



## Virtual articulators, virtual occlusal records and virtual patients in dentistry

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### Abstract

Digital technology is broadly used in almost every part of medicine. As tools of digital technology, augmented reality and virtual reality have been adopted in all disciplines of dentistry and dental education. In particular, virtual articulators have allowed for a full analysis of occlusion with dental models that can simulate all mandibular movements in static and dynamic positions. When combined with additional software, virtual articulators can also enhance education and practice, allow for quicker and more precise individualized diagnoses and enable discussions of dental treatment planning options with patients during their first appointment. This article reviews the requirements for virtual articulators and occlusal recordings and assesses their advantages and disadvantages in various aspects.

**Keywords:** augmented reality and virtual reality, virtual articulator, virtual dental education, virtual occlusal record, virtual patient

### 1. Introduction

Over the last few decades, newly developed technologies have revolutionized the world of dentistry and paved the way for exciting developments. For example, virtual reality's applications in dentistry are still being developed but have already resulted in many advances (Patzelt et al., 2014). Virtual reality is a simulation of actual reality that generates an artificial place to replace the real world. Technologies and equipment that are created in virtual environments but have real-world applications are called 'virtual reality technologies and equipment'. The applications of virtual reality in clinical and laboratory procedures have had an impressive influence on research, development and industrial manufacturing and have provided better education and training to dental students by simulating real-world situations through a combination of virtual articulators, computer-aided design, and computer-aided manufacturing (CAD/CAM) technologies, digital face bows, visualizations and virtual dental patients (Bisler et al., 2002; Bhambhani et al., 2013).

'Single visit dentistry' is the most important concept in current practice for patients and dentists. Thanks to newly developed CAD/CAM technologies, a digital impression can be made and a restoration designed in a computer in a few minutes, then milled from a block in an hour. However, with the restricted accuracy of the interocclusal relation in a mechanical articulator, these restorations are merely static designs that have to be adjusted in the mouth or in the articulator during the functional movements of the mandible,

and even semi-adjustable mechanical articulators cannot redesign the occlusal surface of a restoration accurately and precisely while mandibular motions are occurring in real time. These problems can be resolved by using a virtual articulator instead of a mechanical articulator (Solaberrieta et al., 2009).

### 2. Selection of articulator

An articulator is an important factor in patient outcomes that requires the dentist's full skill and care. In this sense, which type is selected has a direct impact on the efficiency and success of removable and fixed prostheses, as well as other dental practices. Most articulators are used to demonstrate only the intercuspation relation in a static situation, like a hinge. However, the mandible does not work like a simple hinge. Even its rotational movement takes place in three planes: sagittal, frontal and horizontal. Parameters such as condylar angle, Bennett angle and immediate side shift should be adjusted as they would be with a mechanical articulator. Under these adjustments, the occlusal surface design of any prosthesis in the mouth must allow for free space between the opposite tooth and prosthesis in order to avoid collisions. It is crucial to control the occlusal interferences and premature contacts, since these issues may result in serious pathologies. Using fully adjustable articulators can prevent this problem since they can simulate all mandibular motions with a high sensitivity. However, rehabilitating teeth using this type of articulator not only costs time, but also requires extra skill on the part of both the dentist and dental technician (Hobo et al., 1976; Pandita et

al., 2016).

### 2.1. Mechanical dental articulators

The first mechanical articulator was described in 1756. Ever since, hundreds of articulators have been constructed and used (Mitchell and Wilkie, 1978). Mechanical articulators simulate the movement of the mandible and the temporomandibular joints. They are the most important devices for both dentists and dental technicians, because they are commonly used in the production of dental prostheses, as well as in the diagnosis and analysis of the occlusal relationship (Fig. 1).

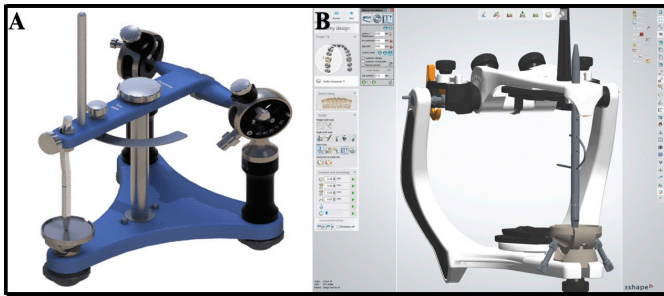


Fig. 1. a: Mechanical dental articulator, b: Virtual articulator

However, they have many restrictions. For example, the dynamic interrelation of the jaws cannot be demonstrated by a mechanical articulator during the chewing process. In addition, time-dependent muscle-guided movement patterns, the resilience of the soft tissue and the real border structure of the mechanical joint cannot be recorded sensitively during chewing (Mitchell and Wilkie, 1978; Solaberrieta et al., 2009). However, with the time-consuming measurements and more complex tool as the axiograph, individual occlusal parameters like protrusive and lateral movements can be recorded (Solaberrieta et al., 2018). Furthermore, comparatively location of occlusal plane can be transferred by using face bow. Mechanical articulators also cause numerous problems during dental technical procedures because of their dental material quality leading to deformations of the plaster and bite registration materials. These problems restrict repositioning the casts into the right bite position and tooth mobility cannot be transferred by a cast. Because of these restrictions, a real dynamic occlusal relationship cannot be established with a mechanical articulator (Gugwad et al., 2011; Maestre-Ferrín et al., 2012; Shadakshari et al., 2012; Singh et al., 2014; Korlakunte and Aljanakh, 2014; Luthra et al., 2015).

### 2.2. Virtual dental articulators

Virtual dental articulators use a computer program called a 'software articulator' (Fig. 1). Thanks to their visualization and simulation of all mandibular movements, they have led to more and more virtual reality applications in dentistry, particularly in regard to the analysis of complex dynamic and static interocclusal relations against each other (Bisler et al., 2002). Combined with CAD/CAM technology, virtual models are obtained and utilized for both the diagnosis and treatment planning of prosthetic rehabilitation, ranging from a single crown to complex cases involving full mouth rehabilitation, and clarify the process from the initial step to the final result of

the treatment. When these factors are taken into consideration, this system offers great advantages not only for prosthetics, but also for orthodontics and dental implant surgery because of its precise measurements. For example, it allows a dentist to replace fragments of jaw bones and fix them into the correct position, realign teeth, create a smile design using artificial optimized teeth, detect and prevent occlusal collisions and analyze the morphology of a patient's teeth (bruxism) by means of dynamic monitoring in three dimensions (3D) of the mandible, maxilla or both (Ryakhovskiy and Ryakhovskiy, 2020). Using this technology, a dentist can also monitor dynamic movements and make specific observations about areas of concern, such as the motion of the temporomandibular joint (Maestre-Ferrín et al., 2012). Virtual articulators can also be used in education to teach students about the function of the articulators, the different movements of the lower jaw, the intermaxillary relations and their influence on the occlusal surface (Sabalic and Schoener, 2017).

### 2.3. Evaluation and classification of virtual articulators

Two main types of virtual articulators exist: 'mathematically simulated articulators' and 'completely adjustable articulators'

### 2.4. Mathematically simulated articulators

This type of articulator, which was first designed by Szentpétery, depended on a mathematical simulation of articulator movements (Szentpétery, 1997). This device enables a dentist to reproduce the movement of a mechanical articulator, making it a fully adjustable 3D virtual articulator (Luthra et al., 2015). Furthermore, mathematical simulation supplies measures that are not obtainable with some mechanical dental articulators, such as condyle angle, Bennett angle, and movements of retrusion, laterotrusion or protrusion in the setting. With these measures, the articulator automatically simulates the movement of the mandible, like a mechanical dental articulator would (Mitchell and Wilkie, 1978; Solaberrieta et al., 2009). These properties make the mathematically simulated articulator far more versatile than a mechanical dental articulator. However, because of the mathematical approach, an average value is used like in the mechanical dental articulator. Consequently, the individual movements for each patient cannot be tracked easily. Examples of mathematically similar articulators include the Stratos 200 (Ivoclar Vivadent; Amherst, NY) and Szentpétery's virtual articulators (Fig. 2). (Gugwad et al., 2011; Korlakunte and Aljanakh, 2014; Bhayana et al., 2015).

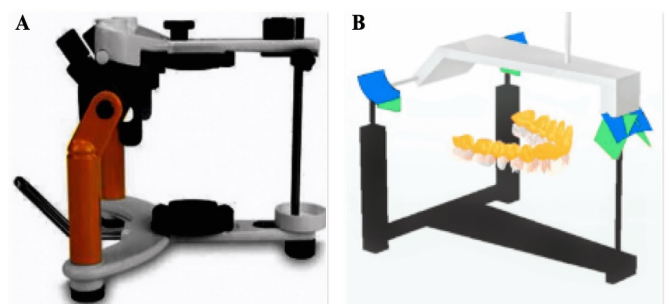


Fig. 2. a: Stratos 200, b: Szentpétery's virtual articulators

## 2.5. Completely adjustable articulators

These articulators were first designed by Gaertner and Kordass and can record and reproduce the precise movements of the lower jaw using an electronic jaw registration system called the 'Jaw Motion Analyser' (JMA) (Fig. 4). This system consists of a basic unit, lower jaw sensor, head bow, bite fork and sensor pen (Gärtner and Kordass, 2003). Its components transmitter and receiver are mounted in the correct position by means of the sensor. The head bow has eight ultrasonic microphones transmitters that make continuously pulse and calculates the pulse between the transmitter and receiver microphone via the triangulation method to determine the location of the patient's mandible (Koralakunte and Aljanakh, 2014). The working procedure is as follows. First, the software should be installed, and the device should be connected to the computer. Next, the clinician should fix the bite fork to the mandible, then place the head bow device on the patient's head and the face supporter on the patient's nose. The patient's TMJ and infraorbital notch should be pointed by a sensor pen following the manufacturer's instructions. Finally, the mandible sensor should be connected to the bite fork. The device will then track the movement of the mandible identifying issues such as retrusion, protrusion and laterotrusion. These movements will then be converted to numbers that can be used to program a fully adjustable articulator, such as KaVo Protarevo 7 (KaVo Dental GmbH), SAM 2 (SAM Präzisionstechnik GmbH), Artex CR (Amann Girrbach AG) or Stratos 300 (Ivoclar Vivadent; Amherst, NY) (Fig. 3).



Fig. 3. a: KaVo Protarevo 7, b: SAM 2, c: Artex CR, d: Stratos 300

In addition, certain movements of the mandible can be exported to a CAD system through XML-files. Mandibular movements along the dental arch can then be viewed by the software, and the same motion can be monitored from different planes by three computer screens. Thanks to the CAD system, this software can visualize and calculate the kinematic and static occlusal collisions and determine the necessary corrections when redesigning the occlusion. Combined with 'Dent-CAM' (Comp. KaVo, DLeutkirch), the software for virtual articulators, which was developed at Greifswald University (Fig. 4), displays the mandibular movement and slice window with three basic screens: the interpretation screen, occlusion screen and section screen. All of the screens show the same motion pattern in different views to highlight

various aspects of the motion and allow for analysis:

- Rendering screen: Premature contacts and occlusal collisions can be analyzed in this screen during the mandibular motion. For instance, the surface of the teeth and interrelation of the teeth can be analyzed during mastication using this screen.
- Occlusion screen: Occlusal contacts between the maxilla and mandibular teeth can be watched as a function of time.
- Section screen: Various frontal aspects can be watched along the dental arches. A series of frontal aspects are demonstrated throughout the dental arch (Kordaß et al., 2002). In addition, the interrelationship between the upper and lower teeth, shape of teeth and height of the cusp can be used to examine the intercuspitation and the height and functional angles of the cusps.

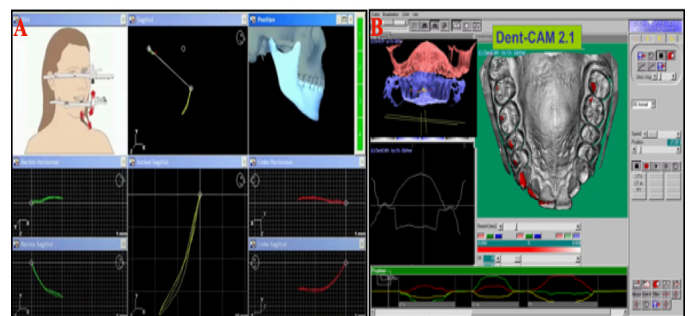


Fig. 4. A: Jaw motion analyzer, B: Dent-CAM

With the addition of a module to this software, the condylar trajectories can also be analyzed in the horizontal and sagittal planes within a virtual setup. Thanks to this module, the interrelationship between the incisal guidance and the condylar guidance, the impacts of TMJ mobility on the surface of the teeth and the occlusal collisions in both static and kinematic situations can also be analyzed (Bisler et al., 2002; Kordaß et al., 2002; Park, 2017). However, this system also has drawbacks. First, it requires the use of special devices, such as a mandibular motion-tracking system. Second, it lacks a universal digital format to save the movement of the lower jaw. Thus, this system cannot be used with some virtual articulator software package (Park, 2017).

## 2.6. Modjaw

This system uses optical scanning to record all mandible movement without information from a CBCT. By merely capturing jaw movements, kinematics of patient is modelled. Modjaw has been developing itself, including dynamic visuals of model in 3D and 4D automatic calculation of occlusion parameters such as Spee curve, Bennett Angles, condylar slopes etc., creating dynamic map of test contact (Solaberrieta et al., 2018).

## 2.7. Freecorder BlueFox

Freecorder BlueFox is an optical measuring method. Optoelectronic registration device is utilized to register all jaw movement and the individual mandible position. The ultralight carbon reference bow is placed on the ears and it is fitted to the

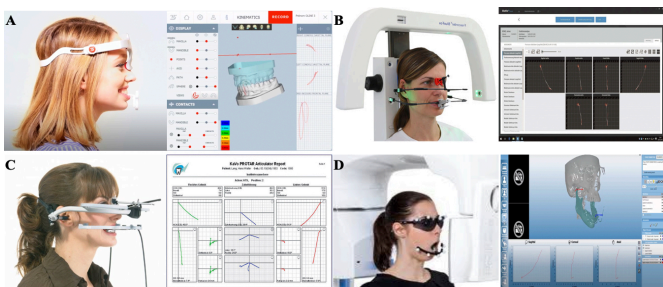
nose's bridge. Other light modular arch is fitted to the mandible to capture its movement. Thanks to special cameras, high resolutions are obtained by capturing 100 times per second. Simple control by computer monitor or touchscreen monitor. The movement information and position information can be integrated in XML that enables date export and import (Dai et al., 2016).

## 2.8. ARCUS digma

With ARCUS digma, the jaw movements can be simply and quickly detected by using ultrasound transmission. Four microphones adopted a bow is fixed to head and a support with three pingers is set on the jaw. This system offers mandibular movement analysis, 3D comparison of arbitrary occlusal positions temporomandibular joint diagnosis and also analysis of muscle activity (EMG) (Lippold et al., 2008; Sójka et al., 2017).

## 2.9. Planmeca 4D jaw motion

Planmeca 4D jaw motion system is CBCT integrated solution for recording, tracking, visualizing, and analyzing jaw movements in 3D. It offers visualization creating a fourth dimension in diagnostics. Integrated Planmeca ProFace camera are used to track mandible movements in relation to the maxilla. It records the movement and position of eight spheres. Half of them is integrated to a glasses and another to a bow. Movement of skull is defined by glasses position. The bow is fitted to lower arch detecting relative distances. Combined with its X-ray system, mandibular movement can be copied by the software (Solaberrieta et al., 2018) (Fig. 5).



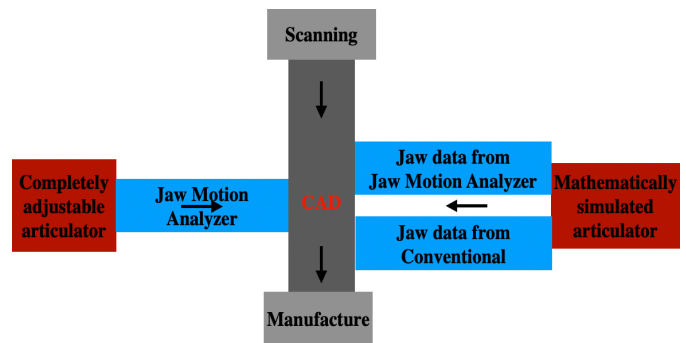
**Fig. 5.** A: Modjaw, B: Freeorder BlueFox, C: Arcus digma, D: Planmeca 4D jaw motion

There are several jaw movement tracing systems. Each of them has been improving their function, software and integration with CAD software. Tracking plates, brackets attached to teeth or modular arches are used to indirectly record the movement of mandible. Denture and dental cast ought to be scanned twice to reproduce mandibular movements, initial separately and second, with the fixed attached elements. The former one captures the teeth surface and the latter makes the relative interval from the references to the teeth. Hence, after getting the references, the registered movements and the relative distance, the mandibular arch can be reproduced. Initial positions of the mandible and skull need to be fixed and measured even as recording merely relative positions. Even this measurement could be done at any time of motion capture. Each system uses special software package which enables the

processing the data. However, in some instances initial measurement can be taken to use it as reference. Registration of mandibular movement for dental diagnosis, planning and treatment (Solaberrieta et al., 2018).

## 2.10. Data registration for virtual articulators

Intraoral scanners (IOS), which are devices that take a digital impression of a patient's teeth, represent an important advancement in virtual technology within dentistry. Two different systems are available. The first one, a photographic technology scanner system, records individual images of an object. The other one, a video technology scanner system, works similarly to a video camera recording at high speed. During the first stage of using an IOS, such as the Laser Scan 3D (Willytec, Munich, Germany), an image of the occlusal part of the teeth, of the whole dental arches, and of the interocclusal relations are taken. After scanning, the collected information is converted to digital data and sent to the electronic processing system. Digital data are compiled by the software program, then the image is visualized on the computer screen where it can be manipulated (Fig. 6). (Gärtner and Kordass, 2003; Abad-Coronel et al., 2019).



**Fig. 6.** Schematic diagram of integration of data

## 2.11. Virtual occlusal record

Virtual articulators are designed to mimic the function of mechanical articulators and require a patient's information to be inputted into dental digital design software. Virtual environments allow one to examine static occlusal and proximal relationships. Therefore, studies have analyzed clinical achievements using static digital articulation. Some studies have compared virtual and mechanical articulators at the maximum intercuspation position using contact point patterns. However, specific patterns of mandibular movement, such as protrusion, laterotrusion and retrusion were not set in depth and the researchers did not analyze the effect of alterations to these setting parameters, consequently leading them to the conclusion that there is no significant difference between virtual and mechanical articulators (Gärtner and Kordass, 2003; Yee et al., 2018a, 2018b) Others used 2D and 3D software to superpose and evaluate distortions in the data from virtual models, but only at the maximum intercuspation in a static position. Thus, within these studies, both systems are comparable and result in acceptable accuracy (Wriedt et al., 2013; Solaberrieta et al., 2015; Arslan et al., 2017).

It is widely accepted that there is no significant difference between virtual and mechanical articulators in a static position, but this assumption cannot reflect reality. For example; the mandible is a mobile bone and dislocates inferiorly, anteriorly and posteriorly, and virtual articulators have far more advantages in anticipating and dealing with these problems. Virtual articulators have special devices, such as JMA, for recording the specific movements of the lower jaws of patients; in addition, these movements can be recorded in an animation (Kusnoto and Evans, 2002; Quimby et al., 2004; Fleming et al., 2011; Cuperus et al., 2012; Sweeney et al., 2015). Accuracy and precision are important criteria for these systems. While accuracy is defined as how close the measurements are to the accurate value of the original sample, precision refers to the degree of reproducibility or the agreement between repeated measurements (Ziegler, 2009; Ender and Mehl, 2013; Güth et al., 2013; Atieh et al., 2017).

The dynamic motion of the mandible is affected by many specific factors for each patient. Therefore, user-defined settings, such as sagittal condylar inclination (SCI), immediate lateral translation and lateral condylar inclination, should be transferred from a mechanical articulator to a virtual articulator, depending on the classification and type of the virtual articulator (Fig. 7) (Szentpétery, 1997; Gärtner and Kordass, 2003).

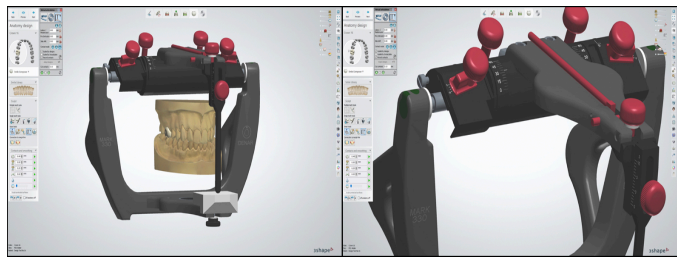


Fig. 7. Denar Mark 330 articulator

This process is important for increasing the accuracy of the diagnosis and treatment planning (Solaberrietta et al., 2015). Regarding the accuracy and the precision, many studies have compared the virtual occlusal record to the mechanical one, and while there is no significant difference in static relation, there is also no sufficient information on the dynamic relation (Hsu et al., 2019).

**2.12. Advantages and disadvantages of virtual articulators**

Advantages:

- Give rise to better communication between the dentist, dental technician and patient
- Work with CAD/CAM systems to design the occlusal surface
- Examine not only the static but also the dynamic occlusion
- Analyze the gnathic and joint conditions
- Eliminate the problems caused by manufacturing and can visualize certain regions in 3D

- Simplify the procedures for the dentist and technician
- Are more time-efficient
- Simulate the real patient, helping to modify the restoration and educate the patient

Disadvantages:

- Lead to high purchasing and managing costs, because virtual articulators require supplemental technology, such as digital sensors, digital scanners, software and multiple articulator models that can mimic mechanical articulators based on the patient requirements
- Require technical information, such as data input, the recording scanner’s data and motion parameters, and knowledge of mechanical articulators, CAD/CAM technology and software (Koralakunte and Aljanakh, 2014; Agnini et al., 2015).

**2.13. Virtual patients in dentistry**

Digital technologies have had a strong impact on almost every part of life, including dental medicine. Various software packages have directed clinical practices, education of dental students and laboratory techniques to virtual-based processes (Eaton et al., 2008). These softwares are of great importance in dentistry and are used in almost every department, including diagnosis, treatment simulation, training and all steps of patient follow-up (Luciano et al., 2009; Curnier, 2010; Dutã et al., 2011; Nkenke et al., 2012; Schoenbaum, 2012).

In general, diagnostic methods utilising virtual patients include cone beam computed tomography (CBCT), working casts, face scans (FS) and photography; recently, treatment concepts based on digital workflows with intraoral scanning (IOS), the rapid manufacturing of dental prostheses and computer-assisted implant surgery have also been adopted (Fig. 8) (Patel, 2010). In light of these developments, virtual dental patients (VDPs) that replicate the superficial surface of the skin combined with the underlying bony structures of the skull and teeth including the oral soft tissue layers are needed (Lee et al., 2012; Lin et al., 2013).

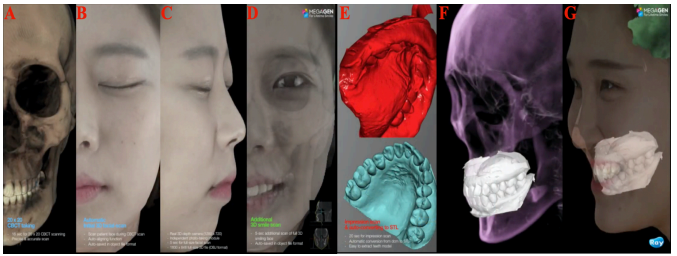


Fig. 8. A: CBCT, B-C: Frontal and lateral FS, D: Superimposing CBCT onto FS, E: Impression scan, F: Superimposing IOS onto CBCT, G: Superimposition of IOS + CBCT + FS

Virtual patients have many advantages:

- Make it possible to present the entire treatment plan in 3D to a patient

- Help with shaping the patient's expectations
- Allow for the creation of several alternative treatment plans
- Non-invasively simulate the progress step-by-step
- Support the cost-effectiveness of treatment by decreasing the number of patient visits, enhancing the doctor's productivity and the patient's quality of life
- Offer preoperative assessment and allow for a wide range of maxillofacial surgeries due to their high-precision anatomical documentation
- Streamline interdisciplinary communication between the dentist and dental technician
- Enhance student learning of the static and dynamic maxillofacial relationships (Yu and Brewster, 2002; Eaton et al., 2008; Ghanai et al., 2010; Kau, 2011; Orentlicher and Abboud, 2011; Sabalic and Schoener, 2017; <https://www.r2gate.com>, 2020).

Creating VDPs under static conditions requires digital data from various tissues to superimpose the 3D media gathered from IOS, CBCT, FS and the CAD/CAM systems. However, it is important to note that clinicians should combine different formats and files. In addition, these dataset superimposition techniques are not standardized; they are still experimental (Joda et al., 2018).

### 3. Conclusion

Developments in digital dental technology, particularly in virtual reality, have resulted in great advances in accurate and precise static and dynamic simulations in all disciplines of dentistry and in dental education. Thanks to this software, functional occlusion can be examined in different aspects, so that optimized restorations designed to avoid tooth surface collision can be manufactured. In addition, the simulations that are now possible allow students to transition from theoretical learning models to real patient situations. In the future, these systems should be enhanced with 4D technology in dynamic simulations. For these reasons, virtual reality has revolutionized dentistry and will continue to enhance dental practices for the foreseeable future.

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