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Design of a Virtual Articulator for the Simulation and Analysis of Mandibular Movements in Dental CAD/CAM

E. Solaberrieta, O. Etxaniz, R. Minguez, J. Muniozguren, A. Arias

Graphic Design and Engineering Projects Department, The University of the Basque Country,
Urkixo zumarkalea z/g, 48013, Bilbao, Spain
eneko.solaberrieta@ehu.es

Abstract
This paper presents a research project aiming at designing a Virtual Articulator in order to simulate and analyze mandibular movements of the human jaw. Its main goal is to improve the design of dental prostheses, adding kinematic analysis to the design process. First, plaster models are scanned. Second, the type of articulator is selected. Third, the prosthesis is statically modelled. Fourth, excursive movements are simulated using a CAD system, analyzing occlusal collisions to adequate/modify the design. Finally, the current shortcomings of virtual articulator simulation are discussed in detail and a research prospect is advanced.

Keywords:
Dental Virtual Articulator, Occlusal contact, Collision Detection, Dental CAD/CAM

1 INTRODUCTION

This project arises out of the need to design a Dental Virtual Articulator in order to simulate and analyze mandibular movements of the human jaw. This can be achieved by means of CAD systems and Reverse Engineering tools.

This development has been made at the Product Design Laboratory (PDL, www.ehu.es/PDL), in the Faculty of Engineering of Bilbao (The University of the Basque Country). This Laboratory has focused its investigation efforts on Reverse Engineering and Rapid Prototyping knowledge areas and is currently looking for new fields of application for these new design methods in an effort to promote technological transference with neighbouring companies.

The PDL is developing the design of this virtual articulator in collaboration with the Department of Prosthetic of the Martin-Luther University of Halle. In addition, the Dentistry Department at our university (The University of the Basque Country), has supported this project with some useful advice.

In this first step, different articulators have been selected to be modelled through different CAD systems (SolidEdge and CATIA). The design process has been carried out using measuring tools and Reverse Engineering tools available at the PDL. These tools are: Handyscan REVscan 3D scanner and its software (VXscan), Reverse Engineering and Computer-Aided Inspection Software (Geomagic Studio and Qualify), Rapidform XOR, as well as ATOS I rev.2 GOM 3D scanner.

Once the articulator is digitized, the next stage is to obtain the upper and lower dentures digitally. Apart from this, it is necessary to register the relative location of the occlusal surface referred to the intercondylar axis. This is achieved by means of the face bow. Afterwards, the design of the dental prosthesis is developed using the CAD system and finally, mandibular movements are simulated. The final purpose is to optimize the design of the dental prosthesis whilst avoiding collisions during the excursive movements.

2 STATE OF THE ART

Nowadays, around 90% of technical dental work is carried out using the wax-up technique to generate the cast framework and then, the design work finishes with the hand ceramic phase (drop by drop) (Figure 1).

Figure 1: Design of a tooth by hand

After comparing the results of cast framework and CNC machining (computer aided system) [1], the conclusion is that CNC machining has obtained results of the same accuracy in less time. Besides this, there are several advantages in producing computer-aided prostheses such as time, data registration, material resistance, control of several parameters, etc. Therefore, nowadays there is no doubt as to the vast potential offered by CAD/CAM-systems. Throughout the last years, thanks to 3D scanning and computing developments, some very relevant improvements have been made in digital dentistry.

However, digital dentistry is still unable to offer some possibilities. Standing out among them is the kinematic design of occlusal surfaces. Focusing on this particular field, as there is no possibility of applying real movements in dental CAD systems, most of them are not as good as typical mechanical dental articulators. Current CAD/CAM-systems can only work as simple mechanical occluders, allowing for just one rotation movement along a hinge, so the dental prosthetist must design statically. Once the prosthesis is designed, the generated denture must go back to the mechanical dental articulator and apply the movements manually on the articulator so that occlusal collisions can be eliminated.

2.1 Mechanical dental articulators

Mechanical dental articulators (Figure 2) are tools that simulate the movements of the human lower jaw and the TemporoMandibular Joints (TMJ-s). They have been used for more than 100 years for different purposes in dentistry (Figure 3). They have become indispensable instruments for dentists in their diagnostic activity as they simulate specific patients for dental technicians in their laboratory work.

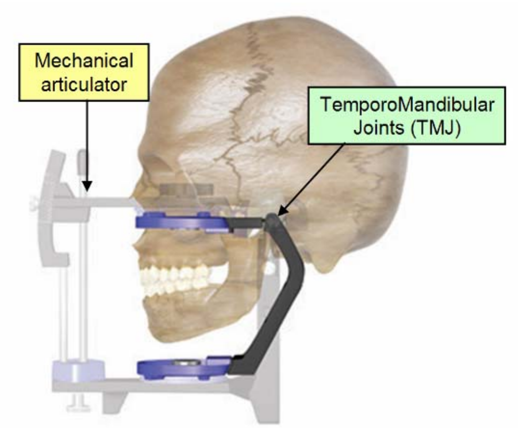

Figure 2: Human skull and mechanical dental articulator

They enable technicians to carry out a study of occlusal relations between dental arches and to detect harmful occlusal interferences on models before more sophisticated occlusal equilibration procedures are performed on the patient. This equilibration of partial and full dentures is also carried out in dental articulators. Together with the use of the wax-up technique, articulators enable technicians to construct fixed or removable prostheses in the dental laboratory according to the particularities of the different movements of each patient. Nowadays, this procedure is considered standard, so current efficient dentistry necessarily involves the use of mechanical dental articulators.

(a) (b) (c)

Figure 3: Occludator, Dentatus ARL and Protar articulators

Over the last 120 years, hundreds of different articulators have been constructed [2-4]. Throughout these years there has been no remarkable development on articulators. Today's articulators are handy, functional and more precise in both construction and operation. Among them, many differences can be pointed out: adjustment, cost, Arcon and Non-Arcon, versatility, etc.

In order to reproduce the individual parameters of the patient the articulator must be adjustable. The setting data are measured on the patient and, using the face bow, the relative location of the occlusal plane is transferred from the patient to the mechanical dental articulator (Figure 4).

2.2 Face bow

To ensure that movements in an articulator are as similar as possible to those of the human masticatory system, models have to be mounted onto the articulator with the help of a so called face bow. This ensures a relationship between the plaster models and the joints of the articulator similar to the relationship between the jaws of the patient and his/her TMJ-s (Figure 4). Therefore, upper and lower models have to be oriented to each other with a high degree of precision in the so called intercuspal position with the help of a wax or silicone bite.

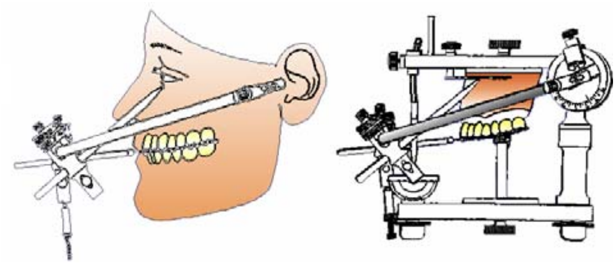

Figure 4: Face-bow mounted on the patient and on the articulator

2.3 Dental CAD/CAM Systems

Dental CAD/CAM systems constitute a new way to produce dental prostheses. There is no doubt as to these high-tech instruments taking over dentistry in the future. The dentists who already offer the most advanced technologies at their dental laboratories are starting to call "dentistry of single visit". In a few minutes, the dentist is able to obtain the necessary electronic impression with a scanner and then, it will take him/her about 20 minutes to have the tooth designed in a computer and afterwards, He/she will have it milled from one ceramic block in less than an hour.

However, considering the limited accuracy of the occlusal surface, this type of restoration can only match the possibilities offered by simple occludators (static design). The system can not take into consideration functional movements, so the occlusal surface of the new tooth has to be manually trimmed to these movements in the mouth or in an articulator. Even a really high-tech-system such as the Cerec3 [5-7], the latest CAD/CAM development, presents this severe handicap despite being able to make an occlusal surface fit the antagonists in intercuspal position. This shortcoming is common to nearly all laboratory CAD/CAM systems. Unfortunately, in order to take these movements into account, it is not possible to integrate any mechanical dental articulator in such systems.

As a consequence, all dental CAD/CAM systems aim to deliver similarly precise occlusal surfaces analogous to the occlusal surfaces obtained when working with adjustable mechanical dental articulators. These systems should use kinematic methods for occlusal surface construction or correction.

3 CAD/CAM DENTAL LABORATORY

The new design paradigm is fully based on computer-aided tools and on virtual modelling and simulation [8]. As explained above, nowadays it is not possible to perform the whole design process on a computer- aided system.

Figure 5: The latest technology dental laboratory

The main goal of this project is to identify the fundamental phases of the development process of dental prostheses as well as to verify the adequacy and limits of current hand-made tools and technologies such as the wax-up technique.

The design process has been intended to implement the best practices used by dental technicians, always ensuring high-level products independently of the craftsmanship of the expert manufacturing the dental prostheses. It integrates the following tools (Figure 5): reverse engineering tools for the automatic (or semiautomatic) acquisition of the patient's occlusal morphology, a modeller that allows the designer to represent both the articulator and the existing dentures of the patient and an environment for collision-based simulation to reproduce the real behaviour of the human mandible and to verify potential interferences.

Thus, the process to obtain the final design of the dental prosthesis consists of several steps according both to the specifically adopted CAE tools and to the obtained partial results [9].

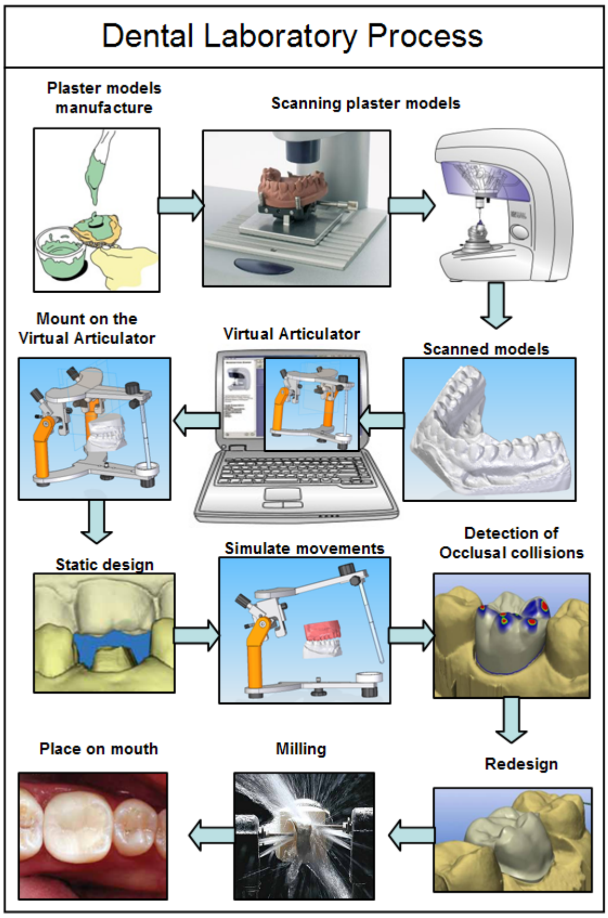

Figure 6: The new design paradigm

The first step consists in a reverse engineering process: plaster models of upper and lower parts of the jaw are scanned to obtain a digitalized set of data of the patient. In this phase, the real geometry of the mouth and its relative location are reconstructed in a CAD system using the face bow.

In the second phase, the type of articulator is selected depending on the required accuracy and/or on the patient's setting data available in each case.

Once the dental prosthesis is modelled, the functional simulation is performed in order to obtain the interfering collision points which could produce a disease in the temporomandibular joints, which may end up producing a disease in the temporomadibular joints. Excursive movements, such as protrusion and laterotrusion, are simulated using a CAD system, analyzing possible occlusal collisions so that the design can be adequately modified.

Finally, the dental prosthesis is milled and tested on the mouth of the patient.

4 VIRTUAL ARTICULATOR DESIGN PROCESS

This step deals with the creation of the digital model of different types of mechanical dental articulators.

4.1 Selection of the articulator

The selected articulator [10], and even more importantly, the skill and care, with which it is used, have a direct effect/impact on the success of fixed or removable restorations. If the dentist's only concern is the relationship of the antagonist teeth at the point of maximum intercuspation, the design and the use of an articulator will be greatly simplified. Since the intercuspation position is static, the articulator will need to act only as a rigid hinge, which is little more than a handle for the model.

The mandible, however, does not act as a simple hinge. Rather than this, it is capable of rotating around axes in three planes. The occlusal morphology of any restoration for the mouth must accommodate the free passage of the antagonist teeth without interfering with the movement of the mandible.

Because of their potential to produce pathologies, occlusal interferences must not be incorporated into restorations placed by the dentist. One way of preventing this problem is the use of fully adjustable articulators which simulate mandibular movements with a high degree of precision. Treatments using these articulators are time-consuming and demand a great skill from both dentist and technician. As a result, the cost of such treatments does not make it feasible for minor routine treatment plans.

Nowadays, most single crowns and fixed partial dentures are fabricated on small hinge articulators that have a limited capacity to simulate mandibular movement or even none at all. While many of the inaccuracies produced by this type of instruments may be corrected in the mouth using valuable chair time, the final result is an occlusion that is less than optimal. Unfortunately, many of these inaccuracies are not acknowledged and they are allowed to remain in the mouth as occlusal interferences which frequently produce symptoms of occlusal disease.

For this project several semiadjustable articulators have been chosen. The following aspects have been taken into consideration: resulting accuracy, cost, time and TMJ´s type. The articulators that have been modelled are the ones shown in Figure 7. They are the Hanau H2 and the Ivoclar Stratos 200.

Figure 7: Hanau H2 and Ivoclar Stratos 200 articulators

4.2 Process

Once the articulators are selected, their structures and shapes are analyzed in order to clarify how to use the Reverse Engineering and measuring tools. The general structure, this is, upper and lower bodies, is similar in both articulators, but the TMJ-s, which are the most important part of the articulators, present a great variety of configurations.

Hanau H2

The first articulator that has been modelled has simple geometrical bodies (cylinder, prismatic bodies and spheres). Therefore, once several physical measures have been taken, modelling each part has not been a difficult task.

Figure 8: Modelling process of Hanau H2

However, the ATOS I 3D scanner has been used in order to have the drafts located on the correct position in space, as shown in the second step of the design process (Figure 8). To get the sections of the scanned point cloud, the Rapidform XOR software has been used. The whole articulator has been constructed combining both measured and scanned parts.

Once the Virtual Articulator is constructed, all the measures are verified. The final step deals with locating the models on the articulator. For this purpose, the relative position of the upper model is scanned using the face bow. Afterwards, the location in the virtual articulator is direct, and the location of the lower model is made using an electronic bite in Centric Relation. Then, the virtual articulator is ready to apply the kinematic simulation using the CATIA CAD system.

Stratos 200

The Ivoclar Stratos 200 has been modelled using a SolidEdge CAD system. As shown in Figure 9, some parts were modelled directly after measuring the mechanical dental articulator. However, the Handyscan 3D scanner has been used, due to its mobility, and almost all the articulator has been scanned.

Using Geomagic point cloud edition software, the useful data has been taken from the millions of points that had been scanned.

Figure 9: Modelling process of Stratos 200

Finally, as it has been done with Hanau H2, the models have been located in the correct position, ready to apply the kinematic analysis.

4.3 Flexibility

The aim of this parameterization is to have the flexibility to fit easily the surface to each patient. Nevertheless, obtaining these data from each patient is not an easy task.

Another advantage of this modelling and parameterization is that it makes it possible to introduce new settings which do not exist on the physical articulator. For instance, at the Hanau H2 articulator the intercondilar distance (Figure 10) can be introduced as a new setting parameter, making the simulation more accurate because the real radius is defined. This can be made with different parameters, making the articulator much more versatile.

Figure 10: Hanau H2 virtual articulator with different intercondilar distances

5 SIMULATING KINEMATICS

As Figure 11 shows, the steps involved in the simulation process become an extension of the product development process.

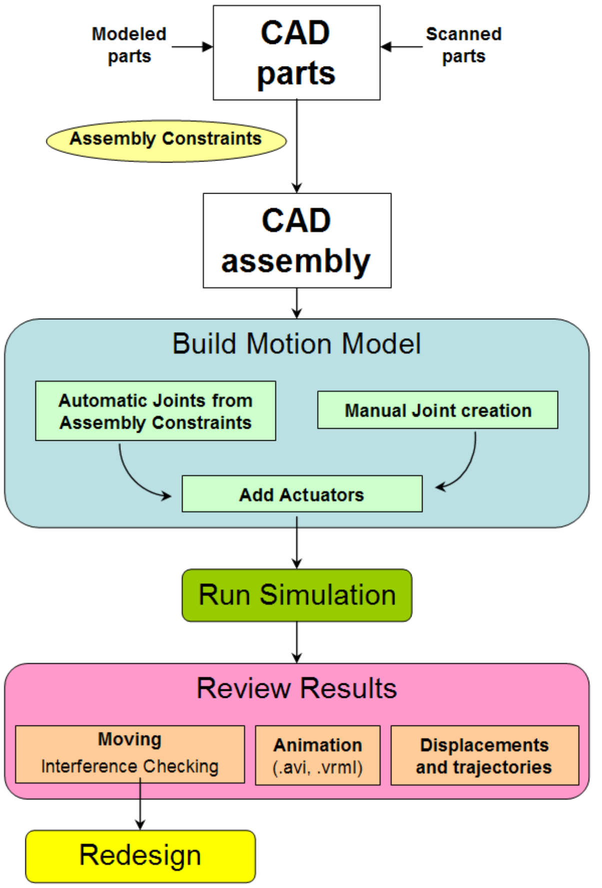

Figure 11: The steps of simulation process

The parts of the articulator modelled in the CAD system and the scanned dentures are converted to solid by means of the Rapidform software and then, they are assembled adding the necessary constraints.

In order to complete this assembling process is finished, mechanical joints will have to be created either by automatically converting the existing assembly constraints or by manually selecting different joints between parts. Then, after adding the commands or actuators, the user will be able to control the DOFs.

Then, the simulation is run and any possible interference on the designed prosthesis is checked out. If there is any collision, the interfering part is removed.

There are several possibilities to generate videos or analyse trajectories of any of the points of the occlusal surface.

Each CAD system has different possibilities and capacities for simulation. The project started using the SolidEdge V18, modelling the Ivoclar Stratos 200 mechanical dental articulator. There were problems to import digitalized models (.stl files). This problem was solved accruing the V20 of SolidEdge, so the virtual articulator was able to simulate excursive movements correctly. However, there has been a limitation when simulating the TMJs parts, because this program is unable to simulate movements based on collision between surfaces. As Figure 12 shows, the structure of the TMJ is made by primitive geometry, as sphere, cones and cylinders. Depending on the movement, the difficulty to simulate is different. Due to symmetric constraint, it has been possible to simulate protrusion through the relation between a cylinder and a changeable protrusion part. However, the SolidEdge CAD system is not able to calculate laterotrusion movements because contact surfaces change at the same time these movements occur. The next step is to overcome these limitations by means of the Dynamic Designer software, based on the MSC.ADAMS simulation engine.

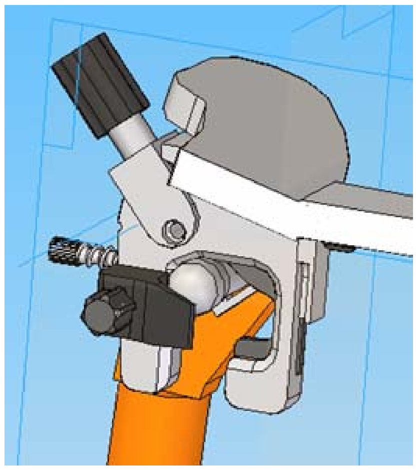

Figure 12: TemporoMandibularJoints of Stratos 200 articulator

Hence, the CATIA DMU-Kinematics module has been used for the next works. This module offers more options than SolidEdge CAD system. So, the movements of the Hanau H2 and Denar Mark II have been simulated more accurately (Figure 13 and 14).

On one hand, the movement of protrusion has been simulated and the trajectory of the first lower left molar has been analysed.

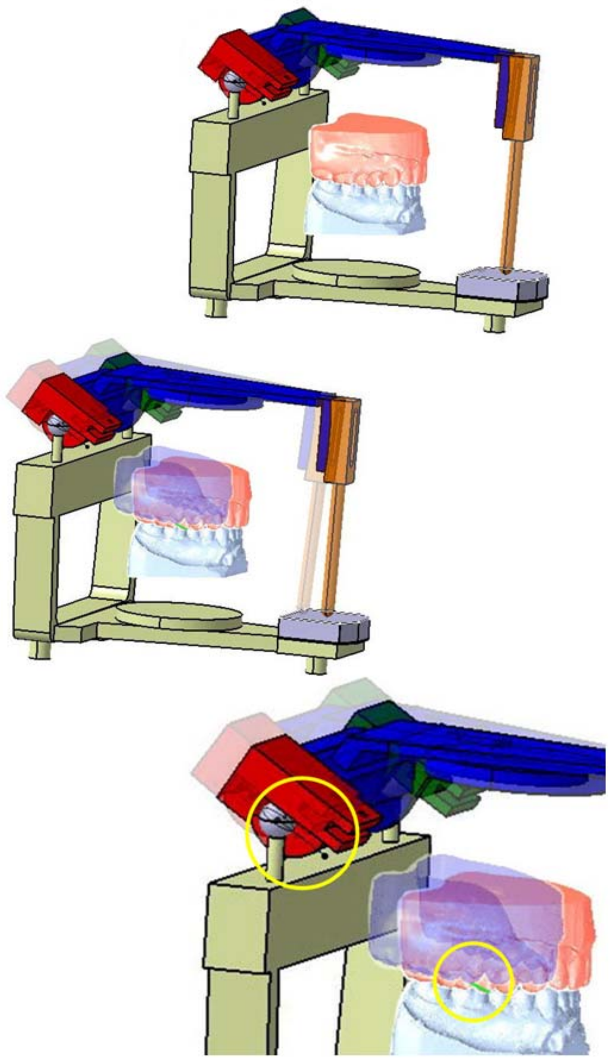

Figure 13: Denar Mark II´s protrusion simulation

On the other hand, the lateral movement has been simulated using different values of the Bennett angle.

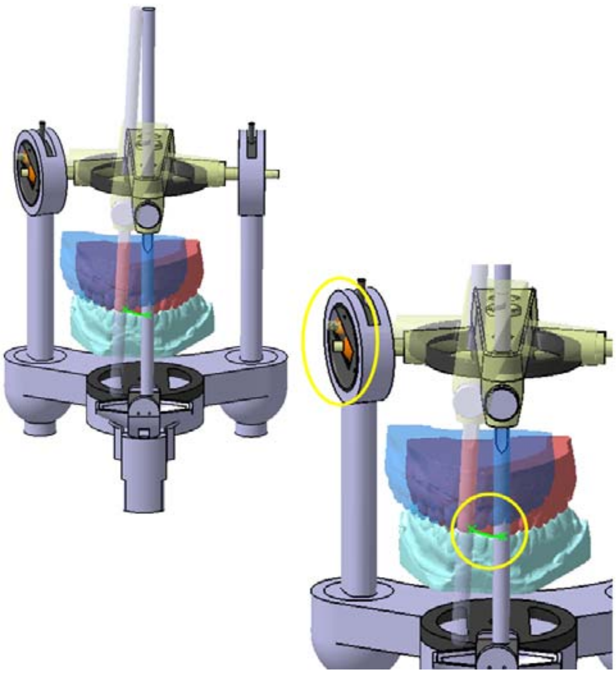

Figure 14: Hanau H2´s lateral movement simulation

Apart from an environment for collision-based simulation, another possibility to reproduce theoretical movements has been explored. Hobo et al. presented [11-13] kinematics studies of mandibular movements in which the trajectory of the centre of TMJ-s is determined by a formula and then, a theoretical movement is applied. When there is no possibility to get the patient's setting data, this is a useful procedure.

6 VIRTUAL DENTAL ARTICULATORS

The Virtual Articulators are able to design prostheses kinematically. They are capable of:

- simulating human mandibular movements,
- moving digitalized occlusal surfaces against each-other according to these movements, and
- correcting digitalized occlusal surfaces to enable smooth and collision-free movements.

Two different approaches have been made till now.

Figure 15: Kordass' Virtual Articulators

The virtual articulator of Kordass and Gaertner [14] from the Greifswald University in Germany was designed to record the exact movement paths of the mandible with an electronic jaw movement registration system called Jaw Motion Analyser and move digitised dental arches along these movement paths on the a computer (Figure 15). This software is able to calculate and visualise static and kinematic occlusal collisions. It is further planned to integrate the system into the design and correction of occlusal surfaces in CAD-systems.

Szentpétery's virtual dental articulator from the Martin-Luther University of Halle [15] is based on a mathematical simulation of the articulator movements. It is a fully adjustable three-dimensional virtual dental articulator capable of reproducing the movements of an articulator (Figure 16). In addition, mathematical simulation contributes to offer possibilities not offered by some mechanical dental articulators, such as curved Bennet movement or different movements in identical settings. This makes it more versatile than a mechanical dental articulator. On the other hand, since it is a mathematical approach, it behaves as an average value articulator, and therefore, is not possible to obtain easily the individualized movement paths of each patient.

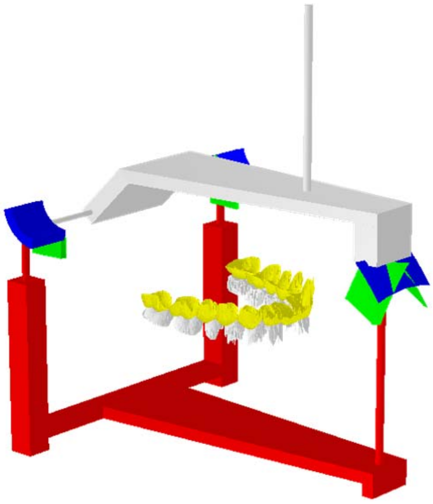

Figure 16: Szentpétery's Virtual Articulators

This handicap was really well solved in Kordass´ Virtual articulator. However, it must be pointed out that it needs a sophisticated and expensive electronic jaw recording system.

Hence, this project was focused on developing a different virtual articulator based on mechanical dental articulators. Knowing which setting parameters can be registered and transferred to the patient, the user can choose which is the most adequate articulator to use in the simulation. Therefore, the implementation of this Virtual Articulator makes it easier for the user (prosthetist or dentist) to manage it and it allows for a comparison between results. One of the purposes of this work is to compare the differences between using a virtual articulator and a mechanical one.

7 CONCLUSIONS

The two main practical implications of this research project are the improvement of existing dental CAD-CAM systems by adding the kinematics and the analysis of the simulations of different articulators, since each articulator has an individual pattern of movement.

The research project identified several limitations on CAD systems on this specific kinematical application. These problems have been solved throughout the design process.

Another remarkable conclusion is the flexibility and versatility offered by this type of Virtual Articulator. The technician can choose the type and adjustment of the articulator, and what is more, add non existing setting parameters on the virtual articulator.

The experience acquired highlighted how custom-fit products can be translated into a highly qualitative improvement when innovative computer-aided tools integrating all necessary functionalities to carry out the various dental prosthesis (crowns, bridges, partial or complete dentures) designs in an unique Virtual Articulator are implemented.

Ultimately, the prosthetist still relies exclusively on his/her know-how and on standard technical solutions. On these bases, we envisage the need for a development process of custom-fit products based on the virtual environment assisting the whole design process. This process integrates all the necessary tools and performs a collaborative-based approach where each activity is directly supported by the acquired knowledge of the specific domain. Thus, mechanical articulators are not needed any more.

8 FUTURE WORK

This research project will go on developing a Virtual Articulator software that integrates the correcting software for CAD/CAM system directly into the process of construction of crowns and bridges

An educational module will be constructed for didactic objectives in order to:

-demonstrate and illustrate the functions of dental articulators and the human masticatory system

-simulate different types of excursive movements and its influence on the occlusal surface.

-analyze the role and influence of different parameter settings [16] on articulator movements.

-analyze of the occlusion of digitized occlusal surfaces of natural dental arches.

A digital face-bow is another aspect of this project which allows for a more precise location of the occlusal surface. At present, the face bow has to be mounted on the patient and then brought to the dental mechanical articulator. The aim is to reduce and simplify this process of transferring these data to the computer.

Another advantage that is not available on mechanical dental articulators is the possibility to produce an individualized fosa cavity, introducing the setting data on the parameterized fosa surface with the Rapid Prototyping machine. Although this is an 'extra' that is not in the intended direction of the project, it does make the mechanical articulator more versatile.

Finally, it is important to remark that several improvements should be made up when obtaining the patient's data. This is a main shortcoming which generates difficulties on the next step, this is, the use of the articulator and the design process. Therefore, a progress in this sense will bring important improvements on the whole process.

9 ACKNOWLEDGEMENTS

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