lines and planes (Fig. 5, lower panel) which will be used for the determination of a repositioning diagnosis.

Before this diagnosis is made, pixels of the 3D model belonging to the maxilla/mandible block must be labeled, as the repositioning diagnosis will be applied to these points. For this step, a virtual osteotomy is manually simulated that separates the skull model into two groups of points (Fig. 6).

As shown in Figure 6, the virtual osteotomy is performed using a parallelepiped cutting pattern that is interactively placed on the skull model and dimensionally adjusted with the manipulation tools provided by the software. These tools are sufficient to obtain a realistic model of surgical cutting.

RESULTS

Maxilla Repositioning Diagnosis

Maxilla repositioning is totally driven by the cephalometric analysis, according to the following three constraints (see Figure 4 for the names of planes and points):

i) The NP point is moved to fit the theoretical NP point position computed from cephalometric analysis (onto the intersection between the CF_1 plane and the sagittal median (SM) plane).

ii) The CF_7 plane is moved to fit the theoretical CF_7 plane.

iii) A given point chosen at the intersection

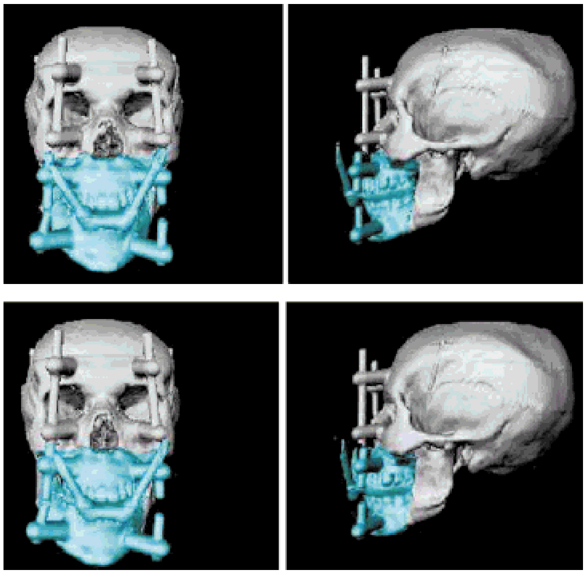

Fig. 7. A diagnosis for the repositioning of the maxilla/mandible block (lower panels), automatically obtained from the 3D cephalometric analysis.

between the two patient incisors is moved so as to be projected onto the sagittal median plane.

Following those constraints, a global displacement of the maxillary structure is computed in terms of translation and rotation. Figure 7 (lower panels) plots the corresponding repositioning diagnosis (NB: mandible position, in relation to the maxilla, remains constant during this operation).

Mandible Repositioning Diagnosis

As the mandible repositioning has to integrate dental occlusion constraints, it was decided to let it be totally driven by dental diagnosis. Cephalometric points and planes resulting from our analysis were here only used to determine the real occlusion plane (CF_7) between the maxilla and mandible (in order to label points according to whether they belonged to the maxilla or to the mandible).

As in standard treatments, orthodontic diagnosis was carried out on dental plaster casts. The only concern was the position of the mandible in relation to the maxilla, in terms of optimal dental occlusion. In contrast to standard orthognathic procedures, however, plaster casts of the teeth did not have to be cut, as there was no need to be concerned about maxilla positioning relative to the rest of the skull.

The initial and final splints were used for the integration of the orthodontic diagnosis into the virtual model of the patient's skull (the intermediary splint is thus removed from the procedure). Inserted into the plaster casts of the teeth, these splints respectively replicate the current and desired positions of the mandible in relation to the maxilla. A 3D optical localizer (Optotrak™, Northern Digital Inc.) is used to quantitatively measure the corresponding displacement from the current position (Fig. 8, left panel) to the desired position (Fig. 8, right panel).

This measurement consists of a global transformation matrix, corresponding to the desired translation and rotation that has to be applied to the

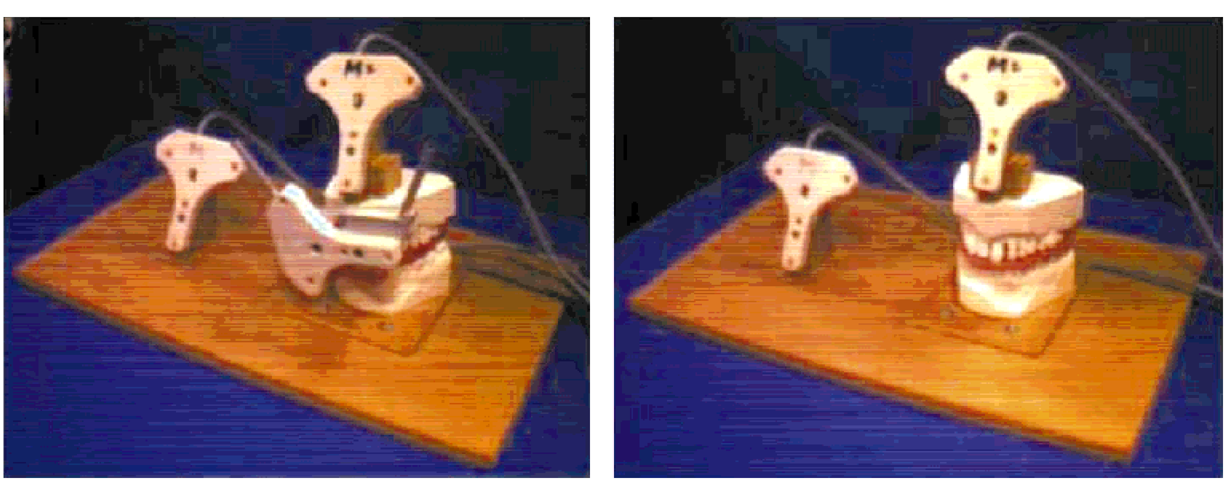

Figure 8. Intercuspidation splints inserted into plaster casts of teeth, localized by the means of optical rigid bodies. Left: actual position; right: desired dental occlusion.

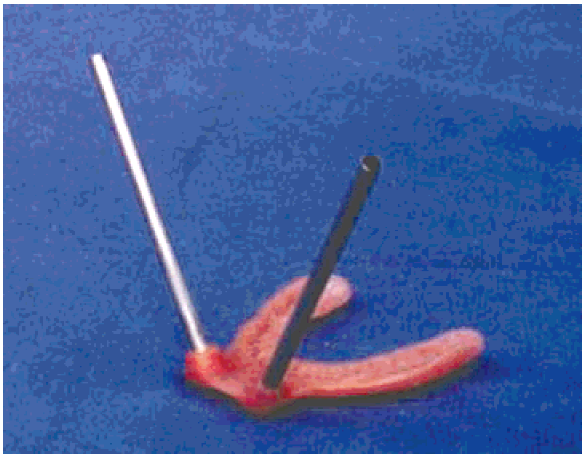

Fig. 9. Initial intercuspidation splint with two aluminum tubes.

mandible. As this transformation is expressed in the localizer referential, it has to be transferred into the CT scans' referential, i.e., into the virtual model space. To do this, an object visible in both modalities (localizer space and CT space) has been introduced into the procedure. This object comprises a pair of aluminum tubes fixed onto the initial intercuspidation splint (Fig. 9).

As these tubes are made from aluminum, they can be detected on CT scans if they are inserted inside the patient's mouth during the CT recordings (Fig. 10, right panel). Moreover, they can also be detected and located in the optical localizer referential (Fig. 10, left panel). Therefore, a simple matching algorithm enables us to compute the transformation from one referential to the other, and thus transpose the mandible correction into the virtual model space (Fig. 11, lower panel).

DISCUSSION

The repositioning diagnosis simulation presented in Figure 11 validates the feasibility of our simulator, as each part of the two tubes is qualitatively realigned with the other ones. These tubes show a maximal deviation of 2 degrees between their axes, which roughly corresponds to a 1.5-mm error in the repositioning procedure. These results mainly validate the concept of a maxillofacial numerical simulator that (1) integrates 3D cephalometry, (2) guarantees a correct dental occlusion, and (3) proposes a semi-automatic diagnosis for maxilla and mandible repositioning. However, the errors obtained are not completely satisfying, as the aim for orthognathic surgery would be to have a precision below one millimeter. The next stage of this work will thus consist of a quantitative evaluation of each point of the global procedure: precision of the computer-assisted 3D cephalometry, precision of the dental occlusion measurement, and repeatabil-

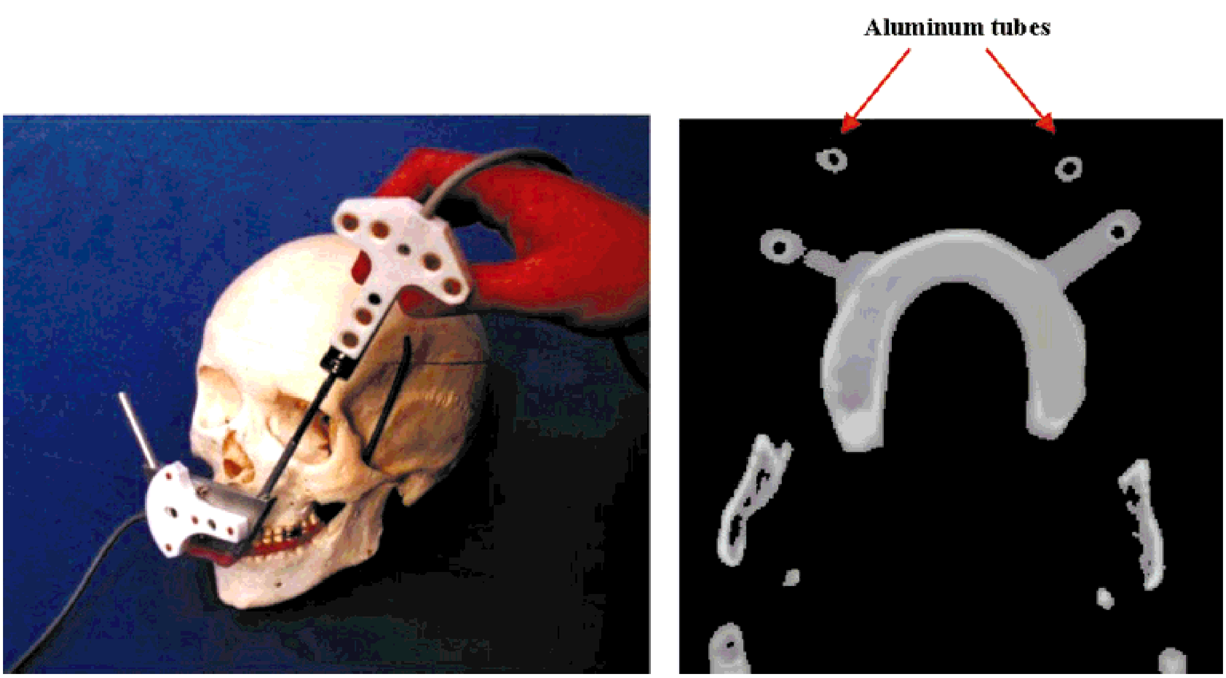

Fig. 10. Measurements of the aluminum tubes' axes in the localizer referential (left) and in the CT scans referential (right).

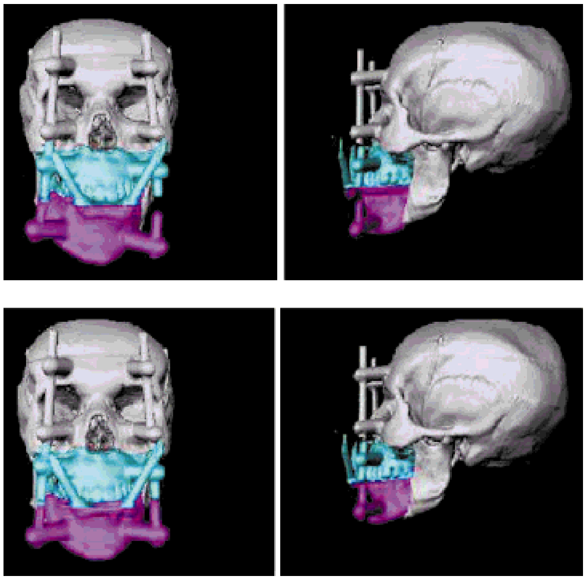

Fig. 11. Integration of the orthodontic mandible repositioning diagnosis (lower panels) into the virtual model of the patient's skull.

ity of the process for the same patient and/or for different kinds of pathology. Moreover, a comparison of the simulator diagnosis with osteotomies provided by surgeons using classical procedures without computer-assisted techniques would be another important evaluation factor.

CONCLUSION

In this paper we have presented an initial evaluation of the feasibility of computer-assisted techniques for maxillofacial surgery, integrating 3D cephalometry and orthodontic information. The first tests have been carried out on a dry skull that was manually cut to simulate a pathological patient. The repositioning diagnosis proposed by the maxillofacial simulator was evaluated through re-alignment of tubes fixed on the cadaver skull before the simulation of the patient dysmorphosis. A first clue to the efficiency of the simulator was provided and discussed. Clinical tests must now be carried out on real patients, and with different types of pathologies. Then, the next phase of this work will consist of transferring the simulated repositioning diagnosis into the operating room.

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