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The virtual articulator in dentistry: concept and development

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The future of dentistry is linked strongly to the use of computer technology. If dentists and dental technicians succeed in obtaining qualifications in areas of information technology, dentistry will be able to keep up with the highly networked information society. Virtual reality (VR) technologies have a strong impact on research, development, and industrial production. VR technologies in dentistry will be used to provide better education and training by simulating complex contexts and enhancing procedures that are traditionally limited, such as work with the mechanical articulator. The diagnosis of dysfunction and dysmorphology demands advanced skills with regard to optimizing occlusal conditions [1]. Decision support for dentists, orthodontists, and dental technicians supplied by a computer tool such as the "virtual articulator" could improve the clinical outcome [1,2–5]. Focusing on concepts and developments, the advantages and clinical consequences of using such tools are discussed.

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Need for a VR articulator

Currently, the mechanical articulator is used for the functional simulation of the effects of dysmorphology and dysocclusion. A mechanical device is limited in its ability to simulate the variability of biologic systems, however (ie, the dynamic conditions of jaw movements and dependent aspects). For instance, mechanical articulators cannot simulate

- The mobility of the teeth when using plaster casts in it
- The distortion and deformation of the mandible during loading conditions (the mandible bends in maximal opening position to the inner side, which entails problems when making impressions of teeth during wide opening)
- The complexity of movement patterns because the movements of the mechanical articulator follow border structures of the mechanical joint, which never represent the effects of resilience of the soft tissue or the time-dependent, muscle-guided movement pattern of chewing

Casts cannot represent the real dynamic conditions of the occlusion in the mouth. Many other problems regarding the technical procedure and dental materials decrease the accuracy of reproduction:

- The deformation of registration material (eg, wax, which is susceptible to heat)
- Repositioning the cast into the bite impressions without leaving any space
- The stability of the articulator itself
- The correct orientation of the cast
- The use of rigid and expanded plaster material

Because of these basic problems, the reproduction of dynamic, excursive contacts seems to lower the reliability. Although they adjusted the articulator with computerized axiographic data, Tamaki et al [6] report that only 82% of the teeth in the mechanical articulator reproduce protrusive contacts and 90% reproduce laterotrusive contacts. 66% of the protrusive and 81% of the laterotrusive contacts were correctly located. The mechanical articulator also creates new contacts. VR is intended to help solve these problems.

In contrast to the conventional mechanical procedure, the VR tools enable three-dimensional navigation through the occlusion based on every point of view while the mandible moves along predefined pathways (as the mechanical articulator would do) or reproduce movement patterns of mastication that never can be simulated in mechanical systems. The digitizing of tooth surfaces opens possibilities in manipulation procedures to improve the occlusion. Computer aided design/computer aided manufacturing (CAD/CAM) techniques or tools for a virtual set-up of the teeth could be linked. Currently, the virtual articulator is concerned with better visualization of details and supports the use of mechanical tools, but it will replace them in the future. Importantly, it would influence the quality of the networking communication between dental practice and laboratory, helping to produce the best-fitted occlusal restorations possible. The VR articulator will be affordable and economical in private practice, with costs perhaps depending on demands for use. No price estimation for the basic module can be specified at the current stage of development. The following discussion presents ideas on how a commercial product could be designed.

Conception of a VR articulator

This article presents concepts and strategies for replacing the mechanical articulator in the future with a virtual one. This virtual articulator will reduce significantly the limitations of the mechanical articulator and, by simulating real patient data, allow analysis of static and dynamic occlusion and gnathic relations and joint conditions. Given the properties of VR, other modules can be added in principle.

For instance, a CAD module is useful in improving the functional occlusion by manipulating the occlusal surface [1,4,7,8]. An orthodontic set-up module allows an individual set-up of selected teeth or a whole arch [5,9]. This makes the planning of orthodontic treatment interesting, because the future occlusion can be simulated to a certain degree. The positioning of implants requires information about the conditions of the bone taken from radiographs or computed tomography (CT) scans. Combining image data and a virtual set-up of the suprastructure, an implant-positioning tool would guide a navigation system to the best implant position.

The various functional options provided by a mechanical articulator also must be implemented [4]. Simulating the mechanical articulator may be useful for combining the results of mechanical and computer-based tools and comparing both techniques in terms of teaching requirements. One of the most interesting options offered by the virtual tools is the ability to "move" and navigate through enlargeable occlusal surfaces to explore the details of functional occlusion that cannot be visualized using casts alone. To study the impact of joint determinants (eg, Bennett angle, slope of condylar guidance, side shift) on occlusal movement patterns, the virtual articulator requires virtual tools for joint-constraint adjustment and collision detection, which simulate the stops of static and dynamic occlusion. Such collision detection is implemented in the most recent version of the VR articulator, which has been developed in cooperation with the Fraunhofer Institute for Computer Graphics (IGD, Darmstadt, Germany) and Kettenbach GmbH & Co KG (Eschenburg, Germany).

Preliminary and matching procedures for adjusting the VR articulator

The use of a three-dimensional laser scanner for digitizing data is the prerequisite to visualizing the tooth on the screen [10]. The three-dimensional laser scanner automatically digitizes a single tooth, complete denture models, or centric relations referred to previously. For digitizing dental arches and bite records, the three-dimensional scanner "Scan 3D" by Willytec (Munich) is used [11]. The reproducibility is 2 μm with the standard objective, and the accuracy after matching is 10 μm. Between 8000 and 14,000 points per second are digitized. Afterward, the data are available for any computerized presentation, manipulation, or navigation.

The methods of programming and adjustment of the VR articulator have been published previously [3,9,12] and are reviewed briefly. Among various registration systems, the ultrasonic measurement system Jaw Motion Analyzer (Comp Zebris, Isny, Germany) is used to record and implement the movement pattern. This system is based on measuring the velocity of ultrasonic impulses emitted from three transmitters attached to the lower sensor. Four receivers are attached to a face bow opposite them. This positioning enables the detection of all rotative and translative components in all degrees of freedom. A special digitizing sensor is used to determine the reference plane, which is composed of the hinge axis infraorbital plane and special points of interest (eg, on the occlusal surface).

Subsequently, the movement data finally can be calculated in relation to the digitized points. Silicon-based jaw relation registrations are used to reproduce the best occlusion in the position of intercuspidation. It is important that the registration remain attached to the upper teeth during opening. The registration then should be stabilized with impression plaster on a metal carrier plate. The digitizing sensor is attached to detect three main reference points on the rear of this metal plate. These three points are used to combine movement data and the digitized dental arches.

First, the impression of the upper teeth is digitized and then the record material and the plaster of the lower teeth are scanned. Both dental arches are correctly related to each other. The digitized impressions of the lower and upper jaw can be combined with the scanned data from casts without losing the predefined jaw relationship. By defining and calculating the same reference, both data sets, which come from three-dimensional scanner and jaw movement recordings, were matched and presented in the virtual articulator.

The VR articulator DentCAM

To demonstrate and test VR tools in dental articulation, the VR articulator DentCAM was developed at the University of Greifswald. DentCAM consists of three main windows, which show the same movement of the teeth from different aspects (Fig. 1).

- The rendering window shows both jaws during dynamic occlusion and can visualize unusual views throughout dynamic patterns of occlusion (ie, the view from the occlusal cups while watching the antagonistic

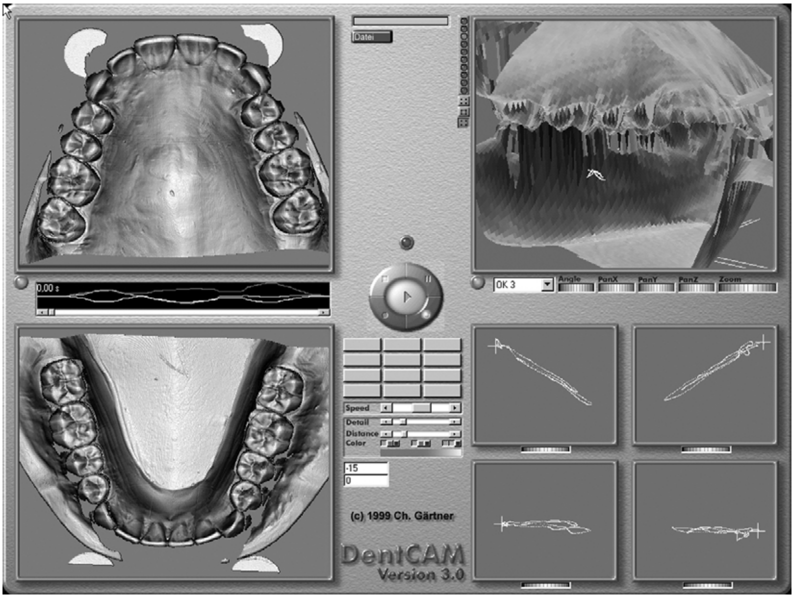

Fig. 1. Interface of the VR articulator DentCAM (occlusal contacts [left], rendering scene and condyle pathways [sagittal and horizontal, right]).

teeth coming close to the intercuspidation position during chewing movements) (Fig. 1, upper right). It also allows the creation and export of animations.

- The occlusion window shows the static and dynamic occlusal contacts sliding over the surfaces of the upper and lower jaw as a function of time (Fig. 1, left). The speed of this movement can be controlled with sliders; a colored differentiation of the contact force is also implemented.
- In a smaller window, the movements of the temporomandibular joint are represented in a sagittal and transversal view, which allows the analysis and diagnosis of interdependencies between tooth contacts and movements of the temporomandibular joint (Fig. 1, lower right).
- The slice window shows any frontal slice throughout the dental arch. This tool helps to analyze the degree of intercuspidation and the height and functional angles of the cusps. With this window, the analysis of guidance and balancing becomes easy (Fig. 2).

Evaluation of the virtual reality articulator DentCAM

The results of validation were recently presented [3,9], and are briefly recapitulated in this article. Comparing the model situation of a mechanical articulator (KaVo, Leutkirch, Germany) to the virtual articulator module,

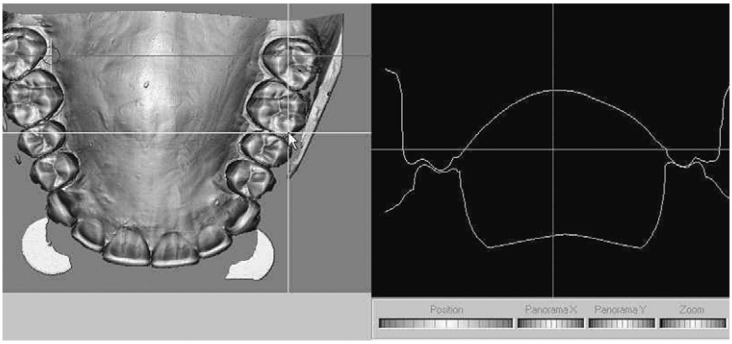

Fig. 2. Visualization of every slice cut through the occlusion.

DentCAM showed approximately the same number of dynamic contacts in lateral movements to the left and right in eight cases (mechanical articulator: 90, virtual articulator: 92). The results demonstrate the correspondence under standardized conditions in relation to the detected number of contacts in both situations [12].

To examine reliability, three operators measured the mandibular movements two times in eight persons. After data implementation, data matching, and programming of the VR articulator, good correspondence was demonstrated in visualizing the number and position of dynamic contacts [9]. With regard to the comparison between the two times of measurements and among the three examiners, the intraclass correlation values are all more than 0.75, which reflects excellent reliability in detection and presentation of dynamic contacts [13].

Modules of DentCAM

In the latest version of DentCAM software, a special orthodontic CAD module was added to simulate the therapeutic result by repositioning single teeth and reforming the dental arch (virtual set-up). Separating single teeth from the complete data set of the upper and lower jaw is a prerequisite to the virtual set-up. DentCAM includes a pointer, which makes it possible to find the tooth-crown margin automatically when positioned in the middle of the occlusal table of molars or premolars or incisal rim or canine top. Continuing tooth by tooth, the procedure results in single-tooth–based data sets that are prepared for special software operations, such as simulation of orthodontic movements. In a case with relative retrusion of maxillary and mandibular anterior teeth, the authors used DentCAM to shift the maxillary anterior teeth to their correct anterior position and design them to produce optimal canine guidance (Fig. 3). Based on the images from the virtual set-up tool, an active protrusion splint is included in the treatment plan [9].

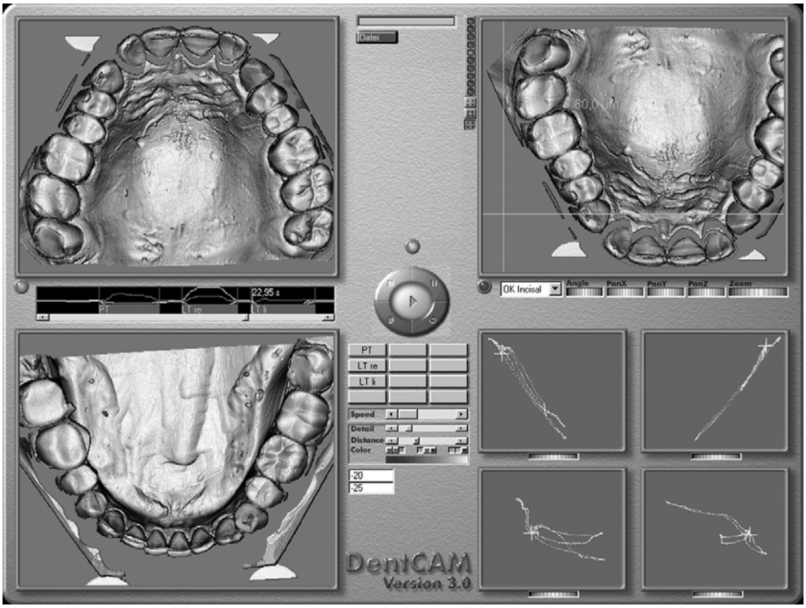

Fig. 3. Orthodontic set-up: optimizing the dynamic occlusion (canine guidance) with protrusion of the upper front.

For the detection of tooth wear, there is another module that semi-automatically analyzes the teeth for signs of wear or bruxism (Fig. 4). The algorithm searches for facets and separates them from the surrounding surface using special segmentation algorithms [5].

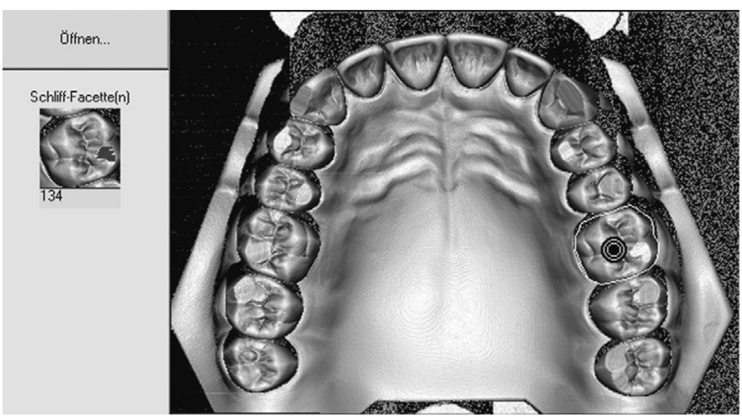

Fig. 4. Automatic detection of tooth wear facets (segmentation of the single teeth while positioning the cursor in the middle of the occlusal table, visualization of facets' localization in the small picture [left]).

To find the best centric occlusion for maxillary and mandibular total prostheses, the artificial teeth could be moved in the same way as described for the orthodontic set-up (Fig. 5) [3].

A CAD module allows the improvement of the functional occlusion by manipulating the occlusal surface [12]. The occlusal profile of the teeth can be designed with increased or decreased cusps to eliminate occlusal interferences in the dynamic pattern and optimize the occlusion. The data set of newly designed and improved occlusal surfaces can be transferred to a milling machine, producing real crowns and fixed restorations with that particular optimized functional occlusion.

Development of the VR articulator in cooperation with the Fraunhofer Institute

To produce the VR articulator as a marketable software tool, the University of Greifswald, Kettenbach GmbH & Co KG, and the Fraunhofer Institute for Computer Graphics (IGD) cooperated to establish the virtual articulator software system. The object of this project is to develop a core system for dental occlusion diagnosis that can be enhanced with additional functionalities for implant planning or orthodontic intervention planning via plug-ins. The virtual articulator core system requires digital three-dimensional representation of the jaws as input data, generates an animation of the jaw movements, and delivers a dynamic and tailored visualization of the occlusion points. If a device for the registration of patient-specific jaw movements is available (eg, the Zebris jaw motion analyzer), the recorded jaw motion can be integrated into the animation. The system offers many possibilities suitable for integration into CAD/CAM technologies and bridging

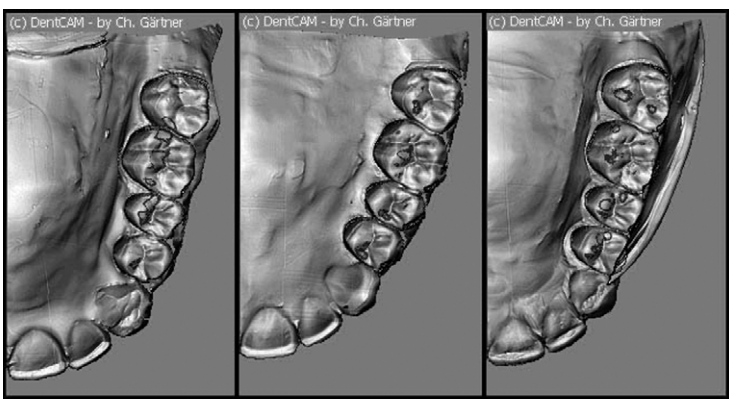

Fig. 5. Improvement of centric stops during bodily medial movement of the molars and premolars (left to right).

the gap between intraoral tooth scanning and computer-aided implant design.

The occlusion diagnosis with the virtual articulator system consists of the following steps (Fig. 6). The first is to generate a three-dimensional digital representation of the jaws using a three-dimensional laser or stripe-projection scanner to obtain three-dimensional digital representations of the teeth. According to the available input data, different planning strategies can be followed:

- If the jaw motion analyzer tool is available, the patient-specific jaw motion can be recorded. The data can be loaded into the virtual articulator software and the three-dimensional movements of the jaws are simulated.
- If the jaw motion analyzer tool is not available, different jaw motions can be defined via parameters, just as with the mechanical articulator (the system gets its bearings from the Protar 7, KaVo). The parameters are illustrated in the motion definition menu. The following movements can be selected: protrusion (parameters: radius of the condylar pathways, maximal protrusion distance horizontal condylar slope), retrusion (parameters: radius of the condylar pathways, maximal retrusion distance), laterotrusion (parameters: maximal protrusion value, Bennett Angle, radius of condylar pathways [left, right], horizontal condylar slope [left, right], shift angle, immediate side shift), opening/closing movement (parameters: maximal opening angle).
- After definition of the motion parameters, collision detection is triggered to recognize the motion constraints, which results in the jaws

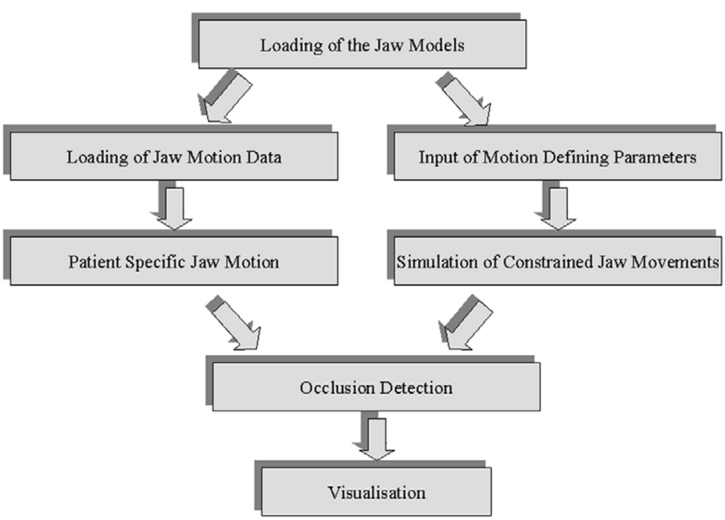

Fig. 6. The virtual articulator planning pipeline.

gliding on each other. For collision detection, a ray-based algorithm is used that is executed in a preprocessing step [14].

- The occlusion detection engine is triggered. For occlusion detection, a distance can be chosen corresponding to the thickness of the occlusion paper used in the mechanical articulator. The occlusion points are calculated according to this defined distance.

Important advantages of the virtual over the mechanical articulator are provided by the tailored visualization possibilities. The system offers the following features (Fig. 7):

- Dynamic visualization of the occlusal conditions is possible, whereas the mechanical articulator offers only a static presentation. When the jaw movement animation is executed, the user can see the occlusion points wandering over the tooth surfaces, synchronized to the jaw movements. The jaw movement animations can be executed easily via a video control panel.
- The system offers separate three-dimensional visualizations of the maxilla and mandible for a top view and an overview of both jaws. A three-dimensional representation of condylar pathways also can be visualized. The jaw models can be manipulated using a section plane, which facilitates a detailed view of every region of interest.

Educational VR settings of the virtual articulator

In the context of learning and teaching, the concept of the virtual articulator provides a natural basis for new VR-based learning environments.

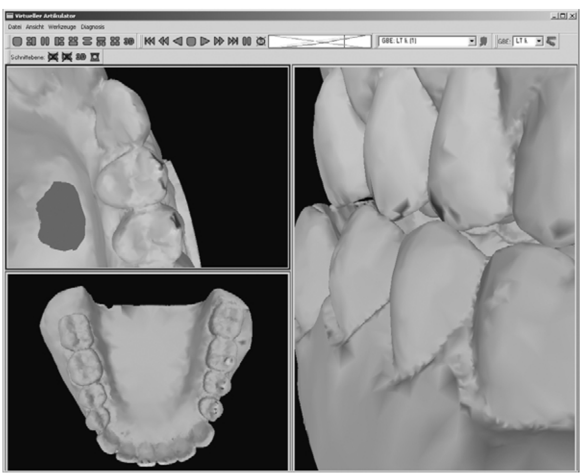

Fig. 7. Virtual articulator user interface: collision detection of dynamic stops.

The objective of our research at Uppsala University was to bring the virtual articulator to other technology platforms for large-scale visualizations and networked collaboration.

In an initial step the authors investigated new forms for visualization of spatial-temporal relationships of jaw articulation in a holo-perspective display environment. This display technology, which is shown in Fig. 8, provides dynamically generated stereo projections of the three-dimensional occlusion situation depending on the users actual head position [15]. The projections are viewed using special stereo shutter glasses to enhance perception of depth. This type of half-immersive visualization surpasses the conventional monitor-based visualization in several ways: using dynamic perspective projection adds motion parallax as another strong visual depth cue into the visualization process. The effect of this is a dramatically increased sensation of spatial depth and enhanced spatial understanding of complex structures. The large size of the display allows visual representation of subtle structures in a real world scale, which enables interactive pointing and annotation when viewed by students and tutors in front of the display. The holo-perspective display can be tilted to a fully horizontal orientation. In this mode, the display resembles a virtual workbench metaphor [16], which is adapted to the conventional laboratory environment in the dental laboratory. The environment as such represents a convenient medium for mediation and collaborative discussion of individual cases.

Although the previously mentioned experimental scenarios proved useful for study scenarios in small tutored groups, they still require availability of

Fig. 8. Dynamically generated stereo projections of the three-dimensional occlusion situation.

advanced hardware facilities and physical presence of students and teachers at appointed laboratory sessions. To further enhance flexibility in learning, we investigated fully virtualized classroom environments as an alternate platform for lecture-based and experiment-based teaching and learning.

The idea behind this approach is to gather students and teachers in a virtual meeting place, which can facilitate the three-dimensional classroom experiments in the form described earlier. As a prerequisite to this, however, the virtual classroom also must provide all conventional means of communication, such as white boards, slide projectors, and voice communication. The authors' approach is based on a fully distributed simulation architecture within which support of specific services can be provided by several different servers in the network. As far as voice communication is concerned, our environment supports the H323 standard through a client interface to OpenH323. Digital slideshow presentations as individually prepared by the teachers may reside on one or several HTTP servers. Under the course of a virtual classroom setting, a presentation script available from an arbitrary HTTP source is used to retrieve references to the slides to be shown under the presentation. By that means high flexibility is accomplished, which also allows the virtual classroom system to process almost immediately the course material that is already available on already existing course homepages.

Students and teachers can log in to a shared classroom and perform in virtual lectures. Interaction is available through Internet voice communication. Each participant in the virtual classroom is visible through its graphical avatar representation. Pointing is an important means of initiating various activities. For that purpose, the user can control a three-dimensional pointer metaphor to activate and carry out different functions, such as drawing on the white board, advancing presentation slides, and handling interactive three-dimensional experiments. Conversation among participants in the VR classroom also can be initiated using the pointer metaphor. When a user in the virtual classroom wants to start conversation, he or she can point on the avatar of the intended conversation partner and then automatically "flies" toward and moves in front of the respective avatar. This action is similar to people approaching one another in the real world to initiate social contact. Another powerful feature in the virtual classroom is the ability for any participant to collect other avatars in its own viewing position and viewing direction. In contrast to what is possible in physical space, this allows individuals in the VR session to have other participants see the world through his or her eyes. This functionality is particularly useful when discussing subtle details, which require common a view of the same thing.

Fig. 9 shows a sample scene in the VR classroom with all the conventional media tools replicated in the virtual space, and in this application example, a simulation of dental jaw articulation is visible. This simulation allows the teacher and the students to explore the function of individual dental anatomy in a manner that is not possible in the real world.

Fig. 9. Scene from the VR classroom.

Outlook

Virtual reality enables new perspectives in visualizing complex relationships in diagnosis of occlusion and function. The new VR articulator provides interesting modules for presenting and analyzing the dynamic contacts of the occlusal surfaces of the maxilla and mandible and the relation to condylar movement.

A three-dimensional scanner for digitizing data is a prerequisite for automatic visualization of single teeth, complete denture models, and the centric relation. The scanned models combined with the data of the movements (matching) enable the virtual movement and diagnosis of dynamic occlusal contacts and interferences. Such software tools will be introduced and tested in terms of their informative capability for the diagnosis of occlusal dysmorphology and dysfunction. The VR articulator is undoubtedly more than an entertaining novelty. The VR articulator reveals new aspects of occlusal surfaces in a fascinating manner and enables navigation through the occlusal surfaces: an ideal teaching aid.

To improve the functional occlusion, the occlusal profile of the teeth can be designed with increased or decreased cusps to eliminate occlusal interferences of the dynamic pattern. The data set of newly designed and improved occlusal surfaces can be transferred to a milling machine, producing real crowns and fixed restorations with that particular, optimized functional occlusion [2,4,7,10,12].

All in all, the VR articulator is a basic tool that deals primarily with the functional aspects of occlusion; however, it also can be regarded as a core tool in many diagnostic and therapeutic procedures and in the CAD/CAM manufacture of dental restorations. The add-on modules will change conventional ways of production and communication in dentistry and begin to replace the mechanical tools.

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