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A GUIDED SURGICAL DRILLING METHOD

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1. Introduction

Implantology is nowadays the most sophisticated technique of oral surgery for the reconstruction of masticatory functionality in totally or partially edentulous patients. This technique consists in replacing the natural tooth roots with *implants* tied to the bony tissue of the maxilla or mandible; the implant has the function to support the *prosthesis* and transmit the occlusal forces.

The current clinical protocol consists of three steps:

- *preoperative step*, in which the surgeon establishes the implant position and the drilling available depth by the analysis of proper radiological exams (usually axial CT scan and panoramic radiography);
- *surgical step*, consisting of the incision of the gingiva, the check of the implant seat, the drilling of a first *pilot hole* (of 2 mm diameter) in the bone tissue, the realisation of the definitive hole, the implant insertion and finally the suture of the gingival edges;
- *prosthesis placing*, executed about six month after the surgery.

The choice of the implant seat depends mainly on the local bone thickness and quality, the position of the mandibular canal and the presence of obstacles [Verstreken, 1996- Del Blaso 1994]. Furthermore, a correct placement of the implants should assure a stress distribution in the bone structure similar to that produced by the natural tooth in order to help the osseointegration and to accelerate the postoperative recovery. Since the implantologist executes the pilot hole guided only by his own experience and ability, it's difficult to reproduce the drilling direction established in the preoperative step. In this paper a method to obtain a surgical guide for the drilling of the pilot hole is presented.

2. Overview of the method

The guided surgical drilling method proposed [Caccamo 2001] consists, firstly, in the realisation of a customised drilling jig (Fig.1a) that has to be positioned inside the mouth of the patient; it has the main purpose to receive the *guide hole*, that is the hole in which the drilling tool will be inserted by the surgeon to realise the pilot hole. It also has the aim to furnish a reference system fixed to the mandible in respect of which the geometrical parameters (position and direction) of the guide hole itself have to be determined for its execution with a drilling tool machine. To this aim three metallic spheres, whose centres define the layer of the *jig reference plane*, are annealed inside it. This plane allows the definition of the *jig reference system* $\{\Omega, x, y, z\}$ shown in figs.1 (a) and (b).

Position and direction of the pilot hole axis are obtained by processing information contained in the CT scans of the mandible of the patient wearing the drilling jig. Each pixel of a CT scan image (named *slice*) is related to the mass density of the tissue at a point of the mandible [Passariello 2000]. The position of the point is referred to a *CT reference system* $\{O, X, Y, Z\}$ shown in fig.1c, in which Z is the axial position at which the scan has been executed and X and Y are the pixel coordinates. After an image preprocessing phase, described in the following, in order to refer position and direction of the hole axis with respect to the jig reference system, at first, the operator has to identify the location of

the centres of the reference spheres in the CT slices by an interactive procedure (fig.2). After this procedure, the software evaluates the parameters for the coordinate transformation from the CT reference frame to the jig one.
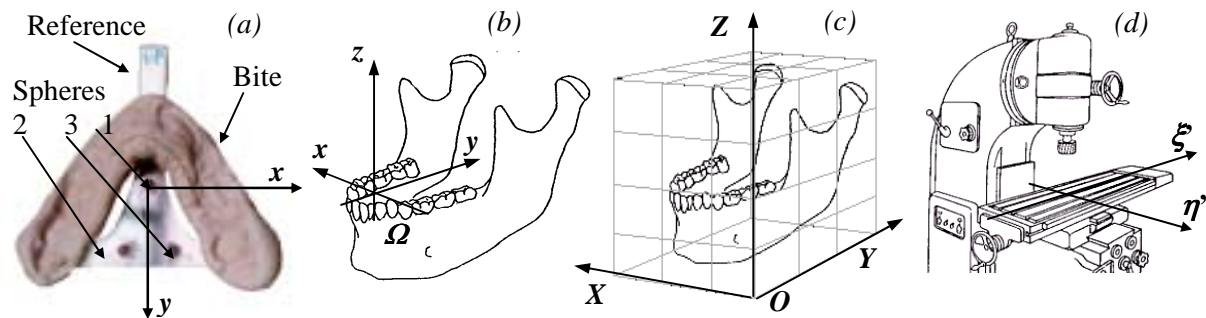

Figure 1. a) The drilling jig, b) jig reference system, c) CT reference system, d) Machine tool axes

The determination of the axis of the implant seat is provided also by an interactive procedure (fig.3): the operator selects the point in a slice (I point in Fig. 3); the system shows the sagittal and the coronal views of the mandible at the selected point and permits to the operator to trace the direction in both. At this stage the drilling location and direction parameters in the jig reference system are automatically evaluated.

In order to drill the guide hole on the jig, a final elaboration is needed: the parameters obtained in the jig reference system have to be converted in translations and rotations to impose to the support of the drilling tool machine (*drilling parameters*) to realise the hole (fig.1d). Usually 2 translations and 2 rotations are needed to execute the guide hole.

The evaluation of the drilling parameters depends on the characteristics of the support and the position of the jig on it. In this work a tool machine allowing 2 translations has been used and a prototypal support allowing 2 rotations has been realised (fig. 4). It is positioned on the machine as in fig.5a. The drilling parameters for such a configuration are automatically evaluated by the software.

Furthermore, by elaborating the CT scan images, a 3D reconstruction of the mandible is obtained.

The practical application of the method consists of the following steps:

- realization of the drilling jig,
- CT scan of the patient's mandible while he is wearing the jig,
- processing of the radiological images for the determination of the implant location and the drilling parameters,
- execution of the guiding hole on the jig by a drilling machine,
- execution of the pilot hole in the mandible by means of the drilling jig.

3. Preprocessing

The CT images are codified in standard DICOM files and have a quantisation of 16 bit. The grey level of the pixels are related to the mass density of the tissue contained in the corresponding volume element in an axial sections according to the Hounsfield Unit scale (HU). The grey levels corresponding to the bone tissue and the teeth are in the range $50 \div 2000$ HU [Passariello 2000].

The program decodifies the DICOM files, extracts the image matrices and store them in an ipermatrix, each element of which is a *voxel*, whose values are expressed in HU. Other information extracted are slice thickness and the pixel dimensions.

Since the Windows environment supports only 8 bit monochromatic images (having 256 grey levels), a compression of the grey scale values of the slices has to be performed in order to correctly visualise them [Gonzalez 1992]. It has been observed that in some cases, in particular in the presence of metal inside the patient's oral cavity, the CT scans are affected by *artefacts*, in the form of saturation of the grey levels in the image. The analysis of the histograms of the images [Gonzalez 1992] has shown that, in many cases, a constant intensity is summed to the whole image and a simple translation of the histogram of the image restores the right relationship between grey levels an HU.

In order to identify the mandibular canal as well as to measure the thickness of the bone, coronal,

sagittal, panoramic and oblique coronal views are needed. To this aim, an algorithm that extracts *multiplanar reformatted images* from the ipermatrix has been properly developed. To enhance the resolution of the reconstructions, a linear interpolation of the pixel values between the slices is performed. Other interactive algorithms allow the measurement of distances and angles on the mandible. [Caccamo 2001]

4. Determination of the jig reference system

The drilling jig consists of two elements: the *reference plate* and the *bite* (fig.1a). The reference plate is a T shaped sheet of Plexiglas, that has the function to support the bite and to allocate the reference elements which are three steel spheres having a diameter of 3 mm. The bite is a resin cast of the patient's dental arches on which the guiding holes have to be drilled. It also allows the anchorage of the jig to the patient's mandible.

The origin Ω of the Cartesian jig reference system is the centre of the sphere n.1, the x axis is parallel to the direction of a segment joining the centres of the spheres n.2 and 3 as shown in fig.1a.

To calculate analytically the cosine directors of the axes of the jig reference system with respect to the CT reference system $\{l_i, m_i, n_i,$ with $i=x, y, z\}$ it is firstly necessary to find the coordinates of the centres of the spheres. This is obtained by an interactive procedure (fig. 2) which is divided in the following steps:

- the slice in which the circle obtained from the intersection of the ith sphere and the scanning plane has the maximum dimension is selected;
- the centre of the circle is indicated by the mouse on the slice, obtaining the X_i, Y_i coordinates;
- the centre of the circle is again indicated in a coronal view automatically displayed by the software, obtaining the Z_i coordinate.
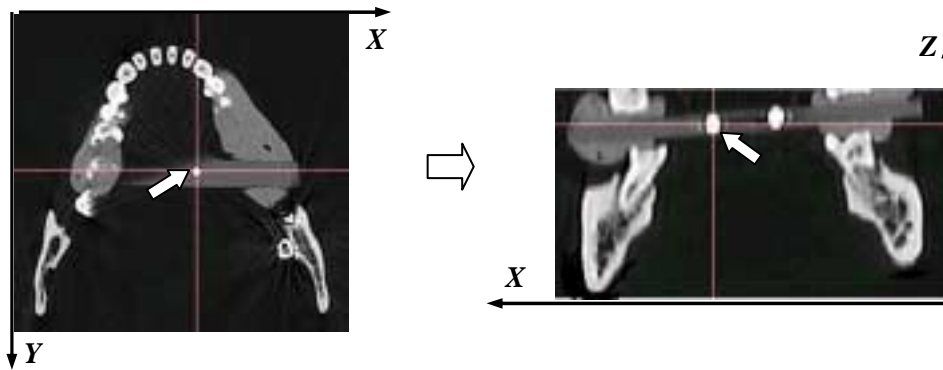
The procedure is repeated for each sphere.

Figure 2. The interactive procedure to locate the position of the centre of the spheres

The equation of the jig reference plane can be written in the form $Z = \alpha X + \beta Y + \gamma$. The parameters α, β and γ can be obtained by solving the following linear system:

$$\begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \end{bmatrix} = \begin{bmatrix} X_1 & Y_1 & 1 \\ X_2 & Y_2 & 1 \\ X_3 & Y_3 & 1 \end{bmatrix} \cdot \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} \tag{1}$$

The parameters $\{l, m, n\}$ respectively for the $x, y,$ and z axes are obtained as follows:

$$l_x = X_3 - X_2, \qquad m_x = Y_3 - Y_2 \quad , \quad n_x = Z_3 - Z_2 \tag{2-4}$$

$$l_y = \det\begin{bmatrix} \beta & -1 \\ m_x & n_x \end{bmatrix} \, , \, m_y = \det\begin{bmatrix} \alpha & -1 \\ l_x & n_x \end{bmatrix} \, , \, n_y = \det\begin{bmatrix} \alpha & \beta \\ l_x & m_x \end{bmatrix} \tag{5-7}$$

$$l_z = -\alpha, \qquad m_z = -\beta \, , \qquad n_z = 1 \tag{8-10}$$

Finally, the matrix allowing the conversion of the coordinates from the CT to the jig reference system can be written, with obvious meaning of symbol, as:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos(\hat{xX})\cos(\hat{xY})\cos(\hat{xZ}) \\ \cos(\hat{yX})\cos(\hat{yY})\cos(\hat{yZ}) \\ \cos(\hat{zX})\cos(\hat{zY})\cos(\hat{zZ}) \end{bmatrix} \cdot \begin{bmatrix} X - X_\Omega \\ Y - Y_\Omega \\ Z - Z_\Omega \end{bmatrix} \qquad (11)$$

5. Determination of the implant seat

In the application of the proposed method the position and the direction of the pilot hole axis are identified by the coordinates of a point and by the angles between the axis itself and one of the reference system axis in the coordinate planes (*position parameters*).
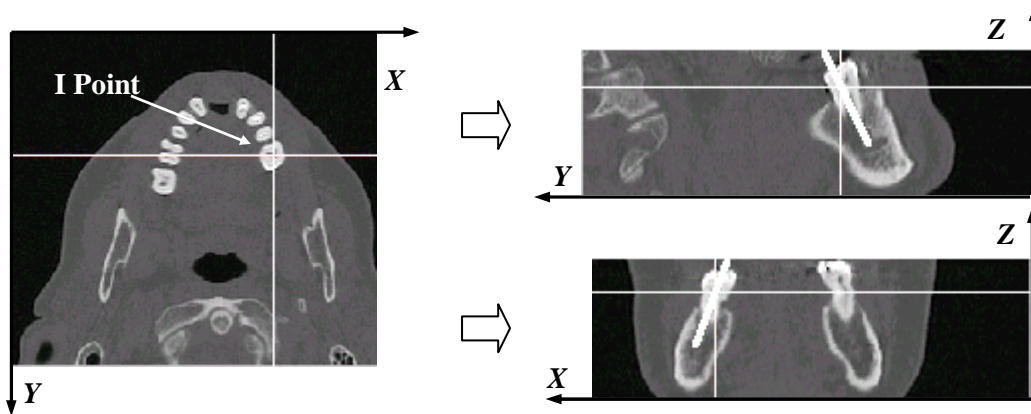

Figure 3. The interactive procedure to positioning the implant seat

In order to determinate the position parameters of the implant seat axis, first a slice of the CT exam is selected, then the point that will be the trace of the implant seat axis (*I* point) is indicated in the slice (fig. 3). The sagittal view (*Y-Z* plane) and the coronal view (*X-Z* plane) containing the *I* point are automatically shown by the software (fig.3) and the operator traces in each one a segment indicating the direction of the implant seat axis. Then the system evaluates the position parameters of the implant seat axis, that is the line passing at the *I* point and having the given directions, referred to the CT coordinate system.

The position parameters in the jig reference system have been chosen to be the coordinates of the point *P* intersection between the implant axis and the jig reference plane, (x_P, y_P, z_P), and the angles between the *z* axis and the projections of the implant seat axis on the *y-z* and the *x-z* planes respectively (φ_x and φ_y). In order to obtain them, first the coordinates of the *P* point are automatically calculated, then, by applying eq.(11), the coordinates of the *I* and *P* points in the jig reference system are obtained, finally, the angles φ_x and φ_y are evaluated by means of the following relationships:

$$\varphi_x = atg\left(\frac{y_I - y_P}{z_I - z_P}\right); \qquad \varphi_y = atg\left(\frac{x_I - x_P}{z_I - z_P}\right) \qquad (12, 13)$$

6. Determination of the drilling parameters

In order to drill the jig, the proper drilling parameters depending on the characteristics of the drilling system have to be determined. In the preliminary experimental testing a prototypal support having two axes of rotation (named ξ and η) has been realised (fig.4). The jig is anchored to the support by 2 cubes made of wood, shaped to guarantee that the axes of rotation of the support have the same directions of the *x* and *y* axes and that their intersection coincides with point Ω. The support is fixed on

the table of the machine tool in such a way that the ξ and η axes are respectively parallel to the ξ' and η' axis of the guide bearing axes of the machine tool and lie in the same vertical planes as shown in fig.4.
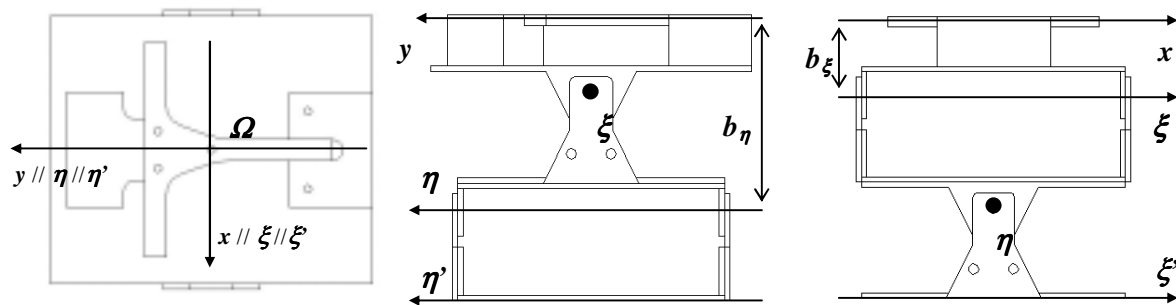

Figure 4. The reference systems in the support

In order to drill the bite, 2 rotations around the ξ and η axes (φ_ξ and φ_η) and 2 translations along the ξ' and η' axis of the machine tool ($\Delta\xi$ and $\Delta\eta$) have to be given. Since rigid rotation are imposed, the φ_ξ and φ_η rotations coincide with φ_x and φ_y respectively:

$$\varphi_\xi = \varphi_x ; \quad \varphi_\eta = \varphi_y ; \tag{14, 15}$$

Since ξ and x axes and η and y axes are parallel, but not coincident, equations to calculate the translations $\Delta\xi$ and $\Delta\eta$ depending on the distance b_ξ and b_η are needed [Caccamo 2001]:

$$\Delta\xi = b_\xi \cdot \text{sen}(\varphi_\eta) + x_P \cdot \cos(\varphi_\eta) \;\; ; \;\; \Delta\eta = b_\eta \cdot \text{sen}(\varphi_\xi) + y_P \cdot \cos(\varphi_\xi). \tag{16, 17}$$

As soon as the interactive procedure to determine the implant seat axis is finished, the software automatically calculates the drilling parameters and saves them in a text file that can be displayed and printed.

The procedure to practically execute the pilot hole on the bite consists in five steps:
- placing and anchorage of the jig on the support,
- placing of the support on the table of the machine tool,
- setting of the translations $\Delta\xi$ and $\Delta\eta$,
- setting of the rotations φ_ξ and φ_η,
- drilling of the bite.

It has been estimated that the prototypal drilling system produces a coarse error in the range $2° \div 4°$.

7. Experimental testing

A preliminary test has been performed to verify the applicability of the method. It consisted into intercept a visible particular on the outer surfaces of a testing cranium; in particular the mental foramens were selected [Caccamo 2001].

The cast of the dental arches with two protruding in which the pilot holes could be drilled out has been provided. After the CT scan and the image processing, the drilling parameters for the right foramen were $\Delta\xi = 15$ mm, $\Delta\eta = -2$ mm, $\varphi_\xi = 18°$ and $\varphi_\eta = -9°$; the drilling parameters for the left foramen were $\Delta\xi = -18$ mm, $\Delta\eta = 1$ mm, $\varphi_\xi = 16°$ and $\varphi_\eta = 10°$.

As a preliminary result, after drilling (fig. 5-a, b), it has been verified that the guide hole successfully leads to the target and the error appear to lie inside the expected range. Taking into account that the distance between the foramen and the point intercepted has been less than 2 mm, being the distance between the pilot hole and the foramen nearly 40 mm, the error in the angle results in the range $2°\div3°$.
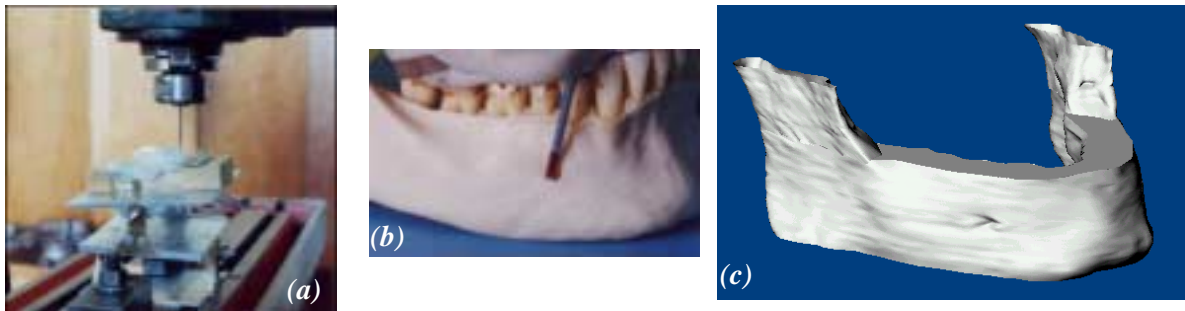
Figure 5. a) The drilling system, b) results of the testing, c) the 3D model of the mandible

8. 3D model

It has also been developed a procedure to obtain the 3D model of the mandible from the DICOM images that will make possible to implement personalized FEM analyses [Tornincasa 1992].

First the CT images are worked out in order to obtain all the external contours of the mandible. In particular a Canny edge detection algorithm is employed [Gonzalez 1992] and all the pixels whose intensity gradient is higher than a proper threshold are selected. In order to obtain only the pixels belonging to the mandible contour, an interactive procedure based on a contour follower method (in particular the *8 neighbours method*) is applied [Caccamo 2001]. The data file containing the coordinates of the centroids of the extracted pixels is processed to obtain a series of NURBS curves [Piegl 1997] stored in *IGES* format [IGES 5.3 1996]. By lofting these curves the 3D model can be obtained. Figure 5.c shows the mandible modelled with Pro/Engineer.

9. Conclusions

A guided surgical drilling method has been presented. The aim of the method is to help the surgeon in determinating the location of the implant seat by software procedures of analysis of the CT scan images and to minimise the need of experience and ability of the surgeon himself during the execution.

Although the limits in the precision of the method have to be more precisely tested, at present it appears that its precision and efficacy mainly depends on the ability of the support in reproducing the drilling parameters determined by the software.

The 3D model obtained could be used to implement personalised FEM analyses.

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