Acta Scientific Dental Sciences

Volume 10 Issue 6 June 2026

Review Article

Review on Basic Elements of Virtual Articulators

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DOI: 10.31080/ASDS.2026.10.2113

Received: April 15, 2026

Published: May 14, 2026

Abstract

Clinical practice of Prosthodontics received the first technical foundation through articulators which got upgraded through the years. Subsequently introduction of digital technology has led to the development of virtual articulators, which can replicate mandibular movements and occlusal relationships within a software rich environment. This review examines the principles, components, and clinical applications of virtual articulators, highlighting their role in contemporary prosthodontics. Virtual articulators utilize digital impressions, jaw relation records, and patient-specific anatomical data to provide a simulated dynamic occlusion with improved visualization capability and precision. Presently available virtual articulator systems differ in their ability to incorporate individual condylar movements, occlusal parameters and integration with CAD/CAM workflows. The advantages of virtual articulators include enhanced diagnostic capability, reproducibility, reduced laboratory errors and improved communication between clinicians and technicians. However, limitations such as dependence on accurate data acquisition, software constraints, and the need for validation of simulated movements remain significant challenges. Current evidence suggests that while virtual articulators show promising potential, their accuracy and clinical reliability are still being refined. Future advancements integrating artificial intelligence and real-time motion tracking may further enhance their applicability. This review underscores the growing importance of virtual articulators as a tool for achieving functional and precise prosthodontic outcomes in the digital era.

Keywords: Articulators; Virtual Articulator; Digital Dentistry; Virtual Facebow; CBCT; Virtual Patient

Abbreviation

VA: Virtual Articulators; MS: Mathematically Simulated; CA: Completely Adjustable; CAD/CAM: Computer-Aided Design and Computer-Aided Manufacturing; JM: Jaw Motion; JMA: Jaw Motion Analyser; DICOM: Digital Imaging and Communications in Medicine; STL: Stereolithography File Format used in 3D Printing.

Introduction

Recently introduced, high tech armamentarium that can assist dental professionals in managing complex situations, require precise digital workflows which might replace fully or partially the traditional methods. Digital methods include the following.

Cone beam computed tomography (CBCT)

CBCT is a sophisticated X-ray imaging system that provides three-dimensional views of dental and maxillofacial structures. Unlike 2D X-rays, which have limitations of distortion and overlapping anatomy, CBCT uses a cone-shaped beam to capture a series of images which undergo a computer reconstruction to form a detailed 3D model. This technology is indispensable for complex procedures like dental implant treatment planning, as it allows dentists to assess bone density, locate nerve pathways and visualize the precise anatomy of the jaw with minimum radiation hazard when compared to medical-grade CT scans.

Intra-oral scanners

Hand held intra-oral scanners are used to create “digital impressions” of a patient’s mouth, effectively replacing the not so comfortable trays and choking viscous materials used in traditional impressions. The scanner works by projecting a light source (laser or structured light) onto the teeth and the adjacent soft tissues while an integrated camera captures thousands of data points to generate a highly accurate 3D model in real-time. This process is comfortable for the patients and provides immediate feedback to the dentist, ensuring accuracy before the patient even leaves the chair.

Dental CAD/CAM software

Dental CAD/CAM software acts as the digital “brain” of the restoration process. Once digital impression is captured, it is imported to CAD software where a technician or dentist can design crowns, bridges or veneers with micron-level precision. The software allows for the manipulation of tooth shape, size, and occlusion to match the patient’s unique morphology. Once the design is finalized, the software converts the 3D model into instructions for the CAM portion—the manufacturing hardware—to convert the virtual design to the real prosthesis.

5-axis milling machines

5-axis milling machines are high-precision subtractive manufacturing tools used to create dental restorations out of solid blocks of ceramic, zirconia or metal. While 3-axis machines which belong to the previous generations have limitations in movement, a 5-axis machine can move the cutting tool and the material block along five different axes simultaneously:

- X-axis: moves the cutting tool left to right
- Y-axis: Manages the depth and forward and backward positioning
- Z-axis: Handles the vertical (up and down) movement
- A-axis: Rotates the work piece along the x-axis (360 degree)
- B-axis (or C-axis): Rotates/tilts the workpiece along the Y-axis such as +25 to -115 degrees

This allows the machine to reach deep areas and complex angles that are impossible for simpler systems, resulting in restorations that fit accurately and require less manual adjustment by the dentist.

3D printers

3D printers belong to the additive manufacturing phase of digital dentistry, building dental appliances layer-by-layer from a liquid resin or powder. 3D printers are frequently used to create surgical guides for implants, orthodontic models, clear aligners, dentures and temporary crowns. Because 3D printing is often faster and less wasteful than milling for certain applications, it allows dental offices to produce multiple custom appliances simultaneously, significantly reducing the turnaround time for patient treatment [1-3].

Prosthodontics had a significant turn of events with the introduction of articulators. The first recorded articulator was developed by Phillip Pfaff (1756) and which was known as plaster slab articulator. Daniel T Evens (1840) developed an articulator which has become very popular amongst dentists. Initially the developers had a fixed idea that in the articulator, the mandibular member should move like the human mandible. Movement capabilities were incorporated through the years of Bonwill (1858), Bennett (190) and Gysi (1910). Rudolph Hanau (1923) developed semi adjustable articulator which still occupies a role model position. Snow (1889) introduced facebow to relate upper jaw with intercondylar axis which is an essential supplementary instrument for the articulator. Another addition like extraoral tracer was introduced by Gysi (1929) which records border position of the mandible in the horizontal plane. This tracing is presently used to verify the centric position in complete denture fabrication. Bergstrom (1950) categorized articulators into Arcon and Non arcon based on the position of the condylar element and the relation with the jaw member. While Hanau H2 is a non arcon articulator, Hanau wide vue is an arcon type [4].

Virtual articulators (VA)

These are computer software tools capable of reproducing jaw relations and simulating mandibular movements in a virtual environment. Two types of virtual articulators are popularly used: 1. Mathematically simulated (MS) 2. Completely adjustable (CA). MS is an average value articulator that works on mathematical formulas to reproduce mandibular movements. This is indicated in cases where inter arch relationship alone will suffice to plan occlusal morphology. CA reproduces mandibular movement paths making use of digital accessories. It can assess morphology of the occlusal plane and thereby avoiding interferences during excursions (Figure 1).

Commonly used software and integrated systems

Several dental CAD systems include VA modules for designing and fabricating different dental prostheses.

- **Exocad:** This is a very popular CAD software which can support both MS and CA virtual articulators. It includes modules of different articulator brands like Denar Mark 330, Bio-art A7 plus and Artex-CR. This software gives freedom for clinicians to adjust condylar path, vertical dimension and Bennett angle.
- **MODJAW and JM Analyser:** These systems use 4D optical technology which is compatible with Exocad. 4D concept is an evolution from static 3D models. Real time movement is incorporated in this through kinematic digital facebow (Figure 2).
- **Jaw motion analyser:** This system uses ultrasonic pulses to record mandibular movements keeping spatial, rotational and translation components. Digital movement data is exported to CAD/CAM system using XML files and is compatible with CBCT.
- **3Shape software:** This software provides a comprehensive suite of digital dentistry solutions for clinics and labs. The system integrates intra oral scanning, CAD/CAM designing and treatment planning. This is applied in the fabrication of restorations, clear aligners and implant planning. 3 Shape software is known for speed scanning and accuracy.

Figure 1: Exocad virtual articulator.

https://exocad.com/our-products/exocad-dentalcad/virtual-articulator

Figure 2: MODJAW jaw motion analyser.

https://t4confident.com/en/modjaw/

History and evolution of VA

The history of virtual articulators reflects a broader conceptual shift from mechanical devices to fully digital workflows that are carried out in dental practice.

Early foundations (Mechanical Articulators)

The concept of articulators evolved in the 18th/19th centuries as mechanical articulators—devices designed to copy jaw movements using hinges and adjustable components. Pioneers like Philip Pfaff and later George Snow contributed significantly to the early designs. In the 20th century these devices further evolved into more sophisticated semi-adjustable and fully adjustable articulators.

Transition to digital (Late 20th Century)

The era of computer technology began with 1980s–1990s and along with that dental profession also evolved to integrate digital technologies. Early virtual articulators emerged as part of CAD/CAM Dentistry. These initial versions were limited to simulating basic hinge movements and lacked patient-specific customization.

Virtual articulator (VA) software was first described by Szentpetery A in the 1990s. The first VA was introduced by Bisler and his team of the University of Griefswald, Germany. This has helped clinicians to go beyond the analogue techniques of using mechanical articulators. Afterwards VA was carefully integrated and applied to CAD/CAM system. VA could include individualized diagnostics and avoided problems with mechanical articulators related to occlusal contacts. Spatial orientation of casts in 3D was also made possible with VA [5].

Present status of virtual articulators

In the beginning VA attracted the dental professional because of its novelty and its digital tag. But very soon it acquired a fundamental status because of the careful integration with artificial intelligence, high speed intra oral scanning and real time jaw tracking. Presently the laboratory simulations used for clinical purposes are very close to the biological reality because of the digital impressions, 3D virtual models and motion data obtained with the assistance of CBCT and jaw tracking facilities. Now VA is integrated routinely into CAD/CAM workflows utilized in all the branches of prosthodontic treatment and in orthognathic treatment planning.

Technicians and clinicians still have an affinity towards mechanical devices like mechanical articulators which records static relations. CAD/CAM procedures followed at present rely to a great extent the static occlusion rather than the dynamic occlusion which is not easy to reproduce. The dental professional aims at replacing traditional impression making with intra oral scanners; static jaw relation records with jaw motion analyser which can record exact movements of mandible and make the digitized dental arches move along the same paths in the computer. Kinematic occlusal errors can be visualized with these tools. Data obtained from intra oral scanner, facial scanner, jaw motion analyser and CBCT can construct a virtual dental patient with dynamic occlusion [6-8].

Accuracy and reliability of VA

Virtual articulators are accurate and reliable when compared to their mechanical counterparts. In fact, they exhibit superior accuracy in replicating static intermaxillary relations. If at all deviations are observed, it is in the range of less than 0.1mm. Dynamic mandibular movement simulation with VA is still developing and under validation. Transfer of analog casts to a virtual space shows 95% of correspondence of contact points. VA systems cannot be interchanged in the course of treatment in order to ensure accuracy. As with any digital equipment, the accuracy is dependent on the input data provided by the supplementary devices like intra oral scanners and alignments with facebow. In the analysis of static occlusal studies, VA can be considered as an evolved mature technology whereas for dynamic analysis of occlusion, it requires further modifications and evaluation [9,10].

Workflow in virtual articulators (step by step procedure)

VA is used to carry out two fundamental functions: 1. Collection of data 2. Transferring the data to the virtual world and it will lead to mounting the virtual models in the virtual articulator. The first step is to take impressions of maxillary arch using digital scanning. Acquisition of the maxillary arch data can be done by direct or indirect methods. When an intra oral scanning (IOS) device is used, the acquisition is termed as direct. When a plaster cast is scanned using Dental laboratory scanner (DLS) the process is termed as indirect. Scanning systems are expected to provide high level of accuracy. ISO 5725-1 defines accuracy comprises of trueness and precision. If a scanner produces a 3D model very close to the actual tooth dimensions, it can be considered as giving high trueness. If repeated scans give nearly identical models, it can be considered as high precision. Whenever possible direct scanning of the occlusal surfaces of the dental arches should be done with few acquisitions to enhance precision. Digital impressions using IOS provides accuracy, patient comfort and indefinite storage capabilities [11,12].

Next step is the occlusal registration in maximum intercuspation and centric relation. The presently used techniques have limitations because of the recording materials, technics, operator experience and circadian influences. When virtual inter occlusal records are used, inter arch distortions were minimal with CAD systems to the range of 0.6%. Virtual static articulation using interocclusal records caused a reduction in inter arch/inter occlusal distance. When models are used the inter occlusal and inter arch distance increases. The morphology of teeth and occlusal relationship are captured by the scanning performed at this stage [13,14].

Position of the maxillary arch is transferred and mounted in a VA using intra oral scans and CBCT images. The hinge axis is identified by the cylinders incorporated in the face bow which are passed through the auditory meatus and the Bergstrom point. It is defined as a point located 10 mm anterior to the center of the spherical insert of the facebow and 7 mm below the Frankfort horizontal plane. The maxillary scan is aligned to the skull model constructed from the CBCT. Now it can function as a kinematic facebow. After the intraoral scan an extended scan is done to capture perioral soft tissues, nasal region and lower third of the face. This will help in aligning with a full face scan. Facial reference planes are highlighted with adhesive targets and 8to10 digital photographs are taken to record cutaneous land marks. Face bow with adhesive target is positioned on the patient, ensuring stability at the external auditory meatus and the glabella (based on the type of face bow used, like Artex). Another facial scan is done with face bow in position and it will help in digital capturing of the face bow and the face.

All the scans done so far viz. intraoral scan, extended scan to capture perioral tissues and the face scans are imported to CAD/CAM software for alignment. Intraoral scan is aligned to perioral scan using teeth as reference. In turn the perioral scan is aligned with the facial scan referencing anatomical landmarks like nose, eyebrows, lips etc. Facial scan is then aligned with the facial scan which has face bow incorporated.

Next step is alignment of facebow with the virtual articulator using references like hinge axis, ear rods of the face bow and the rotation axis of the articulator. The horizontal reference plane of the face bow is oriented parallel to the base of the articulator. From now onwards the virtual simulation of mandibular movements using semi adjustable articulator is possible adhering to digital workflow [15] (Figure 3).

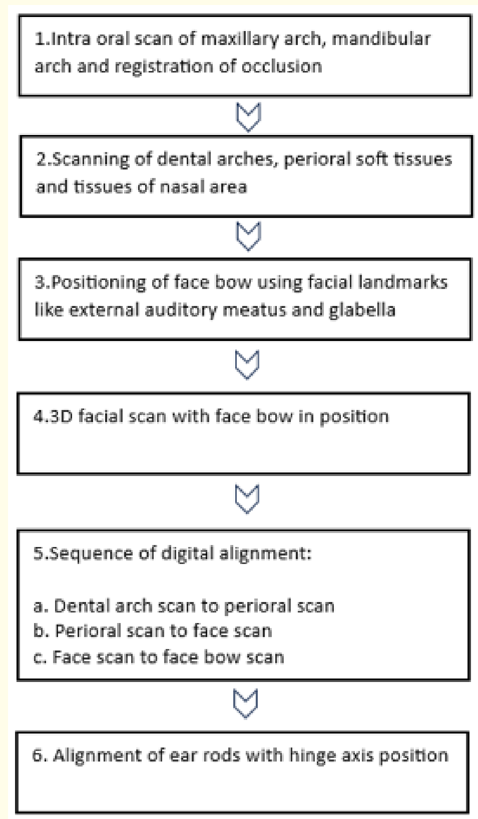

Figure 3: Work flow in Virtual articulator.

VA available in the market

Many dental CAD systems have incorporated VA as a component. VAs are integrated with different hardware such as scanners viz. IOS or DLS. CAD software systems can receive and release STL files and which can be shared with any other open source systems. Completely adjustable (CA) type VA requires files that have recorded jaw movements. Jaw motion analyser (JMA) is used to record the dynamic elements of mastication and occlusion. JMA measures the velocity of ultrasonic sound pulses emitted by transmitters and sensors and thereby record the movements of mandible across spatial, rotational and translational dimensions. Mathematically simulated VAs can be assembled by digitization of mechanical articulators [16]. Popular virtual articulators used in digital dentistry include Exocad virtual articulator, 3Shape dental system, Amann Girrbach ceramill – Artex, Ivoclar stratos 300, Kavo protarevo 7 and Sam2P. Exocad provides numerous options to adapt different articulator brands like Bio-art and Denar mark330. Based on the articulator selected, the following adjustments can be done: condylar angle, vertical dimension, incisal table inclination, Bennett angle etc. [17].

Mounting maxillary arch in VA

A CBCT scan is made that includes maxilla, external acoustic meatus and infra orbital point. The data is exported as DICOM files. Next step is to scan both maxillary and mandibular arches and occlusal relation is registered with intra oral scanner and the data is exported as STL files. The DICOM files are then converted into 3D model and the data is exported in the STL format.

3D skull model is then imported into an STL file editing software. Long shafts of 2mm diameter and 200 mm length are made and aligned, one each to upper border of ear canal and to Bergstrom point to indicate the hinge axis. The shafts are used to align the skull model with VA. Skull model with shafts are now exported into STL format. Skull model and optical scans are now loaded into CAD software (Exocad) and superimposed.

Both the hinge axis of the skull and the joint axis of the VA are aligned and the reference plane (FH plane) is made parallel to the upper arm of the articulator. The mandibular arch is then loaded to align with the maxilla using occlusal scan in maximum intercuspation [18] (Figure 4).

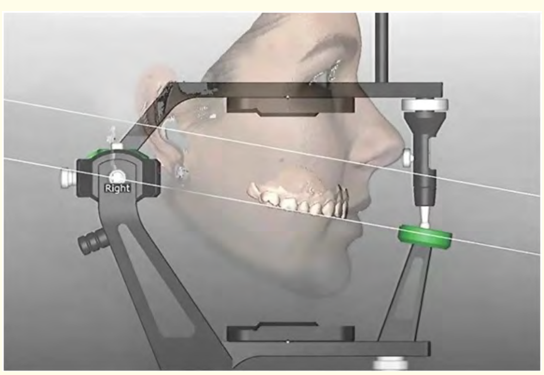

Figure 4: Mounting in VA.
https://ddschoology.com/virtual-articulators/

Programming of VA

Programming of virtual articulator includes acquisition of patient-specific anatomic and functional data, procured from digital impressions, jaw relation and mandibular motion recordings, followed by their integration into CAD software to simulate dynamic jaw movements. This enables replication of condylar guidance and occlusal relationships, thereby enhancing the accuracy of diagnosis and prosthetic rehabilitation [19].

Programming begins with the collection of digital data of the dental arches and craniofacial structures using intraoral scans, digitized casts and cone-beam computed tomography (CBCT) data. These datasets are used for constructing a virtual patient. The spatial relationship between the maxilla and mandible is recorded using digital bite registrations and virtual facebow transfers. This allows proper orientation of the maxillary arch relative to the hinge axis in the software environment [20].

Next step is recording of mandibular movements. Dynamic programming requires capturing of real mandibular movements using jaw tracking systems like Zebris Jaw Motion Analyser, Kavo ARCUS digma, Bio Research JT-3D Jaw tracker, and Modjaw. Key technologies used in these systems are Ultrasonics and Optical Kinesio graphs. These systems record condylar paths, Bennett movement, and excursive movements which are essential for individualized articulator settings. Data Integration into CAD Software is the next stage in programming. Here maxillary and mandibular scans are aligned, occlusal relationships are established and motion data are superimposed on static models. This integration allows simulation of both static and dynamic occlusal contacts within a virtual environment [21].

Once programmed, the virtual articulator simulates: opening and closing movements, protrusive and retrusive movements and lateral excursions. During these movements, the software computes dynamic occlusal contacts and interferences, enabling detailed functional analysis. In fact, premature contacts are identified, occlusal interferences are visualized and cusp-fossa relations are optimized. This improves diagnostic capability and allows preclinical adjustment of restorations, reducing chairside time and errors [22].

The advantages of programming virtual articulators are accurate simulation of patient-specific mandibular movements, integration of digital work flows, improvement in clinician-technician communication and reduction in clinical and lab errors [19]. There are some limitations experienced with programming. If data acquisition is not accurate, the errors may get propagated through the work flow. The system is expensive and requires high learning curve. Standardization and problems with interchangeability between systems are considered as limitations of programming [21].

Future directions

Virtual articulators have great potential in enhancing quality in the treatment of multidisciplinary cases which require collection of huge quantity of data from multiple sources. The ability to simulate mandibular movements with precision is an essential requirement in diagnosis and treatment planning of cases involving Prosthodontics, Orthodontics and Maxillofacial surgery. The predictive capability of virtual articulators can further be improved with the effective use of artificial intelligence. Seamless data integration across disciplines and cloud based storage would further advance the effectiveness and potential of digital dental treatment. Technologies require continuous updating and validation through research for the maintenance of quality [23].

Conclusions

Virtual articulators represent a significant advancement in dentistry especially in prosthodontics; bridging the gap between traditional mechanical simulation and modern digital workflows, precise replication of mandibular movements, occlusal relationships and patient-specific dynamics, enhanced accuracy in diagnosis, planning the treatment and fabrication of prostheses. Despite current limitations—such as dependence on accurate data acquisition and the need for clinician expertise, the integration of virtual articulators with digital impression systems, CAD/CAM technologies and dynamic jaw tracking continues to expand their clinical potential to the extent that they have transformed their role from a recent innovation to a logically adopted tool. As research and technology evolve, virtual articulators are poised to become an indispensable component of digital dentistry, contributing to improved efficiency. Profile of upgradation of dental profession that we are going to experience in the future will have a challenging dimension that may merge the capabilities of man and machine.

Author Contributions

Conceptualization-K. Chandrasekharan Nair, Review of articles- Pradeep Dathan; Viswanath Gurumurthy, T. Mohan kumar, Arathy, Initial draft preparation: Hemalatha Konka, Viswanath Gurumurthy, Pradeep Dathan, Helna, Review and editing- K. Chandrasekharan Nair, Supervision-K. Chandrasekharan Nair.

All the authors have read and agreed to the published version of the manuscript.

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