MIRACLE: A CAD/CAM SYSTEM FOR THE MANUFACTURE OF DENTAL SURGICAL SPLINTS

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Abstract: Nowadays, design and manufacturing process of dental prostheses is very handmade, time consuming and has a raised economic cost. Besides that, there is no objective methodology for the fulfillment of its functional design specifications. This paper presents an overview of MIRACLE project whose objective is the development and validation of an intelligent system for the design, simulation and flexible manufacture of implant-supported dental prostheses. The developed system in MIRACLE is a CAD/CAM system which allows to test the functional characteristics of dental prostheses considering mandible-maxilla interaction (called occlusion) using virtual models, contrary to most commercial solutions where this test is performed using expensive anatomical replicas tested with mechanical articulators and evaluated with patients. Another objective of MIRACLE is to develop a parametric finite elements model (FEM) of the whole prosthesis in order to analyze the failure risk of dental implants and prostheses before its surgical implantation enabling a re-design process. This paper is focused on the CAD/CAM subsystem developed in order to automatize the process of manufacturing surgical guides using several 3D models of the patient dental anatomy. A summarized version of the image processing step will be also presented. The CAD/CAM subsystem has been clinically validated achieving mean errors less than 5 degrees in the placement of the prosthetic crowns.

1 INTRODUCTION

In an implant-supported prosthesis (PDI), the prosthesis is attached to an implant placed directly on the mandibular or maxillary bone of the patient. The process of a PDI implantation has been modified substantially in last years. Approximately five years ago an implantation was made in two phases of the set prosthesis-implants. In a first step, the implant was placed and , after 3-6 months, when the osseointegration between implant and bone took place, the dental prosthesis was placed. Nowadays the implant load protocols are being modified in order to give the implant a fundamentally masticatory function at the moment of their positioning or in the three following days ("load or immediate function").

1.1 State of the Art of Implant-supported Prosthesis

First antecedents of immediate load were given by Ledermann (Ledermann, 1979). He placed an overdenture on 4 implants between the dental foraminae in the same day of the surgery. Later on, Schroeder (Schroeder, 1985), histologically demonstrated an intimate union between bone and implants following the same methodology that Ledermann. Schnitman et al. (Schnitman et al., 1990) obtained a medium and long-term success rate from 88 to 97% for implants with immediate function placed in anterior mandible. The load or immediate function on implants can offer great advantages to the patients (Nuzzolease, ; Uribe et al., 2004) and the osseointegration of implants can take place just a short time after the intervention (Fillies et al., 2005).

The advantages of this type of implants as op-

Figure 1: Example of dental implant fixing process.

posed to implants without immediate load are reduction of treatment time after surgery, stabilization of height of the bone and improvement of patient's aesthetics. Nevertheless, the greater limitations of this method are the risk of implants losses due to lack of retention, the technical difficulty for the manufacture of the prosthesis and the mechanical failure (Esposito et al., 2006) of fixations.

With this new technique, the success of dental prostheses depends to a great extent on its functional benefits and interface adjustment between prosthesis and implant. This fact forces the laboratories to make exact and much more customized designs for each patient. Also, what is more important, we cannot make multiple tests with the patient, as it happened with the previous technique, so it is due to make a design that works perfectly. Figure 1 shows the process of an implant placement.

1.2 State of the Art of Dental CAD/CAM Systems

The first use of CAD/CAM systems in dental field was in early 80s. One of the main application lines was its intraoperative use to dental restoration using ceramic pre-manufactured monoblocks (Mrmann, 2004). The use of structural material of high strength such as structures based on aluminium or zirconium, which can only be prepared in a CAD/CAM system, has increased the lifetime of the restoration leading to a market expansion during last years. The greatest companies of the dental sector have already incorporated specific 3D-design software for dental prostheses which allows to generate virtual models improving the accuracy and the automated manufacture of the support structures of the dental prostheses. On these structures the rest of the prosthesis is made later. Some of these commercial products are: CEREC 3D (Sirona Dental Systems) (Mrmann, 2004), Everest (http://www.kavo-everest.com) and Lava (http://cms.3m.com/cms/US/en/2-21kzikuFW/view.html).

Basically, all these CAD/CAM systems have three functional components (J.Strub et al., 2006):

- Data capture or scanning, in order to obtain the buccal data (dental preparation, adjacent teeth and dental occlusion geometry).

- CAD for a geometric design of the restoration. These CAD systems have some simple functionalities to geometrically modify the restoration to be designed. In any case, simulation tools for functional analysis are provided.

- CAM to restoration fabrication. CAM systems use computer-generated information to shape physical objects, using subtractive methods (part of the material of an initial block is removed in order to generate the desired shape) or additive ones. The additive methods are used in rapid prototyping which are becoming the most used method in modern CAD/CAM dental systems (Gebhardt, 2000; Noorani, 2006).

Nevertheless, these systems only cover partially the prothesis design, excluding simulation of functional and biomechanical behavior. Therefore, MIRACLE project will contribute to develop and to put into dental sector a methodology of "digital mockup" or virtual scale model which is being applied successfully in other industrial areas. The results of the project will allow to do a complete assessment of the final treatment without the need of physical prostheses.

This paper is only focused on the CAD/CAM subsystem developed in order to automatize the process of manufacturing surgical guides using several 3D models of the patient's dental anatomy. With this in mind, in section 2, a brief explanation of MIRACLE is presented and data capture (patient's anatomy importation), registration of different 3D models and dental splint design will be studied in depth. In section 3 a clinical validation of the process of splint design and manufacture, without considering biomechanical analysis and virtual articulator information, will be presented and finally, some conclusions will be discussed in section 4.

2 METHOD

MIRACLE system is able to obtain a virtual model of the prosthesis from the 3D model of the crown, the patient's anatomical models obtained from the CT study and the geometric records of the patient's functional characteristics. This virtual model allows to do the functional and biomechanical validation of prostheses considering their functional benefits based on their anatomical characteristics. Advanced CAM techniques are used for the physical manufacture of prostheses by means of advanced techniques of fast manufacturing such as HSM (High Speed Milling and Rapid Tooling). In order to achieve this goal, high velocity and precise milling machines are used, and also

rapid prototyping/manufacturing equipment based on SLS (Selective laser Sintering and Stereolitography).

2.1 Patient's Anatomy Model Importation and Models Registration

The first step is the capture of the data. The system imports two 3D models of the patient's maxillofacial anatomy: the 3D model obtained from CT scan (CT model) and a high precision 3D model obtained by laser-scanning a physical plaster model (laser model). The information obtained with both models are complementary. On one hand, the CT model provides information from different anatomical structures (cortical bone, trabecular core, mandibular canal) although it usually presents metallic artifacts (specially near the teeth surface) due to the CT scanning process. In this model, the dentist will plan the surgery. On the other hand, the scanned model only provides precise information about the surface of the teeth, without the presence of these artifacts. Besides the data acquisition using a CT scanner, an image processing step is required in order to obtain a precise model of the patient's anatomy.

The aim of the image processing step can be divided into two different but related main lines. Computer-aided dental planning systems must provide all the available information to the dentists/surgeons assuring enough accuracy to take decisions with high reliability. Planning systems usually represent a 3D view of the jaw, allowing the specialist to plan the position of the implant. However, for a precise dental implant planning, an exhaustive segmentation of the jaw tissues is necessary, focusing on the mandibular channel, which holds the dental nerve, because its injury could cause lip numbness. Consequently, on one hand, the project focuses on the improvement of image quality reducing metal artifacts to enhance the 3D reconstruction (Naranjo et al., 2009) and, on the other hand, the aim is to segment the tissues present in the human jaw to provide reliable information to dentists or surgeons. Our segmentation method, presented in (Lloréns et al., 2009), has achieved good results in terms of detection and false alarm probability and merit factors of 96.9993 and 99.7696 for cortical bone and inferior alveolar nerve, respectively.

Once the system has imported the necessary data, and the surgeon has planned the location of the prosthesis in the CT model, the next step is to register the laser model and the CT model including the implants planned by the clinic. All this information must be referred to the same coordinate system in order to design the surgical splint. Hence the need of the registration.

The registration process consists of two steps:

1. A pre-registration stage where the specialist selects manually a set of points in one of the models and its correspondences in the other. After that, the models are coarsely registered using the method proposed by Arun (K.Arun et al., 1987), which uses the Singular Value Decomposition to obtain the registration matrix. Figure 2-a shows the result of this step. On the left, the figure shows the CT model, the locations of the planned implants marked with numbers, and the points selected by the user for the pre-registration.

2. Registration refinement. To improve the precision of the registration the Iterative Closest Point (ICP) algorithm (P.Besl and Mckay, 1992) is used. This algorithm tries to minimize the difference between two clouds of points. In our case, only those areas selected by the specialist, which are present in both models will be taken into account in the ICP algorithm. Figure 2-b shows the final result of the registration process. On the left, the area selected by the user in order to be taken into account in the ICP algorithm is highlighted in red. On the right, the superimposition of both models is shown.

2.2 Surgical Splint Design and Manufacture

The last step in the process of design using the CAD/CAM system will be the design of the surgical splint. The splint is designed using the result of the registration stage and considering the information provided by the laser model (surface of the teeth) and the implant locations, necessary to determine where the holes in the guide will be needed. Figure 3 shows different views of the virtual designed splint.

The system performed the simulation of the prosthetic abutments, crowns and suprastructures, and the relationships with the antagonist arch before surgery. The planning provided information to make *surgical splints* by means of stereolitographic techniques. Stereolithography is a new technology able to provide physical models solidifying selectively an ultraviolet-sensitive liquid resin, by means of a laser beam, reproducing the true maxillary and mandibular anatomic dimensions. With these models, it is possible to make surgical guides that can place the implants *in vivo* in the same places and same directions as those in the planned computer simulation.
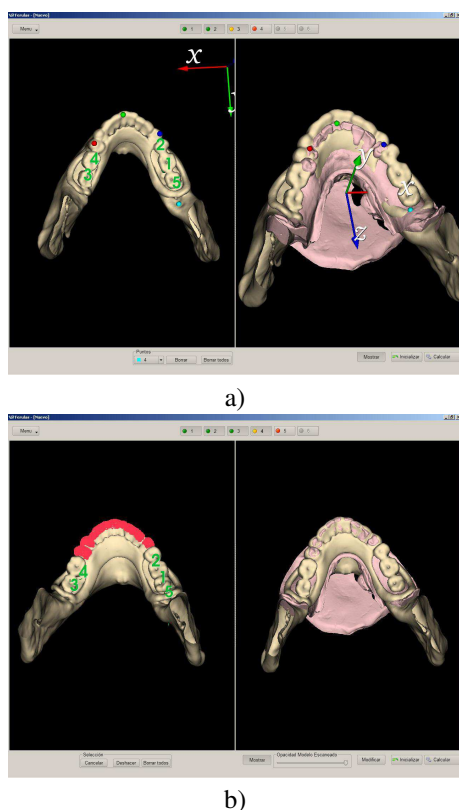
a)

b)

Figure 2: Registration results. a)Pre-registration result. b)ICP algorithm result.

Figure 3: Virtual model of the designed splint.

3 VALIDATION AND RESULTS

In this section the validation of the process of splint design and manufacture, without biomechanics analysis and articulation data, is presented.

A *test set* of 23 patients, with mean age of 35 years, has been considered for this study. All the patients needed rehabilitation treatments from a single dental piece up to the whole jaw (edentulous patients) and all they presented common clinical and psychological parameters. No significant diseases were detected. Particularly, the test set consists of 18 partially edentulous patients and 5 edentulous ones. The patient data required for this study consists of medical history, cast of lower and upper jaw, study of bite registration in an adjustable articulator and radiographic diagnosis CT-scan study with Cone Beam technology. CT data is obtained by means of GE MEDICAL SYSTEMS HiSpeed QXi and Philips Medical Systems - Philips CT Aura.

In order to validate the results obtained by the planning system CT data was processed and the placement of the implants was estimated according some c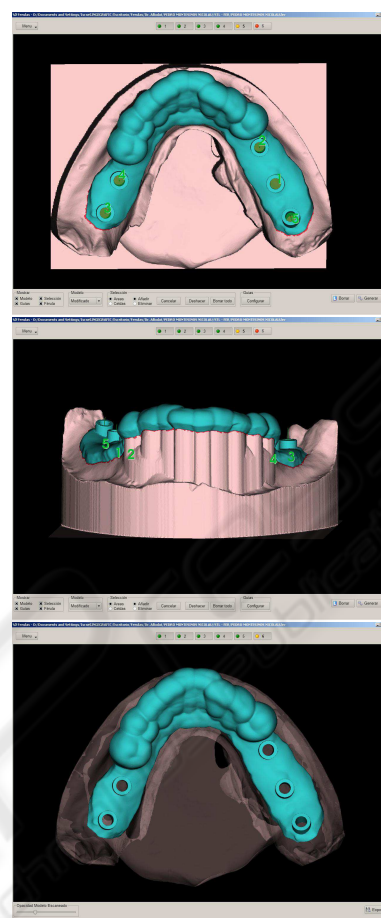riteria. On one hand, according to anatomi-cal criterion, the placement was inferred depending on the osseous suitability. The implant must be surrounded with the largest available bone extension, looking for the largest osseointegration surface. On the other hand, according to prosthetic criterion, starting from the estimated placement as explained above, the placement was adapted to the antagonist teeth. Diameter and length of the implant were refined.

The implant surgery was done using a standard protocol. The patient was anesthetized with lidocaine 2% with 1:100 000 epinephrine. The osteotomy and subsequent implant-drilling procedures were performed using the personalized surgical-guidance template which fitted snugly onto the patient's teeth during the implant procedure. The surgical-guidance template had 2.2-, 2.8-, and 3.5-sleeve apertures, corresponding to each successive drill. Once the final drill was used, standard implant was placed. Forty implants were evaluated (in 23 patients). The mean estimated error was 5.0 degrees. 23 implants (57.5%) were estimated with errors under 5 degrees. Figure 4 shows the results of the different process steps for a

238

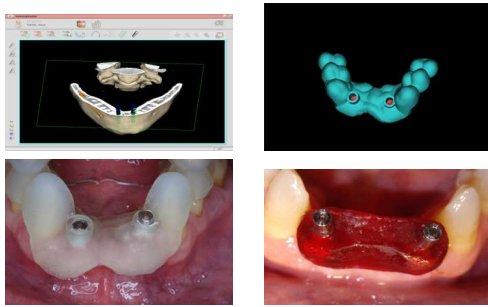patient: surgical planning, splint design, splint manufacture and clinical surgery.

Figure 4: Shaping of splints by means of stereolitography. Planning view, virtual surgical splint and real surgical guide.

4 DISCUSSION

This paper presents MIRACLE project, whose objective is the development and validation of an intelligent system for the design, simulation and flexible manufacture of implant-supported dental prostheses. The system, which is still being developed, is described in this paper. Its efforts are focused on data capturing, surgical planning and surgical guide design and fabrication.

In order to validate the modules of data capturing, image processing, planning system and surgical guide design, an experimental study has been done. Forty implants were evaluated in 23 patients with mean age of 35 years. All implants were placed by two step surgery in the mandible. A surgical template based on the CT images and on the abutment replica of the working models was used for the evaluation of the accuracy of implant placements. The difference between the proposed and real directions was measured by the clinical protocol. After surgery the surgeons tried to fix the prosthetics crowns designed before surgery. Errors under 5 degrees were taken as valid in terms of accuracy. The mean estimated error was 5.0 degrees. 23 implants (57.5%) were estimated with errors under 5 degrees. Consequently, this study proves the accuracy achieved by the system developed in MIRACLE project.

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