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VIRTUAL ARTICULATORS IN DENTISTRY

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RESUMEN

Introducción:

Los avances en odontología protésica han impulsado alternativas a los articuladores mecánicos convencionales (AM). Entre ellas destacan los articuladores virtuales completamente ajustables (AV CA), que, junto con escáneres intraorales y faciales, imágenes CBCT y sistemas de registro del movimiento mandibular, permiten crear un "paciente virtual" capaz de reproducir dinámicas mandibulares individualizadas.

Objetivos:

El objetivo principal fue comparar la eficiencia de los AV CA frente a los AM, evaluada mediante exactitud, veracidad y precisión. El objetivo secundario fue analizar el impacto de los flujos de trabajo digitales en la sostenibilidad clínica y de laboratorio.

Métodos:

Se realizó una revisión estructurada de la literatura en PubMed Central y Medline Complete, incluyendo estudios publicados entre 2015 y 2025. Los criterios de inclusión se centraron en flujos de trabajo digitales, articuladores virtuales, tecnologías asociadas y comparaciones con articuladores convencionales. El proceso PRISMA permitió seleccionar 136 estudios para análisis.

Resultados:

Los AV CA mostraron un rendimiento igual o superior al de los AM en exactitud, reproducibilidad y eficiencia del flujo de trabajo. Los sistemas de registro mandibular aportaron datos dinámicos fiables que mejoran la capacidad diagnóstica, mientras que el montaje basado en CBCT presentó la menor desviación del eje de bisagra. Las técnicas de escaneado facial mediante smartphone y los montajes con arco facial virtual ofrecieron veracidad y precisión adecuadas, aunque con limitaciones dependientes del operador. Los flujos de trabajo digitales también demostraron mejorar la comodidad del paciente y del clínico, reducir el tiempo en sillón y optimizar la comunicación con el laboratorio.

Conclusiones:

Los AV CA representan un avance significativo en odontología digital y protésica, especialmente en casos complejos que requieren una reproducción anatómica y funcional precisa. Su integración adecuada mejora la predictibilidad oclusal, la precisión diagnóstica y la eficiencia clínica. No obstante, su uso debe ser indicación-dependiente, considerando factores como exposición a radiación, experiencia del operador y coste. Cuando están correctamente indicados, contribuyen a resultados más predecibles, eficientes y cómodos.

Palabras Clave:
Odontología, Articuladores virtuales, Odontología protésica, Paciente virtual, Flujo de trabajo digital

ABSTRACT

Introduction:

Advancements in prosthetic dentistry have become increasingly prevalent with the introduction of alternatives to conventional mechanical articulators (MAs). Completely adjustable virtual articulators (CA VAs), combined with several other digital tools, such as intraoral and facial scanners, CBCT imaging, and jaw motion tracking systems have allowed the development of the "virtual patient" by reproducing individualized mandibular dynamics.

Objectives:

The primary objective was evaluating the difference in efficiency (measured through accuracy, trueness, and precision) of CA VAs compared to MAs. The secondary objective is to assess the impact of digital workflows on clinical and laboratory sustainability.

Methods: A structured literature review was conducted using PubMed Central and Medline Complete, including studies published between 2015 and 2025. Inclusion criteria focused on digital workflows, virtual articulators, associated technologies, and comparisons with conventional articulators. A PRISMA-based selection process yielded 136 studies for analysis.

Results: CA VAs demonstrated equal or better performance when compared to MAs in accuracy, workflow efficiency, and reproducibility. Jaw motion tracking systems provide reliably dynamic occlusal data, leading to improved diagnostic and reproducible capability, while CBCT-based mounting produced the lowest hinge-axis deviation. Smartphone-based facial scanning and virtual facebow mounting techniques show adequate and promising trueness and precision, with certain limitations. Digital workflows, when employed correctly, could improve patient and clinician comfort, reduce chairside time, and enhance communication and collaboration with the laboratory.

Conclusions: CA VAs have proven to be a significant advancement in the field of digital and prosthetic dentistry, particularly in complex cases which require precise anatomical and functional reproduction. By their appropriate integration, occlusal predictability,

diagnostic accuracy, and workflow efficiency can be improved. However, clinicians must exercise judgement when employing these systems, as their use should remain indication driven. Factors such as radiation exposure, operator experience, and cost must be taken into consideration. When the case indicates it, the use of CA VAs and associated systems contributes to more comfortable, predictable and efficient outcomes.

KEYWORDS

Dentistry, Virtual Articulators, Prosthetic Dentistry, Virtual patient, Digital Workflow

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1. INTRODUCTION

1.1 Context

In the field of prosthetic dentistry, the analysis of the patient's occlusion plays a significant role in the design of the treatment. To that end, one of the most employed tools is the conventional, semi adjustable articulator, referred to as "mechanical articulator" (MA). (1) Characteristically, it reproduces jaw movement in a limited way and allows for limited customization (for example, the inability to customize intercondylar distance). Moreover, it presents several drawbacks when it comes to patient and physician convenience, mainly linked to the use of the facebow transfer. This process is often uncomfortable for patients and is dependent on operator experience. (1–3)

The trend in recent years in the field of dentistry, and even more so specifically in prosthodontics, has been a movement towards the integration of various digital tools and programs in treatment planning and execution. Such examples include, but are not limited to, intraoral and facial scanners, 3D printers, jaw motion trackers and virtual articulators, all of which aim to increase efficiency, as well as convenience by improving upon the limitations of the conventional workflow. (1,3,4)

1.2 Definitions

A virtual articulator (VA) is a tool that performs the functions of a conventional articulator (and more), in a digital environment – a software. It is important to note, however, that virtual articulators are split into two categories: mathematically simulated (MS), and completely adjustable (CA). (1,2)

1.2.1 Mathematically Simulated VAs

MS VAs are average value articulators, which allow the reproduction of the same movements as MAs, meaning protrusion, retrusion, laterotrusion, condylar path and Bennett angle, without the use of additional tools other than an intraoral scan. MS VAs

therefore share some of the limitations of MAs, namely the lack of dynamic reproducibility and customization. (2)

1.2.2 Completely Adjustable VAs

CA VAs allow for the integration of other useful digital tools such as CBCT scan data, as well as jaw motion tracking, which, combined with intra and extraoral scans, can be used to create a "virtual patient". (5) This can be defined as a fully customizable, individualized reconstruction of the patient's temporomandibular joint (TMJ) and occlusal relationship, often combined with an extraoral scan. (2,5) An important distinction between MS and CA VAs is that MS VAs are cheaper and easier to use (therefore more frequently used), but do not possess the ability of CA VAs to replicate highly specific movements. Therefore, their indications differ, with CA VAs being more necessary in complicated cases where precision is paramount (2), such as in cases of full arch implant rehabilitation, or of complex TMJ disorders. Given that this study is concerned with advanced, individualized workflows, the focus will be placed on CA VAs and their associated tools and systems, seeing as they uniquely allow the full customization and creation of a "virtual patient".

1.3 Associated Tools

The customization of VAs is dependent on the system and tools used. In this context, the CBCT scan is advantageous, as it brings together the extraoral and intraoral scans, providing the necessary reference points and hinge axis using anatomical landmarks. (5,6) This is important to note, as the variability of the hinge axis in MAs translates into large discrepancies in the recording of condyle position (3), leading to an accumulation of errors in the manufacturing of a prosthesis. Therefore, it is common for studies to use the CBCT scan as the gold standard when comparing the different systems available for creating a virtual patient. (3,7–9) The CBCT scan is most useful in complex, interdisciplinary cases, where its use is more adequate than in simple prosthodontic or orthodontic cases. This is because a CBCT scan exposes the patient to an additional dose of radiation, which needs to be justified. (10)

Jaw tracking systems, such as ModJaw (ModJaw, France) or KaVo ARCUSdigma (KAVO, Leutkirch, Germany), play a similar, complementary role, insofar as they contribute to the individualization of the digital reconstruction. Using various types of sensors (such as optical, infrared, or ultrasonic sensors and receivers), they record the movement of the mandible, allowing the exact reproduction of the condylar trajectory during opening and closing. This is done by mathematically converting raw data from these sensors into a readable trajectory path. (3) It is a particularly useful type of system, as it allows the physician not only to personalize the mandibular trajectory in the virtual articulator, but also diagnose temporomandibular joint (TMJ) disorders during movement. (11,12)

Additionally, at the foundation of this type of workflow stands the intraoral scanner (IOS), which provides the model of the dentition to be mounted, in the form of a digital diagnostic or definitive cast. IOSs are a strong component of the digital workflow, allowing the virtual analysis of the static and dynamic occlusion. (13) The various types of IOSs have been shown to depend on certain operator and patient factors. Some operator factors include operator experience, scanning distance and pattern, choice of IOS system, or scanning extension. Patient factors include tooth type, position, and angulation, as well as spaces between teeth/implants, palate characteristics and irregularities, wetness, or presence of existing restorations. (13)

Another type of system that is described in the literature by several authors is that of smartphone-based virtual facebow records. This refers to a more economical and user friendly technique in which a smartphone is used to obtain face scans of the patient wearing a bite fork, which will then later be superimposed with a scan of the fork itself, allowing for the virtual mounting of the digital cast. (8,14)

It is important to note that the term "virtual facebow" is often referred to as a tool used to mount the digital cast in the virtual articulator, which can be done with several of the systems mentioned above. (14,15)

1.4 Justification

While there are currently studies available analyzing the accuracy, trueness, and precision of these systems, there is still a need for more research on the exploration of

their respective workflows in real-world cases, specifically within aspects of sustainability, efficiency, and their comparison with conventional tools. (1–3)

This study serves the purpose of providing an analytic overview on a new kind of workflow, allowing practitioners to be more informed when considering the switch from conventional to digital. For this, highlighting the features of various types of systems, as well as the differences between them can be very useful in helping clinicians stay informed and up to date on current technologies.

2. OBJECTIVES

Therefore, the main research objective was (1) to evaluate the efficiency (measured as a combination of accuracy, trueness, and precision) of completely adjustable virtual articulators and their associated systems in dentistry, and the secondary objective (2), to assess the impact of the derived digital workflow on clinical and laboratory sustainability.

3. MATERIAL AND METHODS

Hence, the following PICO question has been derived: "In prosthetic dentistry, does the use of completely adjustable virtual articulators, compared to conventional mechanical articulators, improve accuracy, workflow efficiency, and sustainability in both clinical and laboratory practice?"

To answer this question, a review was conducted on available databases, namely PubMed Central and Medline Complete. The aim of the search was to identify articles directly related to, and relevant within, the topic of virtual articulators and digital advancements in dentistry. To be as comprehensive as possible, both quantitative, as well as qualitative research studies and articles were included. Parameters for inclusion were as follows: observation period from 2015 to 2025 and direct relevance to the topic. The search was performed in November of 2025.

Relevance was defined as a focus on digitalized workflows, the use of VAs and associated tools in diagnosis and treatment planning/execution, and comparisons with mechanical articulators regarding sustainability and efficiency. Additionally, the

reference lists of selected sources were screened manually to find additional studies, and those that met the inclusion criteria were used. Moreover, duplicates were excluded using the Rayyan , Rayyan Systems, Inc. online application. Priority was given to identify relevant applicable, and reputable, up-to-date sources.

Exclusion criteria were also established, to discard studies not providing relevant information, or not being directly related to at least one of the key parameters mentioned above. Moreover, non-English studies were not included. Review studies were also not included in the results section.

To this end, the following search string involving the appropriate key words was devised, incorporating the necessary Boolean terms: "("virtual articulator" OR "digital articulator" OR "virtual occlusion" OR "digital occlusion" OR "virtual patient") AND ("CBCT" OR "cone beam computed tomography" OR "jaw tracking" OR "mandibular movement" OR "intraoral scanner" OR virtual facebow) AND ("accuracy" OR "trueness" OR "precision" OR "efficiency" OR "sustainability") NOT ("orthodontics" OR "periodontics" OR "pediatric dentistry" OR "endodontics")". **Figure 1** shows the process of selection of the articles employed in this paper.

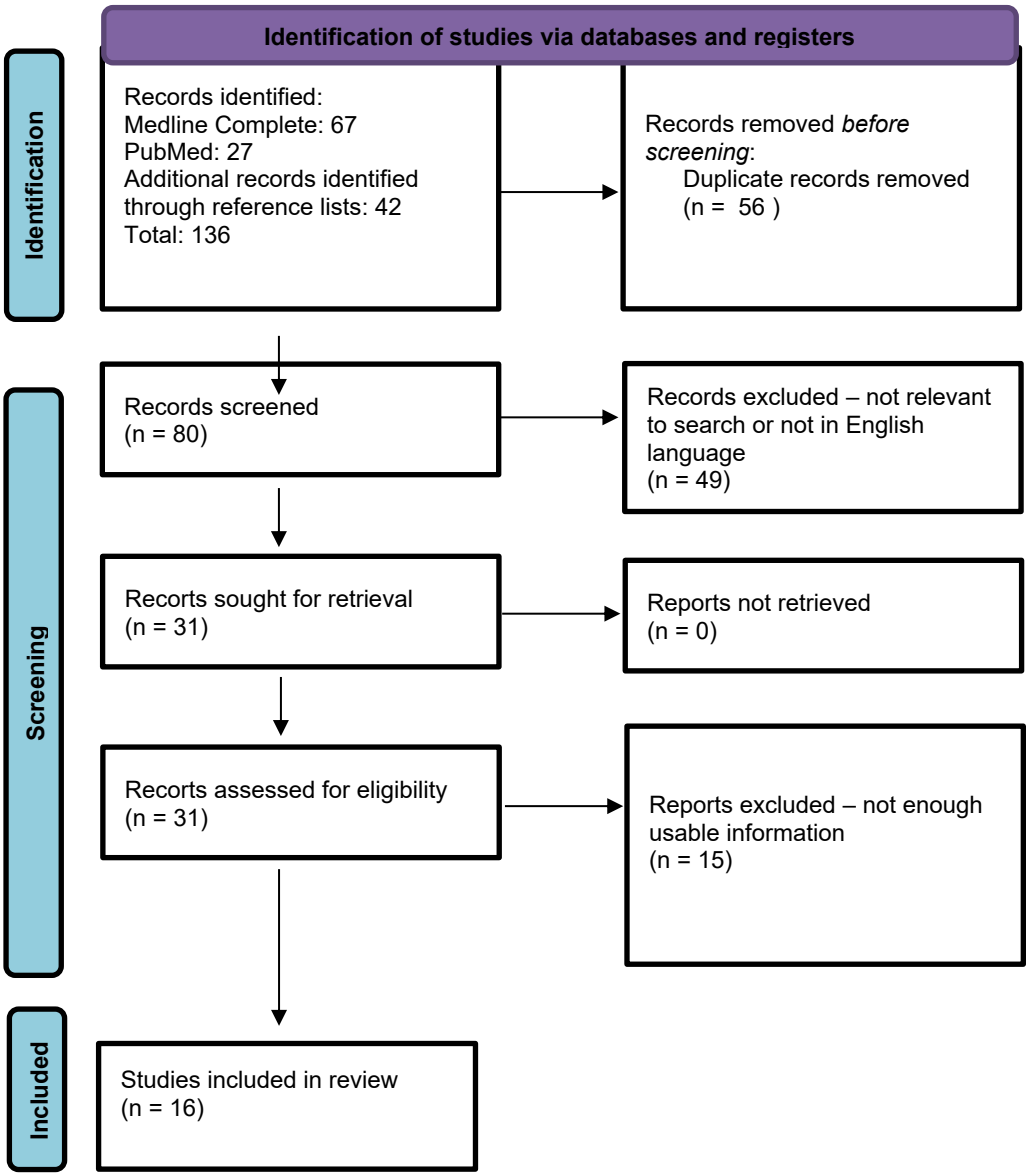


Figure 1: PRISMA flow diagram.

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses; n: number

4. RESULTS

Table 1 shows the list of studies included.

Article	Author	Year	Type of Study	Systems	Gold Standard	Variables	Results
(7)	Yang et al	2025	in vitro	Industrial facial scanner (ID) (EinScan HX; Shining 3D, Hangzhou, China) and a smartphone-based facial scanner (SP) (Heges; Marek Simonik, North Moravia, Czech Republic) installed on a smartphone (iPhone 14 Pro Max; Apple, CA, USA)	CBCT scan	Linear deviations of the maxillary arches and angular deviations of the occlusal planes; two different integration techniques used: virtual facebow scan and nose-teeth scan	No significant difference in trueness between scanners or techniques. Industrial scanner showed superior precision compared to smartphone-based scanner.
(12)	Gu et al	2025	in vivo	Jaw Motion Analyzer system (JMA; Zebris Medical GmbH, Isny, Germany) -ultrasonic- and computer aided diagnosis axiograph system (CADIAX® 4; Gamma Dental, Klosterneuburg, Austria) - electronic	Fully adjustable mechanical articulator	Trajectories and maximum displacements of the bilateral condyles in the sagittal plane during opening as measured with various	Comparable accuracy between systems apart from Bennet Angle. JMA system proved to be superior in terms of comfort and ease of use.

						reference points	
(16)	Yuan et al	2024	in vivo	Intraoral scanner (TRIOS A/S, 3Shape), design software (Ceramill Mind, Amann Girrbach, Koblach, Austria), Artex facebow and articulator (Amann Girrbach, Koblach, Austria), extraoral scanning window (Ceramill Map 400, Amann Girrbach, Koblach, Austria)	Control Group (preoperational)	Position and force of occlusal contacts of crowns, statically and dynamically	Posterior single crowns designed with a virtual articulator restored a better intercuspal occlusion than with a mechanical articulator, and with less dynamic interferences
(17)	Revilla-León et al	2024	in vitro	Industrial scanner (Gom ATOS Q 3D 12 M; Carl Zeiss Industrielle Messtechnik GmbH), facial scanner (InstaRisa 3.0 Facial Scanner; InstaRisa), intraoral scanner (TRIOS 4; 3Shape A/S), and 3 different scan bodies: 3D scan body (3D scan body; Kois Center), AFT (AFT Dental System; AFT Dental System), and Sat 3D (Sat 3D; Sat 3D)	Industrial Scanner	Alignment of reference points and interlandmark distance discrepancy	Operator handling and technique election has an impact on accuracy and trueness. Between the systems, the 3D SB had the best trueness, while AFT and Sat3D obtained superior precision

(18)	Hsu et al	2019	in vitro	Artex-CR articulator (Amann Girrbach, Koblach, Austria), D2000 Dental Lab Desktop Scanner (3Shape, Copenhagen, Denmark), Dental Designer Software (v17.2.1; 3Shape), Fiduciary markers (Grade G25, 1/4" spheres, 0.25" sphericity; BC Precision, Chattanooga, TN)	Mechanical articulator	Average interocclusal separations, sagittal condylar inclination	Trueness and precision of the tested virtual and mechanical articulators were comparable, yet it remains necessary to compare with other articulator systems.
(19)	Solaberrieta et al	2015	in vivo	Panadent axiograph (7600 AP Axi-Path III Recorder; Panadent Corp), Panadent mechanical articulator (1801 AR Model PSH Articulator; Panadent Corp), optical scanner (ATOS Compact Scan 5M; GOM GmbH), Panadent virtual articulator (1801 AR Model PSH Articulator; Panadent Corp)	Mechanical articulator	Deviation of maxillary cast location (measured in mm between reference points)	The digital workflow required less time and provided a deviation that was acceptable for orthodontic use but needed improvement to be accurate enough for use in orthognathic surgery or restoration manufacturing.

(10)	Lin et al	2023	in vivo	Virtual articulator (Artex CR; Amann Girrbach AG, Austria), virtual facebow in CAD software (DentalCAD; exocad GmbH, Germany), optical intraoral scanner (TRIOS; 3Shape A/S, Denmark), optical extraoral scanner (Auto Scan-DS-MIX; Shining 3D, China), facial scanner (Bellus3D Dental Pro; Bellus3D GmbH, USA), 3D scan application for smartphone (Hege 3D scanner; from Apple App Store, developer: Marek Simonik), full-face CBCT scan (i-CAT FLX; DEXIS Dental Imaging Technologies Corporation, USA), kinematic digital facebow (JMAnalyser + ; Zebris Medical GmbH, Germany)	Kinematic facebow	Hinge axis and reference plane deviations between systems	Mounting using a CBCT scan resulted in the lowest hinge axis deviation, and the use of a smartphone based facial scanner can be a suitable radiation-free alternative in simple cases.

(5)	Li et al	2022	technique report	Intraoral scanner (TRIOS 3; 3Shape A/S), CAD software program (exocad; exocad GmbH), open-source 3D software program (Blender, v2.83; The Blender Foundation), 3D printer (SprintRay Pro 95; SprintRay), CBCT scan, 3D scan application for smartphone (Hege 3D scanner; from Apple App Store, developer: Marek Simonik), implant planning software program (BlueSkyPlan v4.70; Blue Sky Bio LLC), 3D facebow (Blender, v2.83),	CBCT scan	Hinge axis, centric relation (CR), vertical dimension of occlusion (VDO)	A fully digital workflow technique is described, showing how to create a virtual patient with reliable CR, VDO, and hinge axis. It is used to bring together the implant and restorative phases in patients that need a complex implant-supported prosthesis.
(3)	Zhao et al	2024	in vivo	Ultrasonic positioning system KaVo ARCUSdigma (KAVO, Leutkirch, Germany), optoelectronic positioning system SDiMatriX (SDiMatriX, Switzerland), optoelectronic positioning Modjaw (Modjaw, France), CBCT scan (Morita, Japan Co, Ltd, Japan), intraoral	CBCT scan	Sagittal condylar inclination (SCI), lateral condylar inclination angle, Bennett angle, Fischer's angle, incisal guide angle	All three systems demonstrated acceptable precision in measuring mandibular trajectory and movement. The precision of the KaVo ARCUSdigma

				scanner (TRIOS, Third Generation Intraoral Scanner, 3Shape, Denmark)			and Modjaw systems were proven satisfactory for prosthodontic use, while the SDiMatriX needs further study.
(15)	Yang et al	2024	technique report	Artex articulator (Artex CR Adjustable; Amann Girrbach, Charlotte, NC), facebow joint support (Joint Support; Amann Girrbach, Charlotte, NC), facebow (Artex Facebow; Amann Girrbach, Charlotte, NC) with a bite fork (Bite Fork; Amann Girrbach, Charlotte, NC) and a transfer table (Transfer Table; Amann Girrbach, Charlotte, NC),industrial scanner (FreeScan UE Pro; Shining 3D, Hangzhou, China), CAD software program (Exocad; exocad GmbH, Darmstadt, Germany),intraoral scanner (TRIOS 3; 3Shape	conventional mounting with mechanical articulator	Alignment of reference points and interlandmark distance discrepancy	This study showcases a digital workflow technique for a chairside virtual facebow transfer using a conventional facebow and an IOS. Using a 3D analysis software program, the accuracy of the technique was proven to be acceptable for clinical use.

				A/S, Copenhagen, Denmark), laboratory scanner (DS-MIX; Shining 3D, Hangzhou, China)			
(8)	Li et al	2022	in vivo	3D scan application for smartphone (Hege 3D scanner; from Apple App Store, developer: Marek Simonik), intraoral scanner (TRIOS Color Pod; 3Shape, Copenhagen, Denmark), open-source 3D computer software (Blender, version 2.80; The Blender Foundation, Amsterdam, Netherlands), CBCT scan (3D Accuitomo 170; J Morita, Kyoto, Japan), desktop scanner (D2000; 3Shape, Copenhagen, Denmark), dental CAD software (Exocad version 2.2; exocad GmbH, Darmstadt, Germany), implant planning software	CBCT scan	Mean deviation (linear and angular) between reference points on virtual facebow records and the CBCT record	High trueness and precision were shown by the smartphone based virtual facebow as compared to CBCT scan data. However, more research is required, and technique can be subject-dependent.

				(Blue Sky Plan; Blue Sky Bio, LLC, Libertyville, IL)			
(9)	D'albis et al	2025	technique report	Intraoral scanner (TRIOS; 3Shape, Copenhagen, Denmark), facial scanning device (iPad Pro 11; Apple Inc., Cupertino, CA, USA), CAD-CAM software (Ceramill mind; AmannGirrbach, Koblach, Austria) with virtual articulator module, Artex facebow (AmannGirrbach, Koblach, Austria)	Conventional mounting with mechanical articulator	Deviation of maxillary cast location (measured in mm between reference points)	The proposed technique showed clinically acceptable accuracy and trueness, as well as increased patient comfort, while avoiding the need for exposing the patient to CBCT radiation.
(6)	Feng et al	2023	technique report	Intraoral scanner (TRIOS 3, 3Shape, Copenhagen, Denmark), 3D facial scanner (Bellus3D ARC System, Bellus3D, California, America), jaw motion tracer (MODJAW, MODJAW, France), CBCT scan (Morita, Japan Co,	Conventional CR and OVD determination techniques	Centric relation (CR) and vertical dimension of occlusion (OVD), maxillomandibular relationship	The proposed technique highlights the use of a CBCT, combined with an intra- and extraoral scan and jaw motion tracking to create

				Ltd, Japan), dental CAD software (Exocad, exocad GmbH, Darmstadt, Germany),			a 4D virtual patient with reliable and repeatable CR, OVD, and maxillomandibular relationship for prosthetic rehabilitation.
(20)	Qiu et al	2024	case report	Jaw motion tracking system (JMA, Zebris; Isny, Germany), intraoral scanner (TRIOS 3, 3Shape; Copenhagen, Denmark), 3D facial scanner (3D face, Jijia; Shanghai, China), T-scan tool (Tekscan, Inc.; South Boston, MA, USA)	Conventional workflow	Occlusal force distribution of restorations, esthetics, periodontal health	This case report highlights the advantages of a fully digital workflow in a complex, multidisciplinary case. It shows that creating a 4D virtual patient can help provide a holistic approach that is comfortable for the patient and produces satisfactory esthetic and functional restorations.

(21)	Cristache et al	2024	case series and proof of concept	intraoral scanner (Carestream Dental LLC, Atlanta, GA, USA), CBCT scan (NewTom Cefla S.C., Imola, Italy), facial scanner (Bellus3D Inc., Campbell, CA, USA), R2GateTM software, version 2.0.0 (MegaGen, Daegu, Republic of Korea), EXOCAD version 3.1 Rijeka (Exocad GmbH, Darmstadt, Germany), Artex articulator (Amann Girrbach, Austria)	Conventional workflow	Hinge axis position, centric relation (CR), intercuspal position (ICP), vertical dimension of occlusion (OVD), mean deviation between planned and actual implant positions	This report describes four cases of failing maxillary dentition treated with a fully digital workflow. Using stackable surgical templates, virtual patient planning, and guided implant placement, the approach enabled immediate full-arch rehabilitation with successful, predictable outcomes.
(11)	Chou et al	2023	methodological study	SIEMENS Emotion 6 CBCT scan (Pittsburgh, PA, USA), color facial 3D scan (RayFace by Ray Inc., Gyeonggi-do, Korea), dual-marker optical tracking system, mathematical model	Conventional workflow	Accuracy of simulated condylar trajectories compared to real tracked trajectories, error quantified	In this study, a mathematical model was developed to create a personalized virtual articulator from CBCT data and optical jaw

	using Fréchet distance between simulated and measured condylar paths.	motion tracking, which can be used for programmable jaw motion and occlusal analysis with high levels of accuracy and reproducibility.

5. DISCUSSION

5.1 Overall performance of CA VAs

Putting everything together, the findings of this review show that virtual articulators and their associated systems are becoming increasingly common in dental practices everywhere, with a wide range of techniques and protocols being described. Across the included studies, there is evidence that CA VAs consistently provide equal or superior performance compared to MAs, especially when it comes to accuracy, workflow efficiency, and reproducibility. For example, Hsu et al. concluded that virtual and mechanical articulators showed comparable trueness and precision but emphasized the need for further comparison across systems. (18) Solaberrieta et al. observed that digital workflows produced acceptable accuracy but still needed refinement for complex surgical cases. (19) It is, however, important to note that the differences observed were heavily reliant on the systems employed, the technique used, and operator training. Additionally, the improvements across all categories are not attributed solely to the articulators themselves, but to the correct integration of complementary systems, such as CBCTs, scanners, and jaw motion tracking.

5.2 The role of CBCT in digital workflows

Across the literature, it has been observed repeatedly that CBCT data has a critical role in establishing hinge axis location and maxillomandibular relationships. Hence, several studies identified the CBCT scan as the most reliable gold standard. (3,5,8,15) Lin et al. concluded that CBCT-based mounting produced the lowest hinge axis deviation of all tested methods. (10) Li et al. concluded that CBCT allowed reliable reconstruction of CR, VDO, and hinge axis in complex implant cases. (5) This therefore supports the idea that in complex rehabilitation cases, with high accuracy requirements, the integration of the CBCT scan in the workflow can vastly improve clinical outcomes. It has proven that by using the CBCT scan, the practitioner can create a virtual patient that more reliably resembles the patient's TMJ and other anatomical features.

On the other hand, the literature also highlights some limitations of the CBCT scan. Namely, it can be concluded that the digital workflows must be indication-driven, not applied universally, considering factors such as radiation exposure, cost, and accessibility. Because of such factors, the use of the CBCT scan should be limited to more complex cases, with the need to justify its use, weighing the potential downsides against the value that it brings to the workflow. It follows that the approach must include ethical and clinical considerations, limiting the use of CBCT scans to cases where their use is paramount (such as complex implant cases, or TMJ disorder cases), and relying on other, more appropriate methods, for simpler prosthodontic cases.

5.3 Jaw motion tracking systems

Across the included studies, the use of jaw motion tracking systems (such as ModJaw, ARCUSDigma, and JMA) is also discussed, showing them to be exceptionally useful tools in the creation of a virtual patient. They are shown to be particularly advantageous in contrast with MAs due to their ability to record patient-specific data in real time, thus recreating the patient's dynamic, functional occlusion by capturing their precise maxillomandibular dynamics. Several studies (3,12) suggested that these systems achieve clinically acceptable precision, with slight differences in their ability to measure

specific parameters (such as the Bennett angle). A key takeaway from the literature is that jaw motion tracking systems improve overall patient comfort, and clinical efficiency (to varying degrees) but are very sensitive to the operator's training and familiarity with the system. (17) The integration of such systems is shown to be a significant advancement in digital dentistry, allowing the clinician to carry out an exceptionally individualized treatment. The use of jaw motion trackers allows operators to analyze each case in more depth, proving to be particularly useful in the diagnosis of deviations or asymmetries in patients' dynamic occlusion. There are discrepancies between systems, however, and operators need to be aware of the limitations and strengths of the system they are going to use. By comparing studies, it can be shown that certain systems perform better with certain parameters, while others struggle. For example, Gu et al. found that the JMA system offered superior comfort and ease of use compared to CADIAX, and Zhao et al. reported that while ModJaw and ARCUSdigma performed well in measuring sagittal condylar inclination, the SDiMatriX system required further validation. Clinicians should take such differences into account when considering the integration of a jaw motion tracker into their practice, by analyzing their needs and their patients' needs.

5.4 Facial scanners and smartphone-based alternatives

Another component of digital workflows that is addressed often in the literature is the facial scanner. Throughout the studies, different authors (such as Li et al., Yang, D'Albis et al.) discuss the use of smartphone-based facial scanners and compare them to industrial ones.(7–9) They highlight various techniques through which smartphones can be used to record facial scans with surprisingly high precision and trueness, for a significantly lower cost. This can be revolutionary, as it lowers the entry barrier for a wide range of clinicians, making it easier to adopt a digital workflow, while at the same time reducing reliance on radiation-based imagery. Naturally, smartphone-based scanners also come with their set of limitations. Notably, while they show promise in simpler, more straightforward cases, they have yet to prove suitable as replacements for CBCT scans or high-end industrial scanners in complex rehabilitation cases. That is

mainly because smartphone-based scanners do not have the same properties as industrial scanners, and tend to be operator dependent, with high technique sensitivity. (8) For example, Yang found no significant difference in trueness, but industrial scanners did show superior precision compared to smartphone-based scanners. (7)

What is also noteworthy is the development of smartphone-based virtual articulators. Techniques are described for the use of smartphone-based systems for maxillary cast mounting for a lower cost, as well as radiation free. This further supports the idea that digital dentistry is becoming more available to smaller clinics that are more limited in resources. However, just like smartphone-based facial scanning systems, smartphone-based articulators are highly dependent on operator technique, as well as lighting conditions and other subject-specific factors. It can therefore be inferred that smartphone-based systems are a promising solution to making digital dentistry more affordable and accessible but require more research for increased reliability and standardized protocols.

5.5 Clinical implications

There are, of course, several clinical implications that can be derived from the review of the selected literature. An observed trend in the studies that were chosen is that most of the authors largely agree that CA VAs do not just serve the purpose of replicating the functions of the MA. They expand them and further develop digital workflows that reshape the diagnosis and treatment planning process, allowing for the utmost individualization for each patient.

One such observable improvement is that of occlusal accuracy, and therefore restorative outcomes. Yuan et al. showed how restorations designed with the use of a virtual articulator presented a more predictable and stable occlusal contact, with fewer dynamic interferences compared to restorations designed with a mechanical articulator. (16) This is a significant finding, as occlusion is a fundamental concept by which the success or failure of a treatment can be determined. Most importantly, being able to more reliably predict the quality of an occlusal contact reduces the need of intraoral adjustments

secondary to placing. This translates into a reduction in chair time, as well as increased patient comfort. Both are factors by which clinical efficiency is improved.

Secondly, another improvement is that of increased diagnostic capabilities. Gu et al. showed that ultrasonic jaw tracking systems could reliably record condylar paths, which enables clinicians to identify deviations that may not be apparent in static records obtained with mechanical articulators. This is a major advancement in functional diagnostics, leading to earlier detection and more targeted treatment planning. (12) The dynamic reproduction of the patient's information can be of utmost importance in the successful diagnosis and therefore treatment of TMJ disorders, functional asymmetries, and parafunctional habits such as bruxism. For example, Chou et al. also concluded that their mathematical model combining CBCT and optical tracking produced highly accurate simulated condylar trajectories, suitable for occlusal analysis. (11)

Thirdly, the effect of CA VAs has shown to be most prominent in the management of complex cases, such as full mouth implant rehabilitation. Cristache et al. suggested that virtual patient planning enabled predictable full-arch rehabilitation with accurate implant placement. (21) In complex cases, the location and correct reproduction of the hinge axis is also of utmost importance, as it is susceptible to the accumulation of small errors. Lin et al. provide evidence that designing a digital workflow based on CBCT scan data is the most reliable way to ensure the accuracy of the virtual patient. This further allows for a reliable prediction of functional behavior under load, improved implant position relative to occlusal forces, and a correct simulation of esthetic outcomes. Due to all these benefits, it follows that the long-term prognosis of the treatment is improved. (10)

One of the other comparisons discussed between CA VAs and MAs across the studies is that of chairside time reduction. By employing a digital workflow, the multiple trial fittings and remounts that are associated with MAs can be avoided. In turn, we reduce the time the patient spends in the chair, which also translates to increased satisfaction and comfort. This is indirectly supported by Yuan et al., who reported fewer dynamic interferences, which can be logically taken to result in fewer adjustments. (16)

Solaberrieta et al. also back up this conclusion, having found that maxillary cast mounting time was reduced by using digital workflows. (19)

Another way in which time is saved, and efficiency is increased by using digital workflows is found in the simplification of communication with dental laboratories. Physical impressions, facebow settings and transfers are prone to distortion or transport damage due to mishandling. Digital files, on the other hand, have no such limitations, and have the benefit of being able to be sent and received instantly. Hence, it follows that there would be lower discrepancy between the planned and final restorations, and as such, occlusal contacts would be more predictable.

One other key feature that is also shown to be improved by the implementation of digital workflows is that of patient comfort. While traditional facebows can be uncomfortable and time consuming, several studies, such as Li et al. and D'Albis et al. show more patient-friendly options such as smartphone-based scanners to be valid ways of mitigating such issues. (8,9)

5.6 Limitations in the integration of digital workflows

Naturally, despite all the advantages shown by these VAs and their associated systems, their integration into clinical practice is not free of limitations. In addition to understanding their benefits, it is important that clinicians also understand these limitations before incorporating these systems into their workflows.

The first notable limitation is that of the high initial cost that is associated to these systems. Particularly for smaller or newly established clinics, it is not always feasible to invest in scanners, CBCT imaging equipment, jaw motion tracking devices, highly advances software or computers. All these systems come with high initial costs that can be prohibitive for clinicians more limited in resources. Not only that, but there can also be associated costs such as subscriptions and maintenance which need to be considered. Additionally, they do not provide an immediate return on investment, so while they may prove to minimize costs in the long term by improving efficiency, they cannot always be justified, particularly in clinics with a low volume of prosthodontic or complex rehabilitation cases. (2,9)

Furthermore, some authors also mention the limitation of operator dependency and steep learning curve. Revilla-Leon et al. provide evidence to suggest operator technique and familiarity with the system significantly influences the accuracy of the result. This can come from errors in scanning, data integration, software navigation, or interpretation of dynamic movement data, and can lead to clinically significant inaccuracies. The learning curve also applies to technicians, who will have to adapt to the virtual articulator software, protocols, and design principles. This limitation can also be tied back to the financial aspect mentioned, as the exhaustive training necessary for clinicians and technicians to correctly manipulate these tools can be expensive and time consuming. (17)

Another limitation is the lack of standardization and interoperability of systems. This is because different manufacturers rely on proprietary systems, file formats, and integration protocols. The reason this can be an issue for clinicians is that it either forces them to commit to one "ecosystem", meaning only using systems made by one manufacturer, or find complex workarounds to make different systems work together. First, committing to one ecosystem can be expensive, and may not always be the most suitable option for a particular clinician. Secondly, finding complex ways to work around incompatibilities between systems can increase the risk of error at best, and at worst can simply not be feasible.

One more noteworthy limitation is found in the lack of significant long-term data on clinical outcomes. Many of the studies show that CA VAs possess clinically acceptable accuracy and efficiency, but there is a lack of focus on long-term data. Given that the studies are mainly either in vitro, technique reports, short-term clinical evaluations, or use small sample sizes, it is not possible to evaluate the effect of digital workflow integration on factors such as long-term complication rate reduction or improved long-term TMJ health. It should therefore be noted that until such data is available, clinicians should exercise caution when interpreting claims about the superiority of digital workflows.

Similarly, one factor that makes it difficult to conclusively declare the superiority of digital workflows is the lack of standardization in the literature. Authors analyze

different systems and tools, using different golden standards, variables, or methods. Hence, generalized conclusions cannot be confidently drawn, and more research is required to provide a fuller, more comprehensive understanding to clinicians about how all the different systems compare to each other.

5.7 Considerations for clinical implementation

Finally, it also requires mentioning that clinicians need to exercise judgement when it comes to case selection. While the various systems analyzed have proven to be useful in a wide variety of clinical situations, not all cases benefit from employing a digital workflow. If digital articulation does not provide meaningful and relevant added value to a case, then the associated costs and other limitations cannot be justified.

6. CONCLUSIONS

6.1 Primary objective

The main objective of this paper was the evaluation of the efficiency of completely adjustable virtual articulators and their associated systems, as interpreted through accuracy, trueness, and precision. The secondary objective was determining the impact of these digital workflows on clinical and laboratory practice. It can be affirmed that both objectives have been successfully addressed through the comprehensive review of the literature.

When it comes to efficiency, it can be drawn from the evidence that CA VAs provide equal or increased performance compared to MAs. They allow for the creation of highly individualized "virtual patients" due to their ability to integrate tools like CBCT scan data, jaw motion analyzers, and facial/intraoral scanners. Thanks to this, precise mandibular and occlusal dynamics can be achieved in a way that is not possible with MAs and conventional workflows. The improved determination of hinge axis, condylar trajectory, and occlusal contact patterns have demonstrated to increase reproducibility and control within the treatment planning, which is of particular importance in complex rehabilitation cases.

6.2 Secondary objective

The second objective is achieved, as the research has shown how the benefits of CA VAs and digital workflows extend further than just accuracy. Their ability to streamline the diagnostic and treatment planning process is particularly advantageous, reducing need for repeated adjustments, and enhancing the communication between clinic and laboratory. It is to be emphasized, however, that in the choosing of a digital system, operator training and system-specific limitations must be considered to properly benefit from the mentioned benefits.

6.3 Final key takeaway

Finally, the most important conclusion that can be drawn from this research is that the integration of CA VAs into clinical practice should be guided by case complexity, clinician expertise, and available resources and ethical considerations. When the necessary conditions are met, CA VAs appear to represent a significant advancement in prosthetic dentistry, allowing for precise, individualized, and predictable treatments.

7. SUSTAINABILITY

One relevant aspect of this research has been the focus on the sustainability implications of digital systems. As such, it can be inferred that by reducing the need for plaster models, impression materials, storage space, and eliminating the need for transport between clinics and laboratories, digital workflows reduce waste and environmental impact.

Another advantage, which can be linked to the conclusion and main objective is that of improved efficiency. This, too, results in a positive effect on sustainability. Fewer remakes and adjustments, reduced chair time, and more direct communication with the laboratory minimize consumable use and energy of both professionals and laboratory technicians. In turn, this could lead to an increase in output potential on both sides.

This ties in with economic sustainability, because despite the high initial cost, digital workflows can become cost-efficient over time, yielding a positive return on investment if correctly taken advantage of.

On the other hand, it is necessary to mention that responsible decision making is also a factor. Tools must be used when clinically necessary, and their integration should be tailored to case complexity to avoid unnecessary resource consumption.

In summary, when applied thoughtfully and selectively, digital workflows can support environmental, operational, and economic sustainability.

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